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Estimation of water use for irrigation in Norwegian agriculture

Pilot study for Statistics Norway / Eurostat

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Sammendrag:

Rapporten presenterer modellberegninger av vannbehovet til jordbruksvanning i perioden 1973-2008 for ulike vekstgrupper i fire regioner av Norge. Et detaljert sammendrag på norsk finnes på s. 49-51.

Summary:

The report presents model simulations of irrigation water requirements over the period 1973-2008 for various crops in four regions of Norway. A detailed summary in English is given on pp. 47-49.

Land/Country:	Norway
Fylke/County:	Oppland
Kommune/Municipality:	Østre Toten
Sted/Lokalitet:	Apelsvoll

Godkjent / Approved

Prosjektleder / Project leader

Ragnar Eltun

Hugh Riley

Contents

1. Background and aims

The background for this study is a pilot project that Statistics Norway is running, financed by Eurostat ("Development of models or best approaches for estimation of the volume of water used for irrigation on individual holdings in Norway – by applying georeferenced datasets, Geographical Information Systems (GIS) and coefficients for irrigation requirements", Agreement no. 40701.2008.001-2008.141).

The primary aim of Bioforsk as 'associated third party' in this project is to provide estimates of irrigation water requirements for a range of agricultural crops in regions of Norway in which irrigation is currently practiced. These estimates will be used by Statistics Norway as coefficients for irrigation requirements in the pilot project.

At a more general level, this study provides a basis for evaluating the likely need for irrigation in various regions of Norway, upon which decisions concerning investments in irrigation equipment may be based. It also serves to illustrate both between-year variability in irrigation requirements and whether any long-term trends or changes have occurred in recent years.

Plate I. A typical scene depicting rain-gun irrigation of spring cereals in Eastern Norway

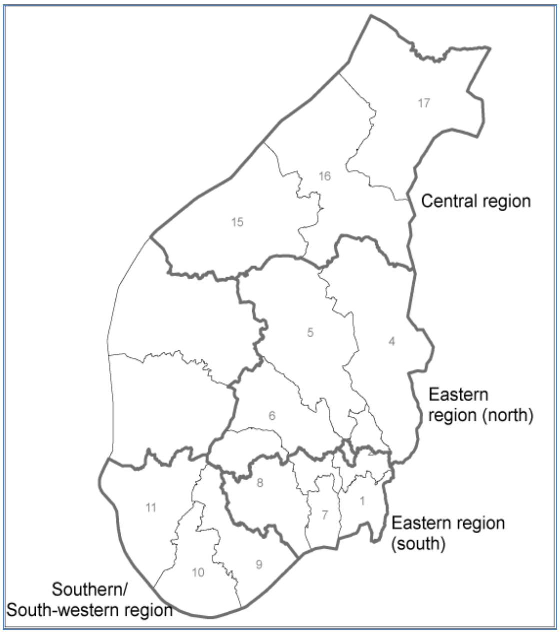
2. Materials and methods

2.1 Selection of irrigation regions

Data from the last full agricultural census in Norway (1999) show that 14% of the country’s agricultural land may be irrigated (ca. 132 000 ha, see Appendix I)). Nearly 50% of this area is in three counties in the northerly part of the Eastern region (Hedmark, Oppland and Akershus) whilst 32% is in four counties in the southerly part of the Eastern region (Østfold, Vestfold, Telemark and Buskerud). About 10% of the irrigated area is in the Southern and South-Western region (Aust-Agder, Vest-Agder, Rogaland), 8% in the Western region (Sogn & Fjordane og Hordaland) and 5% in the Central region (Møre & Romsdal, Sør-Trøndelag, Nord-Trøndelag). The location of these counties is shown in figure 2.1, and the irrigated area in each municipality is shown in figure 2.2.

In this study it was decided to concentrate on the Eastern region, which accounts for over 70% of the irrigated area, and on the Southern, South-Western and Central regions. In this context, Akershus and Buskerud counties are divided between the inland (northerly) and the coastal (southerly) parts of the Eastern region. The division is made between municipalities to the north and to the south of Oslo, respectively. The Southern and South-Western regions are considered as one region.

Irrigation is in all of these regions applied to arable and vegetable crops, for which a suitable water balance model is available. In the Western region (counties 12 and 14), irrigation is mostly used in top-fruit and soft-fruit growing. The requirement for these crops is less easy to estimate. It includes drip/trickle irrigation systems with relatively low water consumption.



Eastern region (north):
2. Akershus (northern part)
4. Hedmark
5. Oppland
6. Buskerud (northern part)

Eastern region (south):
1. Østfold
2. Akershus (southern part)
6. Buskerud (southern part)
7. Vestfold
8. Telemark

Southern/South-Western region:
9. Aust-Agder
10. Vest-Agder
11. Rogaland

Central region:
15. Møre og Romsdal
16. Sør-Trøndelag
17. Nord-Trøndelag

Figure 2.1. Distribution of counties in the irrigation regions used in this study

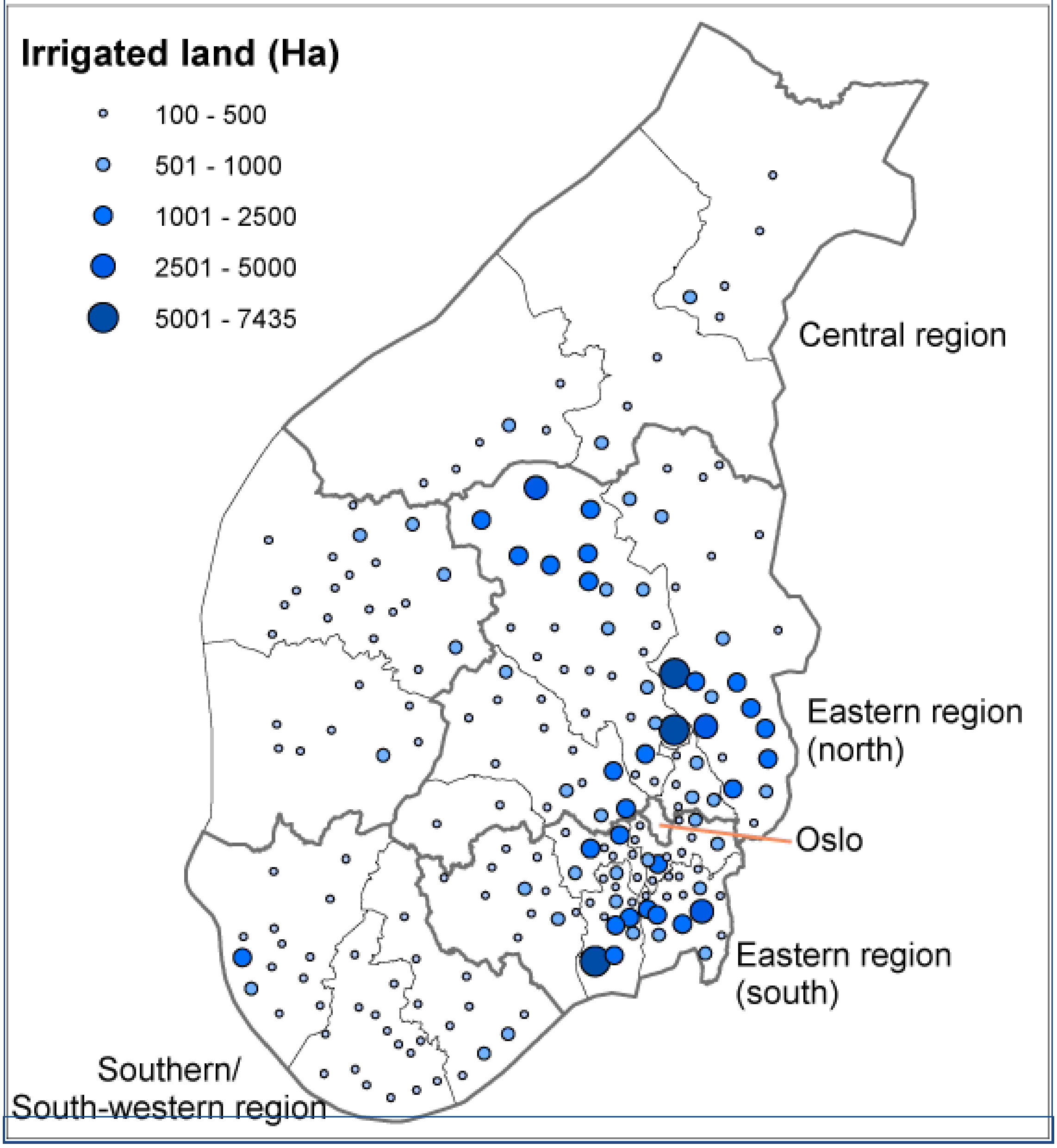


Figure 2.2. Irrigated area in Norwegian municipalities at the 1999 agricultural census (source: Statistics Norway).

2.2 Selection of irrigated crops

No survey data is available on the area of individual crops that are irrigated. In most regions, priority is given to vegetable crops and potato crops. The total vegetable area in Norway is however only about 6 000 ha, or 5% of the total irrigated area. Similarly, whilst potatoes have higher irrigation priority than cereals, their total area is relatively small by comparison (about 15 000 ha potatoes vs. 300 000 ha cereals). Even if the total potato area was irrigated, this accounts for little over 10% of the total irrigated area. Relatively little irrigation of pasture is practiced in Norway, and thus cereals occupy the greatest irrigated area. An exception to this is in the upper part of Gudbrandsdal in Oppland, where irrigation of grassland is common.

2.3 Water balance model

A model that includes water balance calculations and various irrigation strategy options was used in this work (EU-Rotate_N, reference Rahn et al. 2008). The model, originally designed to calculate nitrogen dynamics of arable and vegetable crops, calculates potential evaporation and actual crop evapotranspiration using the FAO approach (Allen et al., 1998). The main parameters that enter into these calculations are those related to the evaporative demand of the atmosphere, summarised by the reference evapotranspiration (ET_0,) and a crop coefficient that varies with crop development. ET_0 may alternatively be input to the model from other sources, for example pan evaporation measured with the Thorsrud 2500 evaporimeter that was previously used in Norway (Hetager & Lystad 1974), or calculated from weather data as described by Riley (2003), using measured pan evaporation as a calibration basis.

2.4 Soil water-holding capacity

Five classes of available soil water capacity have been suggested on the basis of physical properties of common agricultural soils in Norway (Riley, 1994). These range from capacity of 50 mm (extremely drought-prone) to 130 mm (extremely drought-resistant). As it may safely be stated that little irrigation is performed on soils in the latter group, irrigation requirements are calculated here for two levels of soil water retention only, representing the mean of the two drought-prone classes and of the two moderately drought-resistant classes. Available soil water capacities (AWC) within the upper 60 cm of soil were set at 60 mm and 100 mm, respectively (table 2.1). This represents the zone of rooting depth often considered for irrigation purposes. The estimates are based on measurements for a large range of agricultural soils throughout Southern, Eastern and Central Norway (Riley, 1996).

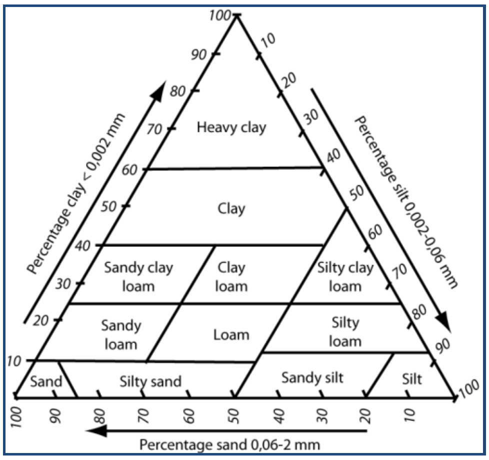
Table 2.1. Soil water retention properties (vol. vol^{-1}) used in irrigation water simulations

Drought sensitivity	Soil depth	Field capacity	Wilting point	Available capacity	Soil textural groups
Drought-prone	> 30 cm < 30 cm	0.15 0.10	0.03 0.02	0.12 0.08	Sand, loamy sand, sandy silt and some loam soils
Drought-resistant	> 30 cm < 30 cm	0.30 0.25	0.10 0.12	0.20 0.13	Loam, clay loam, silt loam and some silty clay loams

These classes of droughtiness are represented by about half of the twelve soil textural groups that are used in Norway (Sveistrup & Njøs, 1984). The textural limits of these groups, together with their equivalent English names, are shown in figure 2.3. Detailed 'theme maps' on soil water-holding capacity are available for most of the agricultural areas mapped by the Norwegian Forest and Landscape Institute. These may be viewed at the following website:

www.skogoglandskap.no/artikler/2008/vannlagringsevne

These maps have four drought sensitivity classes. The AWC values used in this study lie between class 1 and 2 (drought-prone) and between classes 2 and 3 (drought-resistant).



Norwegian name	**English name**
Svært stiv leire	**Heavy clay**
Stiv leire	**Clay**
Siltig mellomleire	**Silty clay loam**
Mellomleire	**Clay loam**
Sandig mellomleire	**Sandy clay loam**
Siltig lettleire	**Silty loam**
Lettleire	**Loam**
Sandig lettleire	**Sandy loam**
Silt	**Silt**
Sandig silt	**Sandy silt**
Siltig sand	**Silty sand**
Sand	**Sand**

Figure 2.3. Norwegian soil textural classification triangle with Norwegian and equivalent English names of the various soil textural classes. Based on Sveistrup and Njøs (1984).

2.5 Regional precipitation

Mean precipitation data for some representative weather stations in various regions are shown in table 2.2. On an annual basis there is wide variation between regions, driest in the inland east, wettest in the west. Within the April-September growing season, however, the differences between regions are smaller, and they are even less in the first part of the growing season, from April to July, when the greatest irrigation demands of many crops are likely to occur.

Table 2.2. Monthly, annual and growing season precipitation sums (mm) for representative weather stations in various regions of Norway. Means of the 25-year period 1973-1998 (Source: Norwegian Meteorological Institute).

Region Weather station	Eastern (north) Kise, Hedmark	Eastern (south) Ås, Akershus	Central Trondheim	South-Western Jæren, Rogaland
January-March	86	142	174	301
April-June	137	150	172	175
July-September	203	242	299	349
October-December	146	238	248	436
Growing season	340	392	471	524
Whole year	570	771	892	1260

A common feature of the precipitation pattern within the growing season is its high annual variability. In the Eastern region, for example, coefficients of variation of 50-60% are common for rainfall in individual months within the growing season, compared to around 20% for the whole season. This means that the irrigation requirement may be much higher in individual years than the mean rainfall data suggest, whilst in other years there may be little or no requirement.

2.6 Regional evaporation

Evaporation has been measured periodically in some regions of Norway using the 'Thorsrud 2500' pan (Hetager & Lystad, 1974), but long-term data are only available in a few cases. The 'Thorsrud 2500' pan evaporimator gives daily values of evaporation from an open water surface placed at the same level as the surrounding area of short-cut grass (figure 2.4). It has been found to give approx. 10-12% lower values than the standard Penman method for calculating potential evaporation from weather data (Riley, 1989). There is also a difference in the seasonal pattern, as the Penman equation appears to indicate higher evaporation values in spring and lower values in autumn, than do the pan measurements. This may be due to the large soil heat flux that occurs in Norway, due to rapid warming in early spring and rapid cooling in autumn. This feature is commonly overlooked in standard applications of the Penman equation, and the pan measurement method may therefore be more realistic under such conditions.

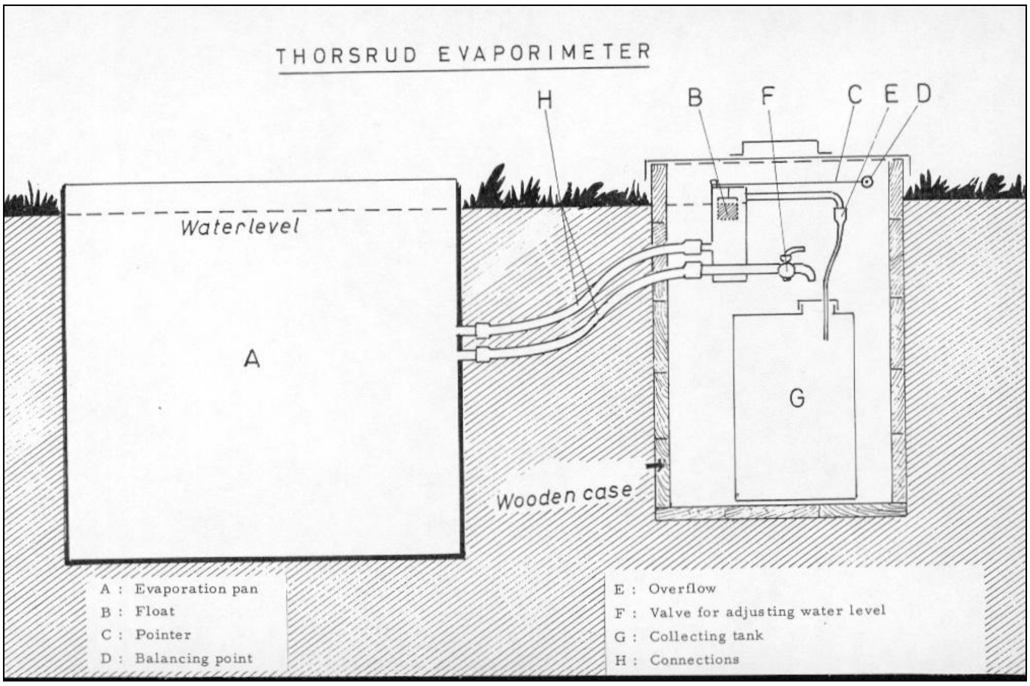


Figure 2.4. The Thorsrud 2500 evaporimeter. Daily evaporation from the container (A) (surface area 0.25 m², depth 0.6 m) is gauged by refilling until the float (B) and pointer (C) reach the balancing point (D). Correction is made by addition of any measured precipitation and by subtraction of any associated overflow (E, F, G).

Mean pan data for some representative locations in various regions are shown in figure 2.5. The evaporation is slightly higher in the southerly, coastal part of the Eastern region (Prestebakke) than in the inland part (Kise), especially early in the growing season, but follows the same general pattern. It is considerably lower in Western (Ullensvang) and Northern regions (Karasjok), due mainly to higher cloudiness and lower incoming radiation. Between-year variation in evaporation is high at all locations, ranging from <2 mm day^{-1} to >4 mm day^{-1} in mid-summer in Eastern Norway, and from ca. 1-3 mm day^{-1} in other regions.

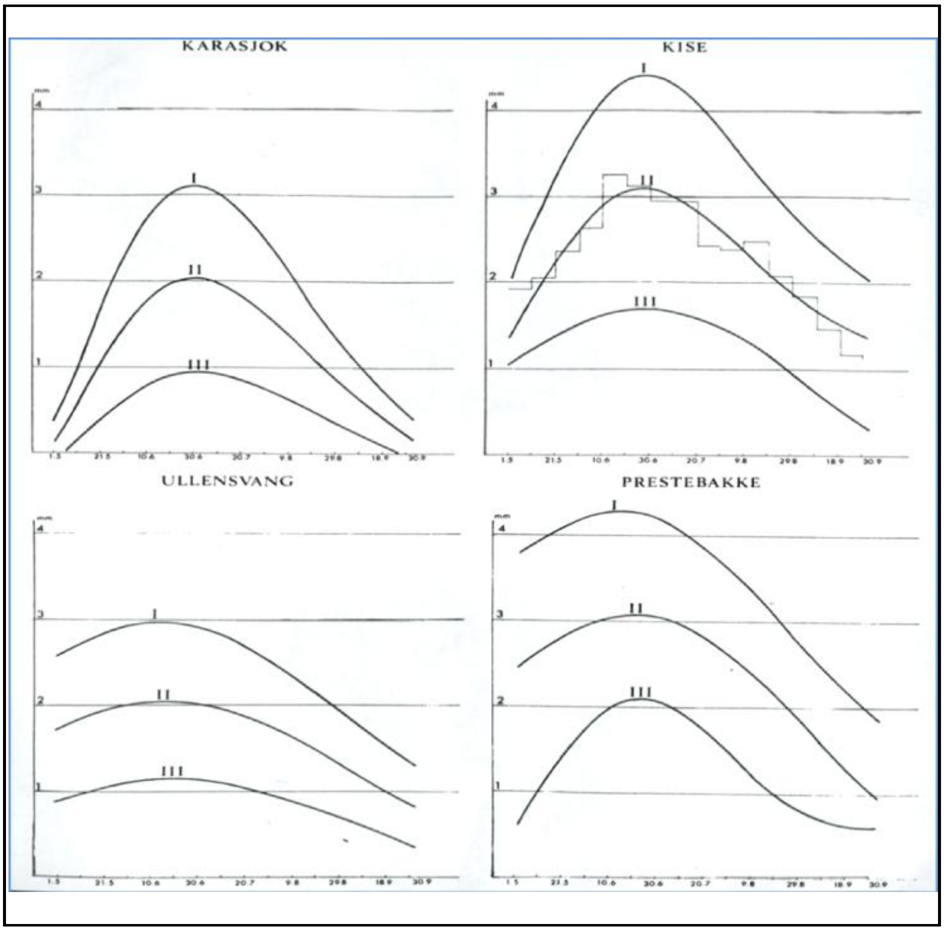


Figure 2.5. Pan evaporation in the growing season (May – Sept.) at representative weather stations in four regions of Norway, based on measurements with a Thorsrud 2500 evaporimeter 1965-1980. (Karasjok = North Norway, Kise = Eastern Norway, northern part, Prestebakke = Eastern Norway, southern part, Ullensvang = Western Norway). I = Maximum curve, II = Mean curve, III = Minimum curve. Taken from Lystad (1981).

2.7 Alternative evaporation estimates

A network of automatic weather stations has been established in agricultural areas since the early 1990's, allowing potential or reference evapotranspiration (ETo) to be calculated, using standard methods such as the Penman equation or the equation included in the EU-Rotate_N model. Alternatively, locally derived equations may be used, such as that of Riley (2003). This equation was calibrated against pan evaporation measured at Kise, Nes på Hedmark, for the period 1987-2003, using the approach used in Sweden by Johansson (1970), in which daily pan evaporation is regressed against an energy term (solar short wave radiation) and a convection/latent heat transfer term (the product of wind-speed and saturated vapour pressure deficit). A seasonal correction factor is also included in the present case (see Appendix II).

A test of the locally derived equation showed good agreement with an independent dataset measured in 2004-2006 at the same location as the original measurements (figure 2.6). The ability of this equation to reflect differences between localities is illustrated using data for 2008 from a number of weather stations (figure 2.7).

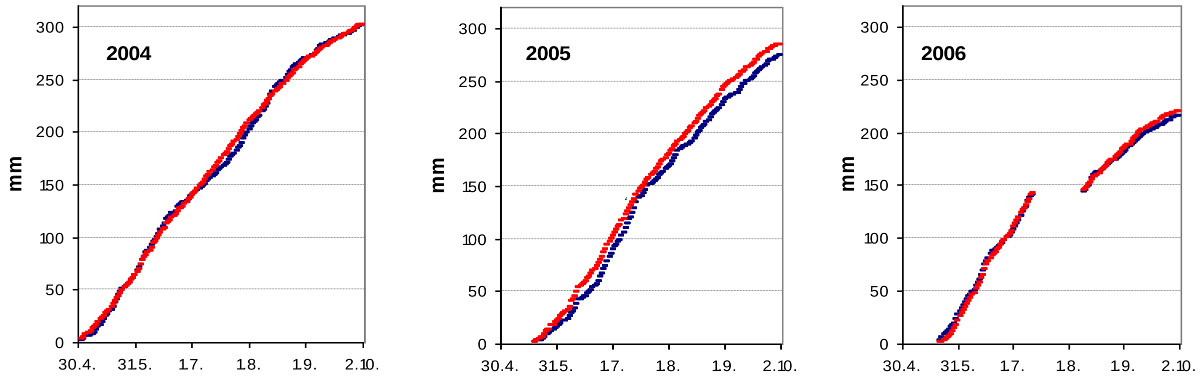


Figure 2.6. Cumulative values of evaporation measured at Nes på Hedmark with a Thorsrud 2500 evaporimeter (blue) and values calculated (red) using the local equation.

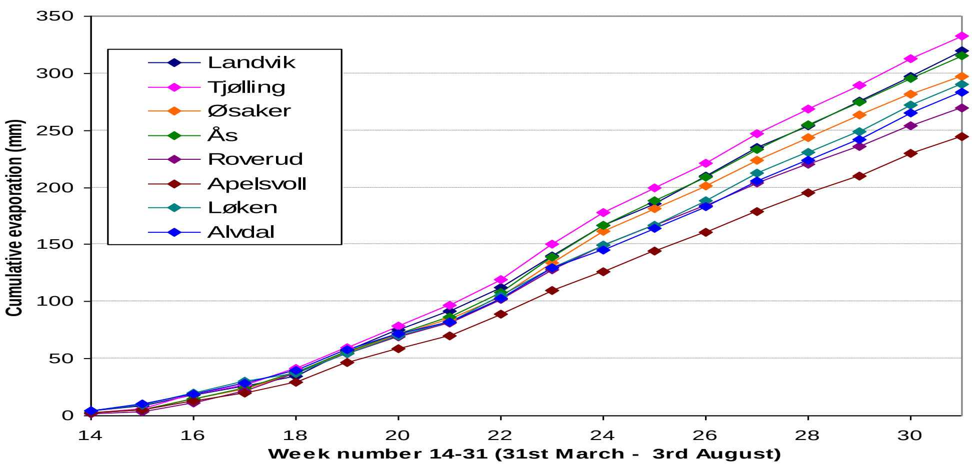


Figure 2.7. Cumulative evaporation values calculated for 2008 using the local equation for a number of Bioforsk's automatic weather stations in Eastern and Southern Norway.

A comparison of the reference evaporation calculated by the method in the EU-Rotate-N model and that using the local equation of Riley (2003) is shown in figure 2.8, for 20 years weather data from Kise (Eastern region). The average annual evaporation sum calculated with the former method was 414 mm, compared to 353 mm with the latter. The average difference of 15% is similar to that found previously between the Penman method and measurements made with the Thorsrud evaporimeter (Riley 1989). The difference between methods varied somewhat between years, ranging from around 25 mm in 1996 to almost 100 mm in 1989 and 1997.

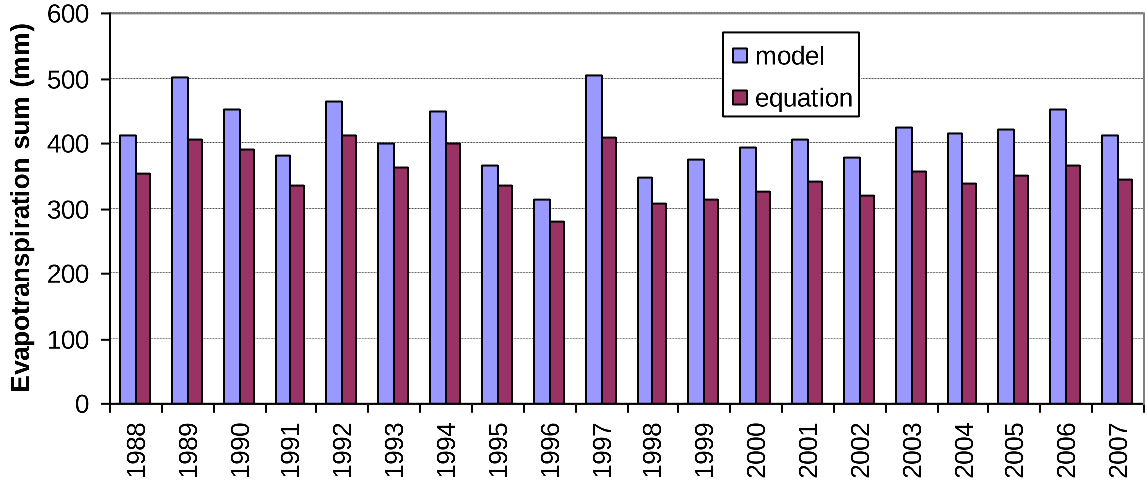


Figure 2.8. Annual sums of reference evapotranspiration at Nes på Hedmark from 1988 to 2007, calculated by the EU-Rotate_N model (blue) and the local equation (red).

No marked seasonal bias was found between the two methods in the present case (figure 2.9). Both predicted a small rise in evaporative demand in late-April/early May. This corresponds with a dry period that normally occurs around seeding. Midsummer values are consistently about 0.5 mm/day lower with the equation than with the model. Autumn values are similar until October, when the equation gives lower values than the model. This falls outside the growing season.

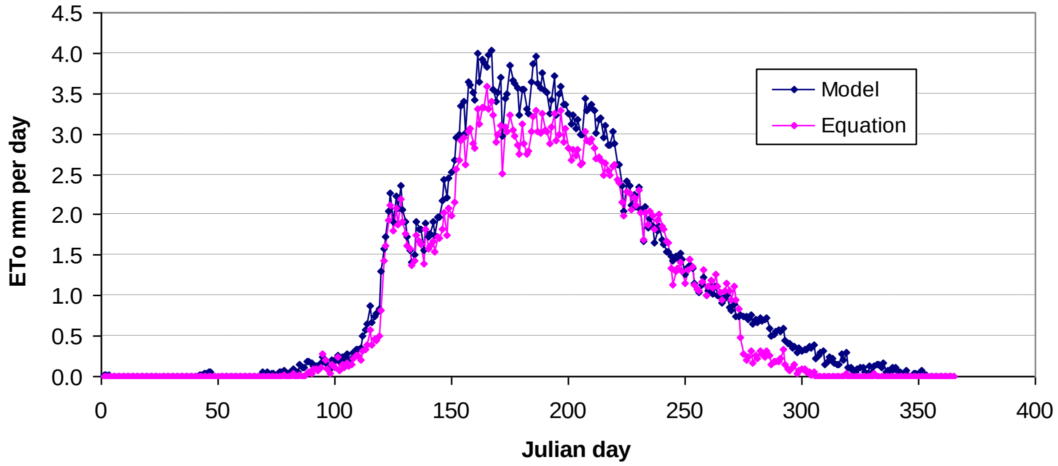


Figure 2.9. Average daily values of reference evapotranspiration at Nes på Hedmark from 1988 to 2007, calculated by the EU-Rotate_N model (blue) and the local equation (red).

2.8 Weather data for selected regions

Weather data from Kise (60°47'N 10°49'E, 128 m a.s.l.) and Ås (59°40'N 10°46'E, 90 m a.s.l.) are used to represent Eastern Norway, (northern and southern parts, respectively). In addition, Særheim (58°46'N 5°39'E, 8 m a.s.l.) and Kvithamar (63°26'N 10°53'E, 28 m a.s.l.) are used for South-Western and Central Norway, respectively. The location of these stations is shown in figure 2.10. One station belongs to the Norwegian University of Life Sciences (Ås) and the others to the Norwegian Institute for Agricultural and Environmental Research (Bioforsk).

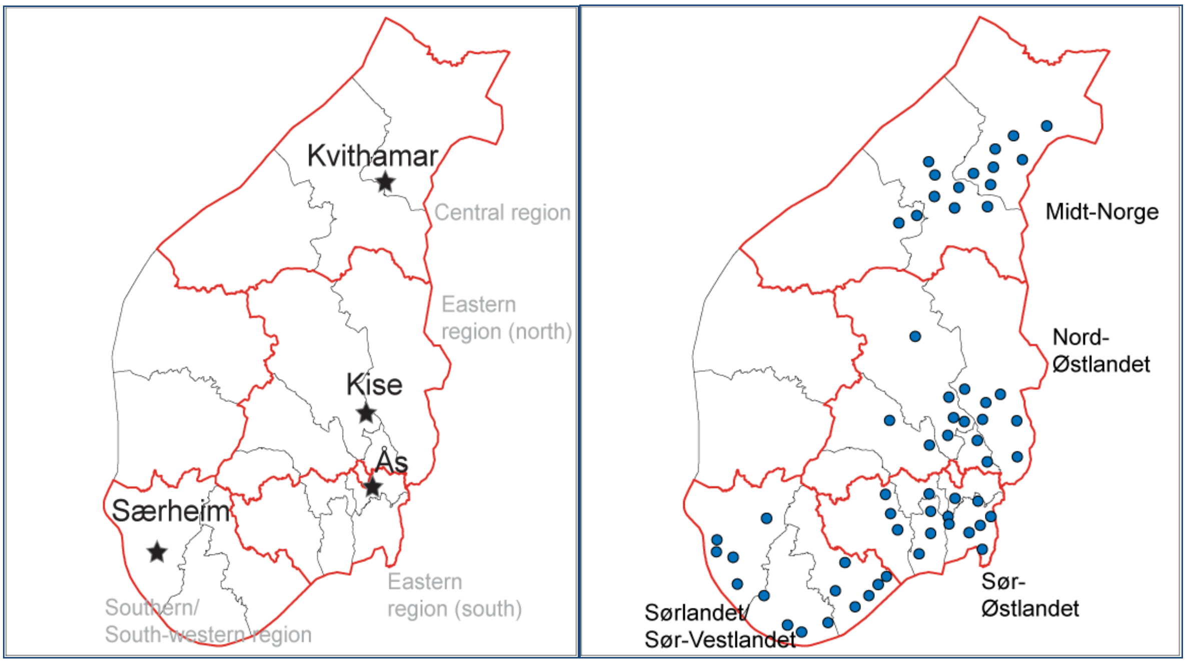


Figure 2.10. The location of the 4 weather stations used in the simulations in this study (left-hand map) and the distribution of the 15 normal precipitation values in each region that were used to evaluate how well the selected stations represent the conditions within regions (right-hand map).

It is generally considered that the evaporative demand in Norway is similar over quite large areas (Lystad, 1981). This is because it is largely governed by climatic factors such as incoming radiation and latent heat transfer, which vary relatively little within regions. Precipitation, on the other hand, is strongly affected by altitude and topography, and may vary considerably within regions.

An assessment of how well the selected weather stations represent average conditions within the four regions was therefore made by comparing the current normal precipitation values (1961-1990) for each station with the mean values for 15 locations within the region concerned (figure 2.10). The latter were selected from official records (Førland, 1993), using data for one location per municipality in the main agricultural parts of the region. The localities were chosen to cover the altitude range within which irrigation is practiced. These data are tabulated in Appendix III. Comparisons of the selected stations with the mean values for 15 localities within each region are shown in figure 2.11.

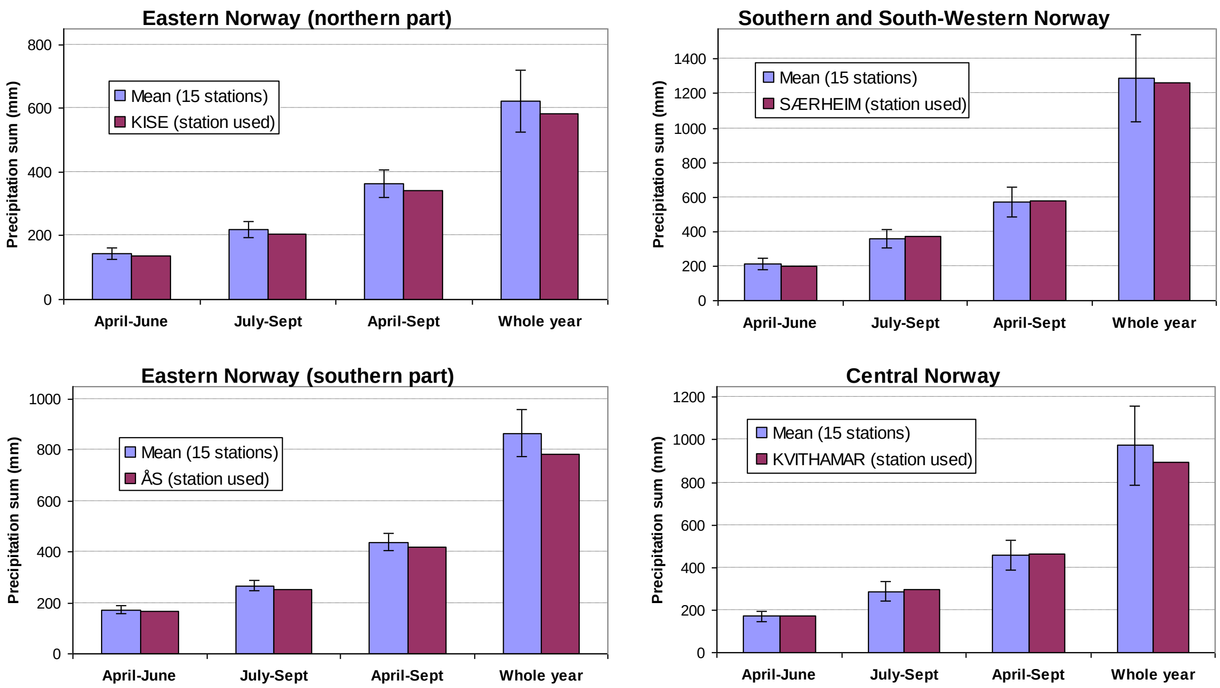


Figure 2.12. Comparisons of normal (1961-1990) precipitation at the 4 weather stations used in the simulations in this study with mean (+/- standard deviation) for 15 locations within each region.

These comparisons show that the normal precipitation of the weather stations selected for the simulation study was in all cases close to the mean value for 15 localities within the region. The coefficients of variation *between localities within the same region* were relatively low within the growing season (8% and 12% in southern and northern parts of the Eastern region, respectively, and 15% elsewhere). The variability between localities for the whole year was somewhat greater (CV = 10-20%), but this has no bearing on the irrigation requirements. Thus it may be concluded that the four selected weather stations were representative for their respective regions.

It was considered important to use long weather data series for the simulations due to the high *between-year variability* in precipitation and evaporation. Data from 1973-2008 are used, thus giving an equal number of years before and after 1990, the year marking the transition from existing to future normal 30-year weather periods. Measured evaporation was used at Kise until 1987, when the weather station was automated. In all other cases evaporation was calculated using the method of Riley (2003). For Særheim and Kvithamar, data from nearby stations were used for the period up to 1987. Wind speed data were adjusted downwards in these cases, due to differences in measurement height and method. Factors of 0.51 and 0.31 were used at Særheim and Kvithamar, respectively. This resulted in similar mean evaporation values for the two periods.

Mean monthly (April-September) data for the variables used in calculating evaporation, together with monthly precipitation and evaporation sums, are given in tables 2.3 - 2.6 for the four regions. Means are calculated for all 36 years and for the first and last 18 years (1973-1990 and 1991-2008). There was relatively little overall difference between these periods in most cases. At the Eastern (northern) location there was for somewhat higher rainfall in May and June in the latter period than in the former period. At the Eastern (southern) location, rainfall was higher in April, June and August in the latter period. In the Central region, it was higher in the latter period than formerly in May and June, and lower in July and August.

In Eastern Norway, overall rainfall for the whole growing season (April-September) is 20% higher at the southern than at the northern location (419 mm vs. 350 mm), whilst the overall reference evaporation is 27% higher (457 mm vs. 360 mm). The former difference reflects closer proximity to the coast at the more southerly location, whist the latter reflects somewhat higher radiation and temperatures, and considerably higher average wind speed. In South-Western Norway, the rainfall sum is higher (551 mm) and evaporation intermediate (383 mm). Much of the extra rainfall comes late in the season here. In Central Norway, the rainfall sum is intermediate (470 mm), but the evaporation sum is lower here than in all the other regions.

A comparison of the average seasonal water balance in the four regions is shown in figure 2.12. There is a clear difference between the Eastern region and the South-Western and Central regions. In the former there is on average a water deficit that increases until July, levels off in August and declines somewhat in September. The average deficit is greatest in the southerly part of the region. In the other regions, there is on average no water deficit, and from August onwards there is a considerable excess of rainfall over evaporation. In relation to irrigation requirements, such average data are less meaningful than the situation that arises in individual years. It is therefore of interest to examine the between-year variability in the water balance.

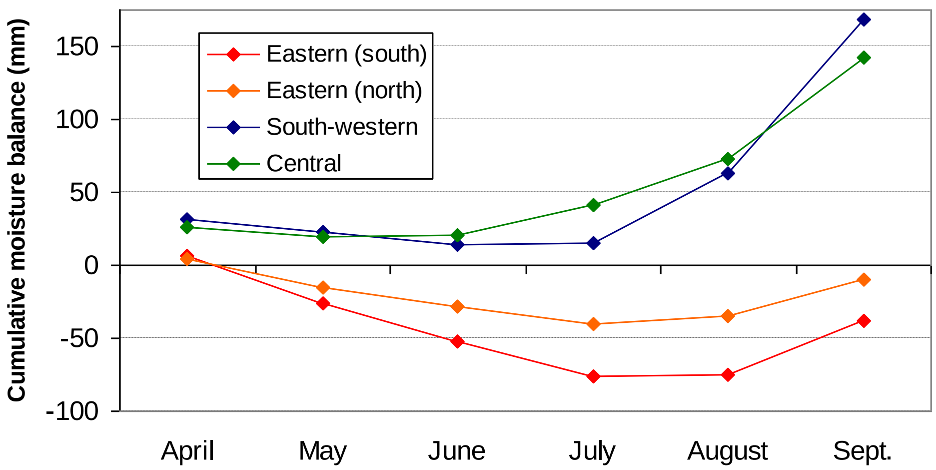


Figure 2.12. Cumulative water balance (sum of precipitation minus reference evaporation) in the four irrigation regions used in this study. Mean data for the period 1973-2008.

The variation in annual potential water balances calculated for spring and early summer (April-June), for mid- and late summer (July-September) and for the whole growing season, is shown in figures 2.13-2.16 for the four regions. These figures clearly illustrate that there is very high between-year variability in the extent of the rainfall deficits and excesses in all regions. They also indicate that deficits are more common in the first half of the season than in the second.

Table 2.3. Weather data used in simulations for the Eastern region (northern part)

	April	May	June	July	August	September
Solar radiation (MJ/m²/day)						
All years	**11.9**	**16.7**	**18.5**	**17.1**	**13.3**	**8.0**
1973-1990	12.0	16.7	18.8	17.3	13.0	7.8
1991-2008	11.7	16.7	18.3	17.0	13.6	8.2
Air temperature (°C)						
All years	**3.2**	**9.1**	**13.5**	**15.9**	**14.7**	**10.2**
1973-1990	2.5	9.1	13.5	15.5	14.2	9.6
1991-2008	3.8	9.1	13.5	16.3	15.3	10.8
Wind speed (m/sec)						
All years	**1.5**	**1.5**	**1.4**	**1.3**	**1.3**	**1.5**
1973-1990	1.7	1.7	1.7	1.6	1.6	1.9
1991-2008	1.3	1.3	1.1	0.9	1.0	1.0
Relative humidity (%)						
All years	**70**	**65**	**66**	**69**	**72**	**75**
1973-1990	68	66	65	67	70	74
1991-2008	71	65	67	71	73	76
Rainfall (mm)						
All years	**33**	**46**	**67**	**69**	**72**	**63**
1973-1990	33	39	62	70	67	68
1991-2008	32	53	72	68	76	57
Pan evaporation (mm)						
All years	**29**	**65**	**80**	**81**	**67**	**38**
1973-1990	31	64	82	84	69	40
1991-2008	28	65	78	78	65	36

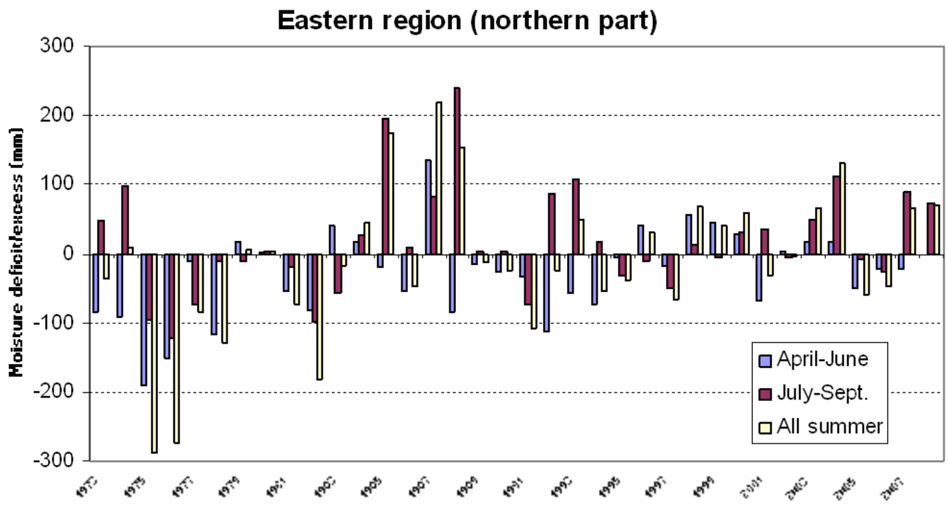


Figure 2.13. Annual water deficit/excess (rainfall minus reference evaporation) for April-June, July-September and the whole growing season in the Eastern region (northern part).

Table 2.4. Weather data used in simulations for the Eastern region (southern part)

	April	May	June	July	August	September
Solar radiation (MJ/m²/day)						
All years	**12.5**	**17.4**	**19.5**	**18.7**	**14.5**	**8.8**
1973-1990	13.2	17.3	20.0	19.1	14.6	8.8
1991-2008	12.5	17.4	19.5	18.7	14.5	8.8
Air temperature (°C)						
All years	**4.6**	**10.6**	**14.4**	**16.4**	**15.3**	**10.8**
1973-1990	4.1	10.7	14.6	16.1	14.9	10.4
1991-2008	5.2	10.5	14.2	16.6	15.8	11.2
Wind speed (m/sec)						
All years	**2.5**	**2.6**	**2.3**	**2.2**	**2.1**	**2.4**
1973-1990	2.3	2.5	2.0	2.0	2.0	2.5
1991-2008	2.7	2.8	2.7	2.3	2.2	2.4
Relative humidity (%)						
All years	**69**	**65**	**67**	**70**	**72**	**77**
1973-1990	64	62	63	65	68	75
1991-2008	74	68	70	74	76	79
Rainfall (mm)						
All years	**44**	**53**	**73**	**79**	**84**	**86**
1973-1990	35	51	68	75	79	90
1991-2008	53	55	77	82	89	82
Pan evaporation (mm)						
All years	**38**	**85**	**99**	**103**	**83**	**49**
1973-1990	38	83	97	104	82	49
1991-2008	38	87	102	103	84	48

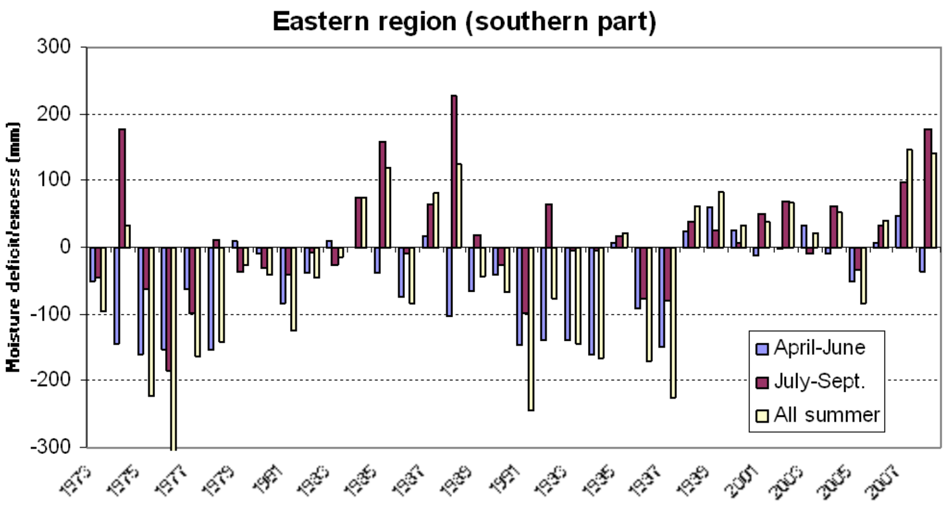


Figure 2.14. Annual water deficit/excess (rainfall minus reference evaporation) for April-June, July-September and the whole growing season in the Eastern region (southern part).

Table 2.5. *Weather data used in simulations for the South-Western region*

	April	May	June	July	August	September
Solar radiation (MJ/m²/day)						
All years	**12.0**	**16.9**	**17.5**	**16.4**	**13.3**	**7.9**
1973-1990	11.5	15.5	16.7	15.4	12.3	7.3
1991-2008	12.5	18.4	18.2	17.4	14.2	8.5
Air temperature (°C)						
All years	**5.9**	**9.7**	**12.3**	**14.4**	**14.6**	**12.0**
1973-1990	5.5	9.9	12.6	14.3	14.3	11.5
1991-2008	6.2	9.5	12.1	14.6	15.0	12.4
Wind speed (m/sec)						
All years	**2.4**	**2.5**	**2.4**	**2.3**	**2.1**	**2.3**
1973-1990	2.4	2.4	2.3	2.4	2.2	2.6
1991-2008	2.4	2.5	2.5	2.2	2.1	2.1
Relative humidity (%)						
All years	**76**	**76**	**80**	**81**	**81**	**80**
1973-1990	76	75	78	79	80	79
1991-2008	76	76	81	83	82	81
Rainfall (mm)						
All years	**66**	**62**	**70**	**84**	**119**	**150**
1973-1990	54	68	63	83	107	164
1991-2008	79	56	77	85	132	136
Pan evaporation (mm)						
All years	**34**	**71**	**79**	**83**	**71**	**45**
1973-1990	34	69	79	86	71	47
1991-2008	35	72	79	81	71	43

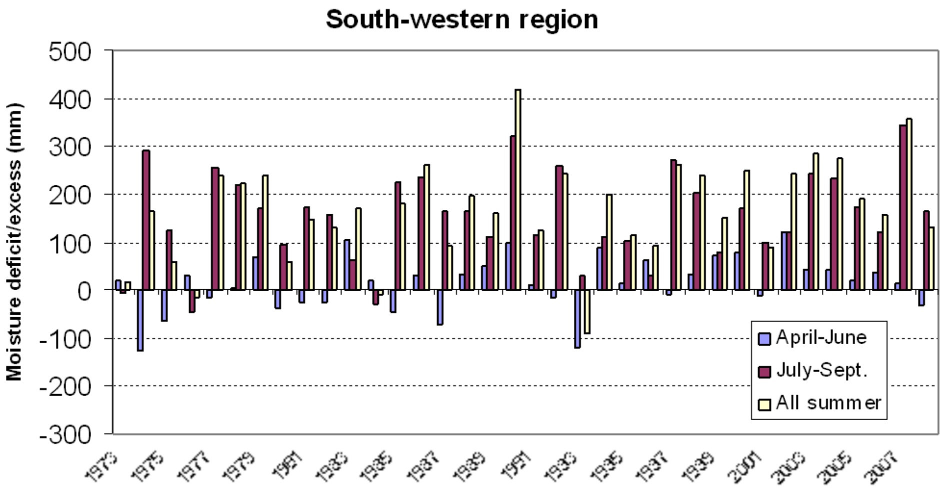


Figure 2.15. Annual water deficit/excess (rainfall minus reference evaporation) for April-June, July-September and the whole growing season in the South-Western region.

Table 2.6. Weather data used in simulations for the Central region

	April	May	June	July	August	September
Solar radiation (MJ/m²/day)						
All years	**10.6**	**15.0**	**15.5**	**14.8**	**11.3**	**6.9**
1973-1990	9.6	14.4	14.9	13.8	10.6	6.3
1991-2008	11.5	15.7	16.2	15.8	12.0	7.4
Air temperature (°C)						
All years	**4.4**	**9.2**	**12.5**	**14.6**	**13.9**	**10.2**
1973-1990	3.8	9.5	12.5	14.1	13.3	9.6
1991-2008	5.0	9.0	12.5	15.0	14.4	10.8
Wind speed (m/sec)						
All years	**1.5**	**1.4**	**1.2**	**1.1**	**1.0**	**1.2**
1973-1990	1.4	1.4	1.3	1.2	1.1	1.3
1991-2008	1.6	1.5	1.2	1.0	1.0	1.1
Relative humidity (%)						
All years	**71**	**69**	**74**	**77**	**78**	**79**
1973-1990	72	68	73	78	79	79
1991-2008	70	70	74	77	78	78
Rainfall (mm)						
All years	**54**	**57**	**72**	**92**	**91**	**104**
1973-1990	56	51	62	110	95	116
1991-2008	53	63	83	75	88	92
Pan evaporation (mm)						
All years	**28**	**63**	**71**	**72**	**59**	**35**
1973-1990	24	60	70	71	58	34
1991-2008	32	65	71	74	61	36

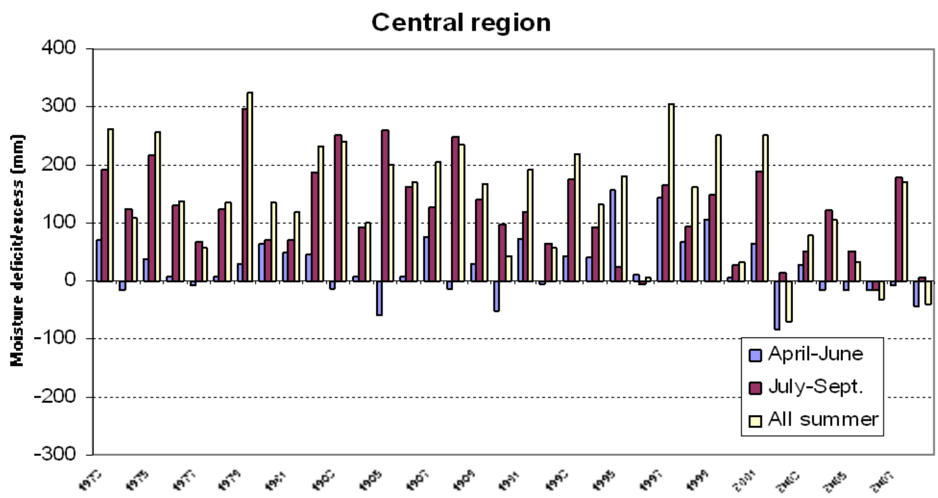


Figure 2.16. Annual water deficit/excess (rainfall minus reference evaporation) for April-June, July-September and the whole growing season in the Central region.

In Eastern Norway, there was severe drought in the mid-late 1970's, in some years during the 1980's and in the early 1990's. The latter was more severe at the southern than at the northern location. In more recent years the incidence of severe deficits has been less marked. For the growing season as a whole, there has been little water deficit (< 25 mm) in almost half of all years (45% and 47% at northern and southern locations). Moderate deficits (25-125 mm) have occurred in 42% and 28% of the years at these two locations, and severe deficits in 14% and 25% of the years, respectively.

In the other regions, there were relatively few years with large rainfall deficits, and hardly any years was there an overall deficit for the whole growing season. There is thus wide variation between years and between regions in the likely need for irrigation water to agricultural crops. Individual crop requirements depend on the distribution of rainfall during the period of growing season at which they are most sensitive to water shortage. Irrigation requirement may therefore arise even in the absence of an overall rainfall deficit.

2.9 Irrigation strategies

The EU-Rotate_N model has several alternatives for the triggering of irrigation events. In the present work, irrigation is triggered when the soil water deficit (i.e. field capacity minus actual content) reaches a certain level. We have considered the deficit within the upper 60 cm of soil, in which the majority of crops roots are found. Two further choices must be made:

How large a deficit may crops tolerate before appreciable yield loss occurs, relative to the available water holding capacity (AWC) of the soil (i.e. the critical deficit)?

How much irrigation water should be applied on each occasion when the critical deficit is reached (i.e. what proportion of the deficit should be replenished)?

Irrigation is normally applied at deficits of between one and two thirds of AWC. Studies of the effects of various irrigation strategies (e.g. Riley, 1989) have shown that little yield loss is incurred before about half of the AWC is depleted. This value is therefore adopted here as the standard, i.e. irrigation is normally applied when the deficit reaches 30 mm on drought-prone soil (AWC=60 mm) and 50 mm on moderately drought-resistant soil (AWC=100 mm).

The amount of irrigation water applied on each occasion will depend on the capacity of the irrigation system, the soil type etc. In practice, less is often applied than that required for the soil to reach field capacity again. This may result in more frequent irrigation requirement, but it also reduces the risk that irrigation water may subsequently be lost to drainage. A value of 50% of the deficit is adopted here as the standard (i.e. 15 mm on drought-prone soil and 25 mm on moderately drought-resistant soil).

The final consideration for irrigation strategy is the length of the period during which individual crops are sensitive to drought. This has been investigated for many crops in numerous field trials at Kise (Riley & Dragland, 1988;1991), and the values chosen here are based on this research (table 2.15).

Table 2.15. Dates used for sowing/planting/harvesting and the dates between which irrigation is performed whenever the soil water deficit reaches 50% of the available water capacity

Crop	Sowing/planting	Irrigation start	Irrigation end	Harvesting
Spring cereals	1st May	25th May	24th July	25th Aug.
Main-crop potatoes	10th May	15th June	25st Aug.	14th Sept.
Early potatoes	10th April	10th May	25th June	1st July
Late vegetables[1]	20th May	1st July	20th Sept.	7th Oct.

[1] Simulations were made for carrots, the vegetable crop with the greatest area in Norway

2.10 Model settings

A description of the way in which the water balance model calculates evaporation from bare soil and actual crop transpiration, based on reference evaporation, is given in Appendix IV.

Two model settings are required for the calculation of the former, the amount of readily evaporable water (REW) and the soil depth (Z) subject to evaporation (e). REW-values of 6 and 9 mm were used in this study for drought-prone and drought-resistant soils, respectively, whilst Ze was set to 0.1 m in both cases. The drainage coefficient was set at 1.0, indicating that rapid free drainage occurs. This assumption is justified for most irrigated soils in Norway.

The model uses a range of crop coefficients with which to estimate actual transpiration from reference evapotranspiration, depending on the likely green crop cover (or leaf area index, LAI) at different stages of growth. The lengths of each period chosen for use in this work, based on previous experience with water balance models, are shown in table 2.16.

Table 2.16. Crop coefficient intervals (days) used in the model to calculate actual transpiration

Crop	Initial (<10% ground cover)	Development (LAI < ca. 3)	Mid-season (LAI > 3)	Late season (senescence)
Spring cereals	15	20	40	30
Main-crop potatoes	25	30	50	20
Early potatoes	20	25	30	5
Late vegetables	30	40	50	20

3. Results of simulations

3.1 Sensitivity analyses

In order to assess the extent to which the choice of reference evaporation (ETo) estimate was likely to affect the calculated irrigation water requirements, a preliminary comparison was made using 20 years weather data from Kise (Eastern region - north), assuming spring wheat crops to be grown each year. This comparison was made using the standard values for irrigation strategy choices 1 and 2 given in section 2.9.

Further sensitivity analyses were performed, using the same weather data set, to assess the effect of alternative values for irrigation strategy Choice 1 (the size of the critical water deficit) and Choice 2 (the proportion of the deficit replenished). In one comparison Choice 1 was varied between 30% and 70% of AWC, whilst maintaining Choice 2 at 50% of the deficit, whilst in another comparison Choice 2 was varied between 30% and 70% of the deficit whilst maintaining Choice 1 at 50% of AWC. These simulations were performed with moderately drought-resistant soil, and with reference ETo calculated using the local equation.

3.1.1 Sensitivity to choice of reference evaporation

The total irrigation amounts and the number of irrigation events calculated by the model using the alternative estimates of reference evaporation are shown for spring wheat in table 3.1. The average number of irrigation events required on drought-prone soils was almost double that required on more drought-resistant soils, whereas the total amounts of water required were only about 12-13% higher. This reflects the fact that drought-prone soils are irrigated more often, but with less water on each occasion. For both soil classes, the average amount of water required and the average number of applications were about 40% higher when calculated with the model reference evaporation than with the equation.

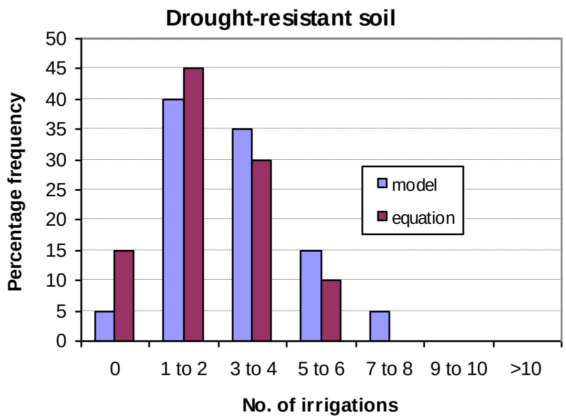
High between-year variability in irrigation requirement is evident from the above calculations. Plots of the frequency distributions for the two classes of soil and the two reference ETo-methods are shown in figure 3.1. The two ETo-methods gave fairly similar distributions on drought-resistant soil, but in the case of drought-prone soil the model ETo gave a much higher frequency of years with extreme irrigation requirement than did the equation ETo. Such frequent irrigation is probably unlikely to be performed in practice, due to limited capacity in terms of both time and equipment. For this reason, the use local equation may be more realistic for the purposes of this study, as it is concerned with estimating likely requirements.

3.1.1 Sensitivity to choice of irrigation strategy

The effects of varying the choice of critical water deficit and the proportion of the deficit replenished at each irrigation event are shown in table 3.2.

Table 3.1. Amounts of irrigation water and the number of irrigations required per year for spring wheat, calculated for moderately drought-resistant and for drought-prone soils, using two estimates of reference evaporation (model used in EU-Rotate_N and local equation of Riley 2003). Weather data from Kise, Nes på Hedmark 1988-2007

	Irrigation amount (mm)				Number of irrigations			
	Drought-resistant		Drought-prone		Drought-resistant		Drought-prone	
Year	Model	Equation	Model	Equation	Model	Equation	Model	Equation
1988	100	75	105	75	4	3	7	5
1989	100	75	105	90	4	3	7	6
1990	75	50	90	60	3	2	6	4
1991	25	25	60	30	1	1	4	2
1992	175	150	165	135	7	6	11	9
1993	100	100	105	90	4	4	7	6
1994	150	125	150	120	6	5	10	8
1995	50	50	60	60	2	2	4	4
1996	25	0	60	45	1	0	4	3
1997	125	75	135	90	5	3	9	6
1998	25	25	30	15	1	1	2	1
1999	0	0	30	15	0	0	2	1
2000	50	25	45	30	2	1	3	2
2001	75	50	75	45	3	2	5	3
2002	25	0	45	30	1	0	3	2
2003	75	25	75	45	3	1	5	3
2004	50	25	75	50	2	1	3	2
2005	100	75	120	75	4	3	8	5
2006	150	100	150	120	6	4	10	8
2007	50	25	45	30	2	1	3	2
Mean	76	54	86	63	3.1	2.2	5.7	4.1
Std. dev.	48	42	42	36	1.9	1.7	2.8	2.4



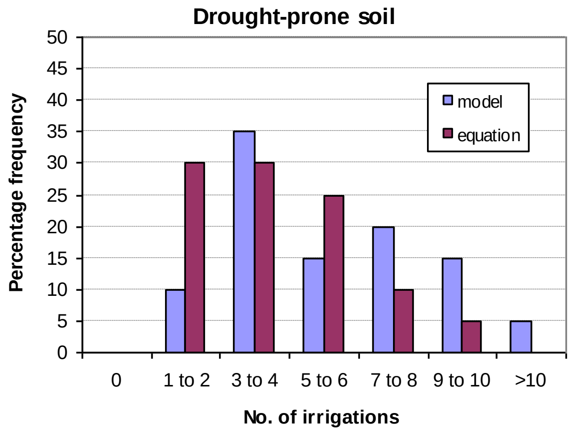


Figure 3.1. Frequency distributions of the number of irrigation events required per year on moderately drought-resistant soil (left) and drought-prone soil (right), using two estimates of reference evaporation (model used in EU-Rotate_N and equation of Riley 2003). Weather data from Kise, Nes på Hedmark 1988-2007.

Table 3.2. Effects of choice of critical moisture deficit and proportion of deficit replenished on the amounts of irrigation water and the number of irrigations required per year for spring wheat, calculated for moderately drought-resistant soil. (Reference evaporation according to the equation of Riley 2003. Weather data from Kise, Nes på Hedmark 1988-2007)

	Comparison of critical deficit (30 : 70 mm)				Comparison of replenishment (15 : 35 mm)			
	Irrig. amount (mm)		No. of irrigations		Irrig. amount (mm)		No. of irrigations	
Year	Def.=30 Irrig.=15	Def.=70 Irrig.=35	Def.=30 Irrig.=15	Def.=70 Irrig.=35	Def.=50 Irrig.=15	Def.=50 Irrig.=35	Def.=50 Irrig.=15	Def.=50 Irrig.=35
1988	90	70	6	2	60	70	4	2
1989	120	70	8	2	75	70	5	2
1990	90	35	6	1	45	70	3	2
1991	75	0	5	0	30	35	2	1
1992	165	105	11	3	135	140	9	4
1993	105	70	7	2	90	105	6	3
1994	150	105	10	3	120	140	8	4
1995	75	35	5	1	30	35	2	1
1996	210	0	14	0	0	0	0	0
1997	105	35	7	1	60	70	4	2
1998	30	0	2	0	15	35	1	1
1999	45	0	3	0	0	0	0	0
2000	45	0	3	0	15	35	1	1
2001	75	35	5	1	30	35	2	1
2002	45	0	3	0	0	0	0	0
2003	30	0	2	0	15	35	1	1
2004	60	0	4	0	15	35	1	1
2005	90	35	6	1	60	70	4	2
2006	135	70	9	2	105	105	7	3
2007	60	0	4	0	30	35	2	1
Mean	90	33	6.0	1.0	47	56	3.1	1.6
Std.dev.	47	37	3.2	1.1	41	42	2.7	1.2

The choice of a low level of critical water deficit (30% of AWC) resulted in very frequent irrigation in some years, and nearly three times the average water requirement indicated when the deficit was allowed to reach 70% of AWC. The latter strategy resulted in no irrigation being applied in almost half the years. Neither of these options appears to be very realistic, and it may be concluded that the choice of a critical water deficit equal to 50% of AWC is a better alternative.

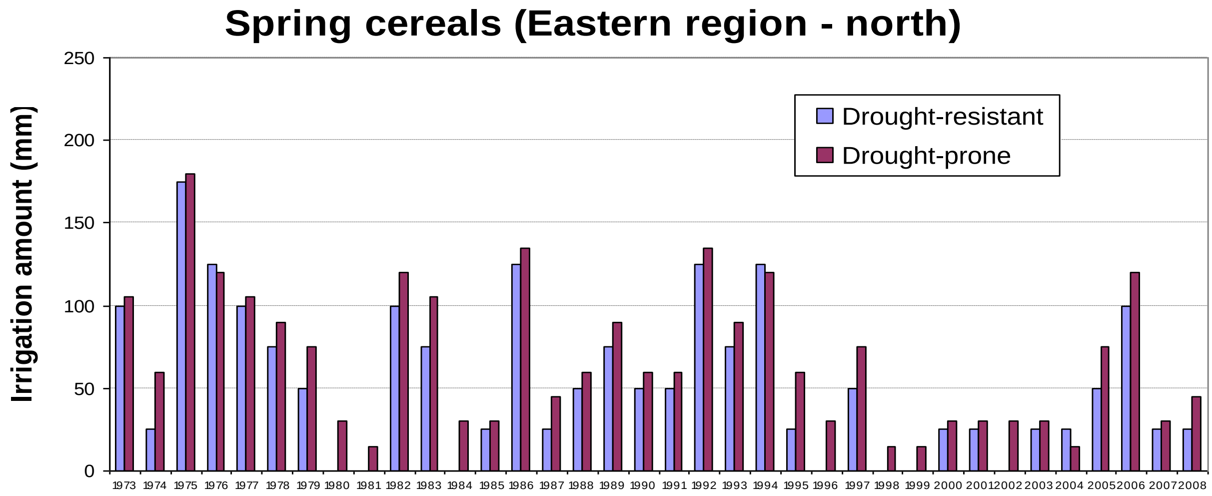
Varying the proportion of the deficit replenished at each time of irrigation naturally had a large effect on the number of irrigation events, but relatively little on the total amount of water used. Replenishing 70% of the deficit gave the same total requirement as replenishing 50% (table 3.1), whilst replenishing only 30% of the deficit gave ca. 15% reduction in the average requirement. The latter strategy gave a very high irrigation frequency in a number of years, which is unlikely to be attainable in practice. The former strategy, on the other hand, in which 70% was replenished on each occasion, gave an irrigation frequency <2 in more than half the years. It may be concluded that replenishing 50% of the deficit on each occasion is a realistic and achievable choice of strategy.

3.2 Simulated irrigation requirement for spring cereals

Irrigation water requirements for cereals are shown in tables 3.3-3.4 and figures 3.2-3.3.

Table 3.3. Irrigation requirement (mm) for spring cereals in Eastern Norway, 1973-2008

	Eastern Norway (northern part)		Eastern Norway (southern part)	
	Drought-resistant	Drought-prone	Drought-resistant	Drought-prone
1973	100	105	100	105
1974	25	60	75	75
1975	175	180	175	180
1976	125	120	175	180
1977	100	105	125	135
1978	75	90	100	135
1979	50	75	75	105
1980	0	30	0	30
1981	0	15	25	45
1982	100	120	50	90
1983	75	105	100	120
1984	0	30	0	30
1985	25	30	25	45
1986	125	135	125	135
1987	25	45	50	60
1988	50	60	75	90
1989	75	90	125	120
1990	50	60	75	75
1991	50	60	125	120
1992	125	135	200	195
1993	75	90	150	150
1994	125	120	250	240
1995	25	60	50	75
1996	0	30	125	120
1997	50	75	150	150
1998	0	15	25	30
1999	0	15	0	30
2000	25	30	25	45
2001	25	30	75	75
2002	0	30	0	30
2003	25	30	25	45
2004	25	15	75	60
2005	50	75	75	105
2006	100	120	100	135
2007	25	30	25	45
2008	25	45	75	105
Mean	**53.5**	**68.3**	**84.0**	**97.5**
Std.dev.	46.0	42.6	60.7	53.0
Max	175	180	250	240
Min	0	15	0	30
Median	50.0	60.0	75.0	97.5



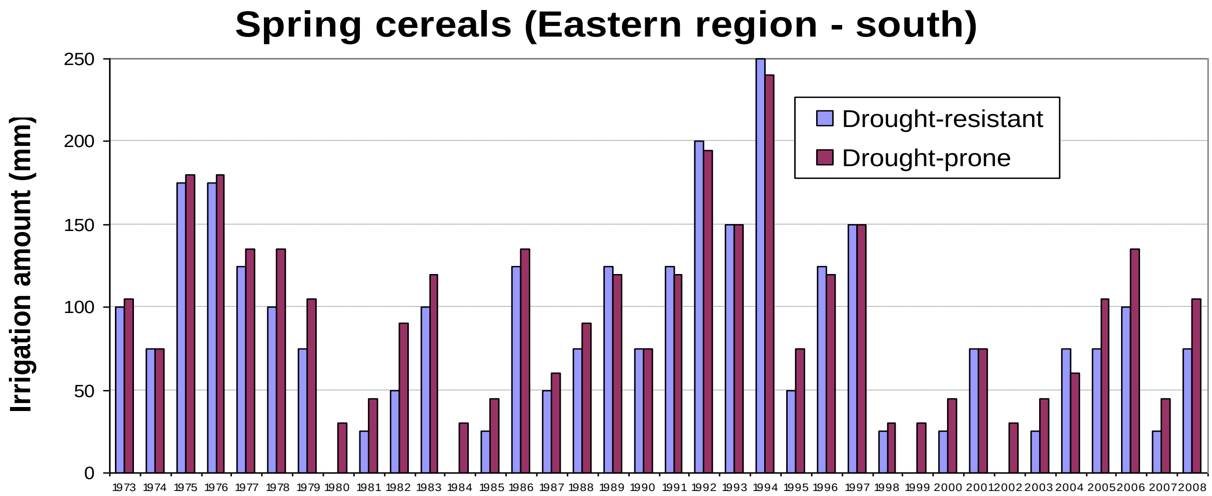


Figure 3.2. Irrigation requirement (mm) for spring cereals in Eastern Norway, 1973-2008.

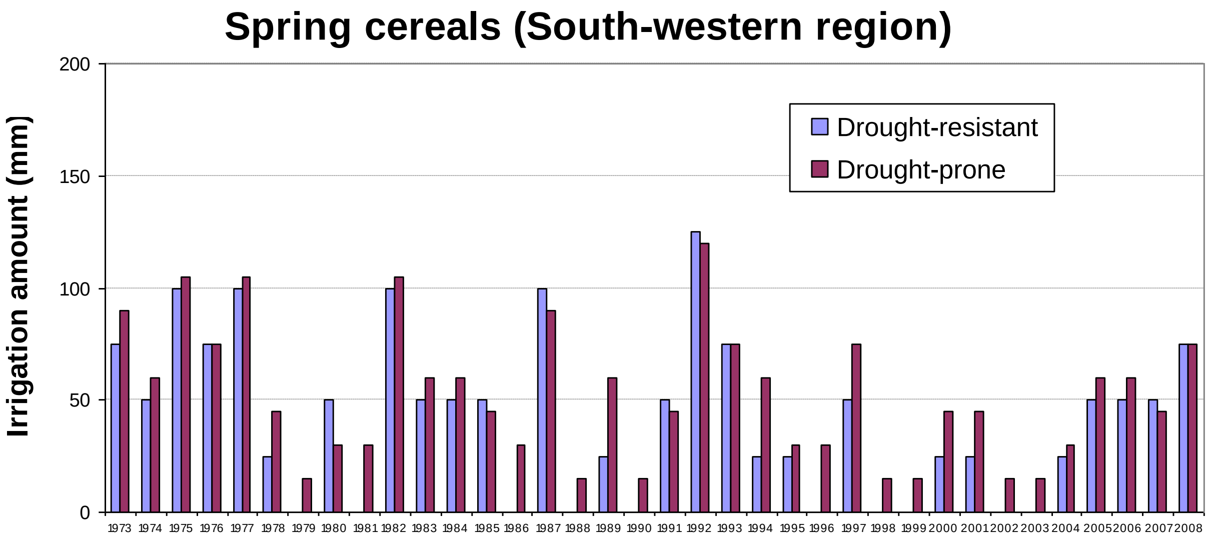
In Eastern Norway, the average irrigation water requirement was 28% higher on drought-prone soils than on more drought-resistant soils at the northern location, and 17% higher at the southern location. The southern location had on average 55% higher requirement on drought-prone soils than at the northern location, and 44% higher requirement on more drought-resistant soils.

The irrigation requirements were lower in the other regions than in Eastern Norway. Relative to the Eastern (southern) location they were on average about half as great in South-Western Norway, and about one third as great in Central Norway.

At all locations, the coefficients of variation between years were extremely high (50-100%). Median requirements were fairly close to the mean requirements. On more drought-resistant soil, the need for a single irrigation or less was indicated in three out of four years in Central Norway, in about half of the years at the Eastern (northern) and South-Western locations and in about one third of the years at the Eastern (southern) location.

Table 3.4. Irrigation requirement (mm) for spring cereals in some other regions, 1973-2008

	South-Western Norway		Central Norway	
	Drought-resistant	Drought-prone	Drought-resistant	Drought-prone
1973	75	90	0	15
1974	50	60	50	60
1975	100	105	25	45
1976	75	75	25	45
1977	100	105	25	45
1978	25	45	25	30
1979	0	15	0	0
1980	50	30	25	45
1981	0	30	0	0
1982	100	105	25	45
1983	50	60	0	15
1984	50	60	25	30
1985	50	45	50	45
1986	0	30	25	30
1987	100	90	25	45
1988	0	15	50	60
1989	25	60	0	30
1990	0	15	75	90
1991	50	45	0	0
1992	125	120	50	60
1993	75	75	0	30
1994	25	60	0	0
1995	25	30	0	15
1996	0	30	0	0
1997	50	75	25	30
1998	0	15	0	0
1999	0	15	0	0
2000	25	45	25	15
2001	25	45	0	15
2002	0	15	75	75
2003	0	15	25	30
2004	25	30	0	30
2005	50	60	50	60
2006	50	60	25	30
2007	50	45	100	120
2008	75	75	25	45
Mean	**41.7**	**40.4**	**23.6**	**34.2**
Std.dev.	35.9	36.4	25.3	27.2
Max	125	125	100	120
Min	0	0	0	0
Median	50.0	37.5	25.0	30.0



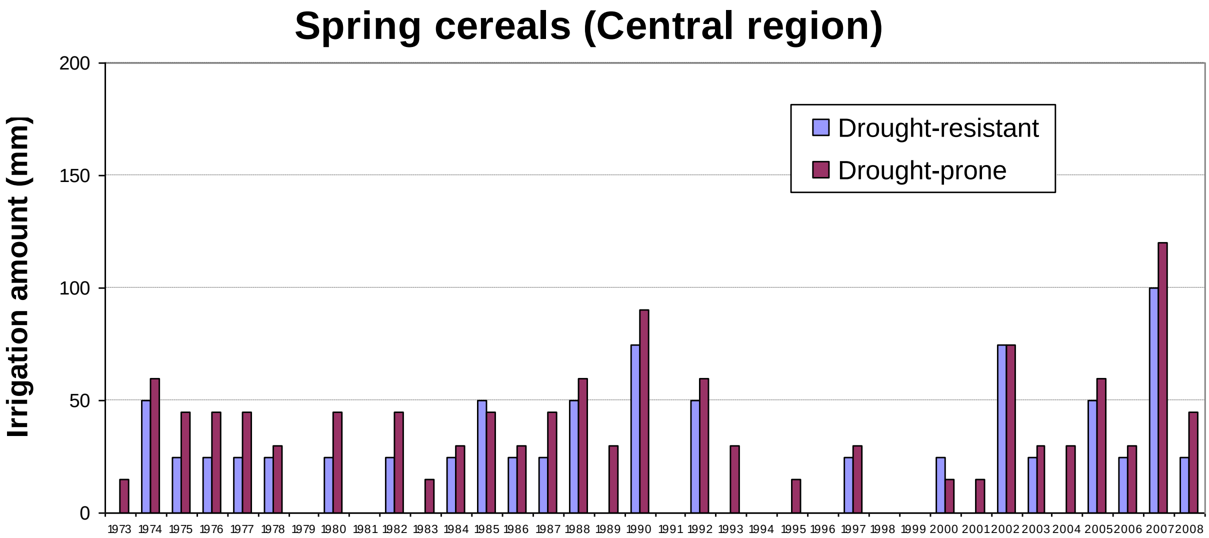


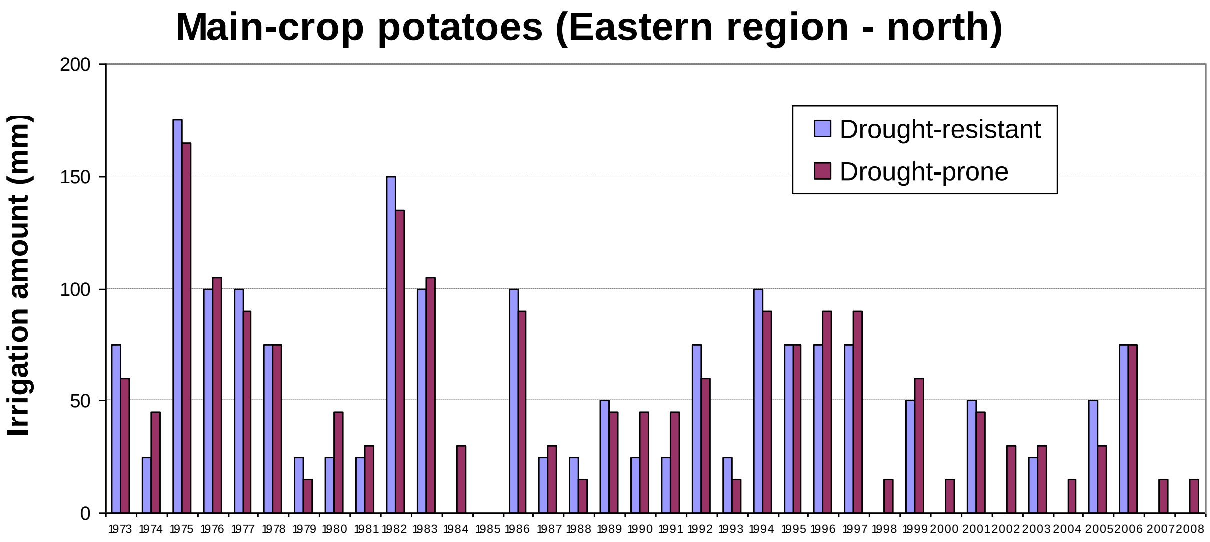
Figure 3.3. Irrigation requirement (mm) for spring cereals in some other regions, 1973-2008.

3.3 Simulated irrigation requirement for potatoes

The amounts of irrigation water required for late (main-crop) potatoes are shown in tables 3.5-3.6 and figures 3.4-3.5.

Table 3.5. Irrigation requirement (mm) for late potatoes in Eastern Norway, 1973-2008

	Eastern Norway (northern region)		Eastern Norway (southern region)	
	Drought-resistant	Drought-prone	Drought-resistant	Drought-prone
1973	75	60	75	75
1974	25	45	100	105
1975	175	165	175	150
1976	100	105	200	195
1977	100	90	125	150
1978	75	75	75	90
1979	25	15	50	60
1980	25	45	50	60
1981	25	30	50	75
1982	150	135	100	105
1983	100	105	125	120
1984	0	30	0	30
1985	0	0	0	30
1986	100	90	75	75
1987	25	30	25	45
1988	25	15	25	45
1989	50	45	100	60
1990	25	45	75	90
1991	25	45	75	90
1992	75	60	125	90
1993	25	15	75	45
1994	100	90	200	180
1995	75	75	75	120
1996	75	90	150	150
1997	75	90	125	120
1998	0	15	25	30
1999	50	60	100	105
2000	0	15	25	45
2001	50	45	50	60
2002	0	30	25	45
2003	25	30	25	45
2004	0	15	25	45
2005	50	30	75	60
2006	75	75	75	90
2007	0	15	0	15
2008	0	15	0	30
Mean	**50.0**	**53.8**	**74.3**	**81.3**
Std.dev.	44.3	38.2	53.9	44.7
Max	175	165	200	195
Min	0	0	0	15
Median	37.5	45.0	75.0	75.0



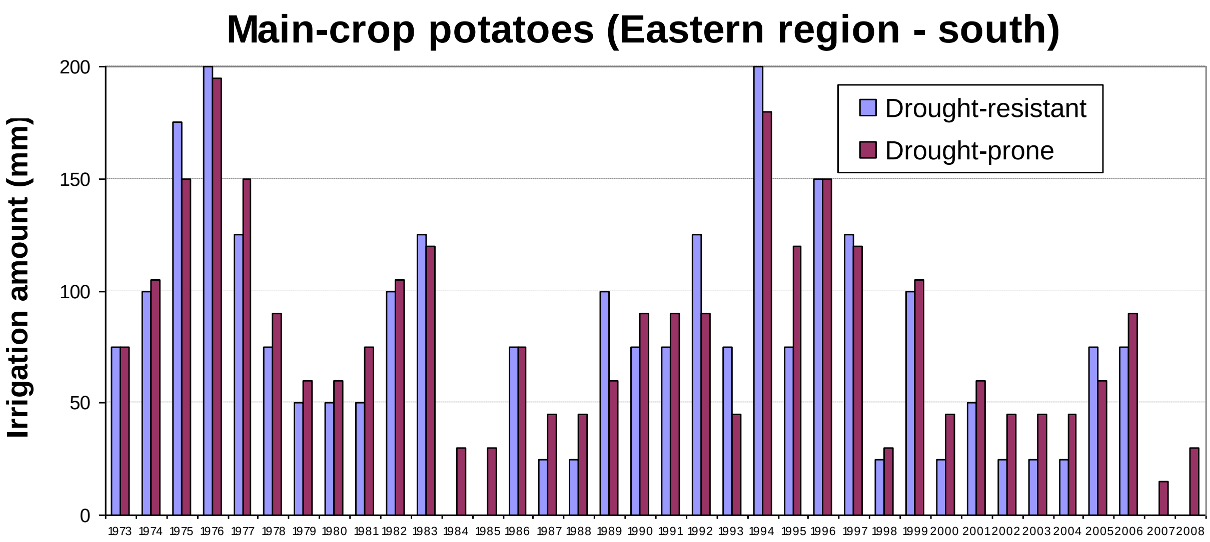


Figure 3.4. Irrigation requirement (mm) for late potatoes in Eastern Norway, 1973-2008.

The irrigation requirement for main-crop potatoes in Eastern Norway was of the same order of magnitude as that for cereals, but the timing of the requirement occurs about 3-4 weeks later in the season. There was less difference between drought-prone and drought-resistant soils for this crop than for cereals, but the difference between the northern and southern location was the same for potatoes as for cereals (about 50% greater at the southern location).

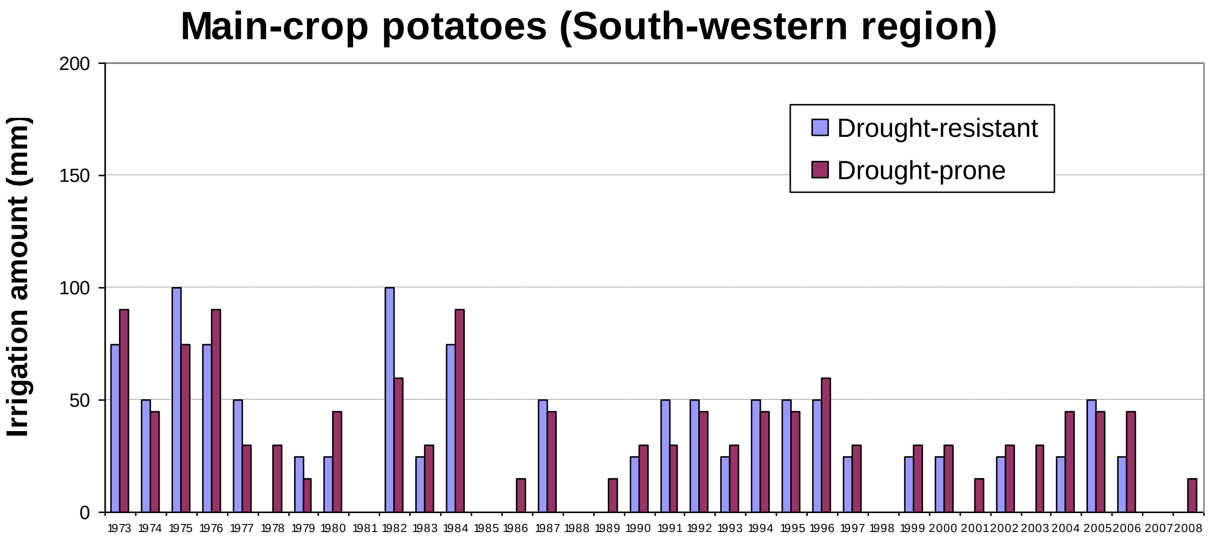
A similar degree of between-year variability in irrigation requirement was found for potatoes as for cereals. In this case the median requirement was somewhat lower than the mean at the northern location but not at the southern location.

The proportion of years with an extremely high irrigation requirement was somewhat lower for potatoes than it was for cereals. This reflects the fact that irrigation of potatoes takes place slightly later in the season, when the incidence of rainfall is often more frequent than earlier.

Table 3.6. Irrigation requirement (mm) for late potatoes in some other regions, 1973-2008

	South-Western Norway		Central Norway	
	Drought-resistant	Drought-prone	Drought-resistant	Drought-prone
1973	75	90	0	0
1974	50	45	25	15
1975	100	75	25	15
1976	75	90	0	15
1977	50	30	0	15
1978	0	30	25	45
1979	25	15	0	15
1980	25	45	50	60
1981	0	0	0	0
1982	100	60	0	15
1983	25	30	0	0
1984	75	90	0	0
1985	0	0	25	0
1986	0	15	0	15
1987	50	45	25	15
1988	0	0	25	15
1989	0	15	0	0
1990	25	30	0	0
1991	50	30	0	15
1992	50	45	0	0
1993	25	30	0	15
1994	50	45	0	30
1995	50	45	0	0
1996	50	60	0	15
1997	25	30	25	45
1998	0	0	0	0
1999	25	30	0	15
2000	25	30	0	15
2001	0	15	0	0
2002	25	30	75	90
2003	0	30	25	45
2004	25	45	50	60
2005	50	45	25	30
2006	25	45	50	45
2007	0	0	50	30
2008	0	15	25	45
Mean	**31.9**	**35.4**	**14.6**	**20.4**
Std.dev.	29.0	24.6	20.2	21.6
Max	100	90	75	90
Min	0	0	0	0
Median	25.0	30.0	0.0	15.0

The irrigation requirement for main-crop potatoes in South-Western and Central Norway was lower than that for cereals, and in both cases considerably lower than that for potatoes in Eastern Norway. The requirements appeared to be somewhat lower in recent years in South-Western Norway, whereas the opposite was the case in Central Norway.



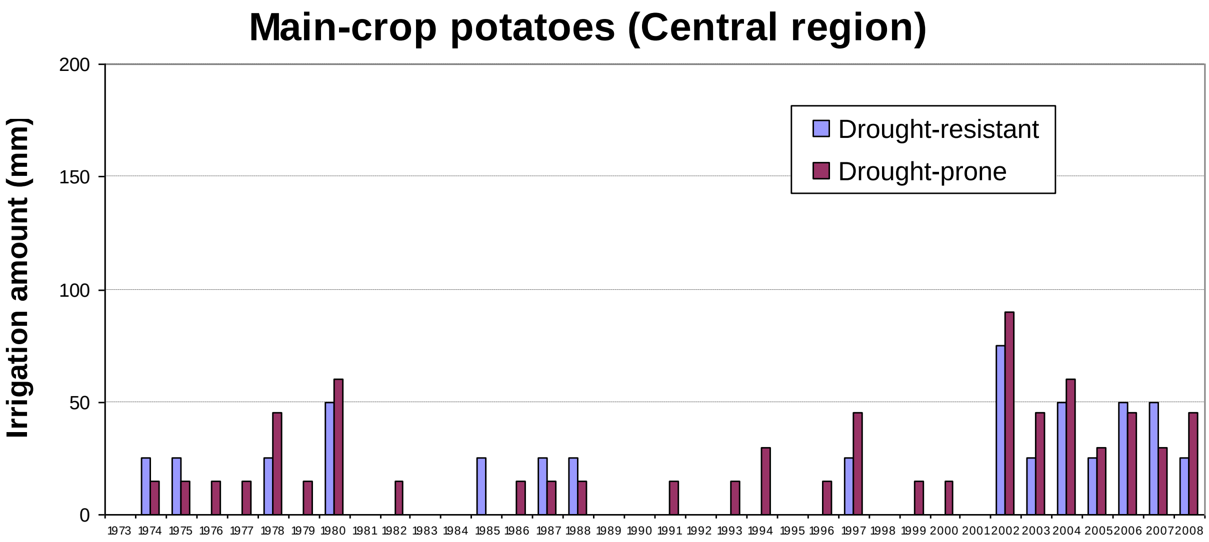


Figure 3.5. Irrigation requirement (mm) for late potatoes in some other regions, 1973-2008.

The amounts of irrigation water required for early potatoes are shown in tables 3.7-3.8 and figures 3.6-3.7. The requirement for this crop was much lower than that for main-crop potatoes, due to their much shorter growing season and because less soil drying has normally occurred by the time they reach a drought-susceptible stage of growth. The very low requirement that was simulated for the Eastern (northern) region has little practical relevance, as early potatoes are not grown in this area. In the more southerly region, the average requirement is only a single irrigation per season, though it is known that many growers practice a much higher intensity. The simulations indicated a requirement of two or more irrigation events per season in only one quarter of the years in this region, and hardly ever in other regions.

Table 3.7. Irrigation requirement (mm) for early potatoes in Eastern Norway, 1973-2008

	Eastern Norway (northern region)		Eastern Norway (southern region)	
	Drought-resistant	Drought-prone	Drought-resistant	Drought-prone
1973	25	15	25	15
1974	0	0	25	15
1975	25	15	50	30
1976	25	15	25	15
1977	0	0	25	15
1978	25	15	50	30
1979	0	0	0	0
1980	0	0	0	0
1981	0	0	0	0
1982	25	15	25	15
1983	25	15	25	30
1984	0	0	0	15
1985	0	0	0	0
1986	0	0	25	15
1987	0	0	0	0
1988	0	0	25	30
1989	0	0	25	15
1990	25	15	50	15
1991	0	0	25	0
1992	50	30	75	60
1993	0	0	50	45
1994	25	0	75	45
1995	0	0	0	0
1996	0	0	0	0
1997	0	0	50	30
1998	0	0	0	0
1999	0	0	0	0
2000	25	0	25	15
2001	0	0	0	0
2002	0	15	0	15
2003	0	0	0	0
2004	0	0	50	30
2005	0	0	0	0
2006	25	15	25	15
2007	25	15	25	30
2008	25	0	50	30
Mean	**9.7**	**5.0**	**22.9**	**15.8**
Std.dev.	13.7	8.0	22.7	15.6
Max	50	30	75	60
Min	0	0	0	0
Median	0.0	0.0	25.0	15.0

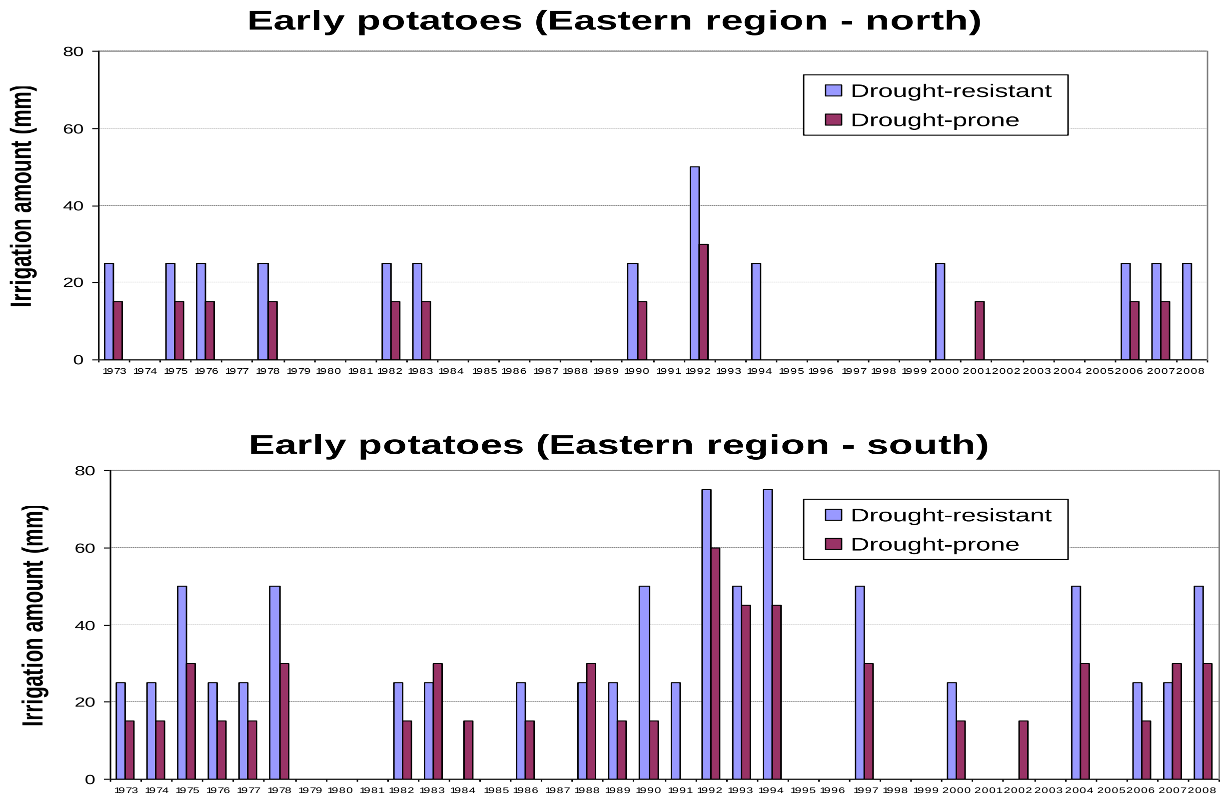


Figure 3.6. Irrigation requirement (mm) for early potatoes in Eastern Norway, 1973-2008.

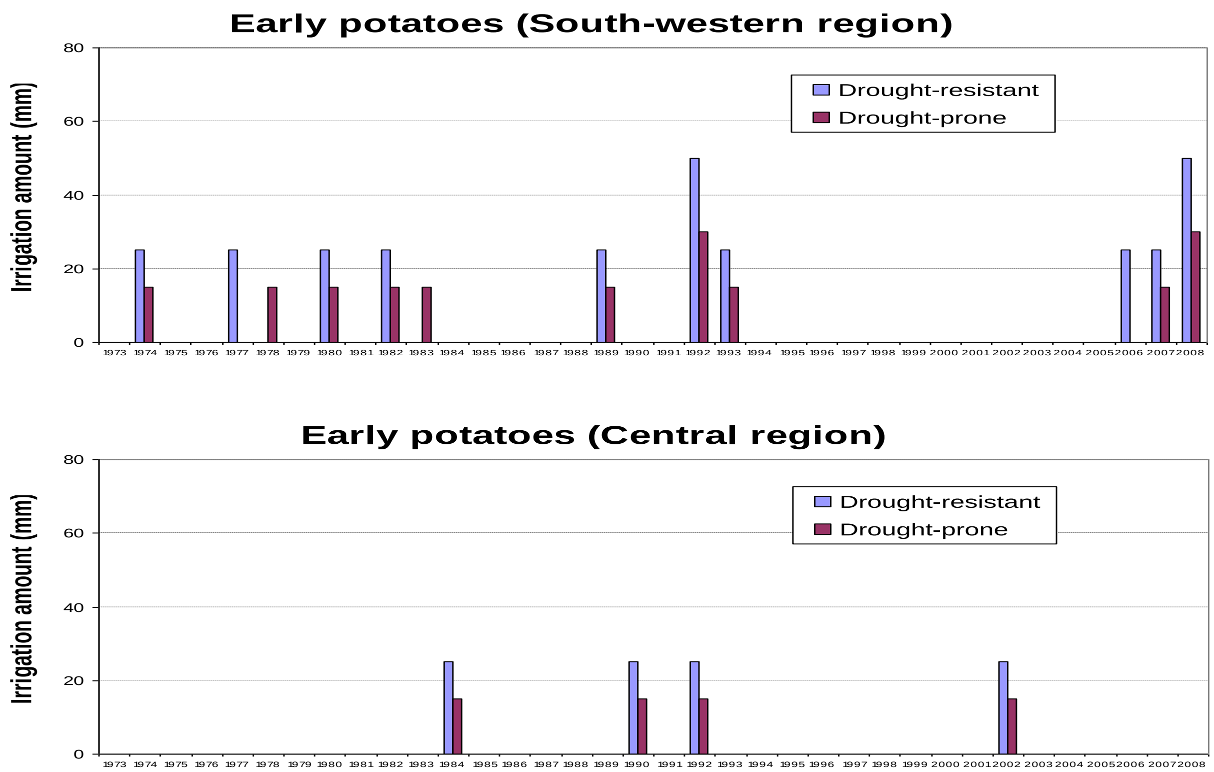


Figure 3.7. Irrigation requirement (mm) for early potatoes in some other regions, 1973-2008.

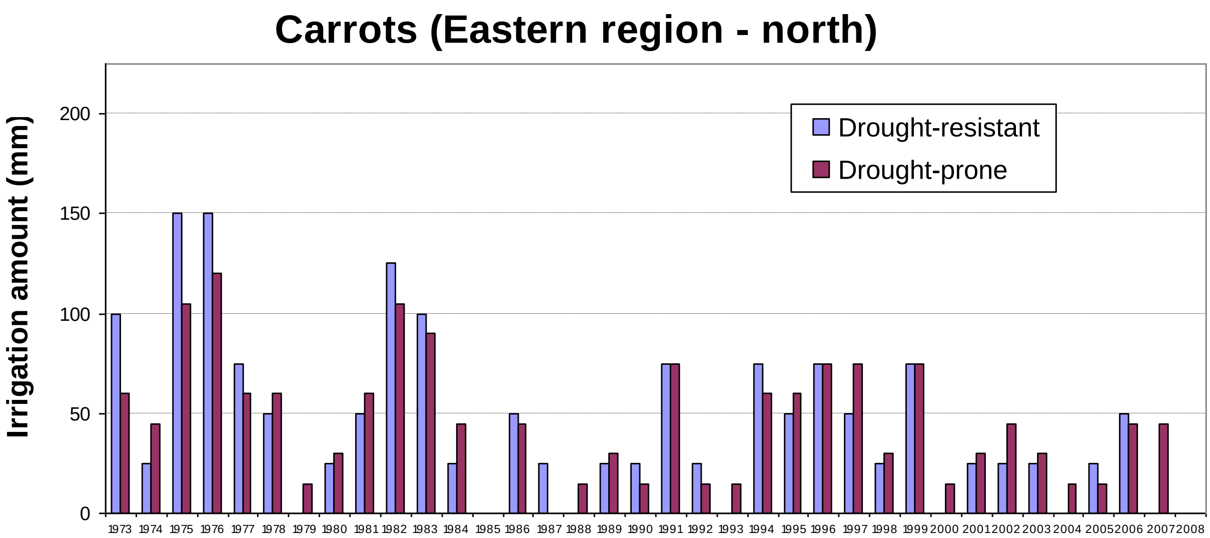
Table 3.8. Irrigation requirement (mm) for early potatoes in some other regions, 1973-2008

	South-Western Norway		Central Norway	
	Drought-resistant	Drought-prone	Drought-resistant	Drought-prone
1973	0	0	0	0
1974	25	15	0	0
1975	0	0	0	0
1976	0	0	0	0
1977	25	0	0	0
1978	0	15	0	0
1979	0	0	0	0
1980	25	15	0	0
1981	0	0	0	0
1982	25	15	0	0
1983	0	15	0	0
1984	0	0	25	15
1985	0	0	0	0
1986	0	0	0	0
1987	0	0	0	0
1988	0	0	0	0
1989	25	15	0	0
1990	0	0	25	15
1991	0	0	0	0
1992	50	30	25	15
1993	25	15	0	0
1994	0	0	0	0
1995	0	0	0	0
1996	0	0	0	0
1997	0	0	0	0
1998	0	0	0	0
1999	0	0	0	0
2000	0	0	0	0
2001	0	0	0	0
2002	0	0	25	15
2003	0	0	0	0
2004	0	0	0	0
2005	0	0	0	0
2006	25	0	0	0
2007	25	15	0	0
2008	50	30	0	0
Mean	**8.3**	**5.0**	**2.8**	**1.7**
Std.dev.	14.6	8.8	8.0	4.8
Max	50	30	25	15
Min	0	0	0	0
Median	0.0	0.0	0.0	0.0

3.4 Simulated irrigation requirement for vegetables

The irrigation requirements for early and mid-season vegetables are likely to be similar to those for early and main-crop potatoes, respectively. Onions and early brassica crops are the main crops in this group. Simulations were made for late carrots to represent late-season vegetable crops. The results are likely to be representative also for vegetables such as swedes and late brassicas.

The amounts of irrigation water required for late carrots are given in tables 3.9 – 3.10 and figures 3.8 - 3.9.



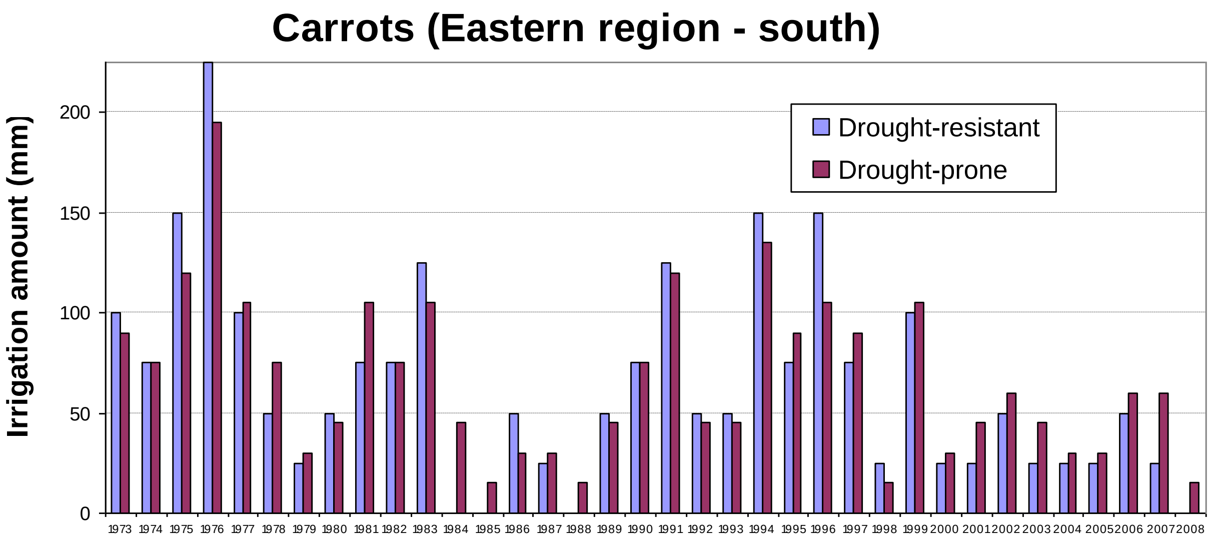


Figure 3.8. Irrigation requirement (mm) for late carrots in Eastern Norway, 1973-2008.

The irrigation requirement for late carrots in the Eastern region was slightly lower than that for main-crop potatoes, but showed a similar pattern between years and between the north and south locations.

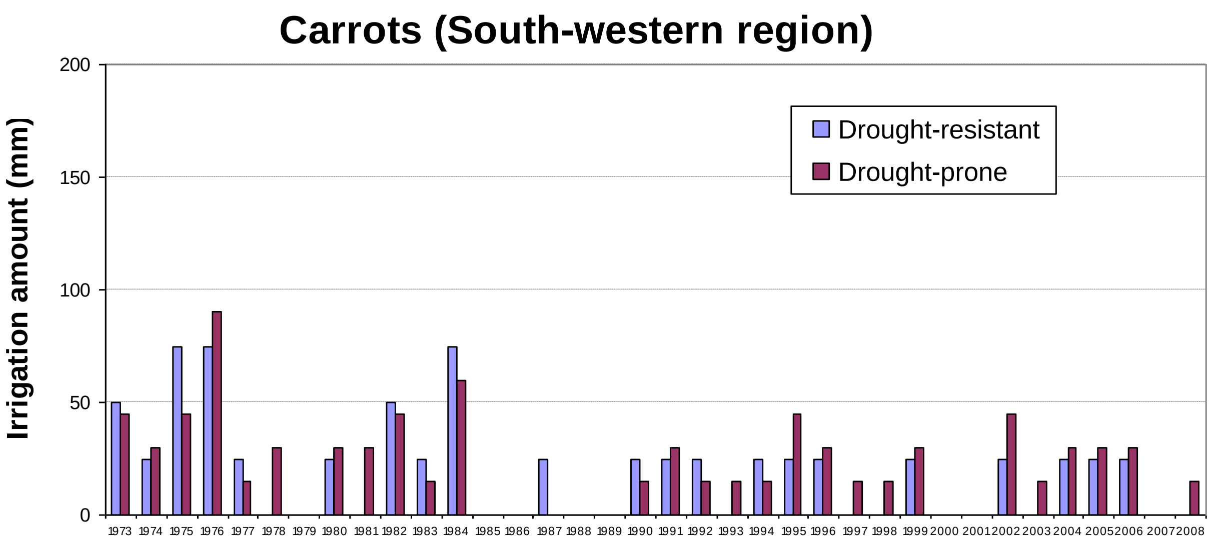
Table 3.9. Irrigation requirement (mm) for late carrots in Eastern Norway, 1973-2008

	Eastern Norway (northern region)		Eastern Norway (southern region)	
	Drought-resistant	Drought-prone	Drought-resistant	Drought-prone
1973	100	60	100	90
1974	25	45	75	75
1975	150	105	150	120
1976	150	120	225	195
1977	75	60	100	105
1978	50	60	50	75
1979	0	15	25	30
1980	25	30	50	45
1981	50	60	75	105
1982	125	105	75	75
1983	100	90	125	105
1984	25	45	0	45
1985	0	0	0	15
1986	50	45	50	30
1987	25	0	25	30
1988	0	15	0	15
1989	25	30	50	45
1990	25	15	75	75
1991	75	75	125	120
1992	25	15	50	45
1993	0	15	50	45
1994	75	60	150	135
1995	50	60	75	90
1996	75	75	150	105
1997	50	75	75	90
1998	25	30	25	15
1999	75	75	100	105
2000	0	15	25	30
2001	25	30	25	45
2002	25	45	50	60
2003	25	30	25	45
2004	0	15	25	30
2005	25	15	25	30
2006	50	45	50	60
2007	0	45	25	60
2008	0	0	0	15
Mean	**44.4**	**45.0**	**63.9**	**66.7**
Std.dev.	41.5	31.3	51.2	40.8
Max	150	120	225	195
Min	0	0	0	15
Median	25.0	45.0	50.0	60.0

Table 3.10. Irrigation requirement (mm) for late carrots in some other regions, 1973-2008

	South-Western Norway		Central Norway	
	Drought-resistant	Drought-prone	Drought-resistant	Drought-prone
1973	50	45	0	0
1974	25	30	0	0
1975	75	45	0	0
1976	75	90	0	0
1977	25	15	0	15
1978	0	30	25	45
1979	0	0	0	15
1980	25	30	25	30
1981	0	30	0	0
1982	50	45	0	15
1983	25	15	0	0
1984	75	60	0	0
1985	0	0	0	0
1986	0	0	0	0
1987	25	0	0	0
1988	0	0	0	15
1989	0	0	0	0
1990	25	15	0	0
1991	25	30	0	0
1992	25	15	0	15
1993	0	15	0	0
1994	25	15	0	15
1995	25	45	0	15
1996	25	30	0	30
1997	0	15	25	30
1998	0	15	0	0
1999	25	30	0	15
2000	0	0	0	0
2001	0	0	0	0
2002	25	45	75	75
2003	0	15	25	15
2004	25	30	50	60
2005	25	30	25	15
2006	25	30	50	45
2007	0	0	25	0
2008	0	15	25	45
Mean	**20.1**	**22.9**	**9.7**	**14.2**
Std.dev.	22.2	20.1	18.2	19.3
Max	75	90	75	75
Min	0	0	0	0
Median	25.0	15.0	0.0	7.5

The irrigation requirement for late carrots was relatively small in the South-Western and Central regions of Norway, as higher rainfall is normal in late summer in these regions. As for potatoes, a somewhat greater requirement has occurred in recent years in the Central region.



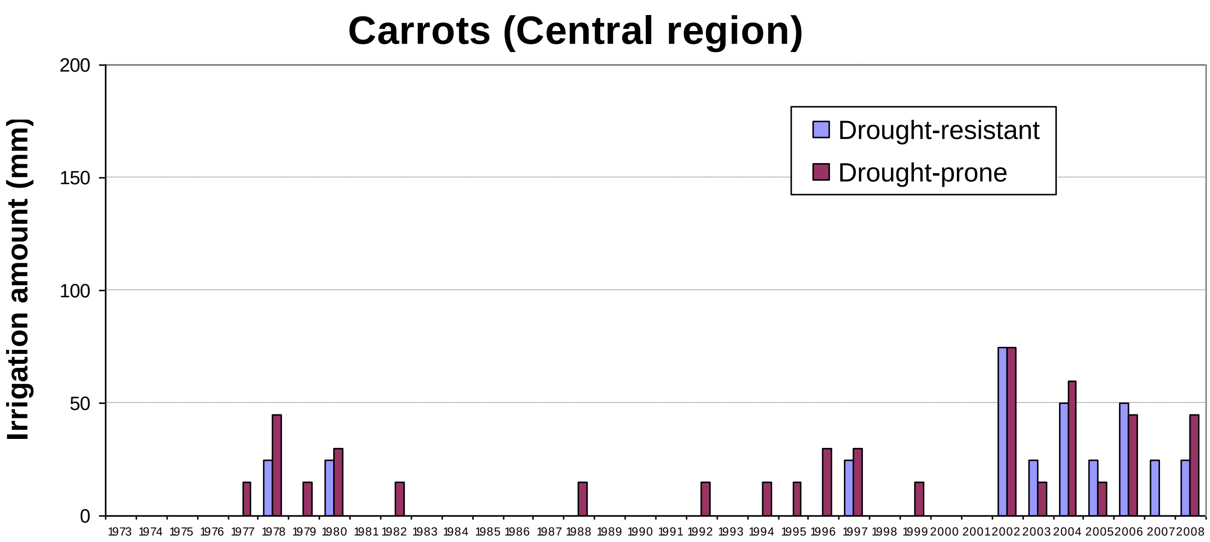


Figure 3.9. Irrigation requirement (mm) for late carrots in some other regions, 1973-2008.

3.5 Mean requirements, comparison of periods and variability

The mean irrigation requirements over the whole period are summarized in figure 3.10. Requirements are for all crops greatest in the Eastern (southern) region, closely followed by the Eastern (northern) region. Although the rainfall is higher in the former than in the latter, so also are the mean temperature and global radiation, resulting in higher evaporative demand. Requirements are much lower in the South-Western region, and even less in Central Norway.

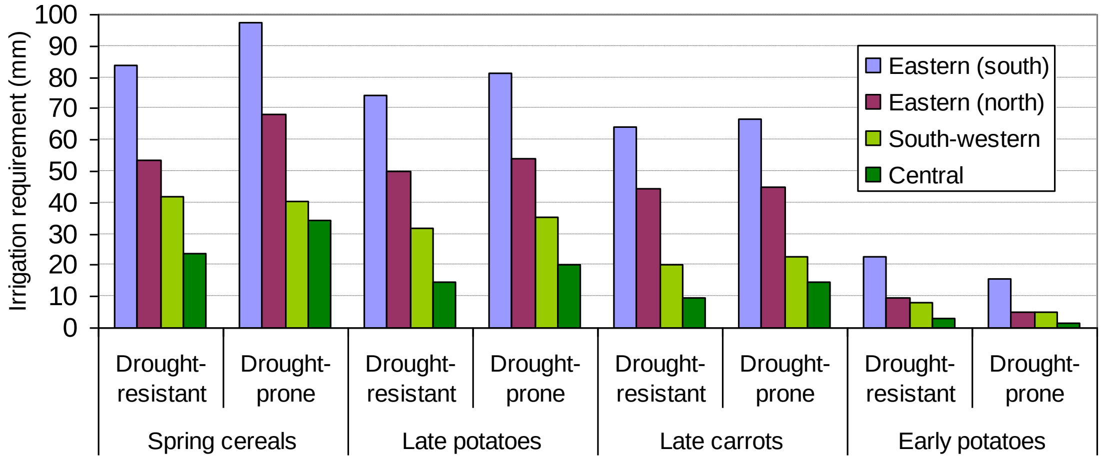


Figure 3.10. Mean irrigation requirement (mm/year) over the period 1973-2008 for various crops in four regions of Norway.

Due to speculation about the effect on irrigation requirement of climate change in recent years, analyses of variance were performed in order to see if there was any statistically significant difference between the first and second halves of the period from 1973 to 2008. Analyses were made for spring cereals and main-crop potatoes. These confirmed that the differences between regions are significant but in no case did they reveal any significant difference between the first and the second halves of the period (analysis details not shown).

The high degree of variability between years in the requirements for irrigation water means that farmers should plan the capacity of their irrigation equipment at a higher level than that necessary for the average requirements, in order to be able to meet the water demand in years with more severe drought. Histograms of the percentage frequency of irrigation requirements are shown in figure 3.11 and cumulative percentages of years in relation to increasing demand are shown in figure 3.12. The figures refer to spring cereals and main-crop potatoes. These figures show that in Central Norway less than two irrigation events are required in about 80% of years on drought-resistant soil. At the other extreme, in the Eastern (southern) region, this occurs in about 30% of years.

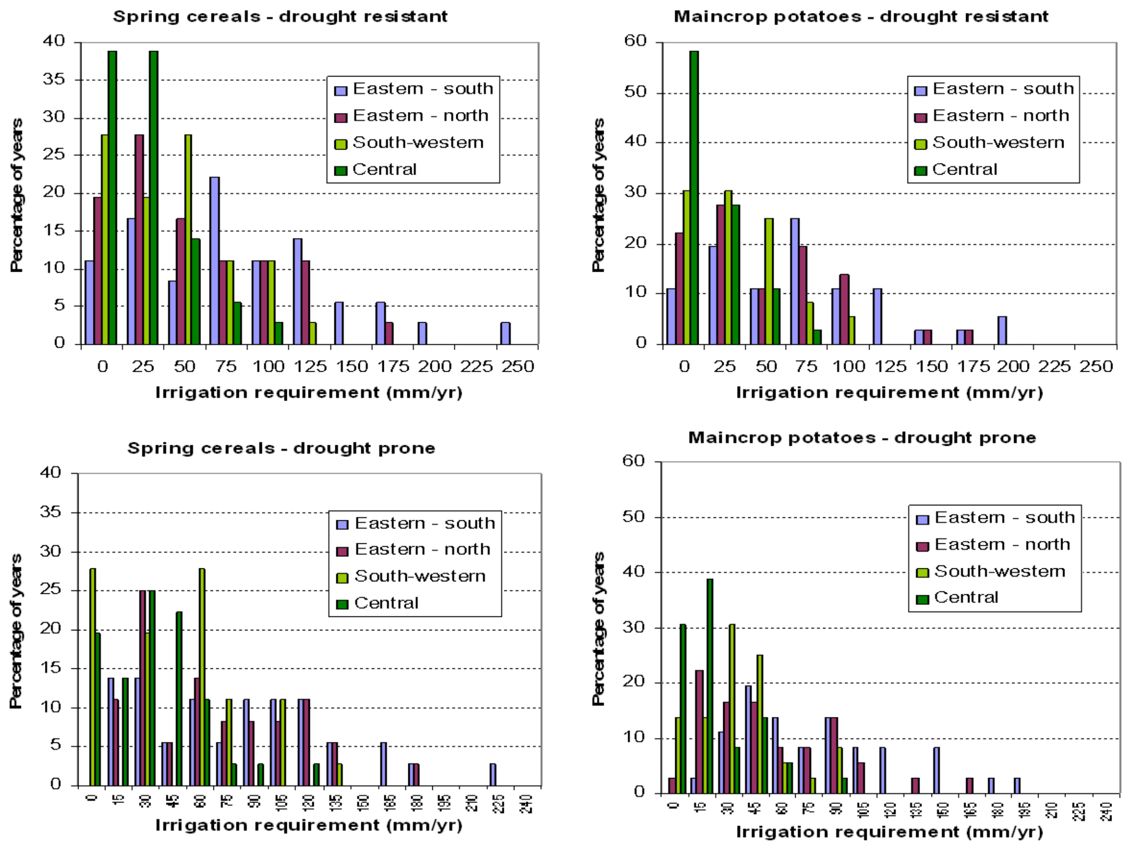


Figure 3.11. Histograms showing the percentage frequency of years with increasing levels of irrigation requirement in four agricultural regions of Norway. Based on data for 1973-2008.

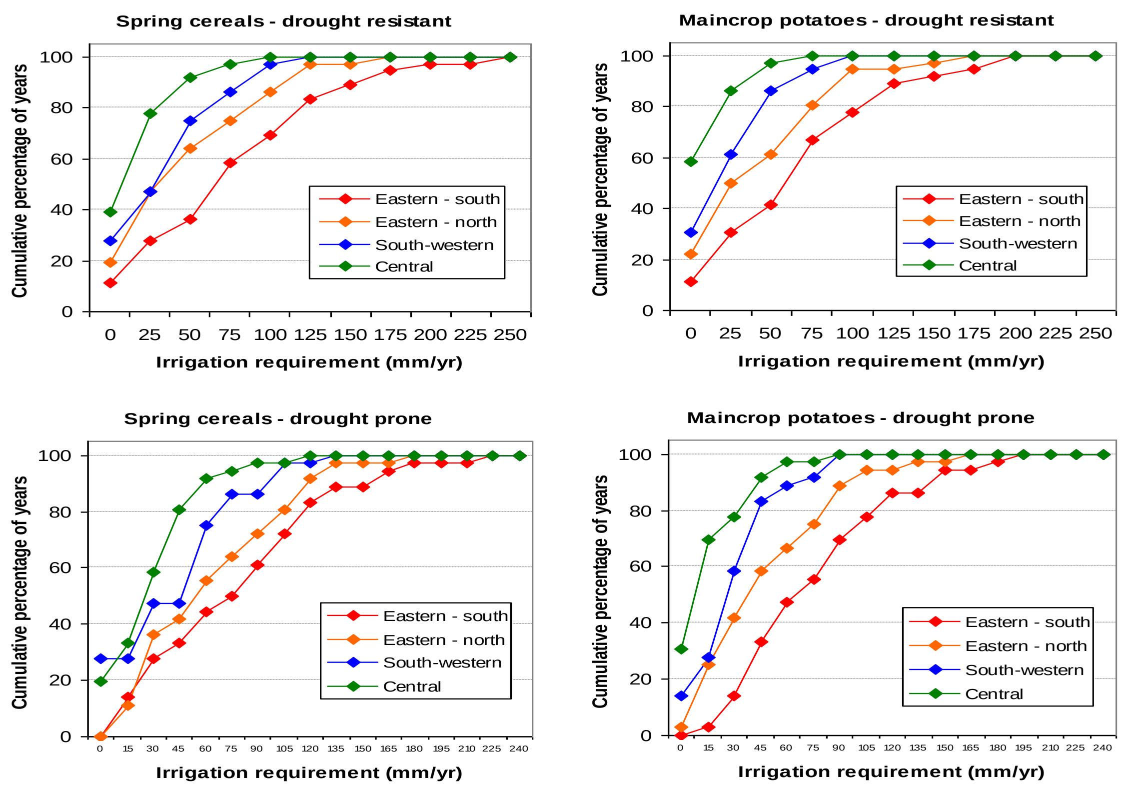


Figure 3.12. Cumulative percentages of years in relation to increasing levels of irrigation requirement in four agricultural regions of Norway. Based on data for 1973-2008.

In order to estimate the irrigation capacity required in order to meet demands in relation to the percentage of all years, quadratic equations were derived from the data in figure 3.12, by regressing the requirement against the cumulative percentage of years. These equations (not shown) accounted in almost all cases for around 95-97% of the variation and were used to calculate the data in table 3.11. This table shows that, in order to meet demands in 80% of all years, an irrigation capacity is needed that is on average half as much again as the mean requirement. To meet demands in 90% of all years, the capacity must often be doubled, whilst to meet demands every year a capacity of around three times the mean requirement is needed.

Table 3.11. Irrigation capacities (mm/year) required in order to meet demands in increasing proportions of years over the period 1973-2008, relative to mean requirements for all years

	Eastern region (south)		Eastern region (north)		South-Western region		Central region	
% of years	Drought-resistant	Drought-prone	Drought-resistant	Drought-prone	Drought-resistant	Drought-prone	Drought-resistant	Drought-prone
<u>Spring cereals</u>								
40	34	46	12	36	9	21	0	6
50	51	63	24	50	17	32	0	11
60	73	84	40	67	28	45	0	20
70	101	107	62	86	43	61	6	33
80	135	134	88	108	62	80	26	51
90	174	164	119	133	84	101	55	72
100	218	198	155	160	110	126	93	97
Mean	*84*	*98*	*54*	*68*	*42*	*40*	*24*	*34*
<u>Late potatoes</u>								
40	30	44	10	20	3	13	0	0
50	45	59	21	32	8	20	0	0
60	64	76	37	47	17	29	0	2
70	87	96	58	65	30	41	0	13
80	115	119	84	87	48	54	13	28
90	147	145	116	113	69	70	37	50
100	183	174	152	141	94	88	74	76
Mean	*74*	*81*	*50*	*54*	*32*	*35*	*15*	*20*

4. Comparisons with actual irrigation practice

4.1 Survey of irrigation water use in Hedmark and Oppland counties

No official statistics exist for irrigation water use in Norway. Very few farmers keep accurate records of their irrigation practice. Information was collected by senior research technician Erling Berentsen from four collective irrigation operators who supply water to a number of farms, and with one farmer who has kept records for a field runoff study tables 4.1 and 4.2). All of these were within a 30 km radius of the weather station used to calculate irrigation requirements at the northern location of Eastern Norway. The dominant crops irrigated were cereals and potatoes (in an approximately 3 to 1 ratio), with smaller areas of vegetables (onions, carrots and some brassicas) and grass. The soils are mainly loams, with intermediate water-holding capacity (some drought-prone, some more drought-resistant). The area covered by these suppliers represents 2% of the total irrigated area in Norway.

Table 4.1 Names and details of irrigation water suppliers interviewed

Name	Place	Area (ha)	Period	Dominant crops
Balke & Hveem	Østre Toten	678.5	1990-2008	Vegetables/arable
Mjøsregn	Østre Toten	371.6	1990-2008	Cereals/potato
Hoff	Østre Toten	1200.0	1990-2008	Cereals/potato
Nes	Nes på Hedmark	400.0	1996-2008	Cereals/potato
Bye study field	Nes på Hedmark	4.0	1990-2008	Cereals/potato

Table 4.2. Amounts (m3) of water supplied annually by the various irrigation water suppliers

Year	Balke/Hveem	Hoff	Mjøsregn	Nes	Bye
1990	518705	372452	200334	-	2400
1991	459616	371363	195084	-	2200
1992	635115	869030	288895	-	3600
1993	301637	349521	156559	-	2200
1994	728050	1000533	417000	-	5800
1995	458850	440234	257460	-	0
1996	463062	425957	240940	200350	3200
1997	605231	523416	280800	221800	2400
1998	251888	113895	98882	57700	800
1999	330955	280836	156788	87020	1200
2000	246667	97588	115429	50050	1200
2001	313156	187628	136510	24200	0
2002	308219	159386	90713	31450	4800
2003	218607	184625	81019	26940	1200
2004	410800	163684	122668	48650	2000
2005	327863	231248	126660	105600	2200
2006	620773	518003	240993	219400	2400
2007	343079	123355	62142	77750	1800
2008	333151	205518	115120	140800	3600

The amounts of irrigation were calculated on an aerial basis by simply dividing the amounts of water supplied by the total area which the irrigated systems are designes to supply. This overlooks the fact that parts of these areas may be irrigated more intensively than others. There was thus a difference between suppliers in the average amounts supplied on an area basis (figure 4.1). This also reflects the extent to which cash crops such as vegetables and potatoes are present in each area. The farms supplied by Balke-Hveem, for example, have the highest proportion of such crops, and consequently the highest rate of water use. Despite this weakness, it appeared that there was consistency amongst the suppliers of water with respect to the between-year variation in the use of irrigation water. Nes and Hoff, on the other hand, supply water to farms with a low proportion of cash crops.

The irrigation amounts used on the Bye study field showed greater variation between years than the data from the larger water suppliers. For instance, no irrigation was applied in 1995 and 2001 when the crop was barley (low value), and very high amounts were applied in 1994 and 2002 when the crops were wheat and potatoes, respectively (higher value). The farmer at Bye is known to irrigate earlier in the season and more regularly than the 'average' farmer.

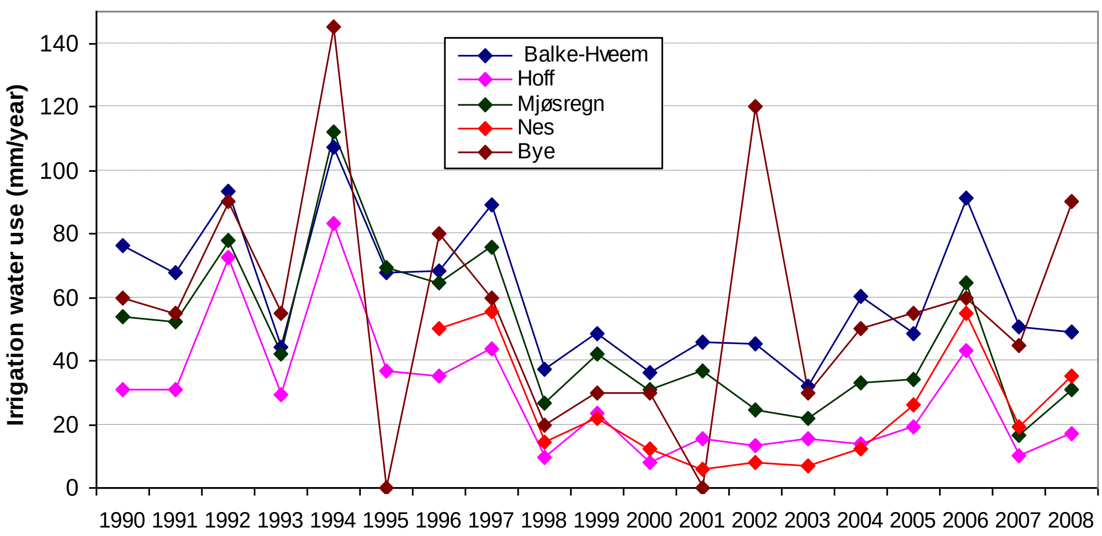


Figure 4.1. Irrigation water amounts (mm) supplied by four irrigation cooperatives and used by one individual farmer (Bye) in the northern part of Eastern Norway, 1990-2008.

4.2 Comparisons of actual water use with simulated demand

Comparisons of the actual amounts of water from the four suppliers (on an area basis) with the requirements by the model are shown in figure 4.2. The latter values are weighted averages of the requirements calculated for cereals and potatoes at the Kise weather station (assuming an average cereal area of 70% and a potato area of 30%). Requirements for both drought-probe and more drought-resistant soils are plotted.

Reasonably good correlations were found between the calculated requirements and the actual amounts of water supplied, with coefficients of determination in the order of 55-85% for the individual suppliers. There was a tendency in all cases for the calculated requirement to exceed the actual amounts supplied at the higher levels of irrigation demand (>80 mm/year). This presumably reflects the technical or economic constraints of the irrigation systems used.

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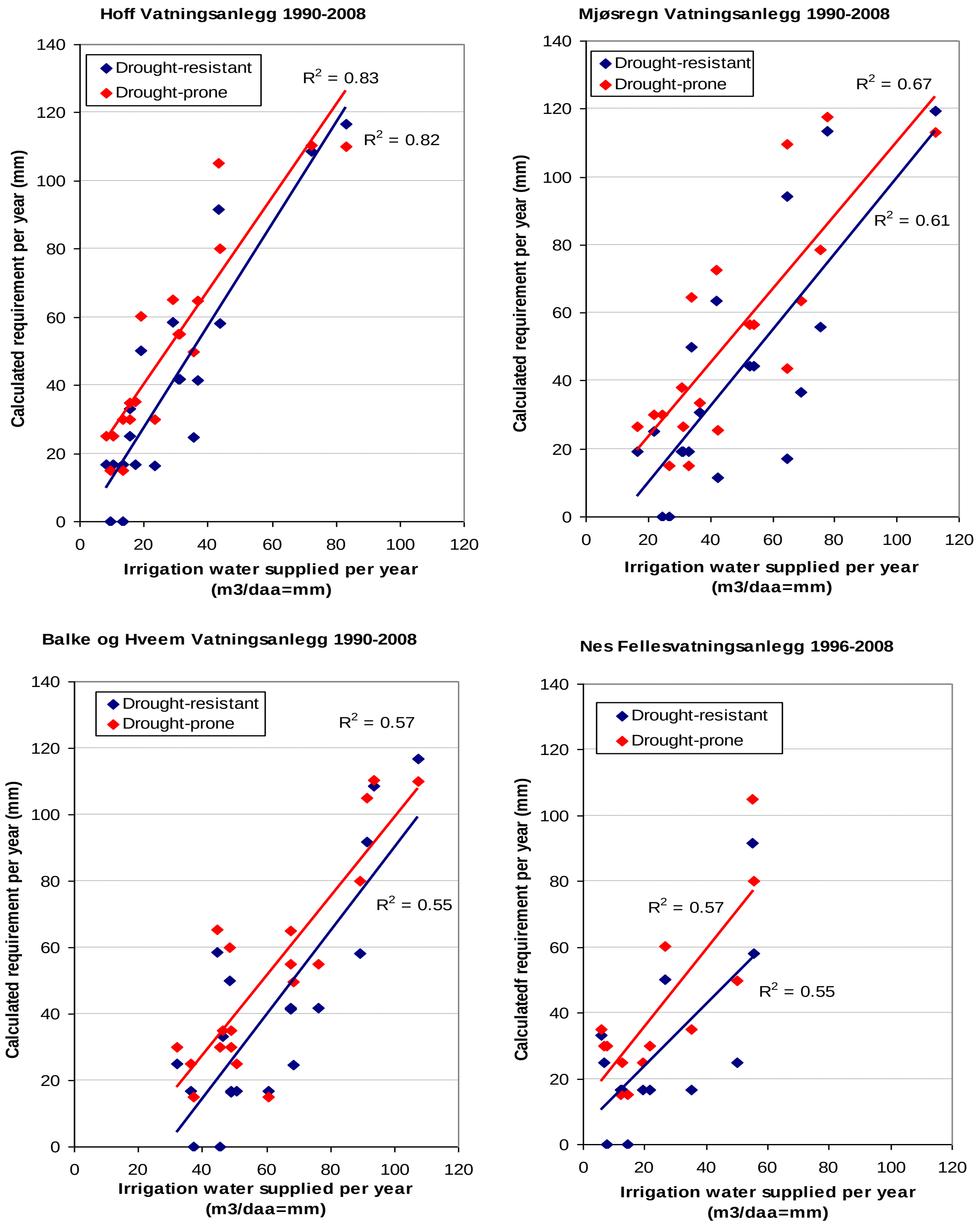
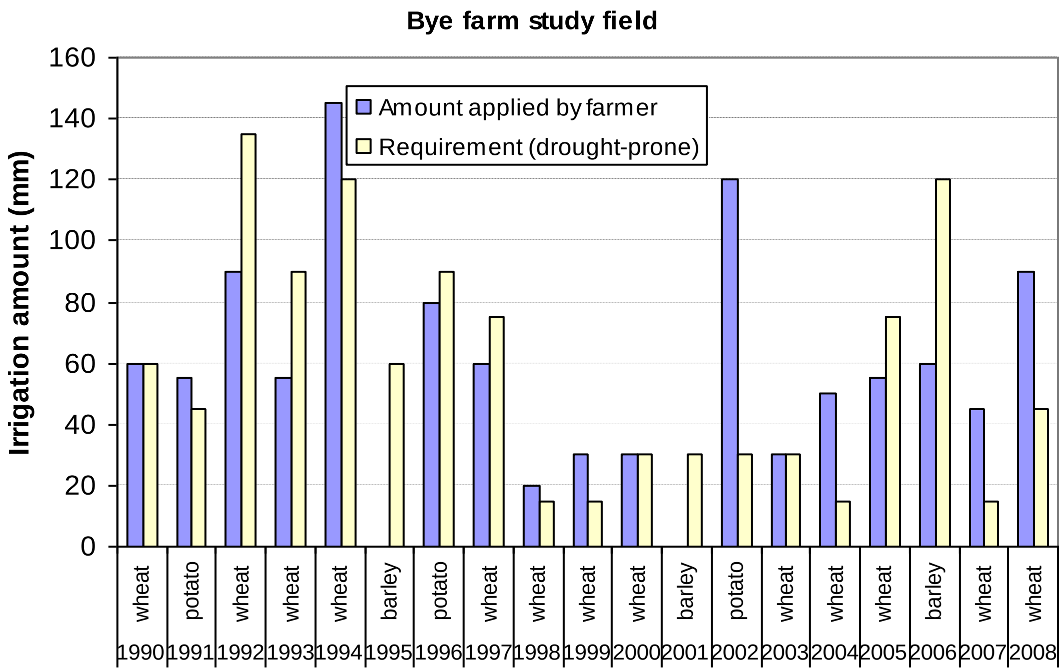


Figure 4.2. Calculated irrigation requirements (mm/year) plotted against water amounts (mm) supplied by four irrigation cooperatives in the northern part of Eastern Norway.

The agreement between the calculated requirements and the amounts of irrigation actually applied was somewhat poorer for the individual field study at Bye farm (figure 4.3). In the years with barley, irrigation was either omitted or lower than optimum, whilst in one potato year (2002), the amount applied was far greater than the calculated requirement. This may have been due to local variations in rainfall patterns, or else the farmer may have started irrigation earlier than normal. Less emphasis may therefore be placed on this result.



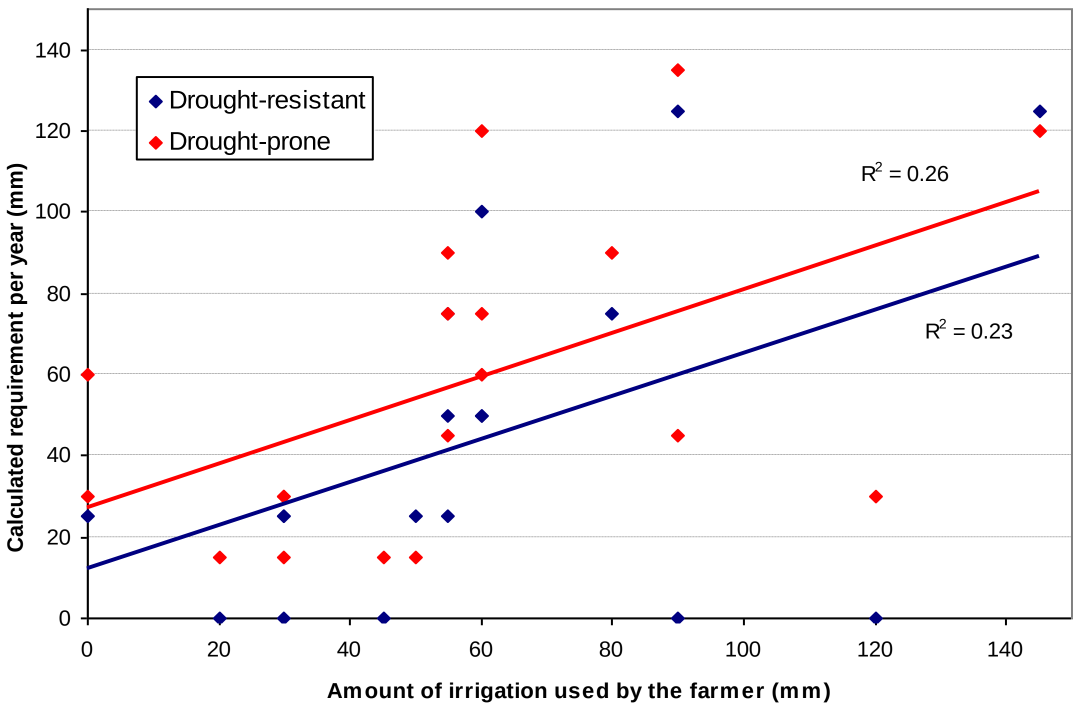


Figure 4.3. Calculated irrigation requirements (mm/year) plotted against water amounts (mm) applied by the farmer at the Bye farm study field.

Given the limitations of the water data collected from the four suppliers and the field study at Bye, with respect to uncertainty about the areas of individual crops irrigated and possible variations in local rainfall patterns, the calculated irrigation requirements accorded reasonably well overall with the actual water use (figure 4.4). The data points cluster fairly uniformly around the 1:1 line, though a tendency for using slightly less water than required is detectable at high levels of demand. This was, however, not reflected in the overall regression equations, so that it may be concluded that average actual water use is in practice close to the calculated requirements.

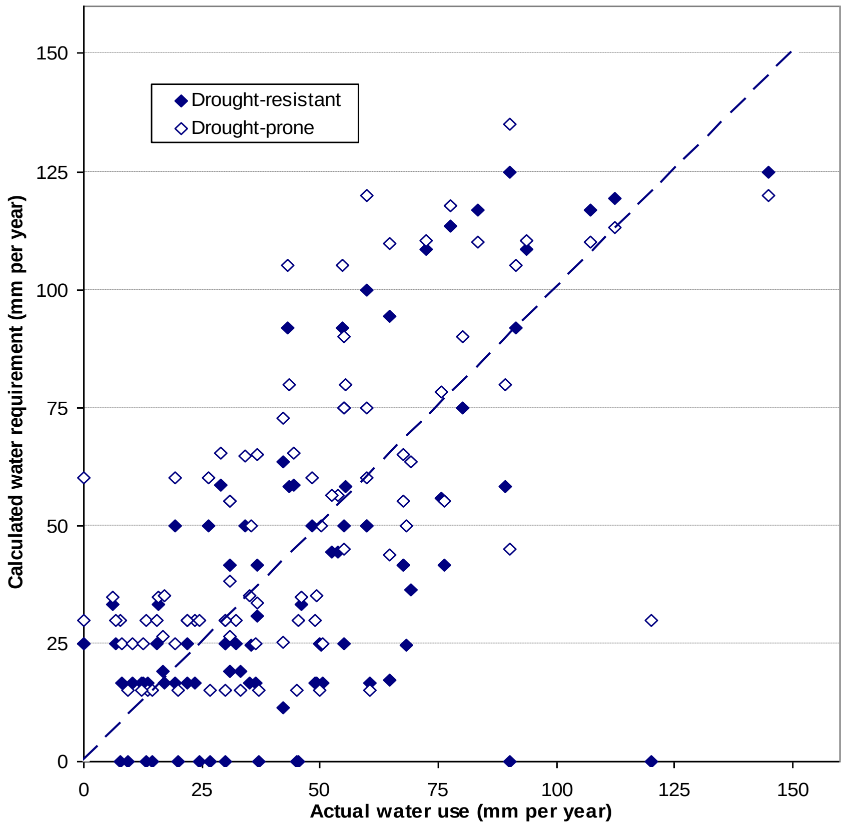


Figure 4.4. Calculated irrigation requirements plotted against water amounts supplied by all five sources of information listed in table 4.1. The dotted line represents the 1:1 line.

5. Conclusion

5.1 Summary in English

This study represents an attempt to quantify the requirements for irrigation water in Norway. The total irrigated area is about 130 000 ha, or 14% of the country's agricultural area. Almost 80% of this is found in the Eastern region (divided in this study into northern and southern parts), 10% in the Southern and South-Western region and 5% in the Central region. Data are lacking on the area of individual crops that are irrigated, but at most 20% of the irrigated area is considered to be used for vegetable crops and potatoes, with cereals occupying much of the remainder.

Emphasis was placed on quantifying requirements for cereals, potatoes and late vegetables in the four regions mentioned. Weather data for 1973-2008 was used from a representative station in each region, thus covering an equal number of years in the existing (1961-1990) and future (1991-2020) 30-year normal periods. The Eastern region has a relatively dry climate, particularly in the first half of the growing season, whilst in other regions there is on average no water deficit. There is, however, high between-year variability in all regions, with large deficits in some years, moderate deficits in other years and little or no deficit in the remainder.

The EU-Rotate_N model (Rahn et al., 2008) was used to calculate irrigation requirements. This model contains an FAO-recommended water balance subroutine, as well as options for selecting the irrigation practices that are most suitable for different crops. All calculations were performed for two classes of soil, representing drought-prone soils, such as sands, and more drought-resistant soils, such as loams, respectively. Irrigation is uncommon in Norway on soils with higher resistance to drought, such as silt, clay loam and peaty soils.

A locally calibrated estimate of reference evaporation was used in the calculations, and a sensitivity analysis was performed to select a suitable irrigation strategy with respect to critical water deficit and percentage refill. The chosen strategy was such that irrigation was applied, in crop-dependent drought-sensitive growth periods only, whenever the deficit reached 50% of the available water capacity within the upper 60 cm of soil. The amount applied on each such occasion was equal to one half of the calculated deficit.

A summary of the mean irrigation water requirements is given in table 5.1 for various crops in the four regions, together with an indication of the variability between years. The average calculated irrigation requirements for spring cereals in the southern part of the Eastern region are around 100 mm per year on drought-prone soil and 85 mm on more drought-resistant soil. The corresponding figures in the northern, more inland part of this region are around 70 mm and 55 mm. In the South-Western region the average requirement is around 40 mm on both soil types, and in the Central region it is around 35 mm on drought-prone soil and 25 mm on more drought-resistant soil.

Average requirements for main-crop potatoes in the southern and northern parts of the Eastern region are around 75-80 and 50-55 mm, respectively, with little difference between soil type. In South-Western and Central Norway, they are around 30-35 mm and 15-20 mm, respectively. Calculated requirements for early potatoes are much lower than for main-crop potatoes, though in practice higher amounts may be used as an intensive irrigation strategy is common in this high-value crop.

Average requirements for late vegetable crops, such as carrot, are a little less than those for main-crop potatoes (ca. 65 and 45 mm in southern and northern parts of the Eastern region, 20-25 and 10-15 mm in South-Western and Central regions, respectively). The relatively low requirement or this crop is due to increasing amounts of precipitation in autumn in all regions.

Table 5.1. Mean and median (1973-2008) irrigation water requirements (mm) by various crops on two classes of soil in four regions of Norway, and variability between years (CV%)

	Østlandet (sør)		Østlandet (nord)		Sør- /Sør-Vest.		Midt Norge	
Droughtiness:	*Resistant*	*Prone*	*Resistant*	*Prone*	*Resistant*	*Prone*	*Resistant*	*Prone*
Spring cereals								
Mean	**84**	**98**	**54**	**68**	**42**	**40**	**24**	**34**
Median	75	98	50	60	50	38	25	30
CV%	72	54	86	62	84	90	107	80
Late potatoes								
Mean	**74**	**81**	**50**	**54**	**32**	**35**	**15**	**20**
Median	75	75	38	45	25	30	20	22
CV%	73	55	89	71	91	69	138	106
Late vegetables								
Mean	**64**	**67**	**44**	**45**	**20**	**23**	**10**	**14**
Median	50	60	25	45	25	15	0	8
CV%	80	61	93	70	110	88	188	136
Early potatoes[1]								
Mean	**23**	**16**	**10**	**5**	**8**	**5**	**3**	**2**
Median	25	15	0	0	0	0	0	0
CV%	99	99	141	160	176	176	286	282

[1] Similar values may be expected for many early vegetable crops

The average irrigation requirements cited above are not, however, representative of the amounts that may be required in individual years, due to the very high coefficients of variation that are commonly found. These are for many crops usually around 60-80% in Eastern Norway, and significantly higher in other regions. The variability is usually slightly higher for the more drought-resistant soil class than for the drought-prone class, due to the smaller water-holding capacity of the latter. The variability in requirement is extremely high for crops that require irrigation early in the season, such as early potatoes, particularly in the Central region. Mean water requirement values are relatively meaningless in such cases.

High variability has implications for the capacity requirements of irrigation systems. The percentage distribution of years with different requirements was calculated for cereals and main-crop potatoes. This showed that on drought-resistant soil in Central Norway, less than two irrigation events are required in about 80% of years. At the other extreme, in the Eastern (southern) region, this occurs in about 30% of years. No statistically significant differences in average requirements were found between the periods 1973-1990 and 1991-2008.

Calculations were made to estimate the irrigation capacity required in order to meet demands in relation to increasing percentages of all years. In order to meet demands in 80% of all years, an irrigation capacity is needed that is on average half as much again as the mean requirement. To meet demands in 90% of all years, the capacity must often be doubled, whilst to meet demands every year a capacity of around three times the mean requirement is needed.

In order to assess the validity of the calculated requirements in relation to current farmer practice, information on water use was collected from a number of irrigation water suppliers in one of the main districts in the inland Eastern region of Norway where irrigation is practiced to cereals, potatoes and vegetables. The area represented by this survey covered about 2% of the total irrigated area of Norway. This information was used to compare actual water use with the calculated requirements. Overall, the agreement was found to be reasonably good, with calculated requirements accounting for 55-85% of the variation in amounts of water supplied over a period of almost 20 years. Thus it may be considered that the model calculations are realistic in relation to actual irrigation water use in Norway.

The overall conclusion is that this report gives a reasonable assessment of the likely irrigation requirements, and their variability, of the major crops irrigated in the dominant arable and vegetable-growing regions of Norway. In relation to actual farmer practice, uncertainty may be attached to some of the estimates given, for instance those for early potatoes. These may in practice be irrigated more intensively than suggested here, i.e. at lower critical water deficits and/or with higher replenishment rates, implying higher water usage. The same may apply to some vegetable crops. Finally, some important omissions in this study should be mentioned, notably the irrigation of top and soft fruit, which is of importance particularly in Western Norway, and of grass leys and pasture, which is important in central upland valleys such as Gudbrandsdal. Further study is needed on these topics.

5.2 Sammendrag på norsk

Rapporten omfatter et forsøk på å kvantifisere vannbehovet til vanning i norsk landbruk. Totalarealet som kan vannes er ca. 1.3 m dekar, eller 14% av landets jordbruksareal. Nesten 80% av dette finnes på Østlandet (delt i denne studien mellom nordlig og sørlig del), 10% i på Sørlandet og Sør-Vestlandet og 5% i Midt-Norge. Det mangler opplysninger om arealet av ulike veksttyper som vannes, men det antas at i høyden 20% brukes til grønnsaker og potet, mens korn utgjør mesteparten av det øvrige vanningsarealet.

Fokuset er rettet mot beregning av vannbehovet til korn, potet og grønnsaker i de fire regionene som er nevnt ovenfor. Værdata for perioden 1973-2008 er brukt fra en representativ målestasjon i hver region. Dette dekker et likt antall år i det eksisterende (1961-1990) og det framtidige (1991-2020) 30-års normalperiode. På Østlandet overstiges nedbøren av potensiell fordamping, spesielt i første halvdel av vekstsesongen. I de andre regionene er det intet nedbørsunderskudd i middel av alle år, men det er store variasjoner mellom år. I alle regioner kan det være store underskudd i noen år og moderate underskudd i andre år.

EU-Rotate_N modellen (Rahn et al., 2008) ble brukt til å simulere vannbehovet til vanning. Denne modellen inneholder en vannbalanse rutine som er anbefalt av FAO, så vel som valgmuligheter som gjør den egnet til å simulere vanningsstrategier til mange ulike vekster. Alle beregninger ble utført for to klasser av jord, for å representere henholdsvis tørkesvak jord, som sand, og middels tørkesterk jord, som lettleire. En regner med at vanning i liten grad praktiseres i Norge på mer tørkesterk jord, som silt, mellomleire og myrjord.

En lokalt kalibrert beregningsmetode for referansefordamping ble brukt i beregningene, og en følsomhetsanalyse ble utført for å finne en passende vanningsstrategi med tanke på fastsetting av det kritiske vannunderskuddet i jorda som utløser vanningsbehov og andelen av dette underskuddet som blir erstattet ved vanning. Strategien som ble valgt var å vanne når underskuddet nådde 50% av den tilgjengelige vannlagringskapasitet i jordas øvre 60 cm, og da med en mengde som tilsvarer halvparten av det beregnete underskuddet. Vanning ble bare gitt i periodene når plantene regnes å være følsomme for tørke, noe som er vekstavhengig.

Et sammendrag av de gjennomsnittlige behovene for vann til vanning er gitt i tabell 5.2 for ulike vekster i de fire regionene, sammen med et uttrykk for variabiliteten mellom år. Midlere behov til vårkorn i den sørlige delen av Østlandet er omkring 100 mm pr. år på tørkesvak jord og 85 mm på middels tørkesterk jord. I den nordlige, innlandsdelen er ca. 70 mm og 55 mm. På Sørlandet og Sør-Vestlandet er middelbehovet ca. 40 mm på begge klasser av jord, mens behovene i Midt-Norge er ca. 35 mm på tørkesvak jord og 25 mm på middels tørkesterk jord.

Tabell 5.2. Middel- og medianbehov (1973-2008) for vann til vanning (mm) av ulike vekster på to klasser av jord i fire regioner av Norge, og et mål på variabiliteten mellom år (CV%)

	Østlandet (sør)		Østlandet (nord)		Sør- /Sør-Vest.		Midt Norge	
Tørkestyrke:	*Middels*	*Svak*	*Middels*	*Svak*	*Middels*	*Svak*	*Middels*	*Svak*
Vårkorn								
Middel	**84**	**98**	**54**	**68**	**42**	**40**	**24**	**34**
Median	75	98	50	60	50	38	25	30
CV%	72	54	86	62	84	90	107	80
Sein potet								
Middel	**74**	**81**	**50**	**54**	**32**	**35**	**15**	**20**
Median	75	75	38	45	25	30	20	22
CV%	73	55	89	71	91	69	138	106
Seine grønnsaker								
Middel	**64**	**67**	**44**	**45**	**20**	**23**	**10**	**14**
Median	50	60	25	45	25	15	0	8
CV%	80	61	93	70	110	88	188	136
Tidligpotet[1]								
Middel	**23**	**16**	**10**	**5**	**8**	**5**	**3**	**2**
Median	25	15	0	0	0	0	0	0
CV%	99	99	141	160	176	176	286	282

[1] Lignende verdier kan ventes også for mange tidlige grønnsakskulturer

Til sein potet i de sørlige og nordlige delene av Østlandet er behovene i middel henholdsvis ca. 75-80 mm og 50-55 mm, med bare små forskjeller på ulike typer jord. På Sørlandet og Sør-Vestlandet er de omkring 30-35 mm og i Midt-Norge bare ca. 15-20 mm. De beregnete behovene til tidligpotet var i gjennomsnitt mye lavere enn til sein potet, men i praksis brukes det trolig større mengder, da en mer intensiv vanningsstrategi velges av mange til den verdifulle veksten.

Midlere vanningsbehov til seine grønnsaker, som gulrot, er noe mindre en behovene til sein potet (ca. 65 og 45 mm i de sørlige og nordlige delene av Østlandet, 20-25 mm på Sørlandet og Sør-Vestlandet og bare 10-15 mm i Midt-Norge). De relativt lave behovene til denne veksten skyldes at nedbørsmengdene øker i alle regionene utover høsten.

De gjennomsnittlige behovene som er nevnt ovenfor er imidlertid ikke representative for vannmengdene som det kan være behov for i enkelte år, på grunn av den store variabiliteten mellom år som finnes i alle regioner. Variasjonskoeffisienter på 60-80% er vanlige for mange vekster på Østlandet, og verdiene er betydelig høyere i de andre regionene. Variabiliteten er ofte noe høyere på mer tørkesterk jord enn på tørkesvak jord, som følge av den lavere vannlagringskapasiteten hos sistnevnte. Variabiliteten er ekstremt stor for vekster som trenger vanning tidlig i sesongen, slik som tidligpotet, spesielt i Midt-Norge. I slike tilfeller er begrepet 'midlere vannbehov' relativt meningsløst.

Stor variabilitet mellom år har innvirkning på kapasitetsbehovene ved dimensjoneringen av vanningsanlegg. Den prosentvise fordelingen av år med ulike behov ble derfor beregnet for vårkorn og sein potet. Dette viste at det i Midt-Norge var behov for mindre enn to vanninger pr. år i 80% av alle år på middels tørkesterk jord. I andre ytterlighet, i den sørlige delen av Østlandet, inntreffer dette i bare omkring 30% av alle år. Det ble ikke funnet noen statistisk sikre forskjeller i middelsbehovene for vann mellom periodene 1973-1990 og 1991-2008.

Beregninger ble også utført for å estimere den maksimale vanningskapasiteten som trengs for å kunne møte behovene i forhold til økende andel av alle år. For å møte behovet i 80% av alle år, trengs en kapasitet som er i gjennomsnitt 50% høyere enn det midlere behovet. Økes kravet til 90% av alle år, må kapasiteten ofte dobles, mens hvis behovet skal møtes hvert eneste år, trengs det en vanningskapasitet som er ca. tre ganger så stor som middelbehovet.

For å kunne vurdere validiteten av de beregnete behovene i forhold til gjeldende praksis hos norske bønder, ble det innhentet opplysninger om vannforbruk til vanning fra et antall større vannforsyningsanlegg i et av de viktigste distriktene der det praktiseres vanning til korn, potet og grønnsaker i den nordlige delen av Østlandet. Arealet som disse anleggene forsyner vann til representerer omkring 2% av totalarealet som kan vannes i Norge. Opplysningene ble brukt for å sammenligne faktisk vannforbruk med de beregnete behovene. Det ble i hovedsak funnet relativt god overensstemmelse mellom praksis og teori. De beregnete behovene i distriktet forklarte 55-85% av variasjonen i vannmengdene som ble levert fra de ulike anleggene over en periode på nesten 20 år. Det kan dermed antas at modellsimuleringene er realistiske sett i forhold til faktisk vannforbruk til jordbruksvanning i Norge.

Hovedkonklusjonen er at denne rapporten gir en rimelig vurdering av de sannsynlige vannbehovene til jordbruksvanning, og deres variabilitet, hos de viktigste åkervekstene og grønnsaker som vannes i landets dominerende jordbruksregioner. I forhold til faktisk dyrkerpraksis, knytter det seg en del usikkerhet til enkelte av estimatene som er gitt, for eksempel de for tidlig potet. Disse vannes trolig mer intensivt enn det som er antydet her, dvs. ved lavere kritiske vannunderskudd og/eller ved å erstatte en høyere andel av underskuddet. Dette ville innebære et høyere vannforbruk. Det samme gjelder trolig for enkelte grønnsaker. Til slutt bør det nevnes noen åpenbare mangler i denne rapporten, nemlig vanningsbehovene til frukt og bær, som er viktige spesielt på Vestlandet, og til eng og beite, som er viktige i sentrale dalstrøk, som den øvre del av Gudbrandsdal. Disse emnene bør undersøkes nærmere.

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7. Appendices

7.1 Appendix I. Irrigation in Norway: Some statistics from the 1999 agricultural survey. Agricultural area, irrigated area, number of farms with irrigation, irrigation method, water source and %-distribution of farms by percentage of area irrigated. (Source: Statistics Norway) *(1 page)*

7.2 Appendix II. Research note 23.10.2003. Estimation of pan evaporation from weather data (Hugh Riley) *(4 pages)*

7.3 Appendix III. Normal (1961-1990) precipitation sums (mm) for a selection of localities in four regions of Norway, compared to the weather stations chosen to represent each region in the simulation study. (Source: E.J. Førland 1993) *(4 pages)*

7.4 Appendix IV. Description of the water balance model incorporated in EU-Rotate_N (Carlos Ramos & Jordi Doltra) *(18 pages)*

Appendix I . *Irrigation in Norway: Some statistics from the 1999 survey (Statistics Norway). Agricultural area, area that may be irrigated, number of farms with irrigation, irrigation method, water source and %-distribution of farms by percentage of area irrigated*

District	Agric. area (ha)		Irrigated area			Equipment used (%)			Water source			Percent of area irrigated				
Region/County	**Total**	**Irrigated**	**% of total**	**% of irrig.**	**No. farms**	**Rain-gun**	**Sprin -kler**	**Trickle drip**	**River, beck**	**Lake, tarn**	**Ground -water**	**<24 %**	**25-49%**	**50-74%**	**75-99%**	**100 %**
Eastern (north)	**292836**	**60079**	**20.5**	**45.5**	**4162**											
Akershus	81408	8169	10.0	6.2	468	63	45	10	56	42	9	15	21	21	21	22
Hedmark	108626	25242	23.2	19.1	1256	69	42	1	63	40	5	12	21	22	22	23
Oppland	102803	26668	25.9	20.2	2438	59	64	1	73	29	3	10	24	27	21	19
Eastern (south)	**199114**	**42300**	**21.2**	**32.0**	**3379**											
Østfold	77134	12472	16.2	9.4	667	71	43	4	48	52	6	7	16	20	25	33
Vestfold	43568	12325	28.3	9.3	829	72	50	7	49	47	15	9	14	18	26	33
Telemark	26189	4242	16.2	3.2	626	40	61	11	61	36	10	15	28	24	15	18
Buskerud	52224	13261	25.4	10.0	1257	59	58	4	71	28	4	11	25	24	19	22
South/South-west	**129139**	**12833**	**9.9**	**9.7**	**1670**											
A.Agder	12037	3339	27.7	2.5	505	36	79	3	55	52	3	13	25	24	18	20
V.Agder	20276	3330	16.4	2.5	497	25	79	7	68	35	6	19	26	22	15	19
Rogaland	96827	6164	6.4	4.7	668	41	61	4	62	40	6	17	29	23	15	15
Central	**226552**	**6181**	**2.7**	**4.7**	**783**											
Møre/Roms.	61580	2036	3.3	1.5	306	21	81	3	88	9	5	18	20	25	18	20
S.Trøndelag	76471	1645	2.2	1.2	204	41	66	3	80	18	5	27	29	21	10	13
N.Trøndelag	88501	2500	2.8	1.9	273	49	67	5	33	65	6	21	25	21	14	21
Western	**94782**	**10664**	**11.3**	**8.1**	**2162**											
Hordaland	47113	3113	6.6	2.4	727	9	83	23	74	21	11	13	22	24	12	29
Sogn/Fjord.	47669	7552	15.8	5.7	1435	18	87	7	85	14	7	12	25	27	14	22
Total	**942424**	**132057**	**14.0**	**100.0**	**12609**	**48**	**64**	**5**	**67**	**33**	**6**	**12**	**23**	**24**	**19**	**22**

Appendix II.

Research note 23.10.2003. Estimation of pan evaporation from weather data (Hugh Riley)

Background:

In Norway, a pan evaporimeter designed by J. Thorsrud at Kise Research Station has been used to estimate potential evapotranspiration (ETo) for agricultural crops for many years. This instrument has a surface area of 0.25 m^2 and a depth of 60 cm. The water surface is kept at ground level. Measurements of evaporation, rainfall and overflow are normally made on a daily basis from May to September. Data obtained with this instrument has been used in much of our research on irrigation requirement, and is still used for advisory purposes.

Several studies in Scandinavia have shown that this and other similar evaporimeters often give slightly lower overall evaporation than that calculated using the Penman equation. There is also a consistent seasonal imbalance, the equation giving higher figures in spring and lower figures in autumn than evaporimeters. This may be due to soil heat flux being ignored. Further, the latter equation gives negative values in winter under Scandinavian conditions.

In Sweden, a small evaporimeter designed by S. Andersson has been used in agricultural research and extension. This is a much smaller instrument than that of Thorsrud, and it responds rapidly to weather variations. Johansson (1969) derived an equation relating measurements from Andersson's evaporimeter to global SW radiation (X_1) and an advection term (X_2), the latter being the product of mean wind-speed and vapour pressure deficit ($w(e_s–e)$), all measured on a daily basis (equation 1). (In this and other equations, radiation is given here in MJ m^{-2}, wind-speed in m s^{-1} at and vapour pressure deficit in mbar).

(1) $ETo\ (mm\ d^{-1}) = 0.14 + 0.0884*X_1 + 0.0975*X_2$ (n=181, R^2 = 0.91)

I have previously found this equation to accord well with Thorsrud evaporimeter data from Kise (Riley 1989). I derived similar equations for both Thorsrud (equation 2) and Andersson (equation 3) evaporimeters, using 1979-82 evaporation data from Kise.

(2) $ETo\ (mm\ d^{-1}) = 0.44 + 0.0662*X_1 + 0.1050*X_2$ (n=593, R^2 = 0.53)
(3) $ETo\ (mm\ d^{-1}) = -0.23 + 0.0992*X_1 + 0.1950*X_2$ (n=546, R^2 = 0.78)

The smaller constant term and larger coefficients in eq. (3) than in eq. (2) reflect the more sensitive response of the Andersson evaporimeter to changes in weather conditions. It yielded on average 16% higher evaporation at Kise than did the Thorsrud evaporimeter, varying from 5% to 22% between the four years.

This study:

This research note describes an attempt to obtain an equation that is generally valid for conditions in Norway (and other similar regions), in order to predict growing season potential evaporation, using data from the many automatic weather stations now in existence. Such data is required for irrigation scheduling. It may also be used in models, such as the EU-rotate_N fertilizer response model presently being developed (which uses pan evaporation as input).

Seventeen seasons' records (1987-2003) of Thorsrud evaporimeter values and weather data from the automatic weather station at Kise are used (a total of 2601 days or 85 months), covering a range of conditions (mean seasonal evaporation sum 320 mm, range 260-400mm). This is considered to be representative of conditions in most agricultural regions of Norway.

Results:
The new dataset yielded an equation (4) with similar coefficients to both eq. (1) and eq. (2). Both terms were statistically significant. Global radiation accounted for about three times as much of the variation in evaporation as did the advection term. Daily values calculated with this equation are plotted against measured values in fig. 1.

(4) ETo (mm d^{-1}) = $0.48 + 0.0717*X_1 + 0.1071*X_2$ (n=2061, $R^2 = 0.51$)

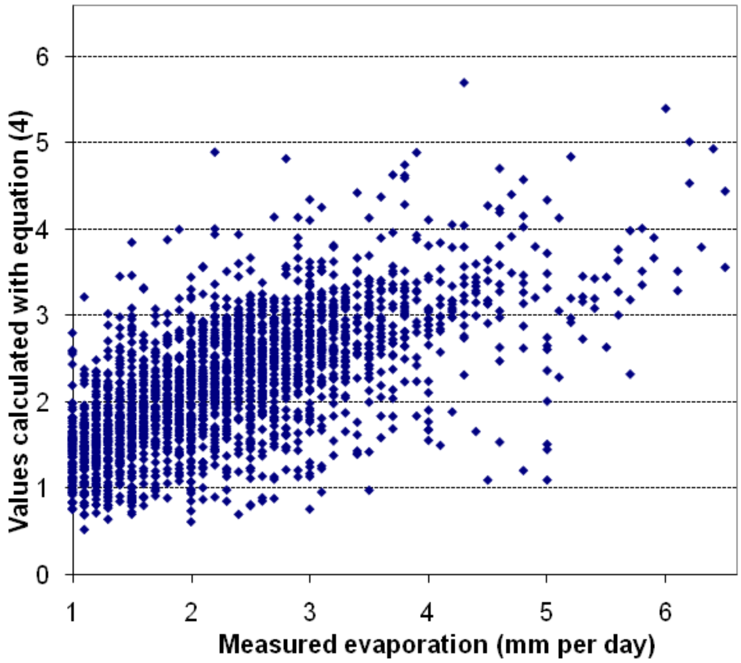


Fig. 1. Daily values of evaporation May- September 1987-2003 at Kise, measured with Thorsrud evaporimeter and calculated from weather data using equation (4).

The large scatter in this figure reflects the relatively slow response of the Thorsrud evaporimeter due to its high thermal capacity. Uncertainty in daily values also derives from the fact that measurements over weekends are often arbitrarily ascribed to individual days. Nevertheless, it is clear that the equation often overestimates low daily evaporation values and underestimates high daily values. A possible reason for this may be that evaporation is higher in June and July than in May and August, whereas the differences in radiation are fairly small.

To account for such a seasonal effect, equation (5) was derived, including a quadratic effect of month number (X_3 , May = 5, May² = 25 etc.). This gave a significant increase in the variance accounted for, and better agreement between measured and calculated values in individual months (fig. 2).

(5) ETo (mm d^{-1}) = $-5.38 + 0.0594* X_1 + 0.1088*X_2 + 1.84*X_3 - 0.134*(X_3)^2$
(n=2061, $R^2 = 0.55$)

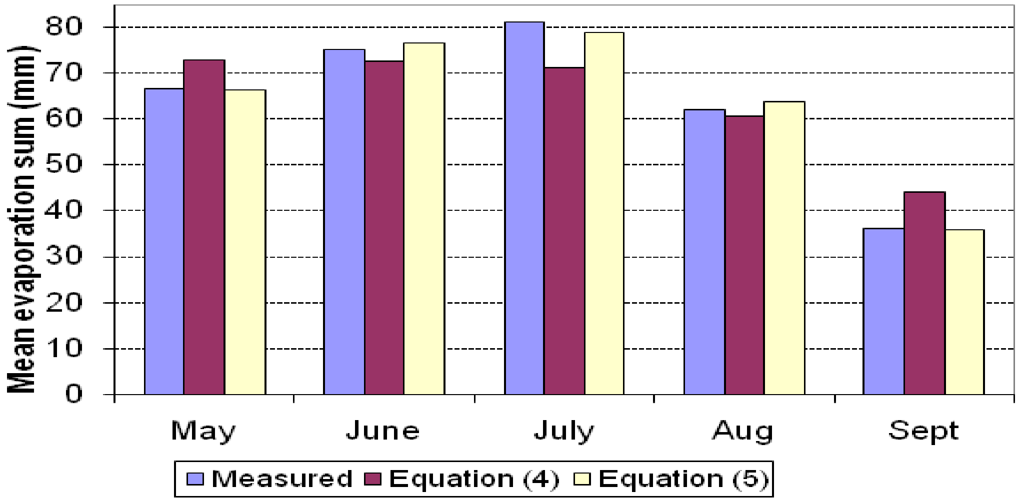


Fig. 2. Mean monthly sums of evaporation May- September 1987-2003 at Kise, measured with Thorsrud evaporimeter and calculated from weather data using equations (4) and (5).

In order to evaluate the equations under the whole range of conditions represented by the dataset, individual calculated monthly sums are plotted against measured values in fig. 3. This figure confirms the better data fit of equation (5), but it also shows that neither equation gave adequate estimates of high evaporation in three of the 85 months (June 1992, July 1994 and July 1996). Regression of monthly sums revealed coefficients of determination of 80% and standard errors of prediction around 7 mm per month. This seems reasonably accurate.

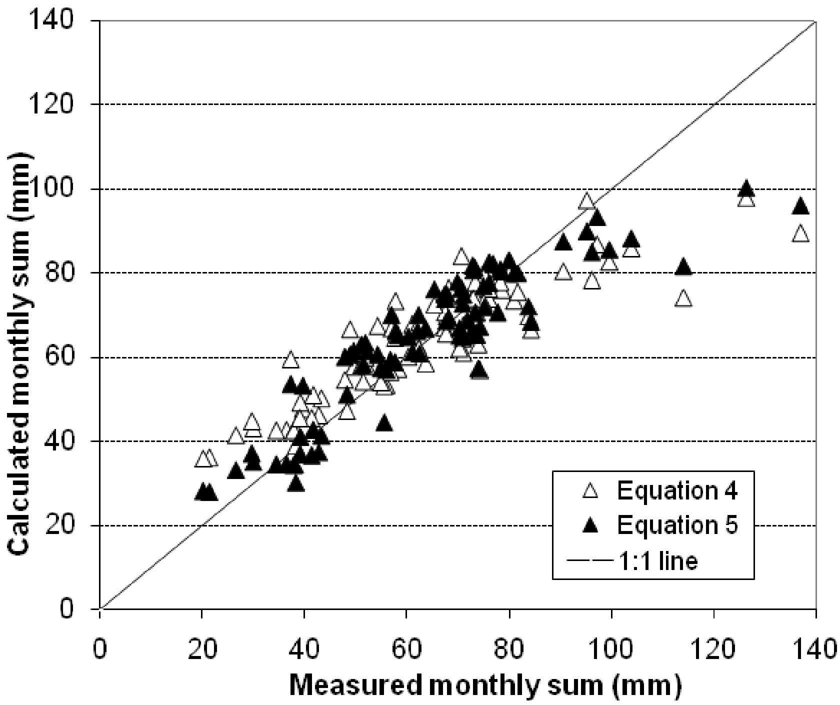


Fig. 3. Individual monthly sums of evaporation calculated from Kise weather data using equations (4) and (5) plotted against measured values for the growing seasons 1987-2003.

Examination of the annual sums for each equation showed very similar values for equations (1) and (2), and for equations (4) and (5). Equation (3), that based on the Andersson evaporimeter, gave values closer to those measured in two years with high evaporation sums (1994 and 1996), but otherwise considerably higher than those obtained with the Thorsrud evaporimeter (fig. 4). Equations (4) and (5) gave higher values than equations (1) and (2).

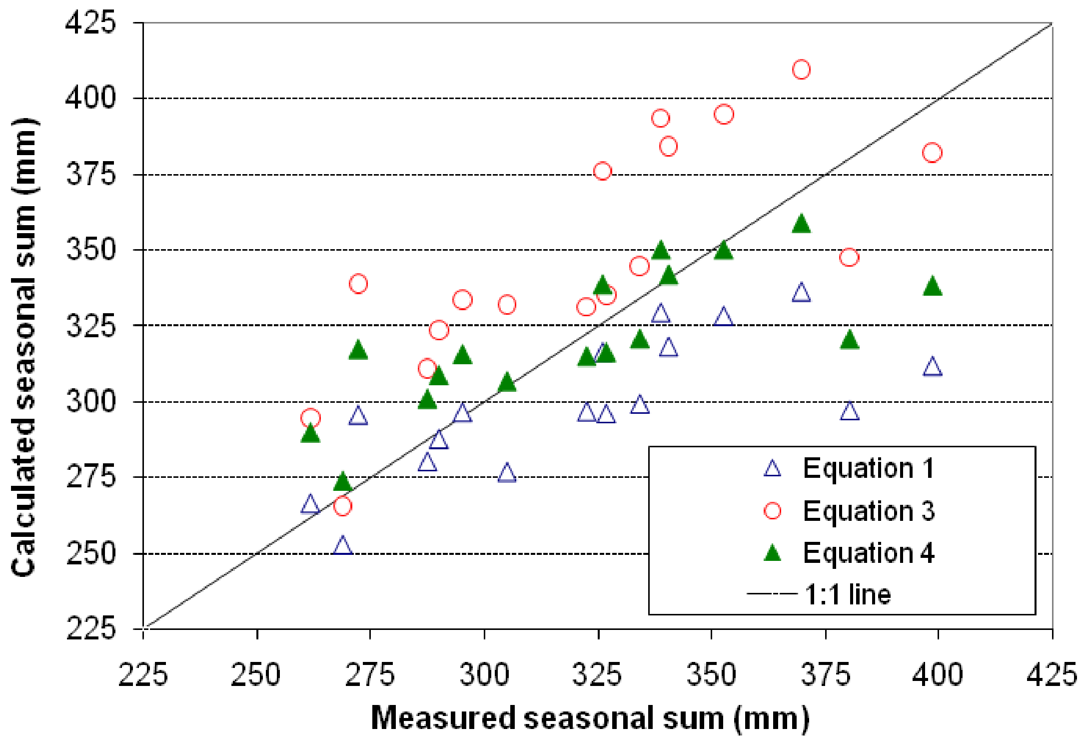


Fig. 4. Individual annual sums of evaporation calculated from Kise weather data using equations (1), (3) and (4) plotted against measured values for 1987-2003.

Summary and conclusion:
A dataset of seventeen growing seasons' pan evaporation and weather data was used to derive equations for predicting potential evaporation from global radiation, wind-speed and vapour pressure deficit. The equations gave in most cases good agreement with measured values, especially when monthly evaporation sums were considered. However, they gave too low values in a few cases with very high evaporation. The best result was obtained with an equation (no. 5) that included 'dummy' variables to account for seasonal effects. Equation (5) may be used to estimate pan evaporation in the period May – September in many parts of Norway, and it can probably also be used without serious error for April and October, for which months it predicts average evaporation at Kise of about 36 and 10 mm, respectively.

References:

Johansson, W. 1969.Meterologiska elements inflytande på avdunstningen från Anderssons evaporimeter. Grundförbättring, 22, 82-105.

Riley, H. 1989. Irrigation of cereals, potato, carrot and onion on a loam soil at various levels of moisture deficit. Norwegian J. Agric. Sciences 3: 117-145.

Appendix III.

Normal (1961-1990) precipitation sums (mm) for a selection of localities in four regions of Norway, compared to the weather stations chosen to represent each region in the simulation study.

Kise for the Eastern region (north):

Station no.	Locality	Mun. code	Municipality	Altitude m a.s.l.	April	May	June	July	Aug.	Sept.	Apr.-June	July-Sept.	Growing season	Year
1220	Jønsberg	417	Stange	218	28	44	60	74	68	61	132	203	335	552
1226	Løten	415	Løten	349	33	48	67	81	71	67	148	219	367	610
604	Flisa	425	Åsnes	184	36	50	67	75	69	70	153	214	367	617
665	Elverum	427	Elverum	188	36	55	71	86	76	77	162	239	401	670
565	Vinger	402	Kongsvinger	175	36	52	68	77	80	79	156	236	392	664
1355	Vinstra	516	Nord-Fron	241	16	34	52	60	55	48	102	163	265	430
1190	Biri	502	Gjøvik	190	37	57	71	87	91	86	165	264	429	754
1171	Einavatn	529	Vestre Toten	406	45	51	72	78	81	77	168	236	404	710
1150	Østre Toten	523	Østre Toten	264	32	44	60	77	72	66	136	215	351	600
493	Hvam	236	Nes i Akershus	162	36	48	64	71	75	78	148	224	372	670
1112	Eidsvoll Verk	237	Eidsvoll	181	44	55	69	76	84	88	168	248	416	789
2410	Ask	605	Ringerike	77	31	44	60	74	73	68	135	215	350	580
2487	Nesbyen II	616	Nes i Buskerud	165	20	40	52	66	63	53	112	182	294	460
2074	Brandbu - Vest	534	Gran	142	37	47	59	73	73	70	143	216	359	640
1255	***KISE***	***412***	***Ringsaker***	***128***	***34***	***44***	***59***	***66***	***76***	***64***	***137***	***206***	***343***	***585***
			Mean	**205**	**33**	**48**	**63**	**75**	**74**	**70**	**144**	**219**	**363**	**622**
			Std. deviation	**84**	**8**	**6**	**7**	**7**	**9**	**11**	**19**	**25**	**44**	**97**

Ås for the Eastern region (south):

Station no.	Locality	Mun. code	Municipality	Altitude m a.s.l.	April	May	June	July	Aug.	Sept.	Apr.-June	July-Sept.	Growing season	Year
195	Ørje	119	Marker	123	56	69	79	92	95	101	204	288	492	829
328	Sander	128	Rakkestad	144	41	54	69	72	84	89	164	245	409	795
393	Trøgstad	122	Trøgstad	158	42	55	67	77	85	89	164	251	415	783
1715	Rygge	136	Rygge	40	43	57	63	73	88	94	163	255	418	829
1729	Jeløy	104	Moss	12	42	59	58	69	86	90	159	245	404	779
113	Prestebakke	101	Halden	157	47	59	78	76	84	98	184	258	442	895
315	Kalnes	102	Sarpsborg	56	42	58	72	73	83	94	172	250	422	853
2686	Drammen	602	Drammen	61	48	70	70	87	100	109	188	296	484	950
2707	Rove	702	Holmestrand	79	49	69	65	79	94	107	183	280	463	945
3000	Larvik	709	Larvik	28	55	70	64	79	109	112	189	300	489	1050
2745	Melsom	720	Stokke	26	54	70	65	79	103	109	189	291	480	1029
3029	Skien II	806	Skien	24	39	63	60	74	97	99	162	270	432	840
3053	Notodden	807	Notodden	34	32	55	56	74	83	84	143	241	384	691
3210	Gvarv	822	Gvarv	26	34	65	64	81	95	96	163	272	435	780
1785	***ÅS***	***214***	***Ås***	***95***	***39***	***60***	***68***	***81***	***83***	***90***	***167***	***254***	***421***	***785***
			Mean	**71**	**44**	**62**	**67**	**78**	**91**	**97**	**173**	**266**	**439**	**856**
			Std. deviation	**52**	**7**	**6**	**7**	**6**	**8**	**9**	**16**	**20**	**34**	**100**

Særheim for the Southern / South-Western region:

Station no.	Locality	Mun. code	Municipality	Altitude m a.s.l.	April	May	June	July	Aug.	Sept.	Apr.-June	July-Sept.	Growing season	Year
4456	Sola	1124	Sola	7	50	68	73	91	115	156	191	362	553	1180
4416	Hognestad	1121	Time	19	56	68	72	94	115	157	196	366	562	1254
4436	Egersund	1101	Eigersund	4	73	85	84	103	133	169	242	405	647	1491
4590	Fister	1133	Hjelmeland	1	63	73	85	105	121	177	181	403	624	1440
4265	Flekkefjord	1004	Flekkefjord	5	91	102	100	119	158	208	293	485	778	1965
4111	Mandal	1002	Mandal	138	72	92	86	98	135	166	250	399	649	1534
4177	Lindesnes	1029	Lindesnes	13	60	71	65	78	102	125	196	305	501	1159
3904	Kjevik	1001	Kristiansand	12	59	86	75	88	141	164	220	393	613	1299
3814	Landvik	904	Grimstad	6	58	82	71	92	113	136	211	341	552	1230
3606	Arendal	903	Arendal	44	52	69	63	79	97	117	184	293	477	1040
3845	Herefoss	928	Birkeland	85	62	87	68	92	116	139	217	347	564	1293
3656	Nelaug	929	Åmli	142	60	86	78	99	109	140	224	348	572	1230
3534	Risør	901	Risør	36	54	76	61	88	110	114	191	312	503	1090
3586	Lyngør	914	Tvedestrand	4	43	64	50	71	91	94	157	256	413	869
4432	***SÆRHEIM***	***1120***	***Klepp***	***14***	***58***	***68***	***74***	***94***	***123***	***158***	***200***	***375***	***575***	***1260***
			Mean	**35**	**61**	**78**	**74**	**93**	**119**	**148**	**210**	**359**	**572**	**1289**
			Std. deviation	**48**	**11**	**11**	**12**	**12**	**18**	**29**	**33**	**56**	**86**	**253**

Kvithamar for the Central region:

Station no.	Locality	Mun. code	Municipality	Altitude m a.s.l.	April	May	June	July	Aug.	Sept.	Apr.-June	July-Sept.	Growing season	Year
6965	Kvarme	1717	Frosta	25	46	44	54	71	70	105	144	246	390	830
7012	Stiklestad	1721	Verdal	49	53	49	63	78	73	108	165	259	424	900
7067	Mære	1702	Steinkjær	20	45	42	53	72	61	98	140	231	371	820
6976	Eggen	1719	Levanger	95	45	42	52	72	64	103	139	239	378	815
6981	Staup	1729	Inderøy	42	43	42	74	68	96	90	159	254	413	780
7091	Berg	1736	Snåsa	127	57	45	67	98	85	133	169	316	485	1040
7155	Ørland	1621	Ørland	9	60	50	66	85	86	133	176	304	480	1048
6618	Øyum	1638	Orkdal	22	53	41	61	86	80	111	155	277	432	965
6715	Leinstrand	1601	Trondheim	11	50	45	60	81	73	102	155	256	411	832
6827	Løksmyr	1653	Melhus	165	63	55	75	96	85	122	193	303	496	1021
6830	Selbu	1664	Selbu	197	49	51	72	98	92	104	172	294	466	840
6603	Lensvik	1622	Agdenes	15	84	61	62	86	80	154	207	320	527	1310
6490	Rindal	1567	Rindal	231	62	49	71	92	90	134	182	316	498	1109
6480	Surnadal	1566	Surnadal	39	83	64	86	117	119	173	233	409	642	1394
6910	***KVITHAMAR***	***1712***	***Stjørdal***	***12***	***49***	***53***	***68***	***94***	***87***	***113***	***170***	***294***	***464***	***892***
			Mean	**71**	**56**	**49**	**66**	**86**	**83**	**119**	**171**	**288**	**458**	**973**
			Std. deviation	**74**	**13**	**7**	**9**	**13**	**14**	**23**	**26**	**45**	**70**	**185**

Appendix IV.

Description of the water balance model incorporated in EU-Rotate_N (C. Ramos & J. Doltra)

Here we will explain how crop evapotranspiration (**ETc**) is calculated. We will follow basically the dual crop coefficient as described by Allen et al. (1998).

In this approach **ETc** is calculated as:

$$\mathbf{ETc = E + T = (Ke + Kcb) \cdot ETo} \qquad (1)$$

Where **E** is soil evaporation and **T** is crop transpiration, **Ke** is the soil evaporation coefficient, **Kcb** is the so called basal crop coefficient, and **ETo** is the reference evapotranspiration.

Calculating transpiration

Daily crop transpiration is calculated by:

$$\mathbf{T = Kcb \cdot ETo} \qquad (2)$$

where the basal crop coefficient **Kcb** is defined as the ratio ETc/ETo when the soil surface is dry but the crop is transpiring at the potential rate, with no restriction due to water stress. This coefficient varies as shown schematically in Fig. 1. We see that **Kcb** varies with crop stage: initial, development, midseason, and late season or maturity. Values for **Kcb** for several vegetable crops are shown in table 1.

Table 2 gives the length of crop stages for several vegetable crops, planting dates and climate regions. These lengths are critical in **ETc** calculation. Allen et al. (1998) give the default lengths of these stages for many crops including vegetables. However, they advise of using locally obtained values when available. Many times the only local data available on crop growth and development is the total length of the crop season; in this case, one can estimate the duration of each stage by correcting the values given in table 2 for a given stage, keeping the same proportion as the total length of the crop season as shown in table 2, that is, multiplying the stage durations listed in table 2 by the ratio: (total crop season duration observed)/(total crop season duration listed in table 2. Snyder (2000) gives % duration of each plant development phase for many vegetable crops, although they differ slightly of those calculated from table 2. Crop Kc coeeficients given by Snyder (2000) are also somewhat different for those given by Allen et al. (1998).

The **initial** stage runs from planting to a groundcover around 10%; the crop **development** stage runs from 10% ground cover to effective full cover (see pags. 95-97 of Allen et al., 1998) For row crops, effective full cover can be reached when leaves of plants from adjacent rows begin to intermingle, and soil shading is nearly complete. In other cases, such as crops taller than 0.5 m, effective full cover is reached when ground cover fraction is about 0.7-0.8, and soil shading do not change significantly with further growth. Another way of determining the occurrence of effective full cover is when the leaf area index (LAI) reaches 3.

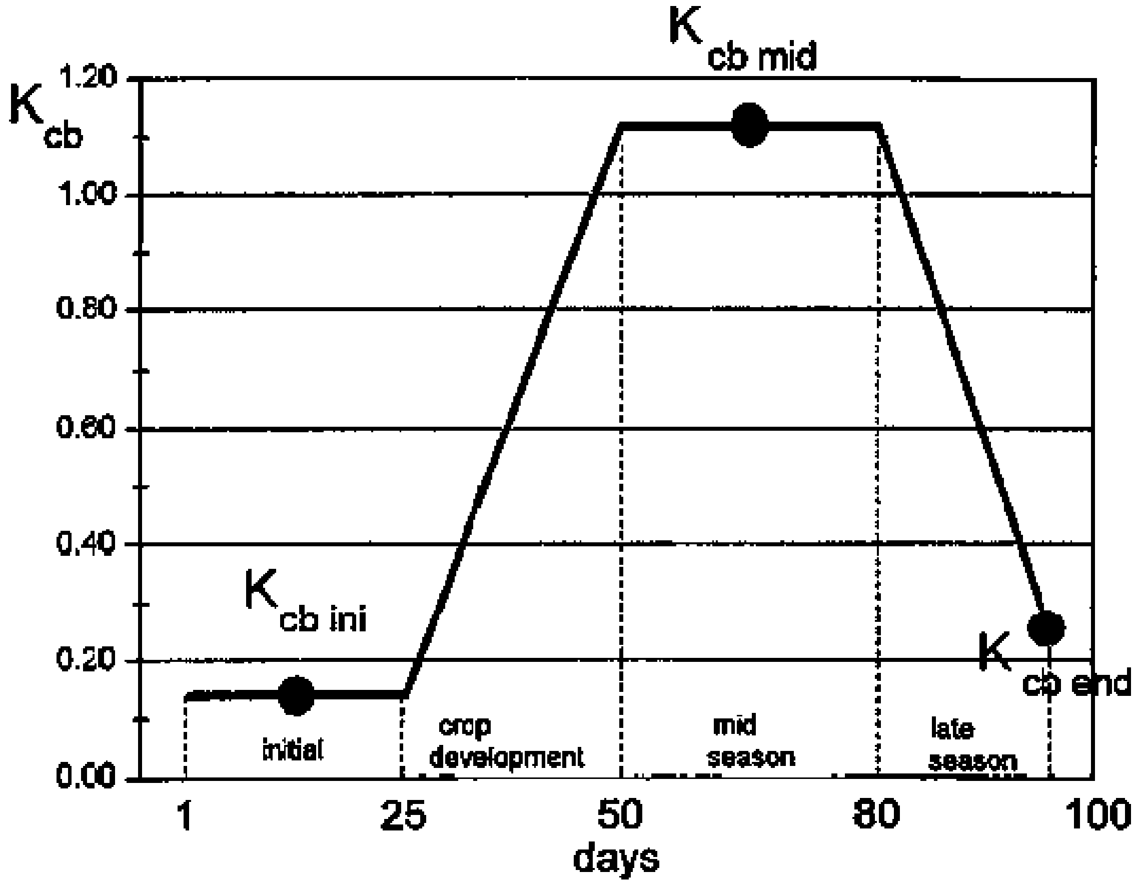


Fig. 1 Basal crop coefficient (K_{cb}) curve for a crop using growth stage lengths of 25, 25, 30 and 20 days (from Allen et al. 1998).

The **mid-season** stage goes from effective full cover to the start of maturity. The yellowing or senescence of leaves indicates the start of the maturity stage. This stage can be short for those vegetables that are harvested before reaching maturity. The **late season or maturity** stage runs from the start of maturity to harvest or full senescence.

Values of **Kcb** given in table 1 are for average climate conditions of daily wind velocity at 2 m height and an air RHmin of 45%. An adjustment of Kcb for mid-season and late season stages when climate conditions are quite different of those mentioned can be done by the formula:

$$K_{cb} = K_{cb(Tab)} + \left[0.04(u_2 - 2) - 0.004(RH_{min} - 45)\right]\left(\frac{h}{3}\right)^{0.3} \quad (3)$$

TABLE 1. Basal crop coefficients, K_c, for non stressed, well-managed vegetable crops in subhumid climates (RH_{min} 45%, u_2 2 m/s) for use with the FAO Penman-Monteith ET_o (from Allen et al., 1998)

Crop			
a. Small Vegetables	**0.15**	**0.95**	**0.85**
Broccoli		0.95	0.85
Brussel Sprouts		0.95	0.85
Cabbage		0.95	0.85
Carrots		0.95	0.85
Cauliflower		0.95	0.85
Celery		0.95	0.90
Garlic		0.90	0.60
Lettuce		0.90	0.90
Onions			
- dry		0.95	0.65
- green		0.90	0.90
- seed		1.05	0.70
Spinach		0.90	0.85
Radishes		0.85	0.75
b. Vegetables - Solanum Family *(Solanaceae)*	**0.15**	**1.10**	**0.70**
Egg Plant		1.00	0.80
Sweet Peppers (bell)		1.00[1]	0.80
Tomato		1.10[1]	0.60-0.80
c. Vegetables - Cucumber Family *(Cucurbitaceae)*	**0.15**	**0.95**	**0.70**
Cantaloupe		0.75	0.50
Cucumber			
- Fresh Market		0.95[1]	0.70
- Machine harvest		0.95	0.80
Pumpkin, Winter Squash		0.95	0.70
Squash, Zucchini		0.90	0.70
Sweet Melons		1.00	0.70
Watermelon		0.95	0.70
d. Perennial Vegetables (with winter dormancy and initially bare or mulched soil)			
Artichokes	0.15	0.95	0.90
Asparagus	0.15	0.90[7]	0.20

[1]*Beans, Peas, Legumes, Tomatoes, Peppers and Cucumbers are sometimes grown on stalks reaching 1.5 to 2 meters in height. In such cases, increased K_{cb} values need to be taken. For green beans, peppers and cucumbers, 1.10 can be taken, and for tomatoes, dry beans and peas, 1.15. Under these conditions h should be increased also.*

[2] *The Kcb end value for potatoes is about 0.35 for long season potatoes with vine kill.*

[3] *The Kcb for asparagus usually remains at Kcb ini during harvest of the spears, due to sparse ground cover. The Kcb mid value is for following regrowth of vegetation following termination of harvest of spears.*

TABLE 2. Lengths of crop development stages for various vegetables, planting periods and climatic regions (days) (from Allen et al., 1998)

Crop	Init. (L_{ini})	Dev. (L_{dev})	Mid (L_{mid})	Late (L_{late})	Total	Plant Date	Region
a. Small Vegetables							
Broccoli	35	45	40	15	135	Sept	Calif. Desert, USA
Cabbage	40	60	50	15	165	Sept	Calif. Desert, USA
Carrots	20	30	50/30	20	100	Oct/Jan	Arid climate
	30	40	60	20	150	Feb/Mar	Mediterranean
	30	50	90	30	200	Oct	Calif. Desert, USA
Cauliflower	35	50	40	15	140	Sept	Calif. Desert, USA
Celery	25	40	95	20	180	Oct	(Semi)Arid
	25	40	45	15	125	April	Mediterranean
	30	55	105	20	210	Jan	(Semi)Arid
Crucifers[1]	20	30	20	10	80	April	Mediterranean
	25	35	25	10	95	February	Mediterranean
	30	35	90	40	195	Oct/Nov	Mediterranean
Lettuce	20	30	15	10	75	April	Mediterranean
	30	40	25	10	105	Nov/Jan	Mediterranean
	25	35	30	10	100	Oct/Nov	Arid Region
	35	50	45	10	140	Feb	Mediterranean
Onion (dry)	15	25	70	40	150	April	Mediterranean
	20	35	110	45	210	Oct; Jan.	Arid Region; Calif.
Onion (green)	25	30	10	5	70	April/May	Mediterranean
	20	45	20	10	95	October	Arid Region
	30	55	55	40	180	March	Calif., USA
Onion (seed)	20	45	165	45	275	Sept	Calif. Desert, USA
Spinach	20	20	15/25	5	60/70	Apr; Sep/Oct	Mediterranean
	20	30	40	10	100	November	Arid Region
Radish	5	10	15	5	35	Mar/Apr	Medit.; Europe
	10	10	15	5	40	Winter	Arid Region
b. Vegetables – Solanum Family *(Solanaceae)*							
Egg plant	30	40	40	20	130\14	October	Arid Region
	30	45	40	25	0	May/June	Mediterranean
Sweet peppers (bell)	25/30	35	40	20	125	April/June	Europe and Medit.
	30	40	110	30	210	October	Arid Region
Tomato	30	40	40	25	135	January	Arid Region
	35	40	50	30	155	Apr/May	Calif., USA
	25	40	60	30	155	Jan	Calif. Desert, USA
	35	45	70	30	180	Oct/Nov	Arid Region
	30	40	45	30	145	April/May	Mediterranean
c. Vegetables - Cucumber Family *(Cucurbitaceae)*							
Cantaloupe	30	45	35	10	120	Jan	Calif., USA
	10	60	25	25	120	Aug	Calif., USA
Cucumber	20	30	40	15	105	June/Aug	Arid Region
	25	35	50	20	130	Nov; Feb	Arid Region
Pumpkin, Winter squash	20	30	30	20	100	Mar, Aug	Mediterranean
	25	35	35	25	120	June	Europe
Squash, Zucchini	25	35	25	15	100	Apr; Dec.	Medit.; Arid Reg.
	20	30	25	15	90	May/June	Medit.; Europe

Under conditions of no water stress, transpiration on a given day is calculated by applying equation (1) and Kcb is determined using the information in Tables 1 and 2. In the next section we will describe how transpiration is determined under conditions of water stress.

Calculating Kcb when there is water stress

When soil water availability is limiting transpiration, then:

$$T = Ks \cdot Kcb \cdot ETo \qquad (4)$$

where Ks is a water stress coefficient that equals 1 under no water stress and is zero when The Ks coefficient varies with soil water availability in the root zone as shown in Fig. 2.

Here we introduce some soil water definitions:

- Total available water (**TAW**)
- Readily available water (**RAW**)
- Soil water depletion
- Critical Soil Water content (**SW_{crit}**)

TAW is the water content in the root zone between FC (field capacity) and PWP (permanent wilting point):

$$\mathbf{TAW = 1000\ (\vartheta_{FC} - \vartheta_{WP})\ Zr} \qquad (5)$$

Where ϑ represents volumetric water contents at field capacity (FC) and wilting point (WP), **Zr** is root depth in meters and **TAW** is given in mm.

RAW represents the ready available water, that is the amount of water that can be extracted from soil between FC and PWP without the plant experiencing any water stress. It is convenient to express **RAW** as a fraction **p** of **TAW**, that is:

$$\mathbf{AW = p \cdot TAW} \qquad \mathbf{(6)}$$

The value of **p** depends on the crop, on the soil texture, and on the evaporative demand, as measured by **ETc** (with no stress). Table 3 gives **p** values for different vegetable crops for **ETc** values of 5 mm/day. For other ETc values **p** can be calculated using:

$$p = p_{table\ 3} + 0.04 \cdot (5 - ETc) \qquad (7)$$

Now, from eq. 5, 6 and 7, we can define the critical soil water content (**SW_{cri},**, mm**)** at which transpiration starts to decrease as:

$$\mathbf{SW_{crit} = [\vartheta_{FC} - p \cdot (\vartheta_{FC} - \vartheta_{WP})] \cdot Zr \cdot 1000} \qquad (8)$$

It is supposed that soil water between FC and SAT (saturation) can be extracted by the plants at the potential rate, and no stress due to a lack of oxygen is considered.

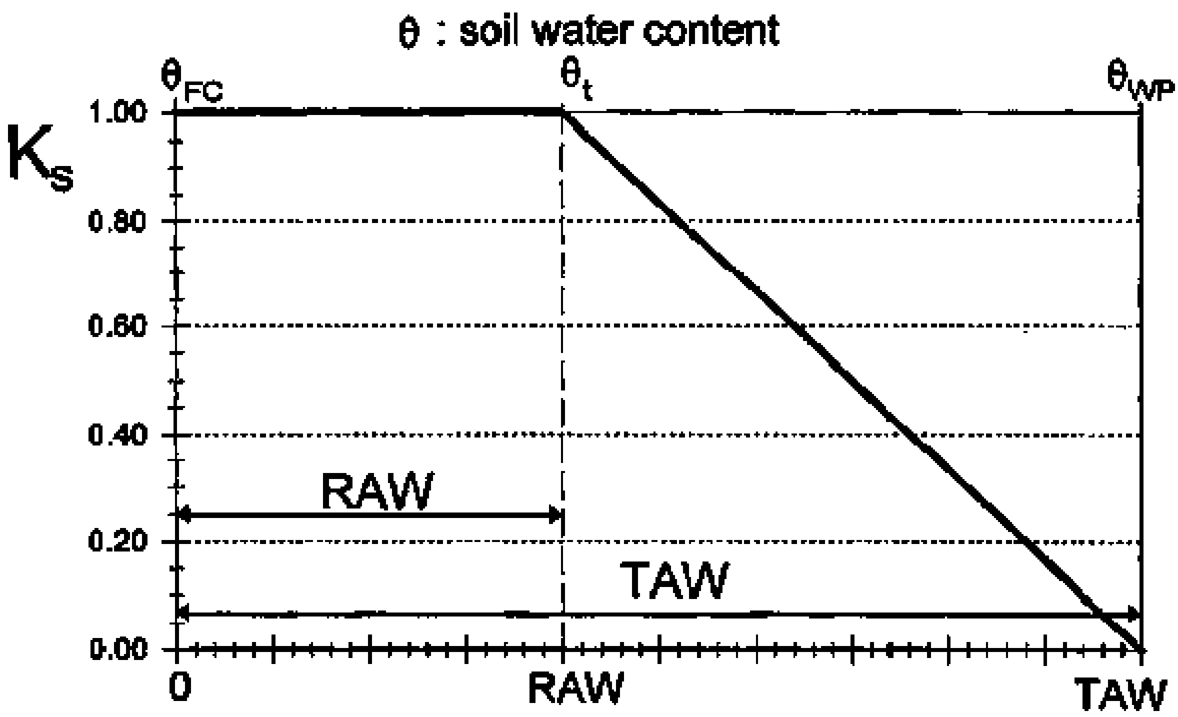


Fig. 2 Variation of the water stress coefficient (Ks) with the soil water content or the corresponding water deficit for the soil root zone (from Allen et al. 1998).

To obtain Ks for a given case on a soil grid, we follow the steps:

- Sum water depth for all cells with roots (ΣW) (i.e.: $\Sigma 50\ \vartheta_{i,j}$)
- Calculate the sum of SW_{crit} for all cells with roots (ΣSW_{crit}) (i.e.: $\Sigma 50\ [\vartheta_{FC} - p\cdot(\vartheta_{FC} - \vartheta_{\mathbf{WP}})]_{i,j}$
- Calculate Ks:
  - If $\Sigma W > \Sigma SW_{crit}$ then $Ks = 1$
  - If $\Sigma 50\cdot\vartheta_{\mathbf{PWpi,j}} < \Sigma W < \Sigma\ SW_{crit}$ then $Ks = (\Sigma W - \Sigma 50\cdot\vartheta_{\mathbf{PWpi,j}})/(\ \Sigma SW_{crit} - \Sigma 50\cdot\vartheta_{\mathbf{Wpi,j}}\ )$
  - If $\Sigma W < \Sigma 50\cdot\vartheta_{\mathbf{Wpi,j}}$ then $Ks = 0$

Table 3. Ranges of maximum effective rooting depth (Z_r), and soil water depletion fraction for no stress (**p**) for some crops (from Allen et al., 1998).

Crop	Maximum Root Depth[1] (m)	Depletion Fraction[2] (for ET ≅ 5 mm/day) p
a. Small Vegetables		
Broccoli	0.4-0.6	0.45
Brussel Sprouts	0.4-0.6	0.45
Cabbage	0.5-0.8	0.45
Carrots	0.5-1.0	0.35
Cauliflower	0.4-0.7	0.45
Celery	0.3-0.5	0.20
Garlic	0.3-0.5	0.30
Lettuce	0.3-0.5	0.30
Onions - dry	0.3-0.6	0.30
- green	0.3-0.6	0.30
- seed	0.3-0.6	0.35
Spinach	0.3-0.5	0.20
Radishes	0.3-0.5	0.30
b. Vegetables – Solanum Family (*Solanaceae*)		
Egg Plant	0.7-1.2	0.45
Sweet Peppers (bell)	0.5-1.0	0.30
Tomato	0.7-1.5	0.40
c. Vegetables – Cucumber Family (*Cucurbitaceae*)		
Cantaloupe	0.9-1.5	0.45
Cucumber – Fresh Market	0.7-1.2	0.50
– Machine harvest	0.7-1.2	0.50
Pumpkin, Winter Squash	1.0-1.5	0.35
Squash, Zucchini	0.6-1.0	0.50
Sweet Melons	0.8-1.5	0.40
Watermelon	0.8-1.5	0.40

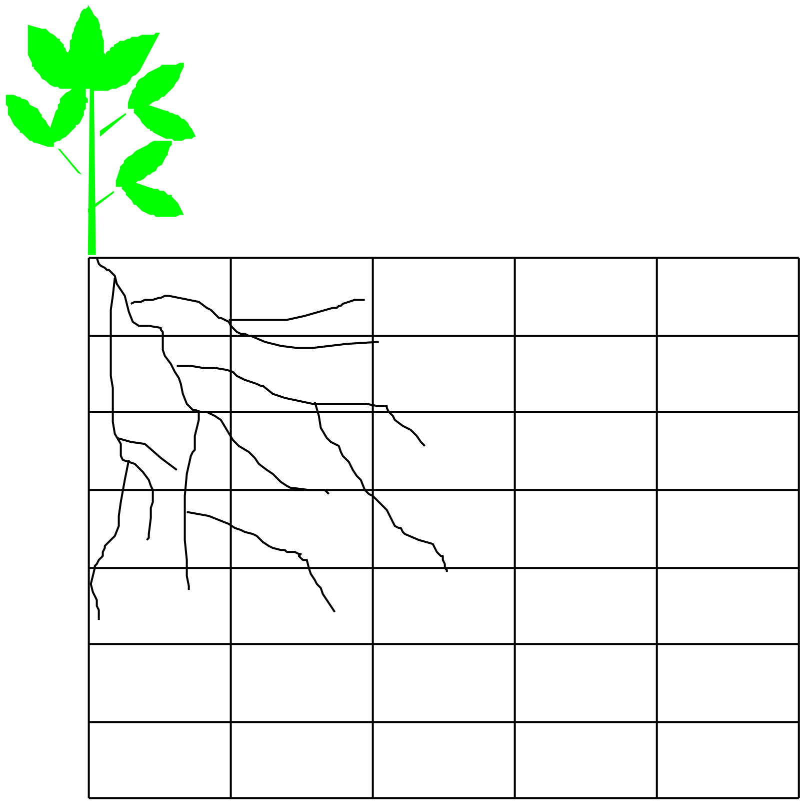
[2] The values for p apply for ETc ≅ 5 mm/day. For different ETc values, p can be adjusted using: $p = p_{table\ 3} + 0.04\cdot(5\text{-}ETc)$

Once we obtain Ks, then transpiration is calculated by equation (4). Now, this transpiration is distributed among all cells with roots. For this, we assume water uptake from each cell is proportional to the proportion of roots in the cell and to its available water content:

$$\mathbf{T_{i,j} = T^*[R_{i,j}\cdot Ks_{i,j} /\Sigma(R_{i,j}{*}Ks_{i,j}]} \qquad (8)$$

where $\mathbf{R_{i,j}}$ is the ratio of root length (or mass) in cell i,j to the total root length, and $\mathbf{Ks}_{i,j}$ is calculated using the same type formula as for the whole soil profile with roots:

- If $\vartheta_{i,j} > \vartheta_{crit\ i,j}$ then $Ks_{i,j} = 1$
- If $\vartheta_{PW\ i,j} < \vartheta_{i,j} < \vartheta_{crit\ i,j}$ then $Ks = (\vartheta_{i,j} - \vartheta_{PW\ i,j})/(\vartheta_{crit\ i,j} - \vartheta_{WP\ i,j})$
- If $\vartheta_{i,j} < \vartheta_{WP\ i,j}$ then $Ks = 0$



Calculating E

Soil evaporation is assumed to occur only from the surface soil layer that usually is taken to be 10 cm thick. In addition, when a crop is present **E** is assumed to occur only in the "exposed" soil surface (that is taken to be equal to **1-fc**, where **fc** stands for fraction cover).

Evaporation is calculated as:

$$E = Ke \cdot ETo \qquad (9)$$

where Ke is the soil evaporation coefficient. This coefficient varies with the fraction of the soil exposed to solar radiation and on the water content of the soil evaporation layer, as described later.

The evaporation coefficient is calculated as:

$$Ke = Kr\ (Kc\ max - Kcb) <= f_{ew}\ Kc\ max \qquad (10)$$

where:

- Ke is the soil evaporation coefficient
- Kcb is the basal crop coefficient
- Kc max is the maximum value of Kc following rain or irrigation
- Kr is a dimensionless evaporation reduction coefficient dependent on the cumulative depth of water depleted (evaporated) from the topsoil (evaporation layer)
- f_{ew} fraction of the soil that is both exposed and wetted, i.e., the fraction of soil surface from which most evaporation occurs.

Equation (10) can also be expressed as:

$$Ke = \min (Kr\ (Kc\ max - Kcb),\ f_{ew}\ Kc\ max) \qquad (11)$$

The calculation procedure consists in determining:

- the upper limit Kc max
- the soil evaporation reduction coefficient Kr
- the exposed and wetted soil fraction f_{ew}

Calculating Kc max

Kc max represents an upper limit on the evaporation and transpiration from any cropped surface and reflects the constraint placed by the available energy for evapotranspiration. Kc max ranges from about 1.05 to 1.30 when using the grass reference ETo:

$$K_{cmax} = \max\left(\left\{1.2 + \left[0.04(u_2 - 2) - 0.004(RH_{min} - 45)\right]\left(\frac{h}{3}\right)^{0.3}\right\}, \left\{K_{cb} + 0.05\right\}\right) \qquad (12)$$

where:

- h is the mean maximum plant height (m) during the period of calculation (initial, development, mid-season, or late-season)
- Kcb is the basal crop coefficient

Equation (12) ensures that Kc max is always greater or equal to the sum Kcb + 0.05. This requirement suggests that wet soil will always increase the value for Kcb by 0.05 following complete wetting of the soil surface, even during periods of full ground cover.

More details on the justification for equation (12) can be found in Allen et al. (1998)

RHmin is the mean value for the daily minimum air relative humidity (%). If this variable is not given in the weather data, it can be derived from them as follows:

$$RH_{min} = \frac{e^{\circ}(T_{dew})}{e^{\circ}(T_{max})} 100 \qquad (13)$$

where Tdew is mean dewpoint temperature and Tmax is mean daily maximum air temperature during the given growth stage. Where dewpoint temperature is not available or is of questionable quality, RHmin can be estimated by substituting mean daily minimum air temperature, Tmin, for Tdew:

$$RH_{min} = \frac{e^{\circ}(T_{min})}{e^{\circ}(T_{max})} 100 \qquad (14)$$

In the case of arid and semi-arid climates, Tmin in equation (14) should be adjusted by subtracting 2°C from the average value of Tmin to better approximate Tdew.

Calculation of the soil evaporation reduction coefficient Kr

Soil evaporation from the exposed soil (not covered by the crop) is assumed to take place in two stages: an energy limiting stage, and a falling rate stage. When the soil surface is wet, Kr is 1. When the water content in the upper soil becomes limiting, Kr decreases and becomes zero when the total amount of water that can be evaporated from the topsoil is depleted (fig. 3).

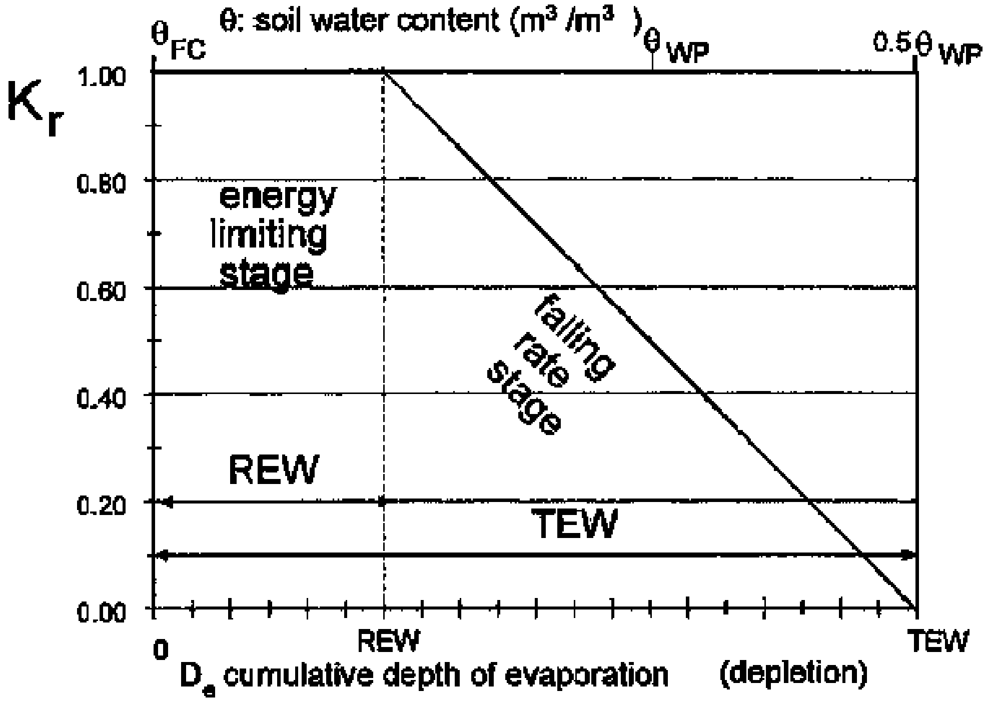


Fig. 3 Variation of the soil evaporation reduction coefficient with soil moisture (after Allen et al., 1998)

In Fig. 3 soil moisture is expressed as volumetric water content (upper axis) or as water depth (lower axis). Some of the additional terms used are:

- TEW: total evaporable water. It is the maximum depth of water that can be evaporated from the soil when the evaporation layer has been initially completely wetted and drained [mm].
- REW: readily evaporable water. It is is the maximum depth of water, below field capacity, that can be evaporated from the evaporation layer without restriction during stage 1). The depth normally ranges from 5 to 12 mm and is generally highest for medium and fine textured soils. Typical values for REW are given in Table 4. In the EUROTATE model, FC and WP are calculated using pedotransfer functions (see below). This parameter is analogous to the Q parameter in the STICS evaporation approach.

Table 4. Typical soil water characteristics for different soil types (after Allen et al., 1998)

Soil type (USDA Soil Texture Classification)	Soil water characteristics			Evaporation parameters	
	FC	WP	(FC - WP)	Amount of water that can be depleted by evaporation	
				stage 1 REW	stages 1 and 2 TEW* (Z_e = 0.10m)
	m^3/m^3	m^3/m^3	m^3/m^3	mm	mm
Sand	0.07 - 0.17	0.02 - 0.07	0.05 - 0.11	2 - 7	6 - 12
Loamy sand	0.11 - 0.19	0.03 - 0.10	0.06 - 0.12	4 - 8	9 - 14
Sandy loam	0.18 - 0.28	0.06 - 0.16	0.11 - 0.15	6 - 10	15 - 20
Loam	0.20 - 0.30	0.07 - 0.17	0.13 - 0.18	8 - 10	16 - 22
Silt loam	0.22 - 0.36	0.09 - 0.21	0.13 - 0.19	8 - 11	18 - 25
Silt	0.28 - 0.36	0.12 - 0.22	0.16 - 0.20	8 - 11	22 - 26
Silt clay loam	0.30 - 0.37	0.17 - 0.24	0.13 - 0.18	8 - 11	22 - 27
Silty clay	0-30 - 0.42	0.17 - 0.29	0.13 - 0.19	8 - 12	22 - 28
Clay	0.32 - 0.40	0.20 - 0.24	0.12 - 0.20	8 - 12	22 - 29

TEW (mm) is estimated using the equation:

$$TEW = 1000\ (\theta_{FC} - 0.5\ \theta_{WP})\ Ze \qquad (15)$$

where:

- θ_{FC} : volumetric soil water content at field capacity [$m^3\ m^{-3}$]
- θ_{WP} : soil water content at wilting point [$m^3\ m^{-3}$]
- Ze depth of the surface soil layer that is subject to drying by way of evaporation [we assume 0.10m].

In the second evaporation stage, the evaporation rate is reducing with soil drying. This stage starts when the soil moisture deficit (De) (that is, the amount of water content, expressed as water depth, below field capacity) exceeds REW. At this point, the soil surface is visibly dry, and the evaporation from the exposed soil decreases as follows:

$$K_r = \frac{TEW - D_{e,i-1}}{TEW - REW} \text{ for } D_{e,\,i-1} > REW \qquad (16)$$

where:

- Kr is a dimensionless evaporation reduction coefficient dependent on the soil water depletion (cumulative depth of evaporation) from the evaporation layer (Kr = 1 when De, i-1 < REW),
- De, i-1 cumulative depth of evaporation from the soil evaporation layer, below field capacity, at the end of day i-1 (the previous day) [mm],

Calculating the exposed and wetted soil fraction

In crops with incomplete ground cover, evaporation from the soil does not occur uniformly over the entire surface, but is greater where exposure to sunlight occurs and where there is more air ventilation.

The location and the fraction of the soil surface exposed to sunlight change to some degree with the time of day and depending on row orientation. The procedure presented here predicts a general averaged fraction of the soil surface from which the majority of evaporation occurs. Diffusive evaporation from the soil beneath the crop canopy is assumed to be largely included in the basal Kcb coefficient.

If the complete soil surface is wetted, by precipitation or sprinkler irrigation, then the fraction of soil surface from which most evaporation occurs, f_{ew}, is essentially defined as (1 - fc), where fc is the average fraction of soil surface covered by vegetation and (1 - fc) is the approximate fraction of soil surface that is exposed. However, for irrigation systems where only a fraction of the ground surface is wetted, f_{ew} must be less or equal to fw, the fraction of the soil surface wetted by irrigation (Figure 4). Therefore, f_{ew} is calculated as:

$$f_{ew} = \min(1 - fc, fw) \qquad (17)$$

where:

- 1 - fc is the average exposed soil fraction not covered (or shaded) by vegetation [its range is taken as 0.01 - 1]
- fw: is the average fraction of soil surface wetted by irrigation or precipitation [0.01 - 1].

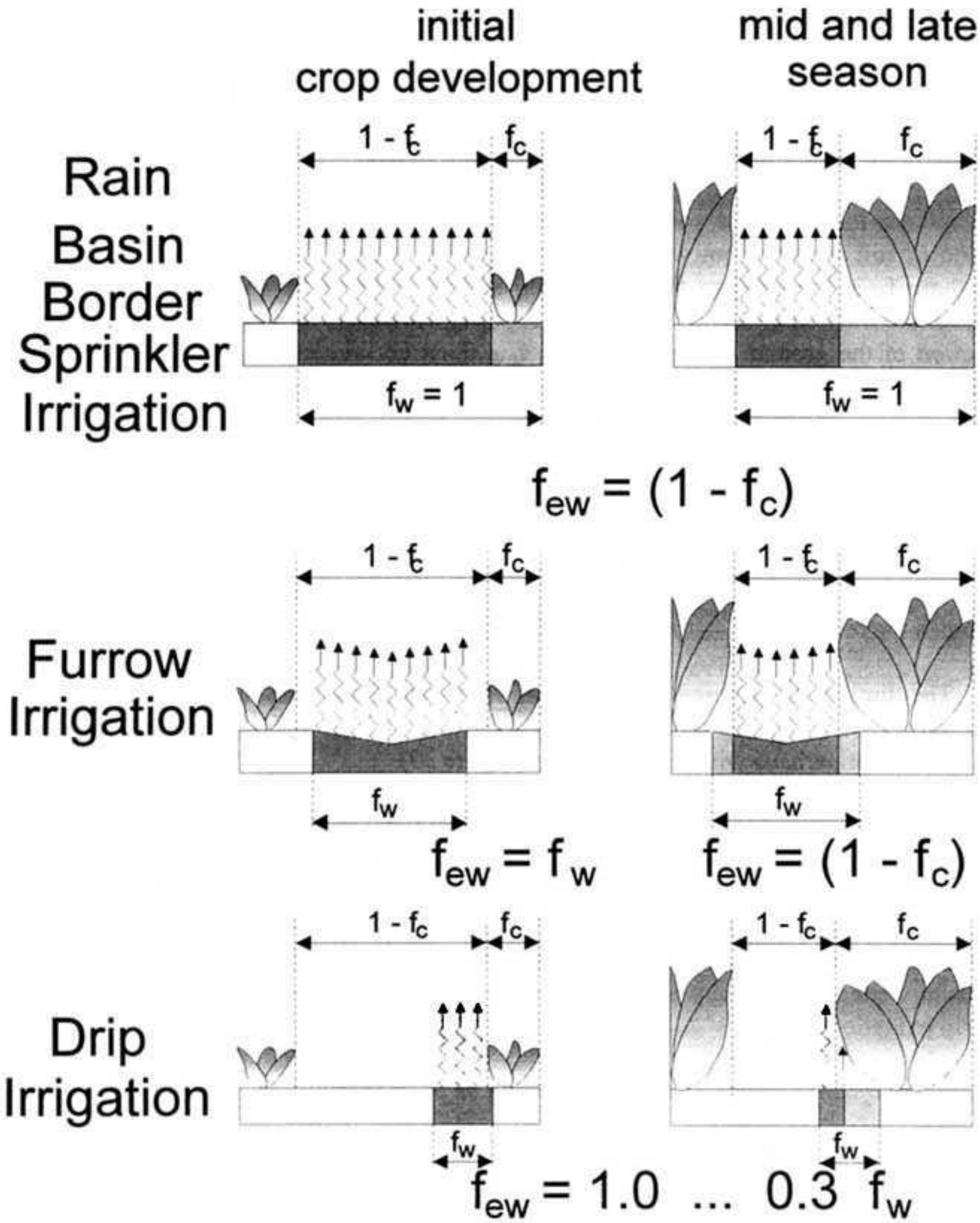


Fig. 4 Variation of f_{ew} (cross-hatched areas) in different situations of groundcover and irrigation system (after Allen et al., 1998)

Equation 17 assumes that the fraction of soil wetted by irrigation occurs within the fraction of soil exposed to sunlight and ventilation. This is generally the case, except perhaps with drip irrigation.

In the case of drip irrigation, where the majority of soil wetted by irrigation may be beneath the canopy and may therefore be shaded, to estimate f_{ew} the value for fw is multiplied by [1-(2/3)fc], as a first approximation.

In summary, $\mathbf{f_{ew}}$ calculation for the different irrigation systems is:

- Basin, border or sprinkler irrigation:
  f_{ew} = 1-fc (17a)
- Furrow irrigation:
  f_{ew} = min (fw, 1-fc) (17b)
- Drip irrigation:
  f_{ew} = min ((1-fc), (1-0.67 fc)fw) (17c)

Determining **fw** on each day

On each day of the application, the following rules can be applied to determine fw for that and subsequent days in a more simplified manner:

- Surface is wetted by irrigation: fw is the fw for the irrigation system
- Surface is wetted by irrigation and rain: fw is 1.0 (precipitation)
- Surface is wetted by significant rain with no irrigation: fw = 1
- Where there is neither irrigation nor significant precipitation: f_w is the f_w of the previous day.

Table 5 presents typical values for fw.

Table 5. Typical values of wetted soil surface fraction, fw, by irrigation or precipitation (after Allen et al., 1998).

Wetting event	f_w
Precipitation	1.0
Sprinkler irrigation	1.0
Basin irrigation	1.0
Border irrigation	1.0
Furrow irrigation (every furrow), narrow bed	0.6...1.0
Furrow irrigation (every furrow), wide bed	0.4... 0.6
Furrow irrigation (alternated furrows)	0.3...0.5
Trickle irrigation	0.3... 0.4

Estimating plant height on each day ($\mathbf{h_i}$)

Plant height on day i is used for estimating fc, and also in Kcb adjustment for climate, therefore, since it is not always measured, it is estimated by the following expression:

$$h_i = \max(Kcb/Kcb\ mid * hmax, h_{i-1}) \quad (18)$$

Determining **fc** on each day

Since usually fc is not available for each day, it can be estimated using the relationship:

$$f_c = \left(\frac{K_{cb} - K_{c\,min}}{K_{c\,max} - K_{c\,min}}\right)^{(1+0.5h)} \qquad (19)$$

where fc is the effective fraction of soil surface covered by vegetation [0 - 0.99],
Kcb is the value for the basal crop coefficient for the particular day or period,
Kc min is the minimum Kc for dry bare soil with no ground cover [≅ 0.15 - 0.20],
Kc max is the maximum Kc immediately after wetting (Equation 12), and
h is mean plant height [m]. Usually, to prevent numerical instability, the following restriction is imposed: difference Kcb - Kc min to ≥ 0.01.

This equation should be used with caution and, whenever possible, validated from field observations. Kc min is the minimum crop coefficient for dry bare soil when transpiration and evaporation from the soil are near baseline (diffusive) levels. Kc min usually is taken as 0.15. The value of Kc min is an integral part of all Kcb coefficients.

Equation 19 substitutes the N-ABLE equation for calculating the fraction cover that has been used in the first EUROTATE model. Therefore, the related parameter WLRT (dry weight when roots are in mid point between rows) will not be necessary anymore to calculate the fraction cover.

Daily water balance of the evaporation layer

The estimation of Ke in the calculation procedure depends on the water content of the evaporation layer (in fact, only of the part of it wetted and exposed, $\mathbf{f_{ew}}$) and calculating this water content requires a daily water balance computation for this part of the surface soil layer. The daily soil water balance equation for the exposed and wetted soil fraction $\mathbf{f_{ew}}$ is (Figure 5):

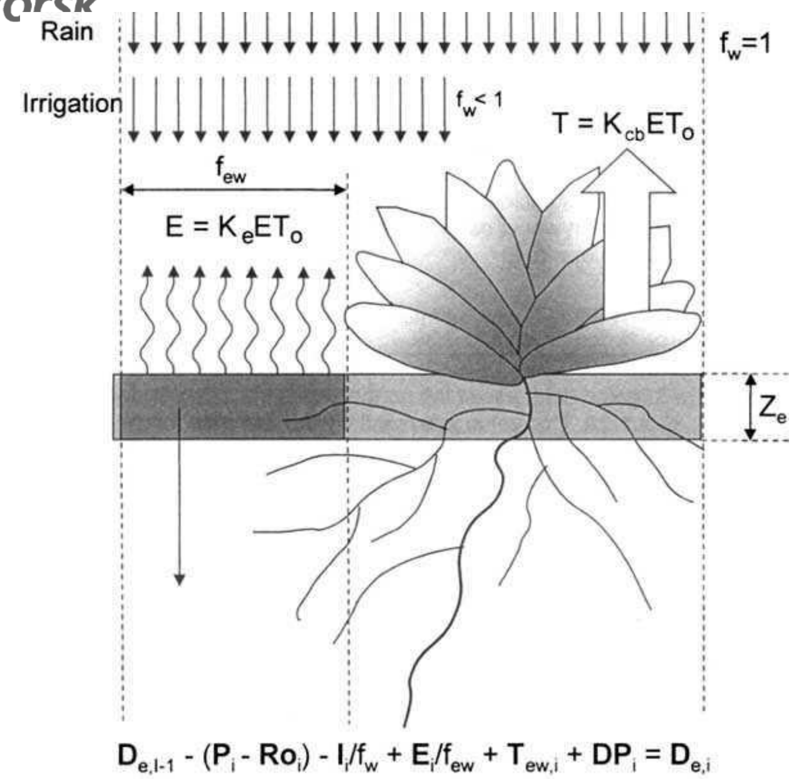


Fig. 5 Water balance of the wetted and exposed part of the evaporation layer (Ze)

This balance is:

$$D_{e,i} = D_{e,i-1} - (P_i - RO_i) - \frac{I_i}{f_w} + \frac{E_i}{f_{ew}} + T_{ew,i} + DP_{e,i} \qquad (20)$$

where:

- **De, i-1** is the cumulative depth of evaporation, below field capacity, from the exposed and wetted fraction of the topsoil at the end of day i-1 [mm]
- **De, i** is the cumulative depth of evaporation, below field capacity, from the exposed and wetted fraction of the topsoil at the end of day i [mm],
- **Pi** is the precipitation on day i [mm],
- **ROi** is the precipitation run off from the soil surface on day i [mm]
- **Ii** is the irrigation depth on day i that infiltrates the soil [mm],
- **Ei** is the evaporation on day i (i.e., Ei = Ke ETo) [mm],
- **Tew, i** is the depth of transpiration from the exposed and wetted fraction of the soil surface layer on day i [mm],
- **DPe,i** is the deep percolation loss from the topsoil layer on day i if soil water content exceeds field capacity [mm].
- **fw** fraction of soil surface wetted by irrigation [0.01 - 1],
- **f_{ew}** is the exposed and wetted soil fraction [0.01 - 1].

Limits on De, i

When topsoil is at field capacity (after drainage has taken place following heavy rain or irrigation), the minimum value for the depletion De, i is zero. When water content of the topsoil is greater than field capacity De, i has negative values. As the soil surface dries below field capacity, De, i increases and in absence of any wetting event will steadily reach its maximum value TEW (Equation 15). At that moment no water is left for evaporation in the upper soil layer, Kr becomes zero, and the value for De, i remains at TEW until the topsoil is wetted once again. The limit imposed on De, i is consequently:

$$De, i \leq TEW \qquad (21)$$

Initial depletion

To initiate the water balance for the evaporating layer, we calculate De, i from its initial soil water content. We can assume that the topsoil is near field capacity following a heavy rain or irrigation when the excess of water has drained, i.e., De, i-1 = 0. If a long period of time has elapsed since the last wetting, we can assume that all evaporable water has been depleted from the evaporation layer at the beginning of calculations, i.e., De, i-1 = TEW = 1000 (ϑ_{FC} – 0.5 ϑ_{WP}) Ze

Precipitation and runoff

Daily precipitation **Pi** in amounts less than about 0.2 ETo is normally entirely evaporated and can usually be ignored in the Ke and water balance calculations. The amount of rainfall lost by runoff can be calculated using the runoff module.

Irrigation

Ii is generally expressed as a depth of water that is equivalent to the mean infiltrated irrigation depth distributed over the entire field. Therefore, the value Ii/fw is used to describe the actual irrigation depth infiltrated over the fraction of the soil that is wetted.

Evaporation

Evaporation beneath the vegetation canopy is assumed to be included in Kcb and is therefore not explicitly quantified. The computed evaporation across the field, Ei, is given by Ke ETo and it is assume to occur only in the exposed, wetted topsoil. Therefore, Ei/few provides for the actual evaporation over the fraction of the soil that is both exposed and wetted.

Transpiration

Except for shallow rooted crops (i.e., where the depth of the maximum rooting zone is < 0.5 to 0.6 m), the amount of transpiration from the evaporating soil layer is small and can be ignored (i.e., Tew = 0). In addition, for row crops, most of the water extracted by the roots may be extracted from beneath the vegetation canopy. Therefore, Tew from the $\mathbf{f_{ew}}$ fraction of soil surface can be assumed to be zero in these cases.

Deep percolation

Following heavy rain or irrigation, downward drainage (percolation) of water from the exposed and wetted evaporation layer is calculated using the drainage algorithm.

As long as the soil water content in the evaporation layer is below field capacity (i.e., De, i > 0), the soil will not drain and DPe, i = 0.

Order of calculation

In making calculations for determining Kcb and Ke, they should proceed in the following order: Kcb, h, Kc max, fc, fw, few, Kr, Ke, E, DPe, De, I, Kc, and ETc.

Summary of calculations for ETc

1. Estimate ETo (using the module already available)
2. Determine the length of the four growth stages (if there is no plants, then we can assume we are in the initial phase: Kc = Kcb ini = 0.15) (if no local data are available, then use those in table 2).
3. Determine the basal crop coefficient, Kcb:
    - Calculate basal crop coefficients for each day of the growing period: select Kcb ini, Kcb mid and Kcb end from Table 2;
        i. Adjust Kcb mid and Kcb end to the local climatic conditions (Equation 3)
        ii. Determine the daily Kcb values (as explained in section: **Calculating transpiration**)
4. Adjust Kcb for water stress (Kcb adjusted = Ks · Kcb)
    - Calculate the water stress coefficient, Ks:
        i. Determine p and SW_{crit} for all cells with roots (equations 5,6 and 7)
        ii. Determine Ks using equations 7a and 7b
5. Determine the evaporation coefficient, **Ke**:
6. Calculate the maximum value of **Kc** (**Kc max**) using equation 12, and determine for each day of the growing period:
    - Plant height, h (equation 18)
    - the fraction of soil covered by vegetation, **fc** (equation 19),
    - the fraction of soil surface wetted by irrigation or precipitation, **fw** (Table 5),
    - the fraction of soil surface from which most evaporation occurs, $\mathbf{f_{ew}}$ (equations 17a, 17b, 17c depending of the type of irrigation),
    - the cumulative depletion from the evaporating soil layer, De, determined by means of a daily soil water balance of the topsoil (equation 20),
    - the corresponding evaporation reduction coefficient, Kr (equation 16), and
    - the soil evaporation coefficient, Ke (equation 11).
7. Determine crop evapotranspiration: ETc = (Kcb adj + Ke) · ETo

Calculations after determining ETc

Once ETc is determined for each day, soil water content of each soil cell is determined taking into account water uptake by roots and all other water redistributions routines considered.

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