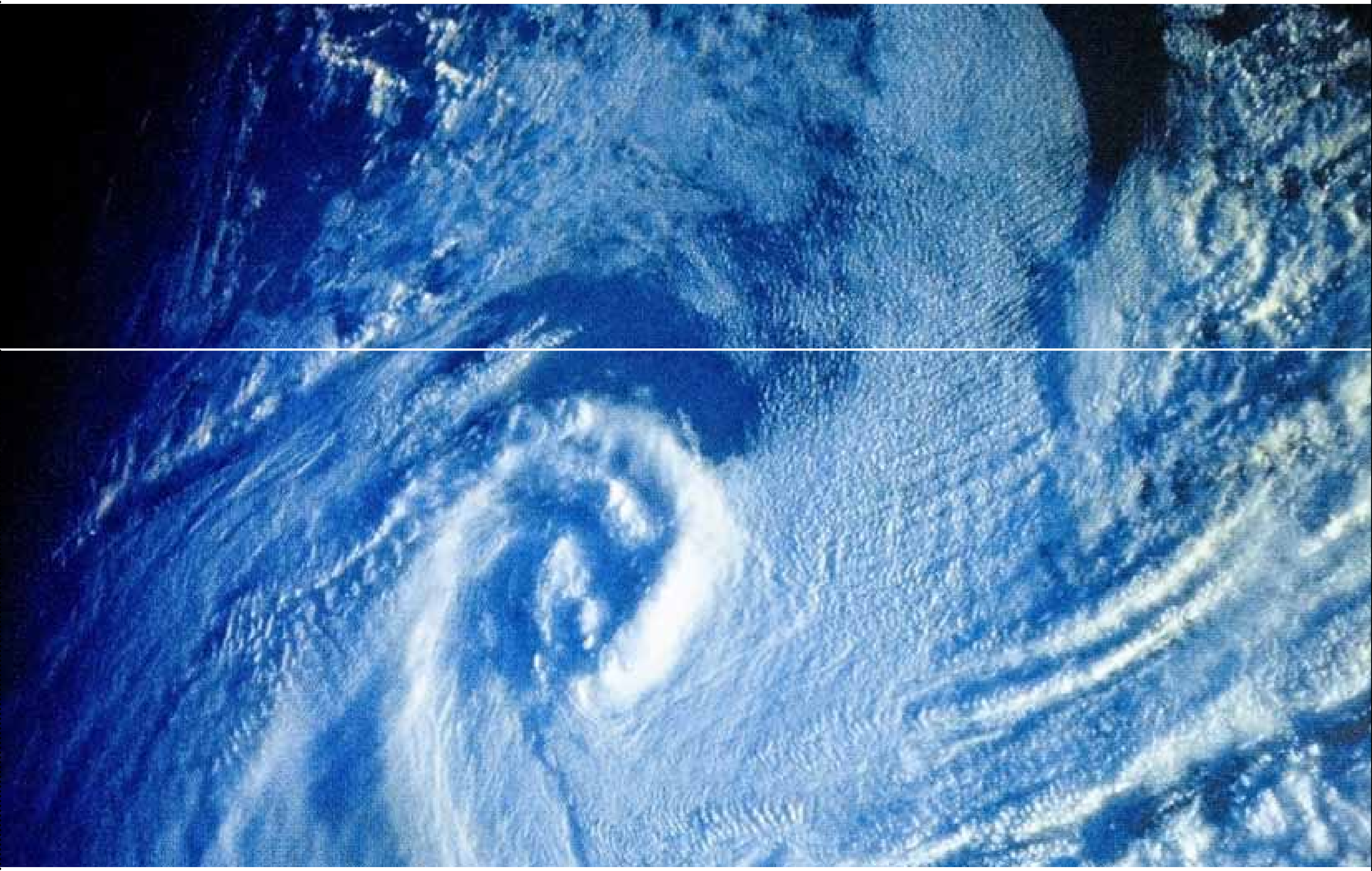

Review of crop salt tolerance in the Netherlands

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ABSTRACT

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Supportive irrigation is practiced in the Netherlands to overcome drought spells in the summer season. In the south-west delta mainly surface water is used of which the salinity is likely to increase. This study investigates the effects of saline irrigation on potatoes, sugar beet, grass, and tulips for different soils using a modeling approach. A comparison was made with a previous study showing the importance of climate and soils on crop reaction when applying supportive irrigation with variable salinities. It was found that the internationally accepted concept of Maas and Hoffman to estimate crop damage due to salts is not sufficiently reliable to establish salinity norms under conditions prevailing in the Netherlands. Recommendations are given for trade-offs between drought and salt damage, modeling improvements, and experimental field research.

Keywords: salinity, crops, chloride, model, transpiration, thresholds, norms

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Contents

Preface

In the Netherlands, the optimization of the supply of fresh water to the various regions has been under study for decades. Ongoing technological developments, anticipated effects of climate change, and changes in socio-economic preferences ask for continuous updates. Also regular model revisions are needed to strengthen their scientific base for subsequent use in scenario studies and operational water management.

One key aspect concerns the data for crop salt tolerance as employed in the national 'Drought models'. These data originate from an earlier study in 2003 and are based on experimental research mainly carried out in the USA. In the present study they have been revised through agro-hydrological modeling to better represent Dutch conditions. Hence, this report describes a review of the crop salt tolerance in the Netherlands as commissioned by the Directorate Water of the Ministry of Traffic, Public Works and Water Management.

The methodology and results were assessed by a panel of foreign experts leading to the conclusion that considering Dutch climatic conditions is a step forward, but that a basic weakness remains in the form of the aforementioned underlying American experimental data. Interestingly, the study also revealed the possibility of a trade-off between salt damage and drought damage. The obvious challenge is to incorporate these findings into the recommendations made by the 'Commission Veerman' to safeguard the future of the Dutch delta.

The authors especially like to thank Reinder Feddes (chairman of the workshop) and the external experts Jan Hopmans, Zvi Plaut and Greet Blom for their very valuable contributions to the workshop. Last but not least, we also wish to express our gratitude towards Neeltje Kielen en Olga Clevering of Rijkswaterstaat Waterdienst (Directorate General of Public Works and Water Management) for their comments and support.

Wageningen, September 2009

Summary

The climate of the Netherlands is a typical moderate sea climate and annual precipitation is always in excess of annual evapotranspiration. During the growing season, however, the evapotranspiration exceeds on average the precipitation by about 100 mm and the variation is considerable. The impact for agriculture is that regularly drought stress in crops occurs. About 50% of the cultivated area has access to irrigation water. In regions with saline ground water, irrigation with ground water is not possible and surface water from the rivers Rhine and Meuse is used to flush the brackish surface (drainage) water system for irrigation purposes. During dry years this external supply with high quality water is insufficient to meet all irrigation demands. Climate change will definitely result in an aggravation of the problems.

In successive drought studies the Ministry of Transport, Public Works, and Water Management (V&W) evaluated the present and expected future water supply situations using a set of models. These models are now being redesigned and the question arose whether the calculation of the agricultural crop damage due to high chloride contents in the Dutch surface water, based on a draft report of Roest et al. (2003), would need a revision. In the following chapters this report will referred to as the 'draft 2003 report'.

The question to review the crop salt damage relations was triggered in particular by the proposed flushing of the lake Volkerak-Zoommeer with seawater to control the algae blooms common in summer. Contrary to the previous 2003 study, the revision of the crop salt damage functions would not only serve the policy decisions on national level, but should also provide material for the discussion with the Dutch farming community.

Chapter 1 gives the general background and objectives of the study.

In **Chapter 2** the methodology for determining the salt damage functions by Roest et al. (2003) is summarized. The basic dataset used in this study originated mainly from the widely used relations derived by Maas and Hoffman in which crop damage is related to the Electrical Conductivity (EC) in the soil saturated paste. To transfer the relation between EC of the saturated soil moisture extract to chloride concentrations in the irrigation water, a number of assumptions based on expert rules were used. This resulted in considerable lower threshold values (at zero damage level) for a number of crops compared with the norms used in the Netherlands before 2003. The results were considered debatable because most field experiments were done in California, where field and climate conditions are different from the Dutch situation.

In **Chapter 3** the assumptions made in the 'draft 2003 report' are addressed. These assumption concern i) the relation between EC and chloride concentrations, ii) the relation between the chloride concentrations in the saturated paste and the

concentrations in the root zone, and iii) the relation between chloride concentrations in the root zone and the concentrations in the irrigation water. The methodology chosen to evaluate these assumptions and to make a better assessment of the thresholds was to apply the 1-D agro-hydrological model SWAP for 12 crop-soil combinations which have a significant acreage in the south-western part of the Netherlands. The relevant soil physical and crop parameters were derived from literature. The supportive sprinkler irrigation gifts were based on average Dutch 'good' practice, i.e. 20 mm applications when the pressure head in the middle of the root zone drops below a certain threshold value.

For each combination, 15 different chloride concentrations, which were kept constant during the growing season, were applied. All combinations were simulated using the weather series 1971-2000 of the KNMI[1]-Vlissingen meteorological station, which is supposed to represent the present climate in the south-western part of the Netherlands.

Next, the simulation results are presented. First, the factor 3 to convert the salinity in the irrigation water to the salinity in the soil moisture of the root zone has been revised: in almost all simulated crop-soil combinations the factor lies below unity. New threshold values were derived for chloride concentration in the irrigation water. The outcome of the simulations clearly demonstrate the importance of soil type: for sandy soils the values are 2-3 times lower compared to those for loamy soils. In general the values for sandy soils in the (extremely) dry year 1976 resemble the values in the 'draft 2003 report'.

In **Chapter 4** both studies are compared and the interpretation of the results is discussed. Attention is paid to the difference between salinity threshold and salinity norms for the irrigation water. The newly derived thresholds should replace the older thresholds for policy making. They should **not** be used as salinity norms for the surface water. A societal debate with stakeholders is needed to determine the acceptable risk levels for salt damage and the trade off between preventing drought damage and accepting salt damage.

In **Chapter 5** conclusions and recommendations are drafted. Supported by the opinion of an international panel of experts from the USA, Israel, and the Netherlands, the conclusion was drawn that the approach to relate reductions in the crop yield to the average soil moisture salinity in the root zone (Maas and Hoffman), which stands central in both studies, needs adaptations to suit Dutch conditions.

Future updates of salt tolerance data are recommended based on the approach used in the present study with parameter values adjusted to the results of field experiments under Dutch conditions. Such field experiments are recommended to be taken up with the utmost expedience.

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[1] Royal Netherlands Meteorological Institute

1 Introduction

1.1 General background

The climate in the Netherlands is typically a moderate sea climate (Cfb according to Köppen[2]). During the winter period (defined as the period between the 1st of October and the 1st of April), evapotranspiration is low and precipitation is always in excess with on average 300 mm. The variation in winter precipitation however is large: from 180 (1%-percentile) to 630 mm (99%-percentile). During the summer half year the evapotranspiration is on average 100 mm more than the precipitation, but the variation in this figure is considerable: between -200 mm (1%-percentile) and 310 mm 99%-percentile).

The climatic conditions have distinct impacts on the water supply of agricultural crops:

- crops grown on soils with a high water holding capacity (say 200 mm, such as loam and clay soils) suffer from drought in years with low rainfall during the growing season only;
- crops grown on soils with a low water holding capacity (say 50 mm, such as sandy soils with ground water depths of more than 2 m) experience drought in most year and severe droughts in dry years.

The economic feasibility of crop irrigation, and therefore additional water supply, depends on the market value of the crop and the drought sensitivity of the soil. Because agriculture is in general intensive, about 15% of the cultivated area has additional water supply facilities. In the southern and eastern part of the country mainly ground water is used for sprinkler irrigation. Ground water is also used for subsurface infiltration in some flat sandy areas with intensive drainage systems. In the western and northern part of the country, surface water is the most common source for both subsurface infiltration and sprinkler irrigation, because the ground water is too saline. Through a rather complex surface water transport system, water from mainly the Rhine and the Meuse (the two main trans-boundary rivers) is transported to almost each regional and local water course. The Ministry of Traffic, Public Works, and Water Management (in Dutch: Verkeer en Waterstaat or V&W) is responsible for the water distribution to the regions, while the regional Water Boards take care of the water distribution within their jurisdiction. Farmers, finally, are responsible for the water supply management on their farms.

The agricultural water supply to the western and northern part of the country faces two main problems:

- To prevent seawater intrusion most of the discharge from the rivers Rhine and Meuse is discharged through the 'Nieuwe Waterweg' – the only remaining open connection to the sea. During dry years, however, the flow is

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[2] McKnight and Darrel, 2003

insufficient to prevent seawater intrusion resulting in occasional closure of fresh water intake points for regional supply, drinking water, as well as other fresh water related activities;
- In some western and northern parts of the country upward seepage flow results in high salt contents of the smaller surface waters. Without flushing these water courses with fresh river water their quality becomes unsuitable for sprinkler irrigation. This flushing requires large amounts of water. Especially during periods of low river discharges this poses a real challenge and during periods of closure of fresh water intake points salt concentrations in the regional and local water courses cannot be kept at desirable levels.

Climate change will have four major impacts with respect to the agricultural water supply:

- It will result in a higher evapotranspiration (due to temperature rise) and may result in a lower precipitation during the growing season. Water shortages during the growing season will increase, varying from slightly to considerably;
- It will increase the occurrence of lower discharges of the Rhine and Meuse during summer months;
- It will result in a sea level rise and therefore in an increase of salt water intrusion in the 'Nieuwe Waterweg';
- Sea level rise also will result in an increase of upward seepage of saline ground water in some (western) coastal parts of the country. In the deep polders the salt content of the seepage will increase independent of climate change. Both developments result in an increase in the salt load in the regional and local watercourses.

In the national drought study[3] of the Ministry of V&W, which was completed in 2005, the present and expected future situations with respect to the water supply were evaluated:

- Strategically – Is there a need to change the supply infrastructure?
- Tactically – E.g. which distribution rules are feasible?
- Operationally – What will be the actual water distribution in periods of shortage?

In the drought study (and their regional refinements) a set of models have been used, including agro-hydrological models, to compute the effects of water management on the agricultural crop transpiration and production. In this way both irrigation requirements and flushing requirements to dilute salinity in the local surface waters could be quantified. The study concluded that no new infrastructure would be required to cope with the effects of climate change on water related function, including agriculture.

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[3] www.droogtestudie.nl

In 2006 new climate predictions were published. Based on preliminary studies it was concluded that large infrastructural investments and changes in operational rules might be required to cope with the effects of climate change[4].

These conclusions were supported by the findings of the Delta Commission who issued the Report “Working together on water” (in Dutch: “Samen werken aan water”) in 2008. The main questions were: “What will be the possible consequences of climate change for the protection level against flooding and for the water management in the Netherlands in general”. Besides the safety issue, the Commission also put potential problems with water availability in dry periods high on the agenda and gave some suggestions for improvement. It was recommended that, next to an optimization of the freshwater supply via the main water systems (Rhine and Meuse), also the main water users (regions), and agriculture in particular, should become more self-supportive. Another recommendation presented referred to water pricing with as potential consequence that the supply of good quality water to regions affected by saline waters would put a severe strain on the economic feasibility of agriculture. The validity of the salt damage functions for agriculture then becomes an important aspect.

All these issues subsequently resulted in a paragraph in the National Water Policy Paper on the fresh water supply. During the coming planning period (2010-2015) the Ministry of V&W has to take a decision on the long-term water supply and salinity prevention, including the required infrastructural works. For this study[5] the models that were used for the drought study are now being redesigned and the question came up whether the calculation of damage due to high chloride contents in the surface water used for sprinkler irrigation would need a revision.

Also the policy decision to turn the Volkerak-Zoommeer into a salt water lake to combat the blue-algae blooms and the ensuing discussions has increased the need to evaluate the present methodology of calculating salt damage to agricultural crops. Measures to compensate for the loss of fresh water supply and to prevent salt intrusion from the salt water lake into fresh water bodies are widely discussed.

Hence the Directorate-General Water of Public Works and Water Management (Rijkswaterstaat) of the Ministry of V&W requested Alterra to urgently undertake a revision of the salt damage functions by:

- Performing model calculations with the agro-hydrological model SWAP, and
- Organizing a meeting with independent international experts to review the methodology applied and the results.

The results of both activities are described in this report.

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[4] Royal Haskoning, 2007, and Deltares, 2008.

[5] Fresh water exploration (in Dutch: Zoetwaterverkenning) which is part of the Delta Programme, sub-programme fresh water supply.

1.2 Objectives of the study

The main objectives of the study are:

- An evaluation of the salt damage functions for agriculture as presented in the draft note of Roest et al. (2003);
- To provide a better scientific base for the methodology to establish salt damage functions in the future.

The underlying objective is that the deliverables of this study can support the much needed debate between Government and stakeholders on salinity norms in the Dutch surface water. This will enable strategic and operational decision making on changes in the water supply to agriculture in relation to salinity and drought damage in agriculture.

1.3 Reading guide

This report is subdivided in the following chapters:

- Chapter 2 summarizes the existing approach and results on salt damage functions for agriculture taken from the draft note (Roest et al., 2003);
- Chapter 3 describes the methodology used and results obtained to adjust the salt damage functions to Dutch conditions;
- Chapter 4 compares both approaches and discusses results as well as the way forward to a better estimation of salt damage in the future;
- Chapter 5 presents the conclusions and major recommendations.

2 Summary of the 2003 study

2.1 Introduction

In the national drought study mentioned in the previous chapter, the conclusion was drafted that the total salt damage in agriculture was about 10% of the total drought damage. For Phase 2 of that study improved data were to be used. Alterra was requested to update the salt tolerance data of field and horticultural crops based on the national and international available literature. In this chapter a short summary of the results of that update is given.

2.2 Simplifications

Of all the different effects of salt on crops (the osmotic effect of salts in the soil; the toxicity of certain elements such as Na, Cl, B; the swelling of (clay) soils; and leaf burn by sprinkling) only the osmotic effects were taken into account in the 2003 study. Effects of differences in salt sensitivity during different growth stages were neglected. The salt stress data were mainly derived from the international literature based on empirical research. The generally accepted salt damage function has a threshold value for soil salinity below which no damage occurs and above which the damage increases linearly with increasing soil salinity (see Figure 1).

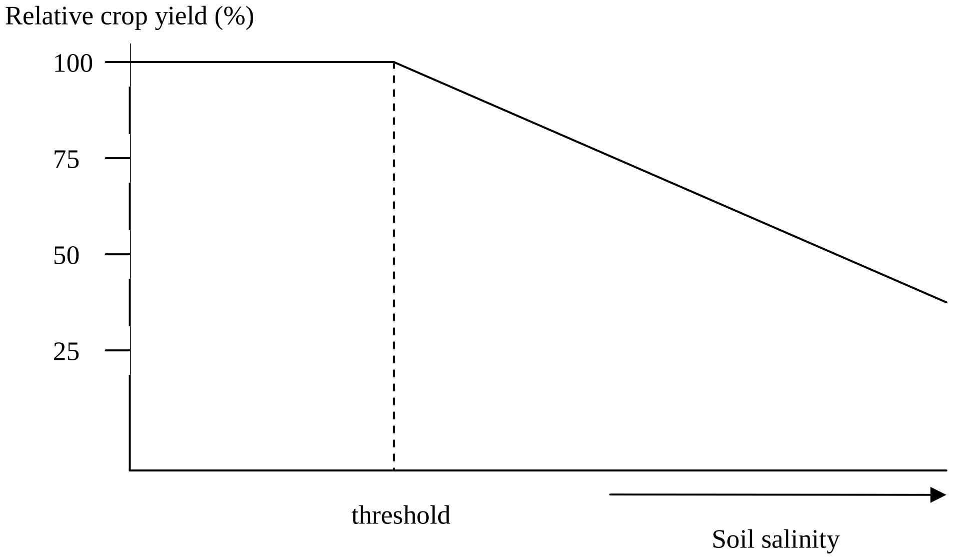

Figure 1 Maas and Hoffman salt damage function.

2.3 Methodology and results

The major difference between the international literature and the Dutch practice is the common use of electrical conductivity as an indicator for salinity internationally and chloride concentration as salinity indicator in the Netherlands. For the interpretation and mutual comparison of the available literature, a number of interpretations were needed:

- In the modeling instrument of Rijkswaterstaat (Mozart) the chloride concentrations at average soil moisture content were needed;
- In some (Dutch) experiments crop yields have been plotted against chloride concentrations in the soil solution at field capacity;
- In the majority of the reported experiments in the international literature salinity is expressed as the electrical conductivity in the (super) saturated soil moisture extract (saturated paste). The following relation which is valid for Dutch surface water was used to convert electrical conductivity to chloride concentrations:

$$c = 151EC^{1,31} \qquad (1)$$

with c as the chloride concentration in mg/l and *EC* the electrical conductivity in dS/m. The relation is valid for the range of EC values between 0 and 10 dS/m (Cultuurtechnisch Vademecum, 1988).

In the 2003 study, the following factors and relations to transform the concentrations in the saturated paste to the concentrations in the crop root zone were used:

$$c_{fc} = 2c_{sp} \qquad (2)$$

with c_{fc} as the chloride concentration in the soil solution at field capacity and c_{sp} the concentration in the saturated paste. The factor 2 used should be considered as a rough estimate for the average value. Depending on soil type the real factor may vary between 1.5 and 2.5.

$$c_m = 1,25c_{fc} \qquad (3)$$

with c_m as the chloride concentration at average soil moisture under irrigated conditions in the model used for the drought study and c_{fc} the concentration at field capacity. The implicit assumption used in this relation is that the average soil moisture content on irrigated fields is about 20% below field capacity. The relation between irrigation water concentration and soil water concentration at field capacity is given by the following relation:

$$c_g = \frac{c_{fc}}{3} \qquad (4)$$

with c_g the irrigation water concentration. With an assumed average leaching of 20%, a salinity profile in the soil is generated which results in an average factor of about 3 for the soil salinity. In practice this factor of course strongly depends on the irrigation regime.

The results of the literature study were translated to the crop clusters as used in the Mozart model for the drought and salt stress estimations. For each individual crop the different literature sources were compared and a choice was made for the most probable appropriate values for Dutch circumstances. As a next step the threshold values and slope for the individual crops were averaged for each crop cluster. Finally, the data were normalized to the moisture content as used by the Mozart model (Table 1). The corresponding irrigation water quality thresholds and slopes have also been included in this table.

Table 1 Average threshold value and slope for crop damage per Mozart crop cluster derived from the literature survey.

	Soil solution Chloride concentration		Irrigation water Chloride concentration	
Crop cluster	threshold mg/l Cl	slope %/mg/l Cl	threshold mg/l Cl	slope %/mg/l Cl
Potato	750	0.016	200	0.061
Grass	3600	0.008	950	0.029
Sugar beet	4850	0.006	1300	0.021
Fodder maize	800	0.009	200	0.034
Grain crops	4850	0.006	1050	0.022
Fruit trees	650	0.026	150	0.099
Horticulture	400	0.189	100	0.709
Vegetables	900	0.016	250	0.059
Greenhouses	500	0.014	150	0.053
Flower bulbs	150	0.018	50	0.068

3 The study of 2009

3.1 Introduction

In the 'Draft report 2003' a number of assumptions were made which need further research. This chapter addresses some of these assumptions, describes the methodology we used to arrive at better founded salinity thresholds, and presents the results in terms of new thresholds for surface irrigation water in agriculture under local Dutch conditions.

There is considerable international consensus on the use of the Maas-Hoffman (1988 and 1990) approach to account for salinity stress on crop yields. However, field studies do not always confirm reported values (Skaggs et al. 2006). Moreover, Dutch climatic conditions differ considerably from those in arid and semi-arid irrigated agriculture and the Maas-Hoff experimental conditions in particular.

In the 'Draft report 2003' simple factors and relations were used to convert the threshold values given by Maas-Hoffman for the salinity in the soil moisture towards thresholds for the chloride concentration in the surface water used for supportive irrigation. These factors were based on average values obtained from literature and expert judgment, again with a clear bias towards irrigated agriculture in arid and semi-arid regions. Some factors and relations will also be used in the new methodology. Hence, their strong and weak points also need further discussion.

3.2 Materials and methods

The use of constant factors to convert between soil moisture concentrations and concentrations in the irrigation water, as applied in the 'Draft report 2003', is a rather crude approach. To make a better assessment of the effects of Dutch weather conditions (with its high variability of rainfall during the crop growing season) on chloride thresholds for supportive crop irrigation, the SWAP agro-hydrological model (Kroes at al., 2008) has been selected. SWAP is a 1-D model for the saturated/unsaturated soil and includes the convective-dispersive transport of chloride. It has been applied for the following 12 crop-soil combinations:

- Potatoes, tulips, sugar beet, and grassland/pasture;
- Sandy, loam, and clay soil;

which are discussed in further detail below.

Soils

For this study, the south-west part of the Netherlands was chosen. All crop-soil combinations occur in significant acreage in this part of the country, with the exception of crops grown on the sandy soils. The south-west is (also historically) most threatened by high surface and soil water salinity. All selected plots are considered representative in terms of drainage conditions following 'good agricultural practice'. Soils used by agriculture are mainly loamy soils with excellent water holding capacity followed by clay soils (Figure 2). Sandy soils in this region are generally not used for agriculture (4% only).

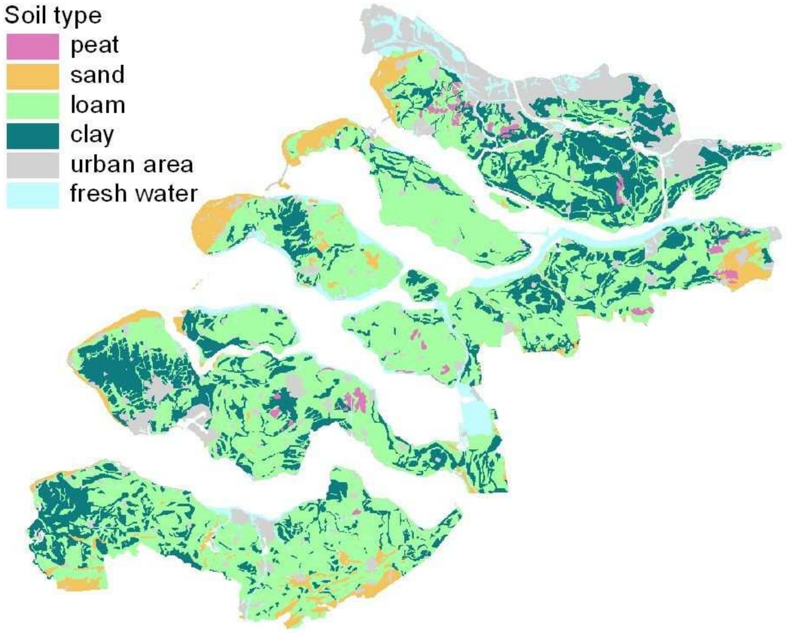

Figure 2 Soil distribution in the south-west delta.

Table 2 Land-use in the south-west delta per soil type.

Crop	Soil type (in % of agricultural area)				Total
	Loam	Clay	Sand	Peat	(in %)
Grass	9.6	5.1	1.7	0.7	17.2
Maize	2.4	1.1	0.4	0.1	4.0
Potato	10.0	3.6	0.2	0.0	13.8
Sugar beet	7.5	3.5	0.1	0.0	11.2
Grain crops	16.7	8.8	0.3	0.1	25.9
Other crops	16.8	6.4	0.7	0.1	23.9
Green houses	0.3	0.1	0.0	0.0	0.5
Fruit trees	2.3	0.7	0.0	0.0	3.1
Flower bulbs	0.3	0.1	0.0	0.0	0.4
Total	65.8	29.4	3.6	1.1	100.0

Crops

The four selected field crops represent some of the major crops (Table 2) in this part of the country with a bias towards covering a rather complete range for salt sensitivity, i.e. from tulips (very sensitive) to sugar beet (tolerant). The 'simple' crop growth module was selected in SWAP. Consequently, Leaf Area Index (LAI) and rooting depth were imposed according to crop phenological stage. Figure 3 gives the crop growth periods for the four crops considered in this study.

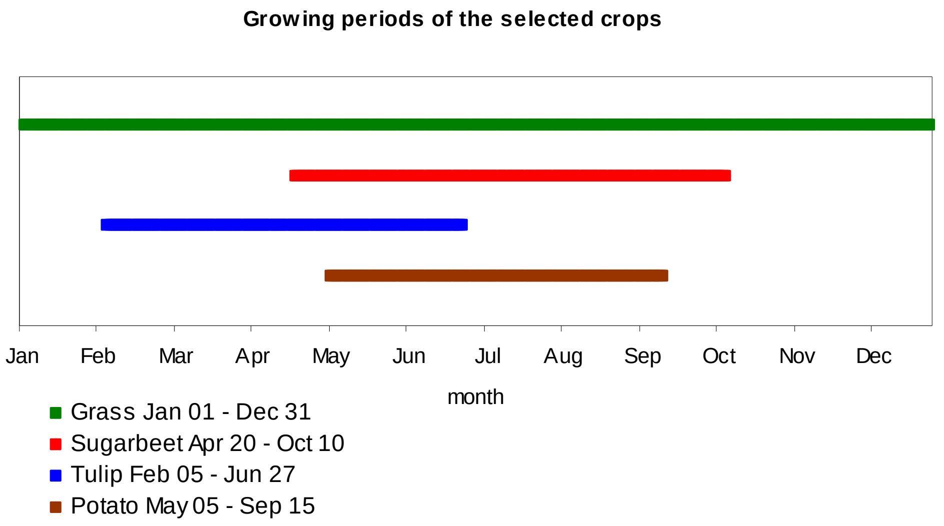

Figure 3 Growing periods of the selected crops (based on LAI).

Irrigation

Supportive irrigation is based on average Dutch 'good practice' sprinkling. Per event quantities of 20 mm are provided with intervals of three days at minimum. Irrigations are triggered by 'virtual' sensors halfway the maximum rooting depths and at soil water pressures exceeding the values given in Table 3. For all 12 specified combinations calculations were performed with 15 different chloride concentrations of 0, 50, 100, 150, 200, 250, 500, 750, 1000, 1250, 1500, 2000, 3000, 4000 and 5000 mg/l in the irrigation water. These concentrations were kept constant during the crop season.

Table 3 Soil moisture pressure thresholds (pF value) for irrigation and rooting depths for the four crops on the different soils.

Crop	pF at halfway maximum root zone depth	Maximum root depth per soil type (in cm)		
		Loam	Clay	Sand
Potato	2.5	45	30	25
Sugar beet	2.6	55	45	35
Grass	2.6	40	30	20
Tulip	2.4	40	na[1]	20

[1] *Tulip bulbs are usually not grown on clay soils*

Meteorology
All combinations were simulated using the weather series 1971-2000 with daily values for temperature, precipitation, radiation, and reference evapotranspiration (Makkink-approach) from the KNMI-Vlissingen meteorological station.

Salinity
Two of the conversion relations used in the 'Draft report 2003' have been applied again in the present study. These are:

- conversion from chloride concentration to electrical conductivity (EC);
- conversion from soil moisture content at field capacity to a moisture content at the saturated paste.

SWAP model
In the SWAP-model the soil column is subdivided into a large number of layers. For each layer the chloride concentrations in the soil moisture are calculated, followed by a dilution factor to convert concentrations at the actual water content to concentrations at saturated paste. This concentration is subsequently modified into EC and then into an EC at saturated paste (EC_e). SWAP finally calculates per individual soil layer a reduction factor between zero and unity to account for salinity stress by comparing the EC_e with the (crop dependent) Maas-Hoffman values for threshold and, if necessary, slope. This reduction factor is multiplied with the potential transpiration. The final stress factor is calculated in a multiplicative way. There is, however, considerable scientific debate on this approach (Shalhevet, 1994; Skaggs et al., 2006; Simunek and Hopmans, 2009; Dudley and Shani, 2003).

Parameters are set in such a way that reductions due to wet stress do not occur (as to rule out ambiguous effects on the end results), while frost reductions are unlikely to occur in the spring and summer season. An exception may occur for tulips as they are planted in December and sprout late winter or early spring. Drought stress is factually suppressed through the use of supportive irrigation. A check is made on the modeling results to confirm this hypothesis.

3.3 Results

The 30-years model simulations for the four crops, three soils and 15 chloride levels of the irrigation water have been used to:

- Verify the concentration factor 3 that is commonly used in irrigation practice to convert the salinity in the irrigation water to salinity in the soil moisture;
- Derive new threshold values for the salinity of the irrigation water above which salt damage becomes apparent.

<u>Conversion from chloride concentration in the irrigation water to chloride concentration at field capacity</u>
The SWAP simulation results have been used to verify whether the factor 3 is also valid for the Dutch climatic and soil conditions. This was checked by plotting model output for irrigation water salinity against the salinity of the soil moisture (Figure 4).

The graph also shows the 1:3 ratio between both variables as used in the 'Draft report 2003' and the 1:1 ratio. For realistic surface water chloride contents of up to 1500 mg/l the simulated ratios lie close to or below unity with the clear exception of 1976. The conversion ratio strongly depends on the meteorological data in the different simulation years: the drier the year the higher the factor.

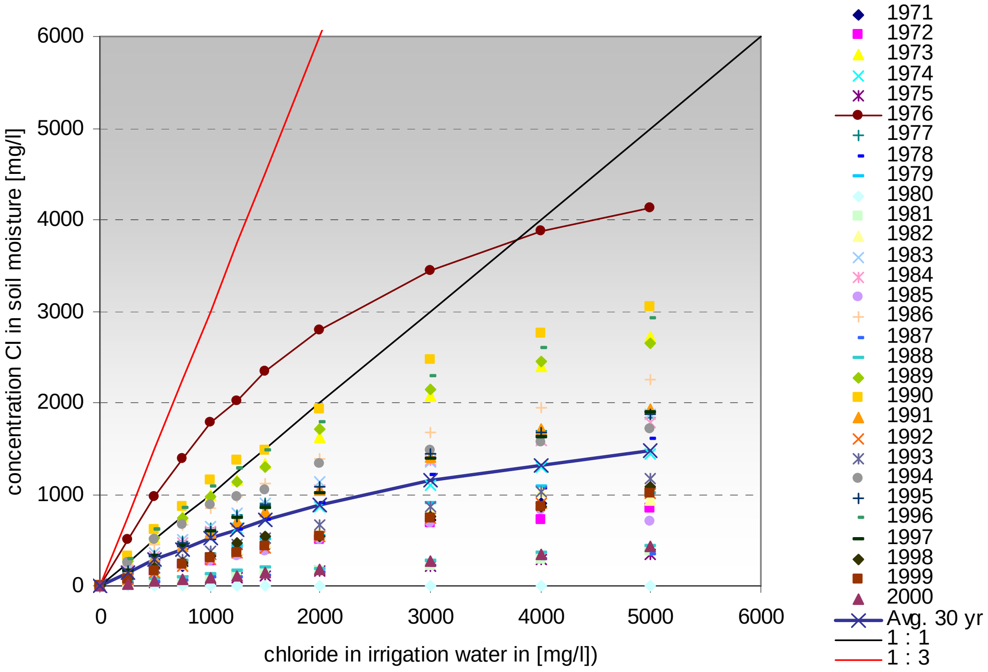

Figure 4 Ratio between average chloride concentration [mg/l] in the soil moisture in the root zone and in the irrigation water for potatoes on sand.

The simulation results indicate that under Dutch conditions with variable rainfall there is no single factor to relate soil moisture salinity with that in surface water. For the driest year in our simulations (1976) the results were used to derive a best estimate for such a factor. Because of the non-linearity between the variables (Figure 4), it was decided to limit chloride concentrations in the irrigation water to an upper bound of 1500 mg/l.

The conversion factors for tulips and sugar beet appear to be much lower than those for potatoes and grass (Table 4). Tulips are grown early in the year (see also Figure 3) and thus under wetter meteorological conditions. Also sugar beet is cultivated under wetter average conditions with a growing season which starts earlier in the spring and ends later in the autumn when compared to potatoes. In addition, sugar beet also requires less irrigations due to its deeper roots.

These results show that even under extremely dry conditions and for the most sensitive soil the factor 3 is far off. In the Netherlands rain replenishes depleted soil moisture, dilutes salts, and in the case of high intensities (which are not uncommon in summer) also leaches the root zone. In conclusion, the value 3 for conversion between irrigation water salinity and soil moisture salinity at field capacity appears to be a gross overestimation and can be considered as unsuitable for Dutch conditions.

Table 4 Average simulated conversion factors between chloride in irrigation water and chloride in soil moisture at field capacity (based on simulations for 1976 and chloride concentrations in the irrigation water up till 1500 mg/l).

Crop	Soil type					
	Loam		Clay		Sand	
	$Cl_{\theta fc}/Cl_{irr}$	R^2	$Cl_{\theta fc}/Cl_{irr}$	R^2	$Cl_{\theta fc}/Cl_{irr}$	R^2
Potato	0.27	1.00	0.76	0.99	1.23	0.98
Grass	0.58	1.00	0.92	1.00	1.36	0.99
Sugar beet	0.05	1.00	0.19	1.00	0.46	1.00
Tulip	0.14	1.00	n.a.	n.a.	0.55	0.98

Threshold values

Threshold values for the chloride concentrations in the irrigation water were derived by plotting the relative crop transpiration against chloride concentration in the irrigation water. The plotted relative crop transpiration is defined as the transpiration at the specified irrigation water salinity divided by the transpiration when the irrigation water salinity is equal to zero.

Figure 5 illustrates as an example how threshold values were obtained. Reductions in actual crop transpiration for tulips on sand occur at chloride concentrations in the irrigation water of about 100 mg/l in the driest years (red line). The figure also shows, as a blue line, the crop response corresponding to the 'Draft report 2003'. The same procedure to derive these threshold values has been repeated for all crop-soil combinations given in Appendix 1. In Table 5 these values are presented for all crops and all soils at zero crop damage level for the driest year.

The results clearly indicate the importance of the soil type on salt tolerance of crops. Crops grown on sandy soils are more sensitive to irrigation water salinity than crops grown on loamy soils. Clay soils take an intermediate position. Roughly speaking, a two to three times higher irrigation water salinity is allowed for the same crop on loamy soils as compared to sandy soils. The main explanation for this large difference are the better soil water retention characteristics of loam and clay when compared to sand resulting in more 'dilution' of the saline irrigation water, as well as the better capillary properties of these soils providing additional low salinity water to the crops.

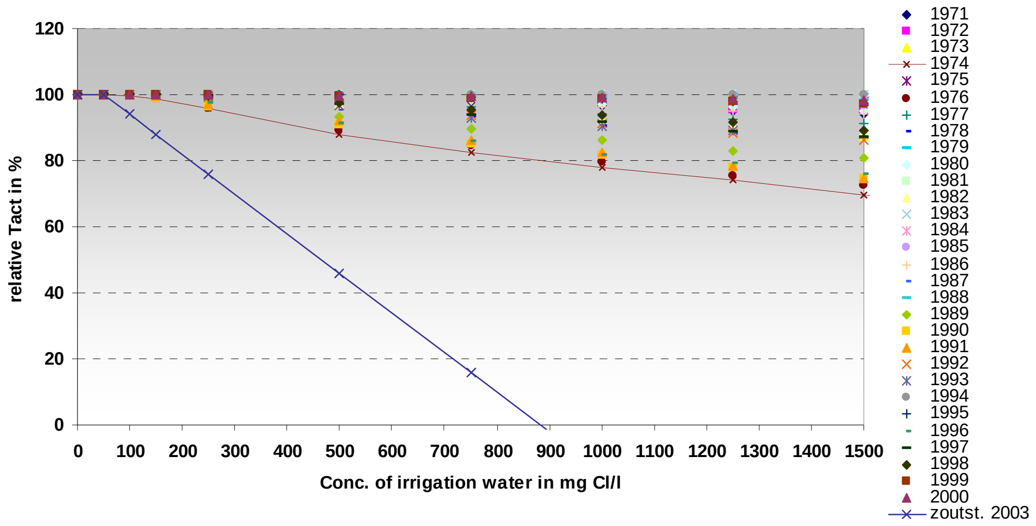

Figure 5 Relative (relative to irrigation with non-saline water) crop transpiration of tulips on sand for different chloride concentrations in the irrigation water and different consecutive hydrological years (30) computed with SWAP with the Maas and Hoffman equations implemented.

Table 5 Threshold values for the chloride concentration (mg/l) in the irrigation water 'without' crop damage in the driest year (1976 for most crops and 1974 for tulips).

Crop	Threshold values irrigation water per soil type (in mg/l Cl and rounded off to multiples of 50)		
	Loam	Clay	Sand
Potato	450	250	200
Grass	1900	900	700
Sugar beet	>5000	3450	1850
Tulip	150	na	100

4 Discussion

4.1 Introduction

First, attention will be paid to the verification of the concepts used in the present modeling approach. It will be shown that the Maas and Hoffman relations as introduced in SWAP work properly. Attention will also be paid to the relation between crop transpiration and crop yield.

Next, the results of the simulations with the SWAP model will be reviewed with an eye on the concept of thresholds, risk management and norms. It will be shown that it may be a wise decision to irrigate with waters far above the salinity thresholds.

This chapter will conclude with some deliberations on the way forward with crop salt damage estimations and the methodology to make more reliable estimates in the future.

4.2 Verification

The objective of this paragraph is to verify whether the different concepts used in the present modeling approach are correct and they will be reviewed one by one.

As the Maas-Hoffman approach stands central to both studies, i.e. Roest et al. (2003) and the present one, it was decided to further investigate two issues directly related to it, namely:

- Verification of the concept as programmed in SWAP by reconstructing the curves based on model output;
- Assessment of the relation between crop transpiration and yield.

Both issues were tested for a single crop (potatoes) on a single soil (sand).

Several other concepts and factors used in either study were also evaluated.

4.2.1 Maas and Hoffman curves

In Figure 6 the relative seasonal crop transpiration simulated with SWAP is plotted against the average seasonal EC over the maximum root zone depth for all 30 years included. The EC is, standard-wise, expressed as a conductivity for the soil saturated paste. The presentation conforms to Maas and Hoffman with the exception that the authors refer to relative crop yield instead of transpiration. This inconsistency is the result of reducing the transpiration in SWAP based on the yield related EC-values provided by Maas and Hoffman. However, it was argued that:

- For establishing threshold values at zero damage level it would not matter whether relative transpiration or relative yield would be used due to their almost 1:1 relation in this EC-range;
- Without the use of a crop growth model it would even be better to follow this approach, in particular for ECs further above the threshold, as the calculated transpiration would now closer resemble the crop yield (thus providing more consistency between SWAP results and the Maas and Hoffman concept).

In general, the match between output and input is reasonably good, although not perfect (Figure 6). What we see here is that the SWAP simulated salinity response starts at a lower threshold then the original Maas and Hoffman curve. Our simulation results also indicate more crop yield reductions than Maas and Hoffman. The scatter is introduced by the fact that in the SWAP simulations individual soil layers in the root zone can contribute to salt stress, whereas the model is unable to cope with root compensation mechanisms for both drought and salinity stress. Hence, transpiration can already be affected where average salinity levels over the root profile do not yet give rise to such reductions.

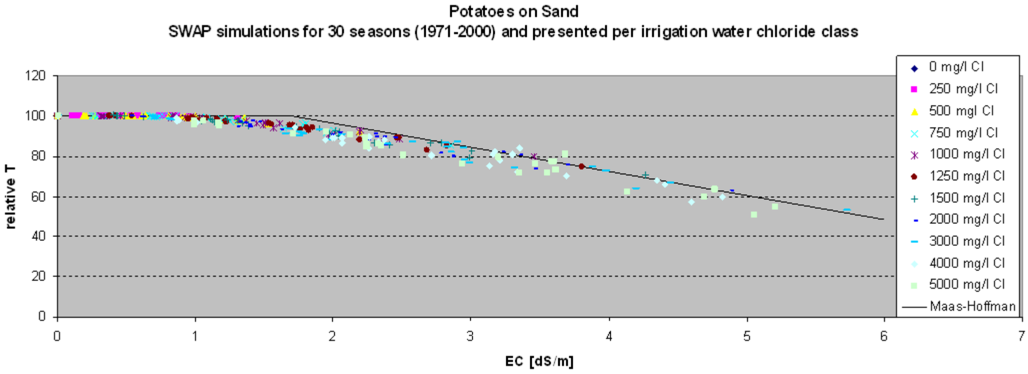

Figure 6 Relative transpiration (relative to irrigation with non-saline water) plotted against the seasonal and depth average value of soil salinity in the crop root zone simulated with SWAP.

To provide more insight in the temporal variability of the EC_e, its time development is shown in Figure 7 for irrigations with a chloride concentration of 1000 mg/l. The same figure also includes the development of the relative transpiration in time. The calculated seasonal mean value of around 1 dS/m for the EC_e lies well below the Maas-Hoffman threshold value of 1.7 dS/m. Nevertheless, after the first and second irrigations (steep rise of the blue line) reductions for the transpiration are computed without exceeding the average Maas-Hoffman threshold. Only after the third irrigation, levels given by Maas-Hoffman are surpassed leading to significant stress. Hereafter summer rainfall at the end of August depresses the root zone salinity well under the Maas-Hoffman threshold.

In conclusion it can be stated that averaging the EC_e over depth and time is the major cause of the deviation between model results and the original values of Maas and Hoffman. It results in an underestimation of the threshold values (the values are too low).

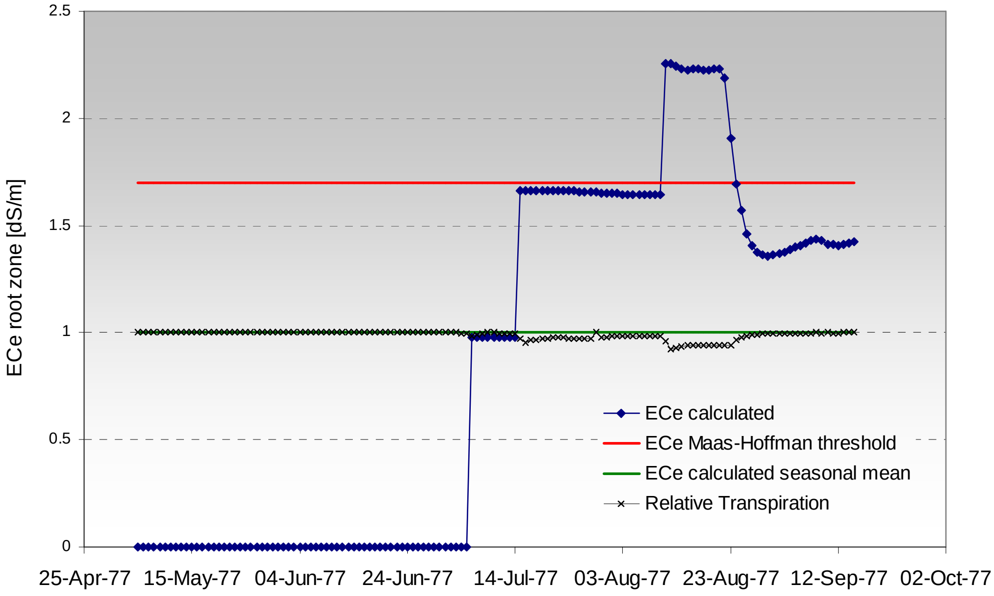

Figure 7 Time development of the average ECe in the crop root zone calculated with SWAP for potato on sand in 1977 with 3x20 mm supportive irrigation of 1000 mg/l chloride.

4.2.2 Crop yield

Maas and Hoffman relate the average salinity over the root zone to the relative crop yield. In SWAP salinity stress is expressed as a reduction in transpiration as shown in Paragraph 4.2.1. This would indicate that the relative transpiration calculated with SWAP is biased, but that this output would be a good indicator of relative crop yield.

In order to verify the above mentioned intentionally introduced artifact, a new series of 30-year runs were made for potatoes on sand with the 11 different chloride concentrations in the irrigation water. For a proper simulation of crop yield, SWAP was run with the 'detailed crop growth' option. This option calculates assimilation based on radiation and temperature, while variables such as LAI and rooting depth are determined dynamically instead of using imposed values.

The results (Figure 8) clearly show that adding such a crop growth module to SWAP and using the Maas and Hoffman crop yield relations as an input would lead to a double counting of reductions. In the modeling approach as used in the present study, the relative crop transpiration is therefore a better estimation of relative crop yield than the relative crop yield obtained with the crop growth module.

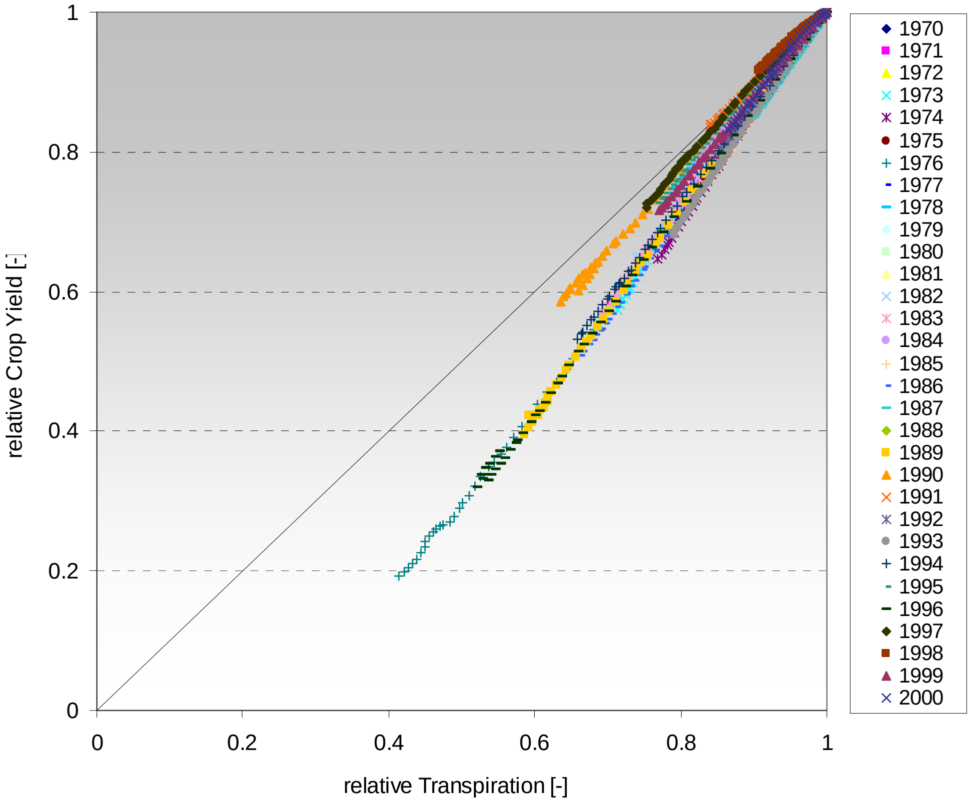

Figure 8 Relation between relative transpiration and crop yield computed by the SWAP-WOFOST combination for potatoes on sand for 30 consecutive hydrological years and 15 salinity levels of the irrigation water.

These results, however, also show a significant inter-yearly variation between crop transpiration and crop yield. Obviously, the advantage of including a crop growth module is that it handles the dynamic relation between crop development and crop yield to stress. Any salt damage occurring early during the growing season will lead to a retarded crop development which cannot be made up later during the growing season. This dynamic feed-back is not included in the present model setup. If we want to include such dynamic feed back in our future modeling, we cannot use Maas and Hoffman directly as model input, because Maas and Hoffman relates to crop yield and not to crop transpiration.

4.2.3 Other concepts and factors

In addition to the factor 3 to convert from chloride concentration at field capacity to the chloride concentration of the irrigation water (see Paragraph 3.3), two other factors were used for conversions in the 'Draft report 2003':

- A factor 1.25 to convert the average soil moisture content during the growing season to the soil moisture content at field capacity;
- A factor 2 to convert the soil moisture content at field capacity to the soil moisture content in the saturated paste.

Both factors will be discussed below. Next to this, the relation between chloride and total salinity will be reviewed, as well as some anomalies notified in the model with respect to salinity calculations.

Chloride concentration conversion from actual moisture to field capacity

To estimate crop damage with the Maas-Hoffman concept, the first step is to convert chloride concentration at the actual average moisture content in the root zone into a concentration at field capacity. This is necessary because the next step is the conversion towards saturated paste for which we use a fixed value.

In Table 6 the results of SWAP modeling are shown expressed as the ratio of chloride concentration at actual moisture content in the root zone over chloride concentration at field capacity as seasonal averages for the four crops and the three soils. The results are derived from a regression analysis over a simulation period of 30 years (crop seasons) and the 15 runs with different irrigation water chloride concentrations.

Table 6 Average simulated conversion factors between actual moisture and field capacity for chloride.

Crop	Soil type						All soils averaged	
	Loam		Clay		Sand			
	$Cl_{\theta act}/Cl_{\theta fc}$	R^2	$Cl_{\theta act}/Cl_{\theta fc}$	R^2	$Cl_{\theta act}/Cl_{\theta fc}$	R^2	$Cl_{\theta act}/Cl_{\theta fc}$	R^2
Potato	1.08	1.00	1.02	1.00	1.16	0.99	1.10	0.99
Grass	1.04	1.00	0.98	1.00	1.07	1.00	1.04	0.99
Sugar beet	1.03	1.00	0.97	1.00	1.38	0.99	1.30	0.98
Tulip	1.01	1.00	na	na	1.07	1.00	1.07	1.00

The correlations are excellent. The differences between the various soils are considerable, where clay appears to have a moisture content slightly above field capacity when averaged over all the growing seasons ($Cl_{\theta act}/Cl_{\theta fc}<1$). This is, however, not unrealistic considering that clay retains water very well and the long and thus wetter growing season of grass and sugar beet.

For sandy soils, the results show the largest differences between the four crops with sugar beet as a notable outlier. Sugar beet is the deepest rooting crop on sand (35 cm) and consequently also has the deepest (virtual) moisture sensor for irrigation (at 17.5 cm depth). Moreover, its sensor is set to trigger events at the lowest soil moisture pressure of all crops (pF>2.6). On drought sensitive soils this combination may lead to average soil moisture contents well below field capacity. Analysis of model results, however, indicates negligible damage due to drought conditions, i.e. less than 0.5 mm transpiration reduction on seasonal basis at maximum.

Looking at the soil averaged values for $Cl_{\theta act}/Cl_{\theta fc}$, it can be concluded that there is a considerable range between the four crops. A regression analysis applied to all soils and all crops yields a ratio equal to 1.07 ($R^2 = 0.99$). However, for establishing thresholds a worst-case approach is more appropriate and the estimate of 1.25 derived in the previous study appears rather accurate in comparison to the soil averaged value of 1.3 for sugar beet.

Conversion from soil saturated paste to moisture content at field capacity

The use of the Maas-Hoffman in SWAP also requires a conversion from the chloride concentration at the actual moisture content in a soil layer to the concentration in the saturated paste. Although the definition of saturated paste is clear, its interpretation can be rather ambiguous. In agricultural research EC's are often obtained from air-dried soil samples diluted with 5 or 10 parts de-mineralized water (gravimetric), after which a 'general' relation is applied to translate the measured value into an EC_e.

In the 'Draft report 2003', a generally accepted factor equal to 2 was used to convert between the chloride concentration at field capacity and the concentration at saturated paste. In SWAP the actual moisture content in each soil layer is calculated and, hence, the conversion to field capacity poses no problem. To arrive at concentrations at the saturated paste a factor 2 has again been imposed. Therefore the same uncertainty as in the 'Draft report 2003' is also introduced here.

Relation between chloride and total salinity

In the international literature relations between crop damage and salts are usually expressed in terms of relative crop yield versus electrical conductivity (EC) of the soil moisture or the irrigation water. Electrical conductivities can be directly measured using EC-meters and are a gauge for the total dissolved salts in the sampled water. In the Netherlands, however, the chloride ion is commonly used as an indicator for salinity. This choice is convenient insofar that the ion shows conservative behavior as it is hardly involved in (bio-)chemical reactions and plant uptake. The question, however, rises whether chloride can be used as a representative indicator for the total salt content of the water. In other words, is chloride an important ion in Dutch surface waters used for supportive irrigation, and if so, is there a reliable relation available between this ion and the EC?

The expression to convert electrical conductivity into a chloride concentration used in Roest at al. (2003) has been taken from the Cultuurtechnisch Vademecum (1988) where it was based on an analysis of a wide range of Dutch surface waters. This supports the hypothesis that chloride is present as a dominant ion and that the given expression is valid as it was based on many samples. Whether this relation will be representative for soil water remains questionable as the chemical composition of this water may differ considerably. On the other hand, use of surface water for supportive irrigation may again change the ion balance of the soil water.

In Figure 9 the relation between EC and chloride concentration is presented from three different sources, namely Cultuurtechnisch Vademecum (1988) as an average for Dutch surface waters, Roest et al. (1993) as an average for Egyptian surface waters in the Nile Delta, and Van Hoorn et al. (1993), established from soil moisture samples in a lysimeter experiment in Italy. The latter source is based on well controlled experiments growing potatoes and wheat on loamy and clay soils while irrigated with water of three different chloride concentrations. It appears that at the lower EC ranges the maximum relative differences in chloride concentration can mount up to some 30%, while in the higher ranges it remains limited to some 10%.

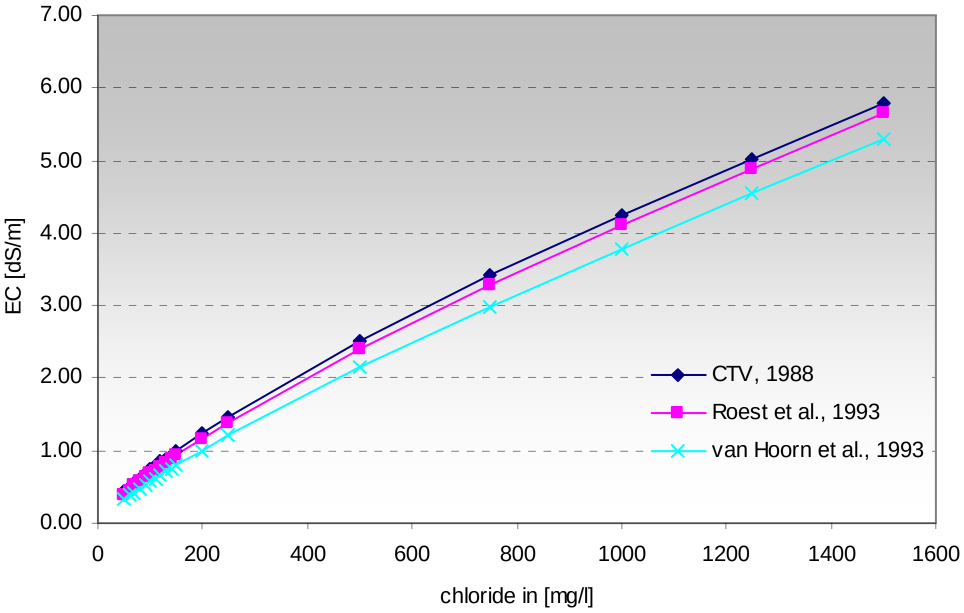

Figure 9 Relation between chloride concentration and electrical conductivity according to different authors.

These data indicate that Dutch surface waters are indeed sodium-chloride dominated as the relation used by Roest et al. (2003) appears to be above (but close to) the relation found in the Nile Delta and the relation found in the Italian experiments. It seems therefore a safe approach to use the original equation (Eq. 2) from the Cultuurtechnisch Vademecum (1988) to convert chloride in the root zone to EC, because the applied irrigation water will be of a sodium-chloride nature and the effects on crop yield may be biased towards an overestimation. The use of this formula in the SWAP input seems therefore justified.

Other model anomalies

A point of attention is the use of the 'simple' crop growth module in SWAP, which excludes secondary effects, such as reductions in root development and Leaf Area

Index (LAI) as a result of water shortages and/or excessive soil moisture salinities. Stunted crop growth (or even premature death) is hence not included and in the model computations crops can pick up transpiration after strained periods at rates in agreement with the imposed LAI's and rooting depths. This affects both the calculated seasonal transpiration (overestimation) and the resulting root zone salinity (generally overestimated as well, depending also on the salinity of the irrigation water).

Finally, no crop damage due to ion toxicity towards given plant species is considered, nor is leaf burning as a result of sprinkling during sunshine included. The simulations, however, do include effects of inter-annually salt accumulation in the soils in case winter rainfall is insufficient to leach the root zone profile.

Irrigation water salinity
In the present study no provision was made during modeling for the anticipated increase in surface water salinity during the summer season in the south-western delta. This aspect needs consideration in a possible follow-up study, although it can be stated in advance that plants become less sensitive to salts towards maturity.

4.3 About salinity thresholds and salinity norms

The current study has some clear advantages over the study done by Roest et al. (2003) as the effects of Dutch weather are evidently visible in the results as well as the differentiation in soils. It clearly shows that results of irrigation with high salinity water turns out differently in different years. This also sheds a different light on the implications of working with thresholds for irrigation water salinity. Even more important are the implications for irrigation water salinity norms. In this context the salinity threshold can be defined as the upper limit of the chloride concentration of the irrigation water that will not cause crop yield reductions. The salinity norm for irrigation water can be defined as the chloride concentration in the irrigation water that is considered acceptable for use in agriculture.

Both thresholds and norms will be discussed in the ensuing paragraphs from the perspective of risk management (accepting some damage occasionally) and from the perspective of the trade-off between accepting some salt damage by preventing a larger drought damage.

4.3.1 Risk management

As has been shown in the previous sections, the threshold for irrigation water salinity strongly depends on the actual weather conditions encountered. Using the salinity threshold as the basis to derive salinity norms is therefore virtually impossible. Each year would need different norms. This is compounded by the fact that the weather conditions of a certain year are not known beforehand. Therefore, and in order to avoid setting norms based on threshold values derived from the driest year, it seems logical to introduce the probability of salt damage into the considerations.

In order to analyze the probability of salinity damage the results of the simulations for the 30 years and the different irrigation water concentrations have been plotted in a different manner. In Figure 10 an example is given of a frequency diagram for potatoes on sand. The user can read on the X-axis for which percentage of the weather series of 30 years the reduction in transpiration (Y-axis) may occur for a selected chloride concentration in the irrigation water. Such diagrams are particularly useful tools to align risk and acceptable limits. Frequency diagrams for all simulations are included in Appendix 1.

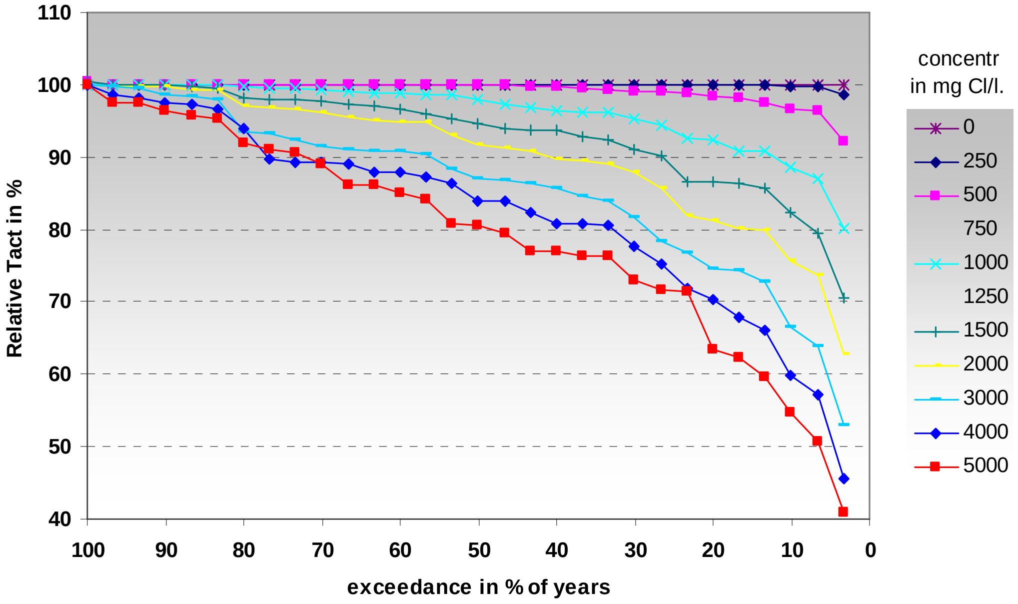

Figure 10 Frequency diagram of the relative crop transpiration (relative to irrigation with non-saline water) against the percentage of years during which these values are exceeded for different irrigation water chloride concentrations as computed with SWAP for potato on sand.

In addition to the threshold (accepting no damage whatsoever during any of the years) introduced in Chapter 3, we also used the frequency diagrams to investigate two alternatives for accepting some salt damage to crops and evaluate what that would mean for the salinity 'norm' of the irrigation water. These are:

- Zero damage (0.1%) in 90% of the years accounted for;
- Maximum damage of 5% in crop transpiration occurring only once in 30 years.

The results of this exercise are presented in Table 7 where also the absolute threshold (no damage during any year) is given. Obviously, depending on the acceptance of small damages, the 'norm' for the irrigation water chloride concentration can be relaxed considerably. If we take the 5% salt damage as maximum during one out of 30 years as the acceptable limit (average damage 0.17%), the norm would be twice as high compared to no damage at all.

4.3.2 Trade-off

All thresholds derived so far are based on limiting salinity damage to crops. Focusing too much on salinity thresholds bears the risk to forget why irrigation is actually done by farmers. Figure 11 demonstrates the frequency distribution of the drought damage for potatoes on the different soils. Depending on the soil type, the relative crop transpiration reduces up to 15% on loamy soils, 35% on clay soils, and even up to 65% on sandy soils. These numbers indicate the possibility to accept some salinity damage in order to avoid a larger drought damage. Given a certain irrigation water salinity, farmers need to decide whether to irrigate their crop with this (high) salinity water and accept some (salt related) crop damage. Irrigation with saline water therefore is also a management decision by farmers.

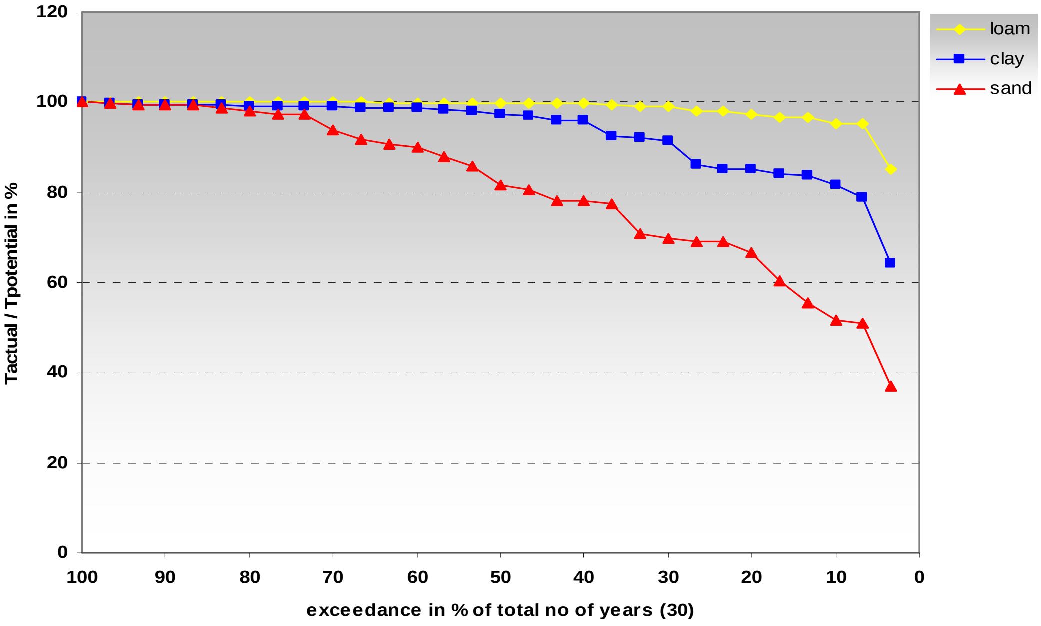

Figure 11 Frequency distribution of relative transpiration for potatoes on different soils under non-irrigated circumstances.

In other words, although supportive irrigation with lower quality water may not be a preferential strategy of farmers, it may result in better crop yields then without any irrigation at all. This is demonstrated in Figure 12 where modeling results for tulips on sand, being the most salt sensitive cultivation, are presented in a slightly different way, i.e. with relative transpiration compared to transpiration without supportive irrigation. For all crop-soil combinations the simulation results are presented in this manner in Appendix 1.

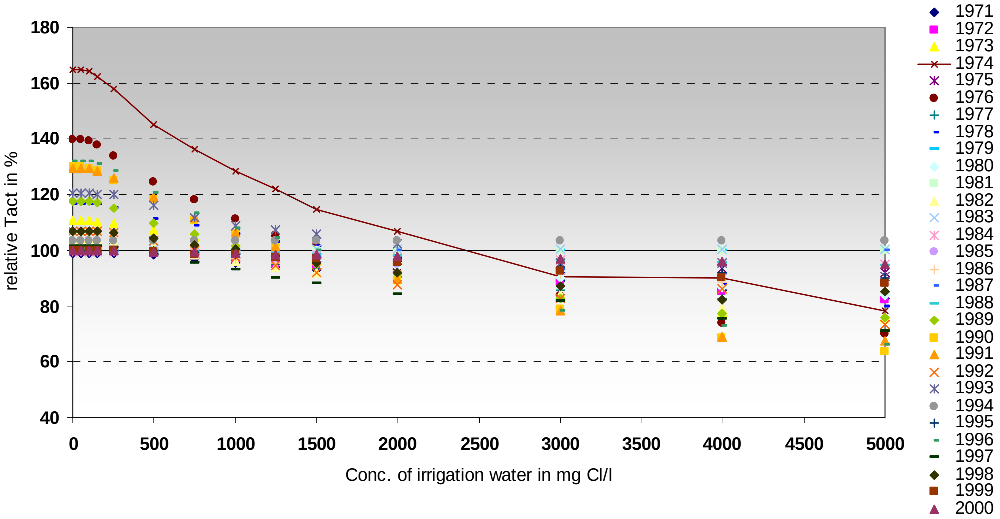

Figure 12 Relative crop transpiration (relative to un-irrigated) for the tulip on sand combination for 30 consecutive hydrological years as a function of the chloride concentration of the irrigation water.

The example given in Figure 12 shows that for tulips on sand under the driest conditions (1974), the crop would transpire better with irrigation water salinities of even up to 2500 mg/l Cl when compared to zero irrigation. For less dry years this break-even point obviously shifts to the left to lower concentrations. Hence, there must be a point where the salt damage to the crop equals the prevented drought damage by applying saline irrigation water. Assuming such a point at the salinity where the crop salt damage equals 50% of the prevented drought damage would give an indication of the salinity where the trade-off between both can be found. For tulips on sand (see Figure 12) this break-even point is at a salinity of about 1250 mg/l, where the benefit of irrigation is about 20% (during 1974) and the salt damage about 10% (during 1997).

These break-even values for drought damage and salt damage have been determined for all crop-soil combinations studied and are included in Table 7 in the last columns. The determination of the break-even point between the trade off between drought damage and crop damage used here should have been based of course on an economic analysis, because irrigation brings along costs as well. They have not been considered in the analysis presented here. The implications of considering the trade-off however are considerable. Norms based on trade-off would be in the order of magnitude of a factor 10 higher than norms based on the threshold (Table 7).

Table 7 Overview table of chloride threshold values in irrigation water under Dutch conditions, including various alternatives.

	Chloride threshold values for irrigation water (in mg/l)													
			Present study											
Crop	CTV	Roest et al. (2003)	No crop damage (based on driest year -1976)			Reduction in relative transpiration <0.1% in 90% of the years			Reduction in relative transpiration <5% during all years			Salt/drought damage trade-off at 'break-even'		
			Sand	Clay	Loam	Sand	Clay	Loam	Sand	Clay	Loam	Sand	Clay	Loam
Potato	600	200	200	250	450	250	300	700	400	650	1400	4000	1750	1750
Grass	600	950	700	900	1900	2600	4150	>5000	3850	>5000	>5000	>5000	4750	>5000
Sugar beet	600	1300	1850	3450	>5000	950	1250	3150	1400	1750	3850	>5000	>5000	>5000
Tulip	300[1]	50[1]	100	na	150	100	na	250	250	na	850	1250	na	na

[1] as an average value for flower bulbs

4.4 The way forward

The results of the present and previous study have been reviewed in a workshop setting by three independent international experts on crop salt tolerance:

- Jan Hopmans. Department of Land, Air, and Water Resources, University of California, Davis, California, USA;
- Zvi Plaut. Israeli Agricultural Research Organization, Israel;
- Greet Blom-Zandstra. Plant Research International, Wageningen-UR.

The main conclusions and advice on the improvement of the methodology used is given in the ensuing paragraphs.

4.4.1 Expert workshop

The whole approach, including the results, has been reviewed. It was concluded that:

1. The approach and parameters as presented by Maas and Hoffman have limited value for deriving salinity standards for Dutch irrigation water. Its threshold and slope values are based on field experiments under different conditions compared to the Netherlands in terms of weather, irrigation practices, and chemical water composition;
2. Despite its limited value for Dutch conditions, the Maas and Hoffmann approach is the only practical available model at the moment. Therefore the model must be used, but local parameters need to be determined;
3. The modeling methodology presented by Alterra is certainly an improvement compared to the previous study (Roest et al., 2003). However, in future modeling the osmotic potential in the soil moisture solution should be used to generate transpiration reductions instead of using Maas and Hoffman directly. This approach was however not yet available. Parameters for transpiration and crop yield reductions should be derived from field experiments;
4. New experimental data are needed to:
    a. Establish well-founded relations between irrigation water salinity on both crop transpiration and crop yield damage under Dutch conditions;
    b. Validate modeling results;
    c. Quantify leaf damage caused by sprinkling crops with saline water;
    d. Assess effects of sodium toxicity on plants.

Several comments and discussions during the expert consultation concentrated on the present study and the way forward to derive better salinity thresholds for the future under Dutch conditions (Table 8).

First of all, irrigation under Dutch conditions supplies only a small portion of the water needed by the crops and as a result soil salinity in the Netherlands responds less to saline irrigation water compared to arid regions. The effect of this different response of soil salinity to irrigation water salinity on the thresholds is large, as shown in the present study.

Table 8 Assumptions used and their qualitative effects on the thresholds derived as diagnosed in the salt tolerance studies evaluation workshop.

Assumptions	Effect on salinity norms	Remarks
Roest et al 2003 Study		
Dutch weather conditions not accounted for	++	Factor 3 (shown in the present study)
Soil conditions not accounted for	important	This Study
Alterra 2009 update (this study)		
Root uptake considered uniform	+	Slight effect expected
Salinity development surface water	++	Depending on crop growth period
Zero salt damage assumption	++	Factor 2 to 10 (shown in present study)
Maas and Hoffman function	+/-	Unknown and uncertain
Irrigation method	-	Slight effect but uncertain

++	norms can be relaxed considerably
+	norms can be relaxed
+/-	uncertain effect on salinity norms
-	norms must be more strict

Because irrigation in The Netherlands is supportive only, the amount of irrigation water needed depends on the water holding capacity of the soil. Sandy soils with a low water buffer need earlier and more irrigation than a loamy soil with a larger water buffer. As a consequence, unlike in arid regions with irrigation, salinity thresholds for irrigation water are soil type dependent in The Netherlands. The effect on the threshold is considerable as shown in the present study (Table 8).

In the present modeling approach the crop root water uptake was considered uniform over the depth of the crop root zone. A modeling approach where the crop would abstract water from those root zone layers where the water is easier available (with less salt) is recommended because it would be closer to reality. A slight effect on the thresholds can be expected under Dutch conditions due to the dynamic nature of rainfall and supportive character of irrigation.

In the Netherlands, the surface water salinity, which is the irrigation water source in the western part of the country, exhibits a seasonal development with a peak somewhere in August. As a consequence crops grown in early spring, such as tulips, are exposed to higher salinities only towards the end of the growing season and the effect on crop yield will be less than evaluated in the present study. The effect of neglecting this salinity profile is expected to be large (Table 8).

The zero salt damage assumption for deriving salinity norms as used in the Netherlands was acknowledged with surprise by the international experts. Zero damage, of course, may be a wish by the farming community, but can seldom be guaranteed by authorities. An important consequence of the zero damage concept is that drought damage could outnumber salt damage by far due to ignoring the trade-off between both. Accepting some salinity damage during some (extreme) years is expected to have a large effect on the salinity norms that are considered acceptable by stakeholders.

The use of the Maas-Hofmann relations poses a number of constraints of which the following are the most important:

1. Relations were mainly derived from field experiments in southern California where a different climate prevails compared to the Netherlands;
2. Crops were irrigated with local waters dominated by Ca, Mg and (bi-)carbonates. Dutch surface waters are classified as of sodium-chloride origin which could lead to a different crop reaction;
3. Californian experiments were conducted under surface irrigation. Dutch practices are based on sprinkling, which may cause an accelerated uptake of Na and Cl through the plant leaf tissues and may cause burning of leaves;
4. Yield and EC_e data were plotted in scatter diagrams from which the thresholds and slopes were derived. This leaves ample space for interpretation and it would be better therefore to work with bandwidths;
5. Irrigation timings in California were set in order to keep the salinity in the root zone constant during the growing season. This implies that the relation between crop damage and EC is controlled by the crop's most sensitive stage as this stage becomes the determining factor in the final crop yield. To use steady-state underlain thresholds and slopes in dynamic salinity modeling could consequently result in an overestimation of crop damage (and underestimation of the transpiration) as the likelihood of exceeding a threshold during a sensitive stage is rather small;
6. Maas-Hoffman presents relative crop yield versus average seasonal EC_e of the root zone. In the present context reductions are applied to crop transpiration and not to crop yield. The relation between transpiration and yield is often assumed to be 1:1, but this varies per crop and often significant deviations from this ratio occur for the lower yields where transpiration reduces less than proportional.

The first four issues are general observations with respect to the use of Maas-Hoffman, but the last two items can lead to an underestimation of the modeled actual transpiration due to the way Maas and Hoffman has been implemented in SWAP (Table 8). On the other hand, without specific information on crop sensitivity to salts during growing stages and without using a detailed crop model, in which the relation between transpiration and yield is formally modeled, the present approach provides a 'best guess' of the actual crop yield.

4.4.2 Future research

The use of the Maas and Hoffman functions as applied in the present approach to derive salinity thresholds under Dutch conditions was considered less than optimal. A future modeling approach would better be based on the inclusion of the osmotic potential in the soil solution. The resulting effects on salinity thresholds estimated with such a dynamic model would then depend on the parameterization used. The effects of such an improved methodology on the salinity thresholds is uncertain, but cannot reliably be done without an experimental basis.

It is recommended to base future updates of crop salt tolerance data on the mentioned dynamic modeling approach with crop parameter values adjusted to the results of field experiments under Dutch conditions. Such field experiments should preferably be taken up with the utmost expedience. The triple line approach as done before in Israel and Spain (Royo and Aragues, 1993; Grattan et al., 1994; Vulkan-Levi et al., 1998) is recommended (Figure 13). In this approach three sprinkler lines are used perpendicular to the crops investigated. The middle line irrigates with saline water and provides water up to the two non-saline lines of sprinklers. In this way a fluent gradient in salinities is created in duplicate, offering a fast insight into the effects of sprinkling with saline water on crops.

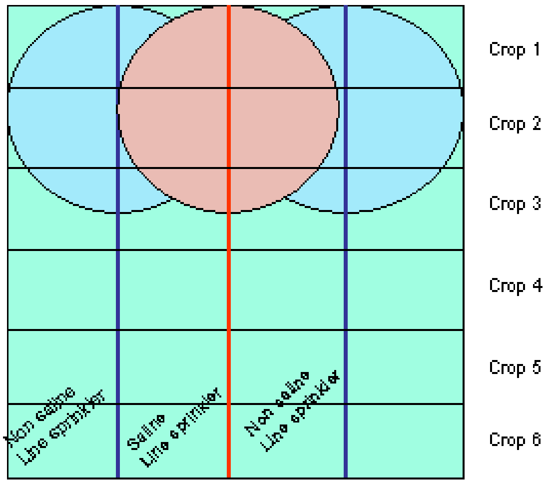

Figure 13 Set-up of a triple sprinkler line experiment.

5 Conclusions and recommendations

5.1 Introduction

Dutch surface waters in the coastal regions will become more saline due to climate changes, restoration of saline-fresh water gradients and an increasing salinity in the lake Volkerak-Zoommeer. These changes will have their impact on water management and affected water users such as agriculture. In order to make sound decisions on coping or counteracting measures, the Dutch government needs to know the extent of crop damage on the national economy caused by the lower availability of good quality water for crop irrigation.

It was against this background of national policy making that Alterra was requested in 2003 by the Ministry of Transport, Public Works, and Water Management to prepare a literature review on the salt tolerance of different crop cultivations grown in the Netherlands. In this study crop response curves to salinity were derived from the international literature:

1. For crop response to salinity in the root zone the internationally widely accepted data of Maas and Hoffman were used, among others;
2. To relate root zone salinity to salinity in sprinkler water a concentration factor of 3 was used. In the arid regions underlying the international literature the factor 3 is a rule of thumb based on 20% leaching under field irrigation conditions.

This study from 2003 also identified a number of methodological shortcomings in its approach being solely based on a simple inventory and simplified relations between the most important variables involved. As a consequence, the same Ministry requested Alterra in 2009 to review the standards again, albeit with a better scientific underpinning with respect to Dutch soil and climatic conditions. The results of this study have been reviewed by three independent international experts from USA, Israel and the Netherlands and are presented in this report.

5.2 Conclusions

The present study which is based on extensive agro-hydrological modeling for potatoes, sugar beet, grass, and tulips under soil, hydrological, and meteorological (1971-2000) conditions as prevailing in the Dutch south-west delta revealed the following conclusions:

- Soil types have a distinct effect on crop reaction to saline irrigation water and sandy soils are the most sensitive among the three soils included in this study;
- Climate has a high impact in a twofold manner:
    - Within seasons: summer rains dilute salts in the root zone (and even leaches them) so that the crop is less affected by saline irrigation during drought spells;
    - Between seasons: under average winter conditions rainfall usually flushes all excess salts from the root zone so that in the next year the new crop can start with a fresh plate.

Hence, it can be concluded that dynamic modeling is a significant methodological improvement towards establishing new salinity standards for irrigation water as compared to the study in 2003.

The largest single insight that the present study revealed is the pronounced difference with the 2003 study for the factor converting the soil moisture salinity into irrigation water salinity. In the arid regions underlying the international literature the factor 3 is a rule of thumb based on a 20% leaching allowance under field irrigation conditions. In the Netherlands irrigation is supportive only and even in extremely dry years crops still benefit from the rainfall. Even for the extremely dry year 1976 the factor 3 cannot be reproduced and turns out to be around 1.2 for sandy soils, 1 for clay soils, and 0.3 for loamy soils.

The analyses also revealed a clear offset. In dry years, irrigation with high salinity waters results in higher yields than without any irrigation at all. Accepting some crop salt damage by irrigation with water above the threshold can thus prevent a much larger crop damage due to drought. Also break-even points have been assessed where the crop salt damage equals the prevented drought damage by applying saline irrigation water.

A new overview table with crop chloride thresholds (Table 7) is included in this report. The reliability of the presented values should however be judged in the light of the following remarks:

- Surface water salinity generally increases within the summer season, reaching its peak in late summer. This has been neglected in both studies. The assumption of a constant salinity during the growing season is expected to result in too strict criteria for Dutch conditions;
- The methodology and results as applied in this study have been presented in a workshop to a panel of international experts from the USA, Israel, and the Netherlands. From the discussions it turned out that the approach to relate reductions in the crop yield to the average soil moisture salinity in the root zone (Maas and Hoffman), which stands central in the model formulation, is not a priori suited to Dutch conditions. The main objections against the approach as presented in this report are the following:
    - The water composition of the irrigation waters used in the Maas and Hoffman experiments is characterized by a relatively high content of Ca and Mg as well carbonates and bi-carbonates. The water used in the south-west delta of the Netherlands for sprinkling is of seawater origin and is therefore dominated by Na and Cl. Crop response to NaCl type of water may be quite different from the crop response to the typical composition of irrigation water in arid regions;
    - The Maas and Hoffman experiments have been performed under steady-state conditions, keeping the soil salinity constant during the growing season. Extrapolation of the Maas and Hoffman relations as done in the present study using a dynamic simulation model is the best possible approach, given the present state of knowledge. The results of this approach are however not necessarily reliable. It needs field testing to suit the local climate, soil and hydrological conditions;
    - The Maas and Hoffman experiments have all been performed using surface irrigation. The practice in the Netherlands is generally based on sprinkling, which

may cause an accelerated uptake of Na and Cl through the plant leaf tissues with potentially toxic effects and additionally may cause burning of the leaves.

5.3 Recommendations

The considerations and conclusions presented in the previous paragraph lead to the following recommendations relating to salinity norms, to the use of salt damage functions in policy evaluations, and to research:

Norms:

- Do not use the threshold values in Roest et al. (2003) as norms for the salinity of the irrigation water;
- Organize a stakeholder debate to determine acceptable norms for the salinity of the irrigation water, taking into account the results of the present study;
- Perform field experiments (together with stakeholders) to determine crop salt damage levels under Dutch conditions.

Salt crop damage:

- Crop salt damage is highly dependent on the soil type and crop damage calculations should therefore be regionally differentiated, based on the soil types common in the region considered;
- Crop salt damage needs to be balanced against drought damage. The trade-off between both salt damage and drought damage will be regionally differentiated, because drought damage is again depending highly on the soil moisture holding capacity of the crop root zone;
- Crop salt damage calculations should further be based on the evolution of the salinity concentration in the Dutch surface water.

Research:

- Perform field research to establish the water and salt dynamics effects by (sprinkler) irrigation to evapotranspiration and crop yield;
- Use these field data to include the soil osmotic potential in the dynamic (SWAP) model to account for the reductions in crop transpiration;
- Use these data to calibrate / validate crop growth models to explain the observed crop yields (including the effects of specific toxicity and leaf burn);
- Change the root water uptake function in SWAP from the present uniform uptake function to a stress dependent (per soil layer) uptake function.

Literature

Abrahamse, A.H., G. Baarse and E. van Beek (1982). *Policy analysis of water management for the Netherlands. Vol. XII: Model for regional hydrology, agricultural water demands and damages from drought and salinity.* RAND Note N-1500/12-NETH.

Aendekerk, Th.G.L. (1999). *Adviesbasis voor de bemesting van boomkwekerijgewassen: pot en containerteelt.* Boomteeltpraktijkonderzoek, Boskoop.

Aendekerk, Th.G.L. (2000). *Adviesbasis voor de bemesting van boomkwekerijgewassen: vollegrondsteelt.* Boomteeltpraktijkonderzoek, Boskoop.

Allen, R.G., L.S. Pereira, D. Raes and M. Smith. (1998). *Crop evapotranspiration. Guidelines for computing crop water requirements.* FAO Irrigation and drainage paper 56, Rome.

Bierhuizen, J.F. en C. Ploegman (1967). *Zouttolerantie van tomaten.* ICW mededeling 104, Wageningen.

Dudley, L.M. and U. Shani (2003). *Modeling plant response to drought and salt stress: reformulation of the root sink term.* Vadose Zone Journal 2:751-758.

Grattan, S.R., A. Royo, and R. Aragues (1994). *Chloride accumulation and partitioning in barley as affected by differential root and foliar salt absorption under saline sprinkler irrigation.* Irrigation Science 14:147-155.

Huinink, J.T.M. (1994). *Bodemgeschiktheidstabellen voor landbouwkundige vormen van bodemgebruik.* IKC-Landbouw, Ede.

Kroes, J.G., J.C. van Dam, P. Groenendijk, R.F.A. Hendriks, C.M.J. Jacbs (2008). *SWAP Version 3.2 – Theory description and user manual.* Alterra-report 1649, Alterra, Wageningen, The Netherland

Landon, T.R. (1984). *Booker tropical soil manual.* Longman, London

Maas, E.V. (1990). *Crop salt tolerance.* http://www.ussl.ars.usda.gov/saltoler.htm

Maas, E.V., and G.J. Hoffman (1977). *Crop salt tolerance – Current assessment.* ASCE Journal of the Irrigation and Drainage Division, IR2, 118-134.

Ploegman, C. (1972). *De invloed van zout beregeningswater bij de gladiool c.v. 'Peter Pears'.* Nota 687. ICW, Wageningen.

Ploegman, C. (1973). *De invloed van zout beregeningswater op de groei en de produktie van de roos var. 'Carol'.* Nota 729. ICW, Wageningen.

Ploegman, C. (1975). *Invloed van infiltratie met chloridehoudend oppervlaktewater op het chloridegehalte in het bodemvocht en de produktie bij tulpen.* Nota 881. ICW, Wageningen.

Ploegman, C. (1976). *Invloed waterkwaliteit bij kasrozen.* Nota 913. ICW, Wageningen.

Ploegman, C. (1978). *Het chloride-ion in de grond in relatie tot de opbrengst bij tulpen.* Landbouwkundig Tijdschrift 90-2.

Ploegman, C. (1981). *Invloed van de zoutconcentratie van het bodemwater op de produktie van drie lelie cultivars.* Nota 1248. ICW, Wageningen.

Ploegman, C. en J.F. Bierhuizen (1970). *Zouttolerantie van komkommer.* Mededeling 126. ICW, Wageningen.

Projectgroep Waternood (1998). *Grondwater als leidraad voor het oppervlaktewater. Een op het grondwaterbeheer georiënteerde aanpak voor inrichting en beheer van oppervlaktewatersystemen.* DLG publicatie 1998/2, Utrecht.

Praktijkonderzoek Rundvee, Schapen en Paarden (PR) (1997). *Handboek voor de melkveehouderij.* Lelystad

Roest C.W.J., P.J.T. van Bakel, and A.A.M.F.R. Smit (2003). *Actualisering van de zouttolerantie van land- en tuinbouwgewassen ten behoeve van de berekening van de zoutschade in Nederland met het RIZA-instrumentarium* (concept version and in English: "*Update salinity tolerance of field and greenhouse crops for the calculation of crop damage in the Netherlands with the RIZA models*", Alterra, Wageningen, The Netherlands.

Royo, A., and R. Aragues (1993). *Validation of salinity crop production functions obtained with the triple line source sprinkler system.* Agronomy Journal. 85: 795-800.

Shalhevet, J. (1994). *Using water of marginal quality for crop production: major issues.* Agricultural Water Management 25:233-269.

Simunek, J., and J.W. Hopmans (2009). *Modeling compensated root water and nutrient uptake.* Ecological Modeling 220:505-521.

Skaggs, T.H., J.A. Poss, P.J. Shouse, and C.M. Grieve (2006). *Irrigating forage crops with saline waters. 1: Volumetric lysimeter studies.* Vadose Zone Journal 5:815-823.

Skaggs, T.H., P.J. Shouse, and J.A. Poss (2006). *Irrigating forage crops with saline waters. 2: Modeling root uptake and drainage.* Vadose Zone Journal 5:824-837.

Sonneveld, C. (1988). *The salt tolerance of greenhouse crops.* Netherlands Journal of Agricultural Science 36 (1988): 63-73.

Sonneveld, C. and W. Voogt. (1983). *Studies on the salt tolerance of some flower crops grown under glass.* Plant and Soil 77, 41-52.

Van Hoom, J.W., N. Katerji, A. Hamdy and M. Mastrorilli. (1993). *Effect of saline water on soil salinity and on water stress, growth and yield of wheat and potatoes.* Agric. Water Management. 23 (1993), pp. 247–265.

Werkgroep Herziening Cultuurtechnisch Vademecum (1988*). Cultuurtechnisch Vademecum*. Utrecht.

Appendix 1 Simulation results (graphical)

Table of Figures

Appendix 1.1 – Average chloride concentration in the root zone for 30 years.

Appendix 1.2 Simulated number of irrigations applied to the potato crop.

Appendix 1.3 Simulated ratio between chloride concentration in the crop root zone and irrigation water for the potato crop.

Appendix 1.4 Simulated relative (relative to irrigation with zero salinity) crop transpiration as response to irrigation salinity up to 1500 mg/l.

Appendix 1.5 Simulated relative (relative to irrigation with zero salinity) crop transpiration as response to irrigation salinity up to 5000 mg/l.

Appendix 1.6 Simulated relative (relative to not irrigated) crop transpiration as response to irrigation salinity up to 5000 mg/l.

Appendix 1.7 Simulated frequency distributions of relative crop transpiration.

Appendix 1.1 – Average chloride concentration in the root zone for 30 years.

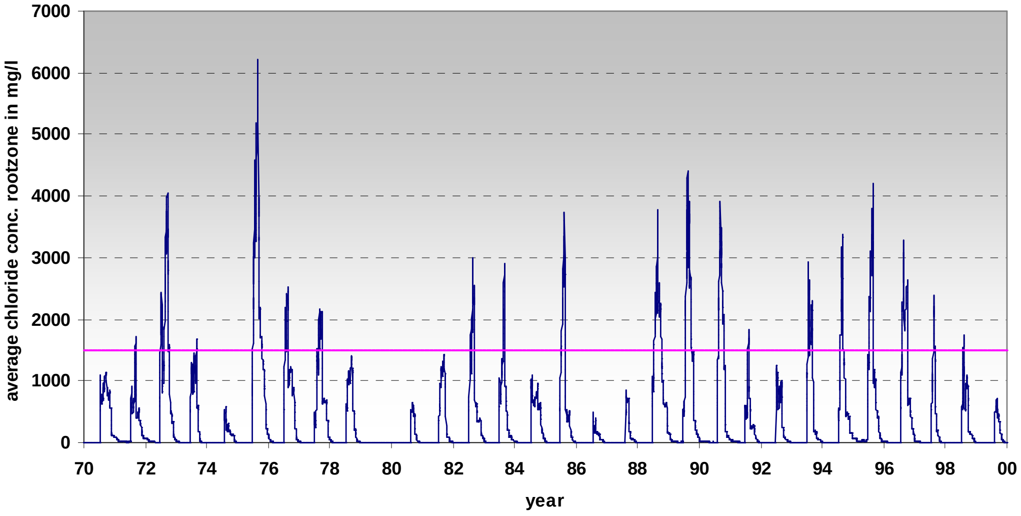

Fig. 1 Chloride concentration in the root zone (mg/l) during the 30 consecutive hydrological years when irrigated with irrigation water of 1500 mg/l chloride. ***Potatoes on sand.***

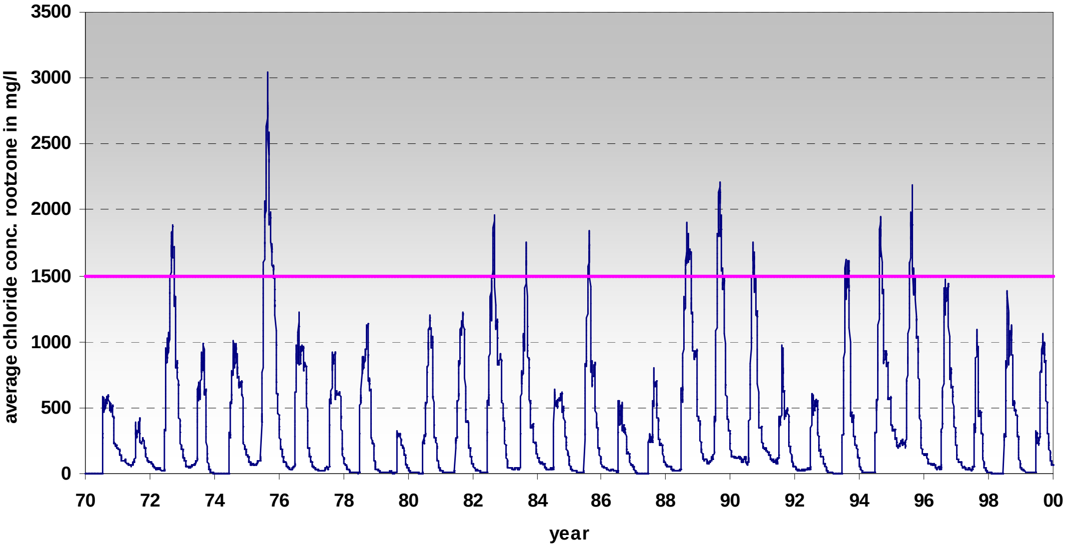

Fig. 2 Chloride concentration in the root zone (mg/l) during the 30 consecutive hydrological years when irrigated with irrigation water of 1500 mg/l chloride. ***Potatoes on clay.***

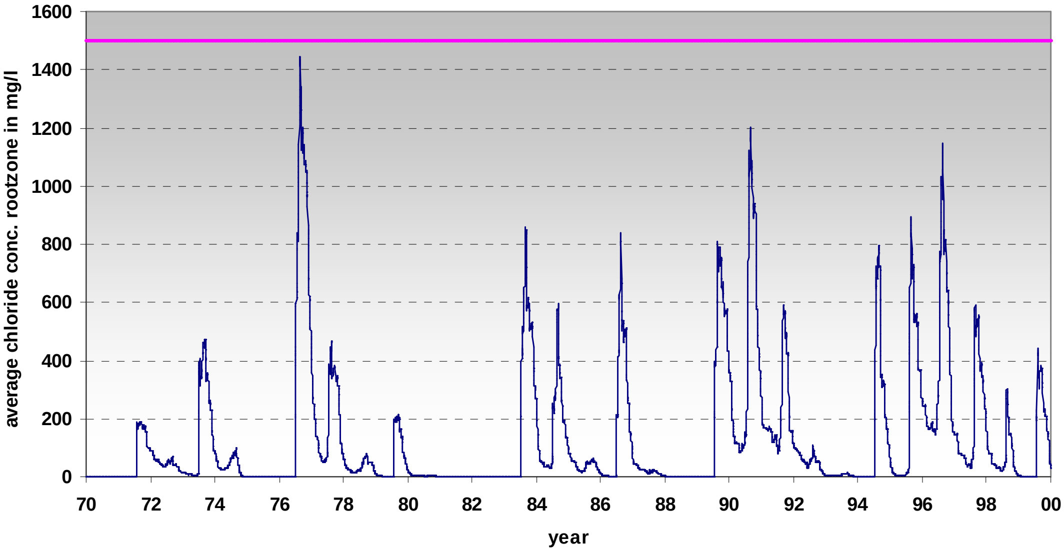

Fig. 3 Chloride concentration in the root zone (mg/l) during the 30 consecutive hydrological years when irrigated with irrigation water of 1500 mg/l chloride. **Potatoes on loam.**

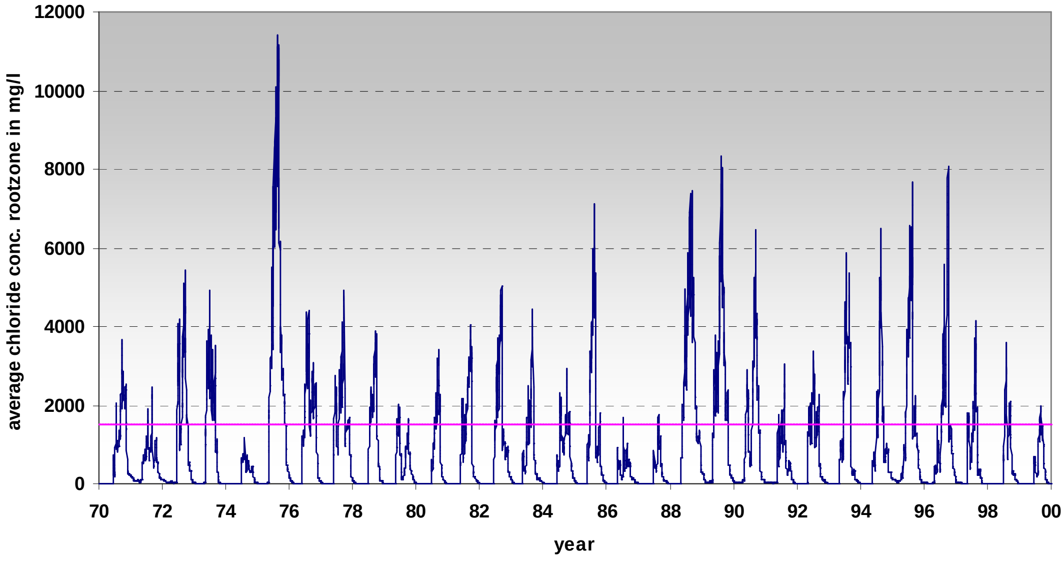

Fig. 4 Chloride concentration in the root zone (mg/l) during the 30 consecutive hydrological years when irrigated with irrigation water of 1500 mg/l chloride. **Grass on sand.**

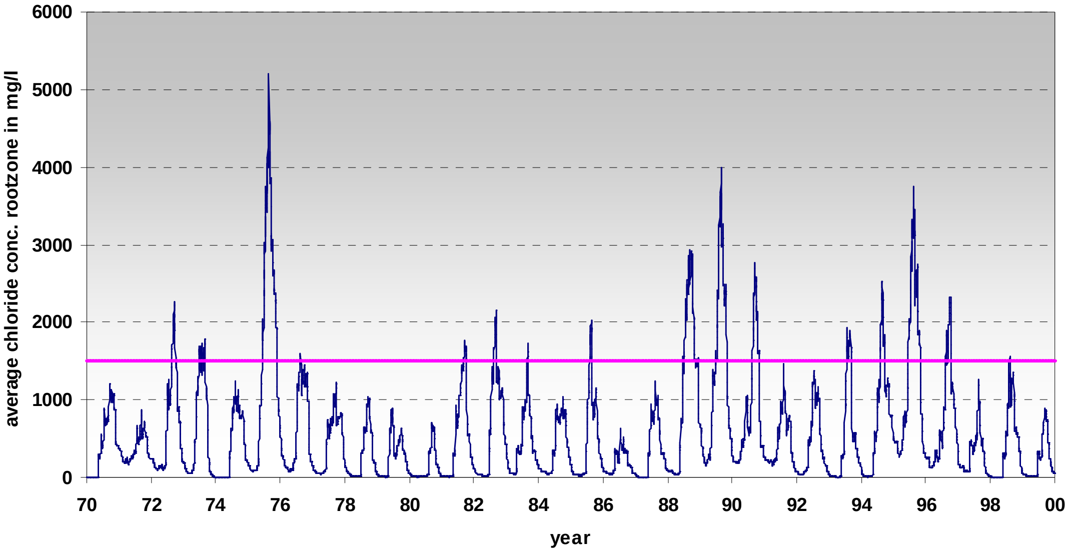

Fig. 5 Chloride concentration in the root zone (mg/l) during the 30 consecutive hydrological years when irrigated with irrigation water of 1500 mg/l chloride. ***Grass on clay.***

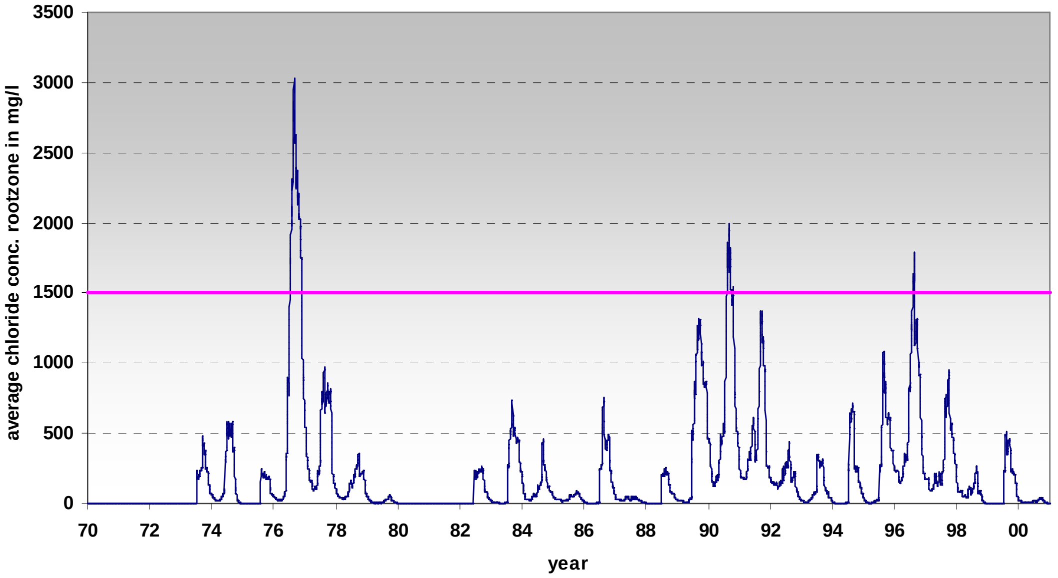

Fig. 6 Chloride concentration in the root zone (mg/l) during the 30 consecutive hydrological years when irrigated with irrigation water of 1500 mg/l chloride. ***Grass on loam.***

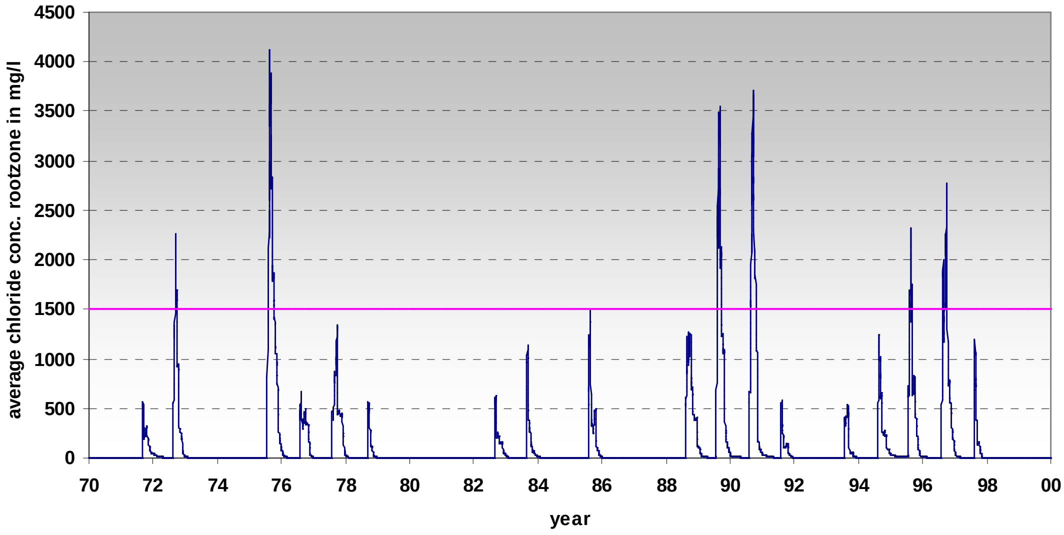

Fig. 7 Chloride concentration in the root zone (mg/l) during the 30 consecutive hydrological years when irrigated with irrigation water of 1500 mg/l chloride. ***Sugar beet on sand.***

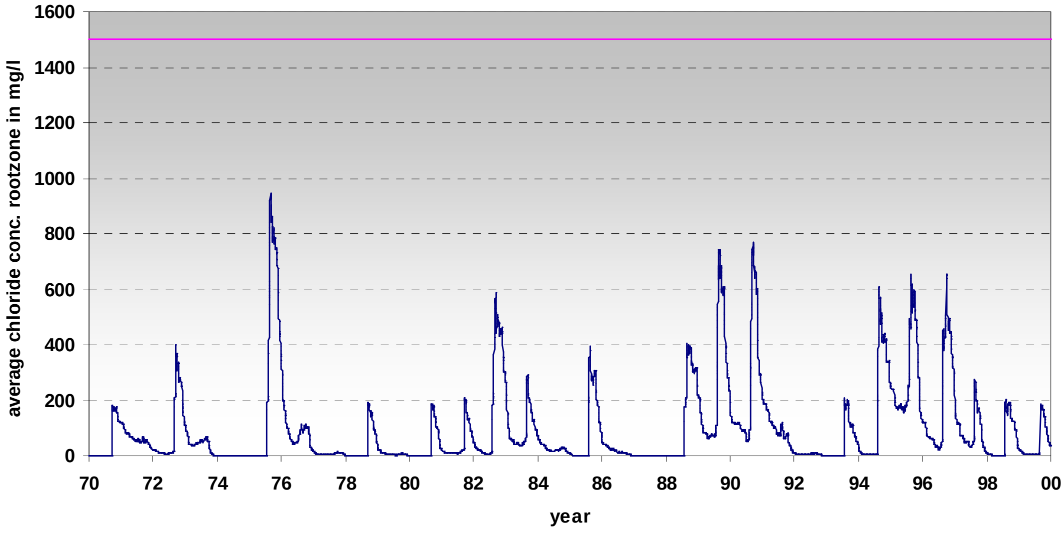

Fig. 8 Chloride concentration in the root zone (mg/l) during the 30 consecutive hydrological years when irrigated with irrigation water of 1500 mg/l chloride. ***Sugar beet on clay.***

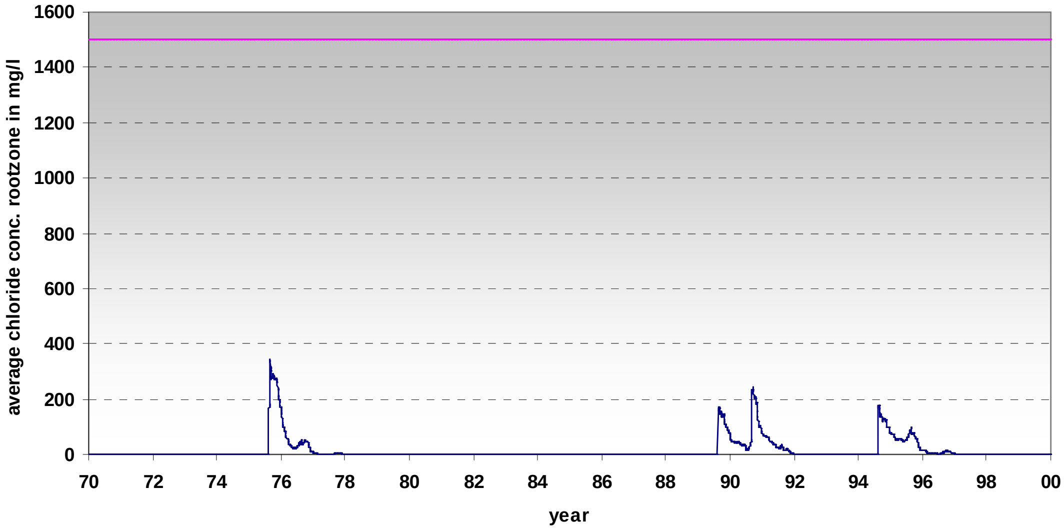

Fig. 9 Chloride concentration in the root zone (mg/l) during the 30 consecutive hydrological years when irrigated with irrigation water of 1500 mg/l chloride. **Sugar beet on loam.**

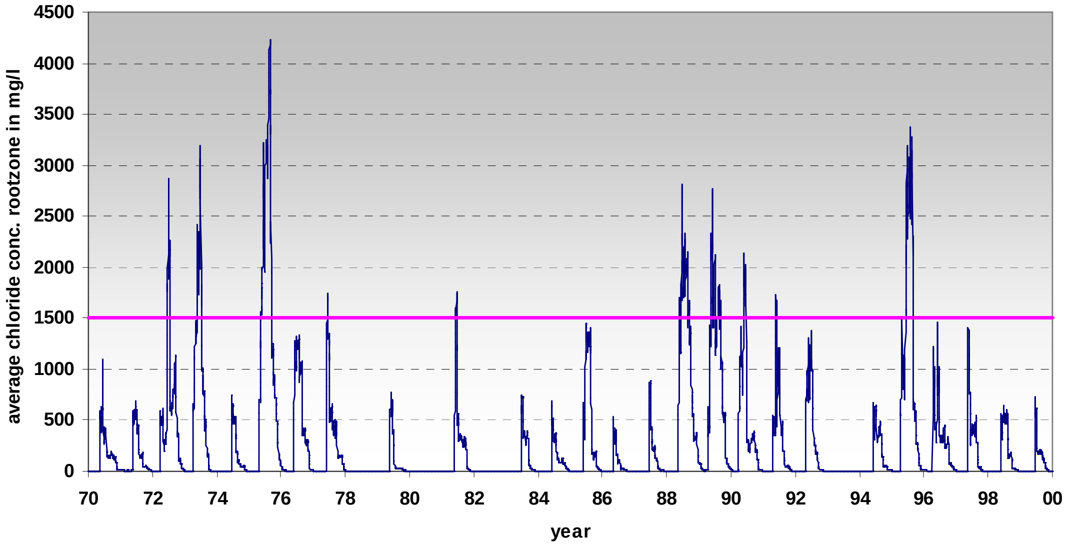

Fig. 10 Chloride concentration in the root zone (mg/l) during the 30 consecutive hydrological years when irrigated with irrigation water of 1500 mg/l chloride. **Tulip on sand.**

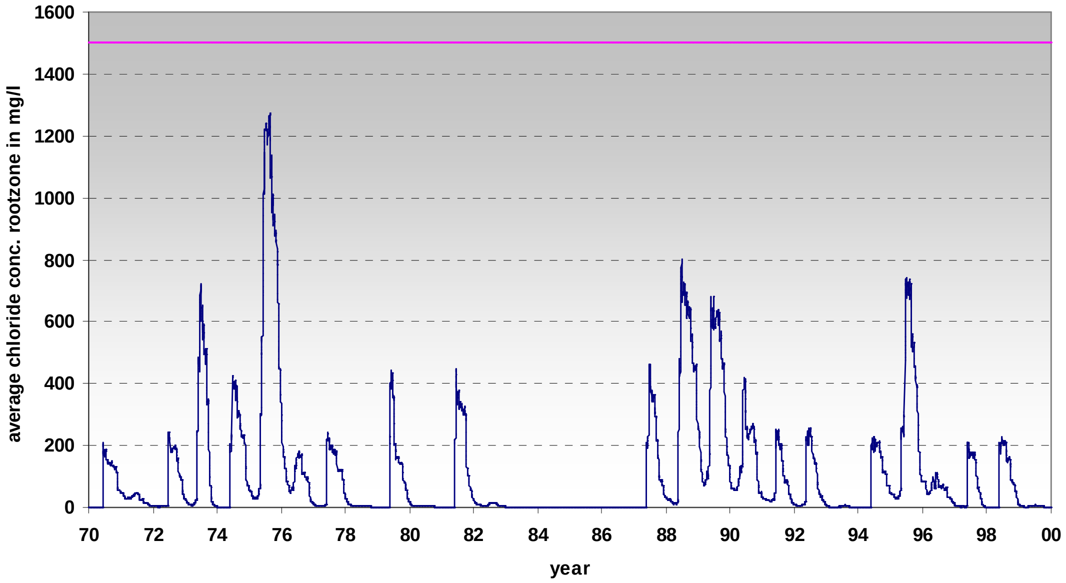

Fig. 11 Chloride concentration in the root zone (mg/l) during the 30 consecutive hydrological years when irrigated with irrigation water of 1500 mg/l chloride. ***Tulip on loam.***

Appendix 1.2 Simulated number of irrigations applied to the potato crop.

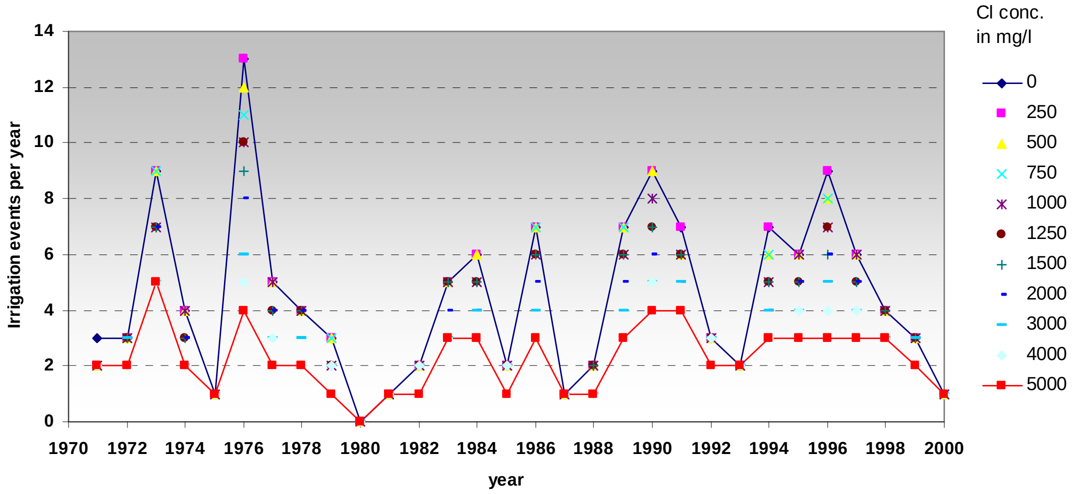

Fig. 12 Number of irrigations (of 20 mm each) applied to potatoes during the 30 consecutive hydrological years when irrigated with different water of different chloride concentrations. ***Sandy soil.***

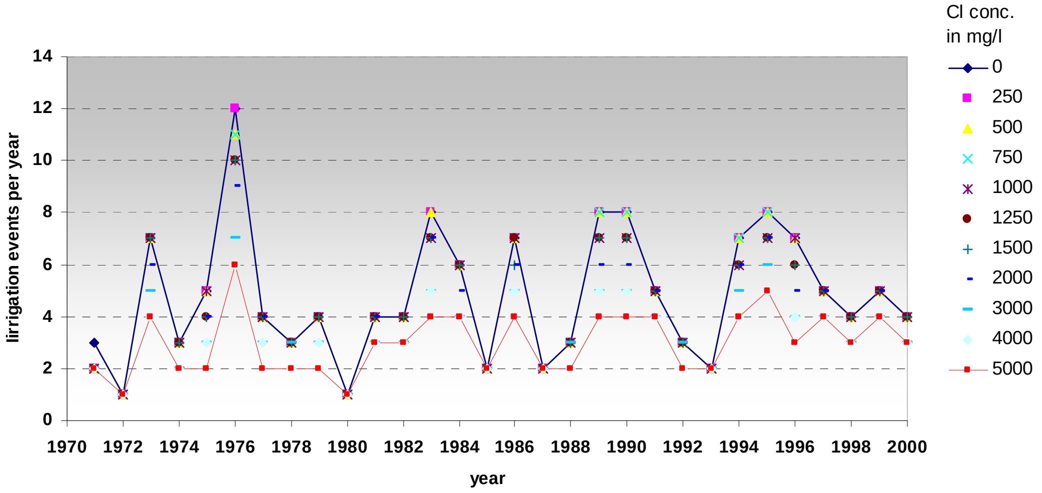

Fig. 13 Number of irrigations (of 20 mm each) applied to potatoes during the 30 consecutive hydrological years when irrigated with different water of different chloride concentrations. ***Clay soil.***

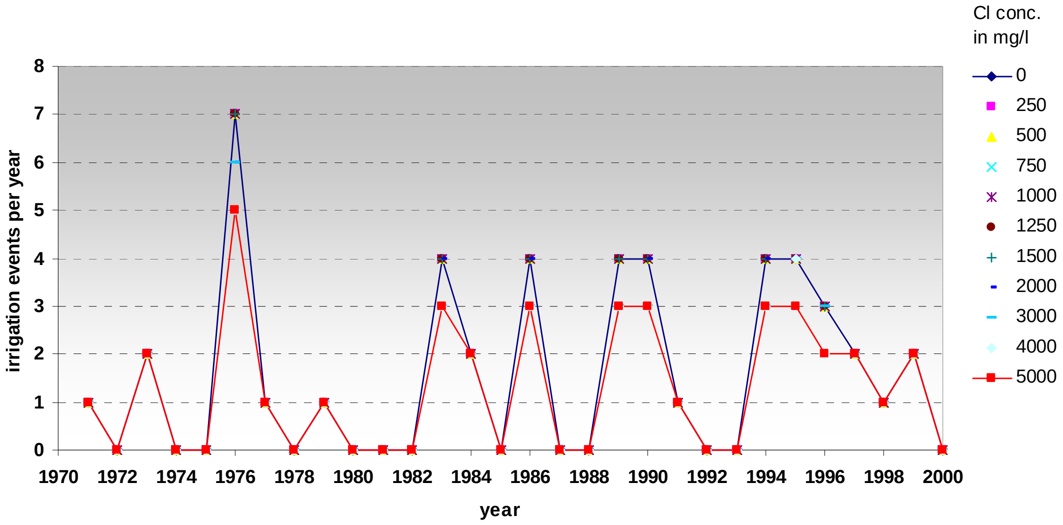

Fig. 14 Number of irrigations (of 20 mm each) applied to potatoes during the 30 consecutive hydrological years when irrigated with different water of different chloride concentrations. ***Loamy soil.***

Appendix 1.3 Simulated ratio between chloride concentration in the crop root zone and irrigation water for the potato crop.

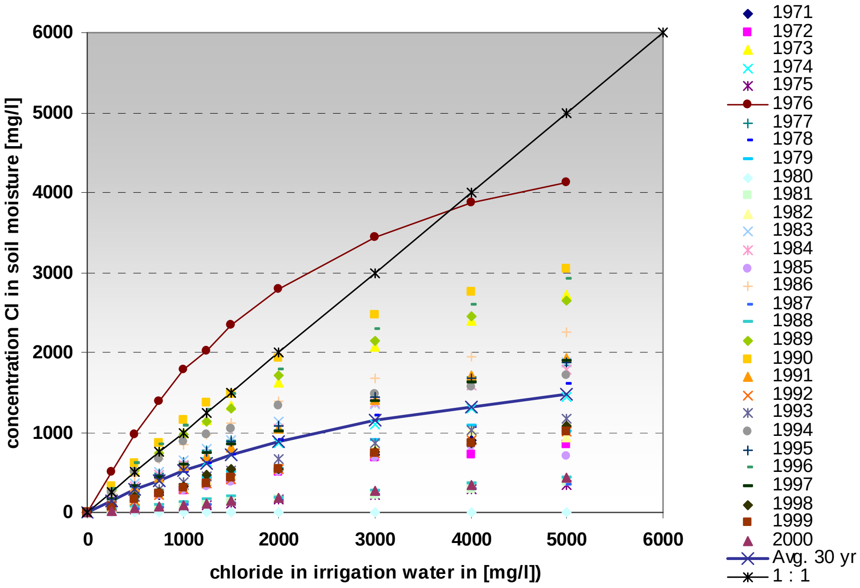

Fig. 15 Ratio between the chloride concentration in the potato crop root zone and in the irrigation water for 30 consecutive hydrological years. ***Sandy soil.***

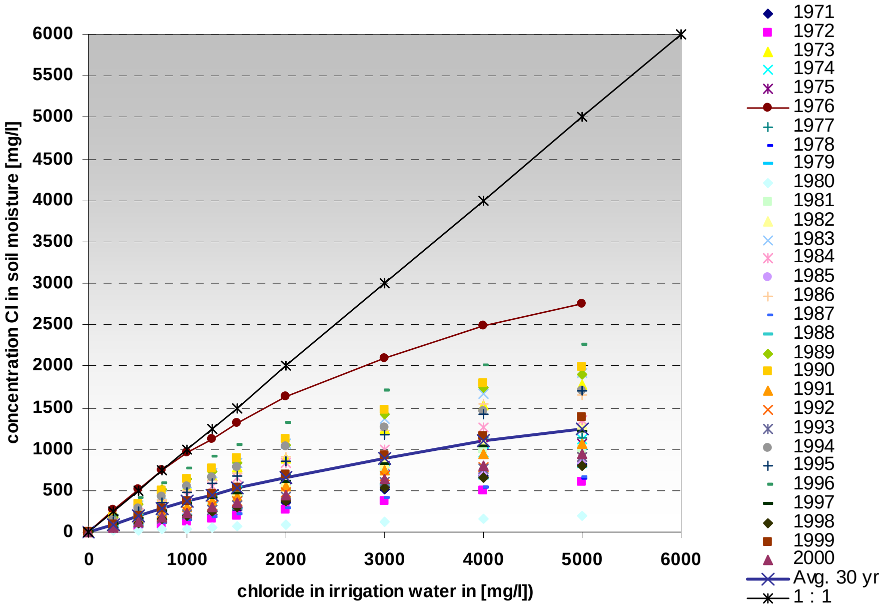

Fig. 16 Ratio between the chloride concentration in the potato crop root zone and in the irrigation water for 30 consecutive hydrological years. ***Clay soil.***

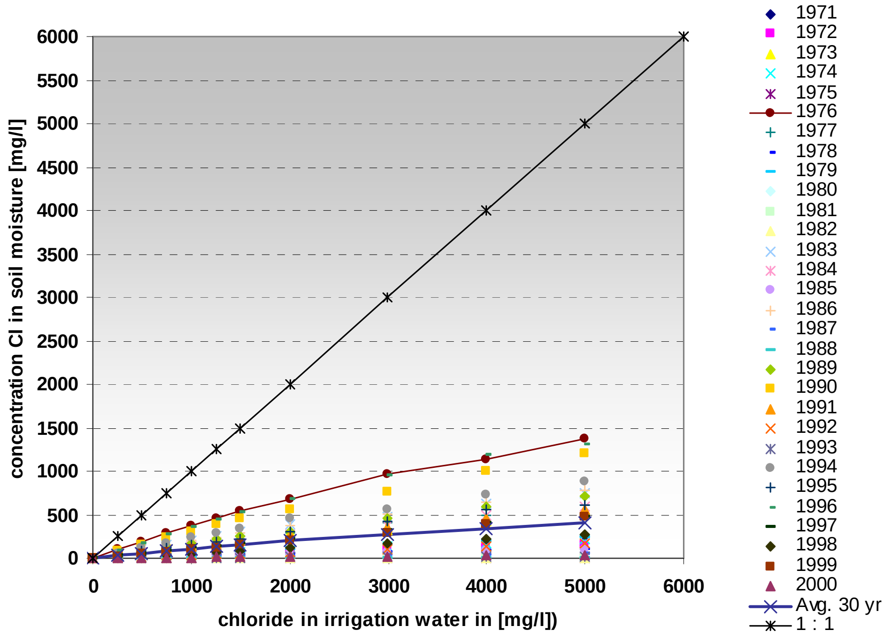

Fig. 17 Ratio between the chloride concentration in the potato crop root zone and in the irrigation water for 30 consecutive hydrological years. ***Loamy soil.***

Appendix 1.4 Simulated relative (relative to irrigation with zero salinity) crop transpiration as response to an irrigation salinity up to 1500 mg/l.

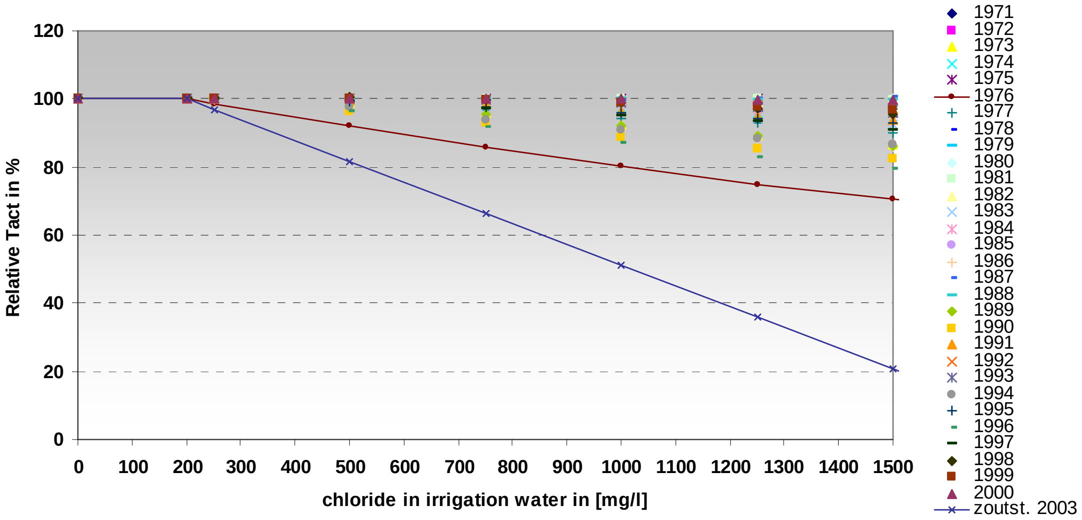

Fig. 18 Relative crop transpiration (relative to irrigation with zero salinity water for 30 consecutive hydrological years and chloride concentrations in the irrigation water up to 1500 mg/l. ***Potato on sand.***

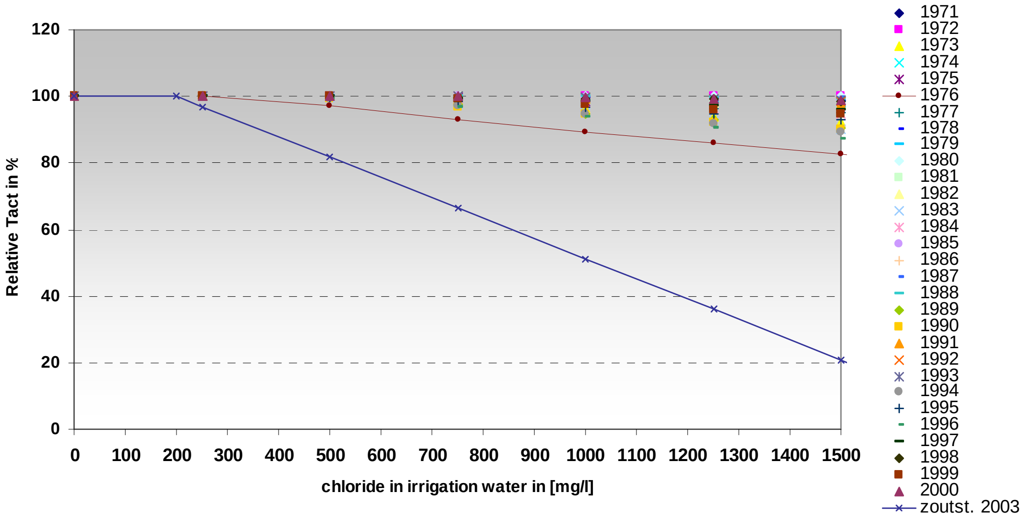

Fig. 19 Relative crop transpiration (relative to irrigation with zero salinity water for 30 consecutive hydrological years and chloride concentrations in the irrigation water up to 1500 mg/l. ***Potato on clay.***

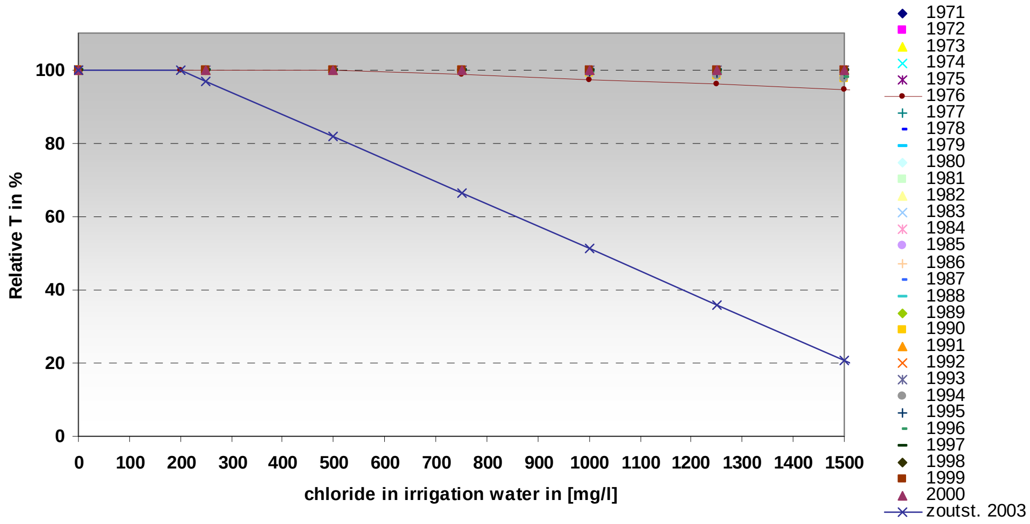

Fig. 20 Relative crop transpiration (relative to irrigation with zero salinity water for 30 consecutive hydrological years and chloride concentrations in the irrigation water up to 1500 mg/l. ***Potato on loam.***

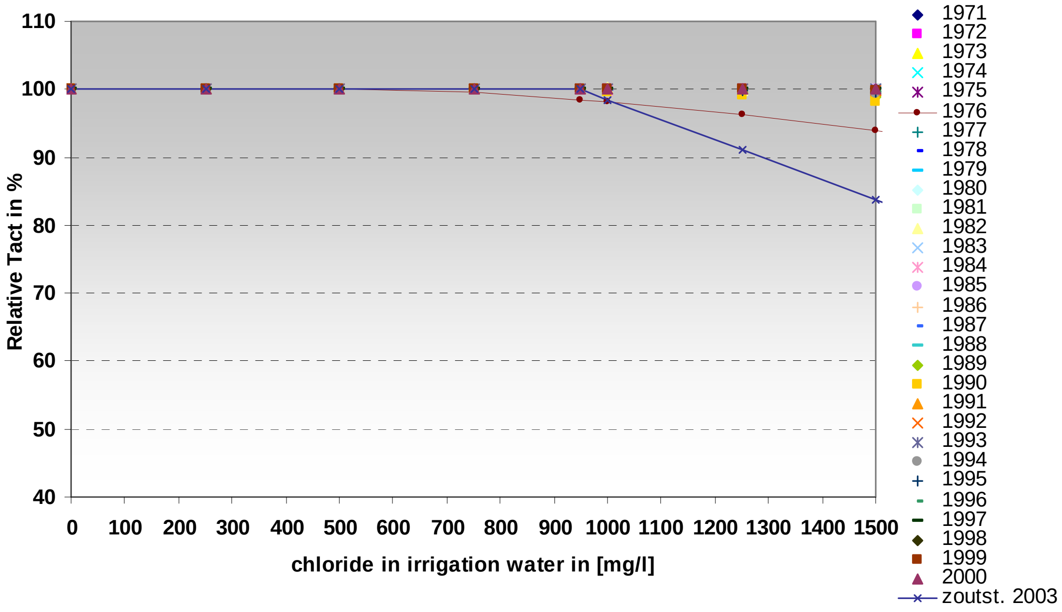

Fig. 21 Relative crop transpiration (relative to irrigation with zero salinity water for 30 consecutive hydrological years and chloride concentrations in the irrigation water up to 1500 mg/l. ***Grass on sand.***

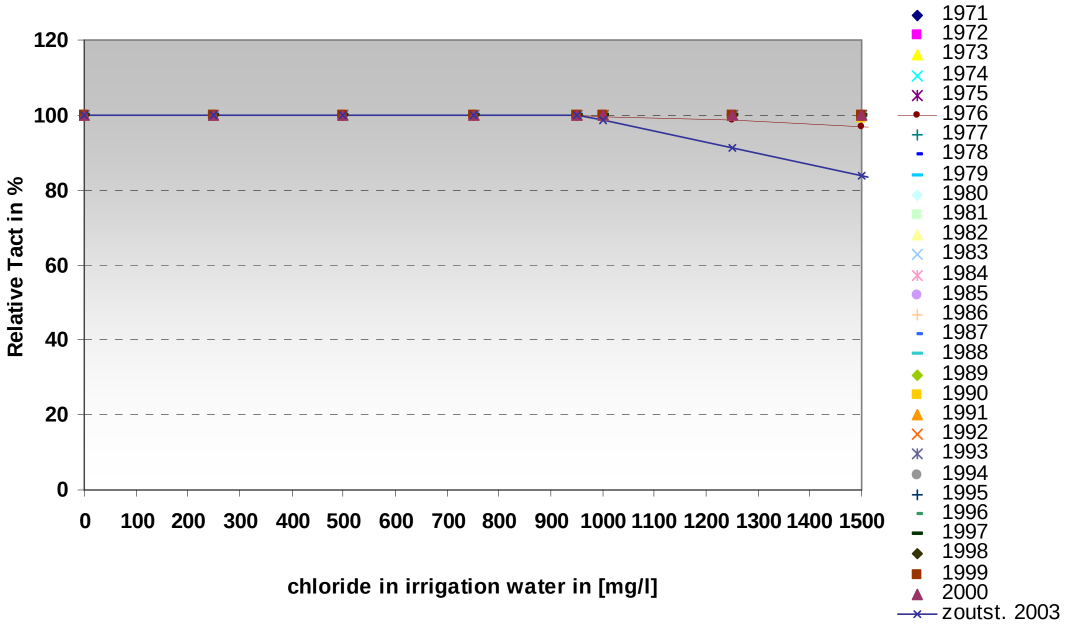

Fig. 22 Relative crop transpiration (relative to irrigation with zero salinity water for 30 consecutive hydrological years and chloride concentrations in the irrigation water up to 1500 mg/l. ***Grass on clay.***

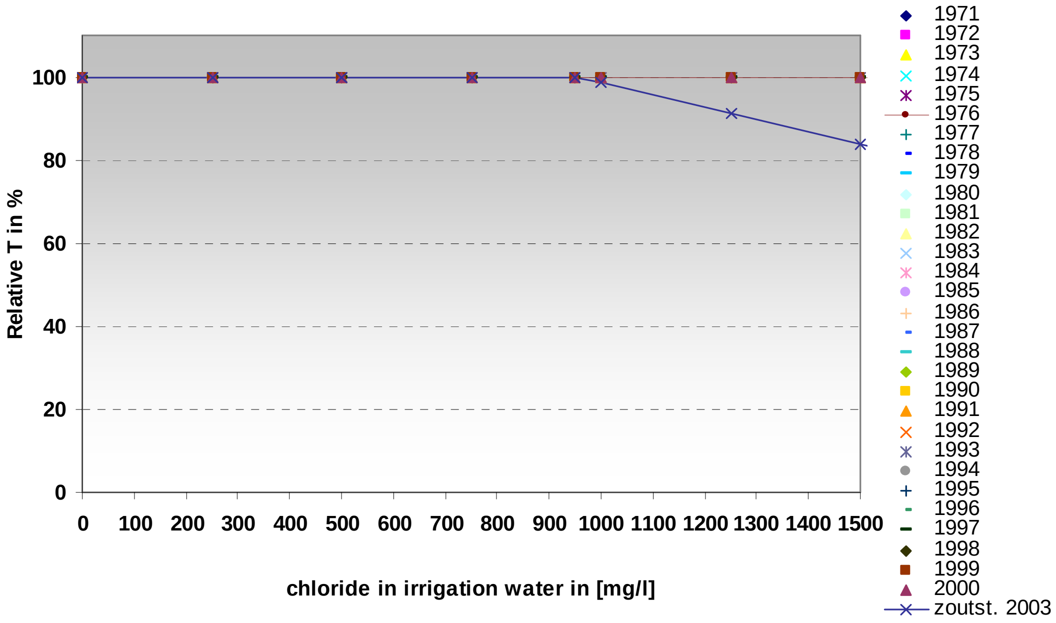

Fig. 23 Relative crop transpiration (relative to irrigation with zero salinity water for 30 consecutive hydrological years and chloride concentrations in the irrigation water up to 1500 mg/l. ***Grass on loam.***

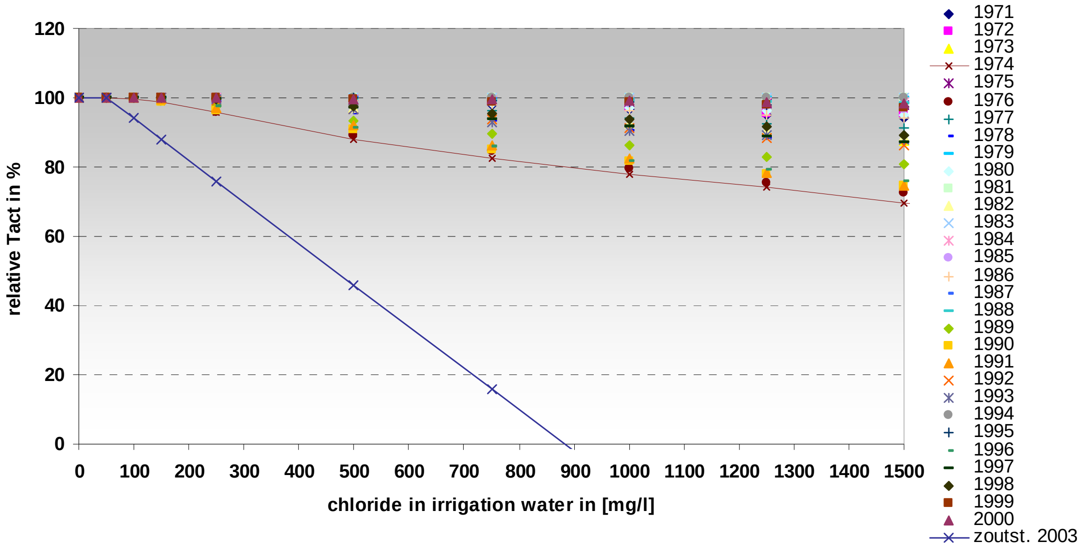

Fig. 24 Relative crop transpiration (relative to irrigation with zero salinity water for 30 consecutive hydrological years and chloride concentrations in the irrigation water up to 1500 mg/l. ***Tulip on sand.***

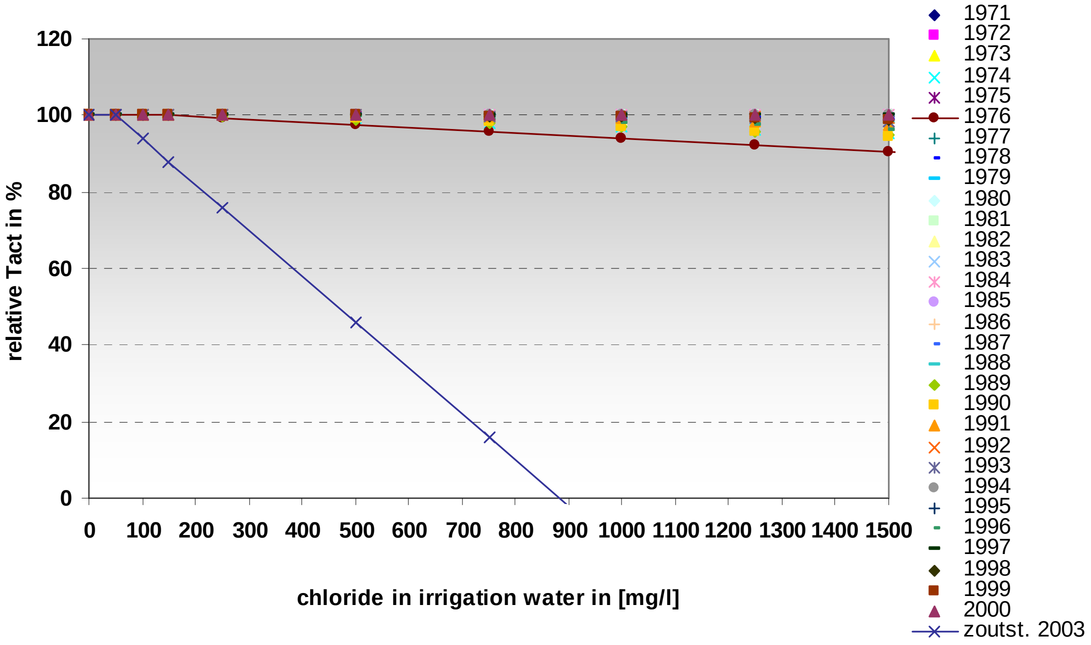

Fig. 25 Relative crop transpiration (relative to irrigation with zero salinity water for 30 consecutive hydrological years and chloride concentrations in the irrigation water up to 1500 mg/l. ***Tulip on loam.***

Appendix 1.5 Simulated relative (relative to irrigation with zero salinity) crop transpiration as response to an irrigation salinity up to 5000 mg/l.

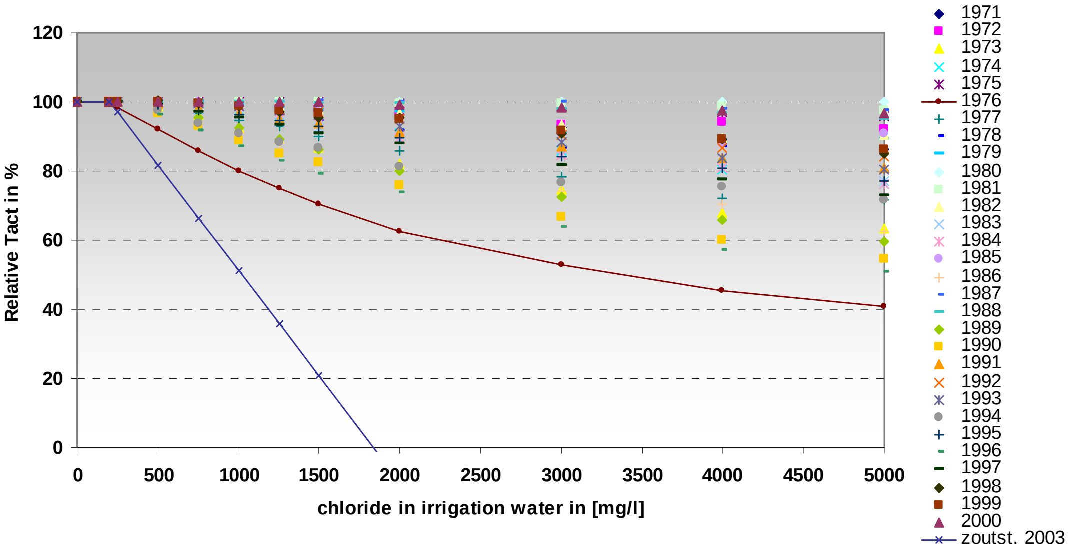

Fig. 26 Relative crop transpiration (relative to irrigation with zero salinity water for 30 consecutive hydrological years and chloride concentrations in the irrigation water up to 5000 mg/l. ***Potato on sand.***

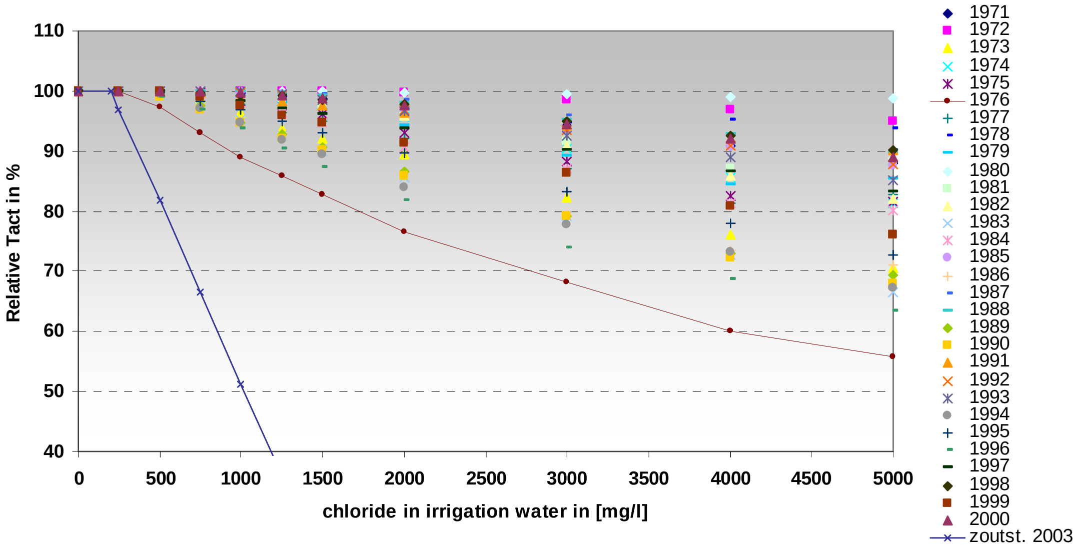

Fig. 27 Relative crop transpiration (relative to irrigation with zero salinity water for 30 consecutive hydrological years and chloride concentrations in the irrigation water up to 5000 mg/l. ***Potato on clay.***

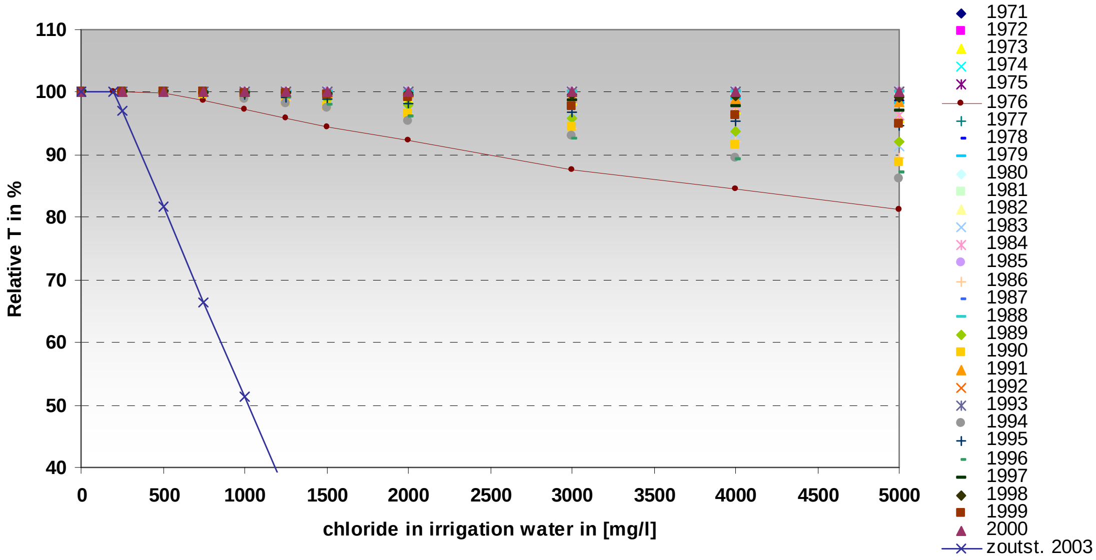

Fig. 28 Relative crop transpiration (relative to irrigation with zero salinity water for 30 consecutive hydrological years and chloride concentrations in the irrigation water up to 5000 mg/l. ***Potato on loam.***

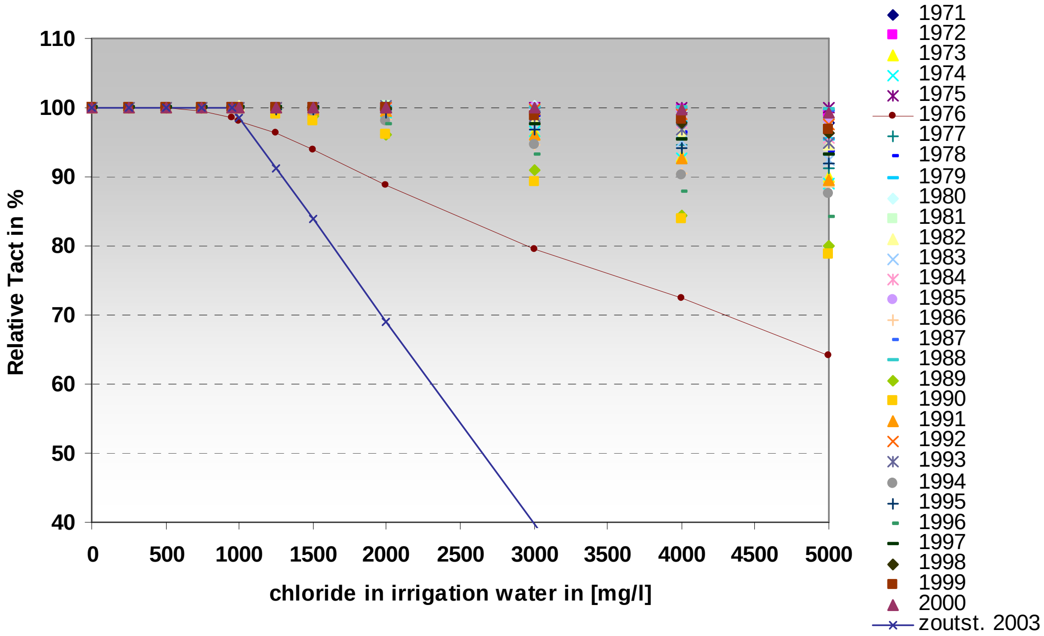

Fig. 29 Relative crop transpiration (relative to irrigation with zero salinity water for 30 consecutive hydrological years and chloride concentrations in the irrigation water up to 5000 mg/l. ***Grass on sand.***

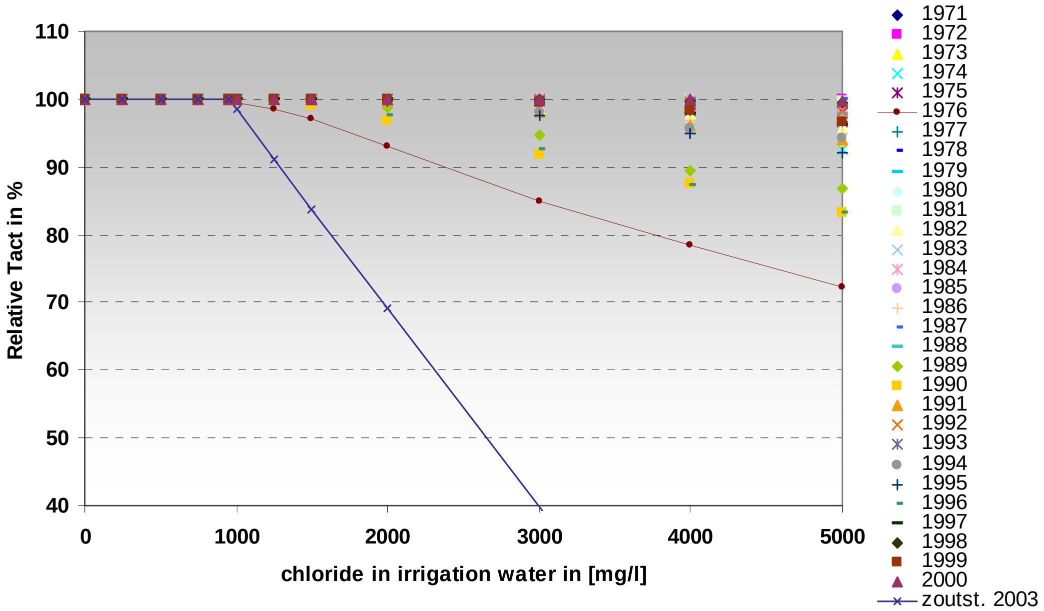

Fig. 30 Relative crop transpiration (relative to irrigation with zero salinity water for 30 consecutive hydrological years and chloride concentrations in the irrigation water up to 5000 mg/l. ***Grass on clay.***

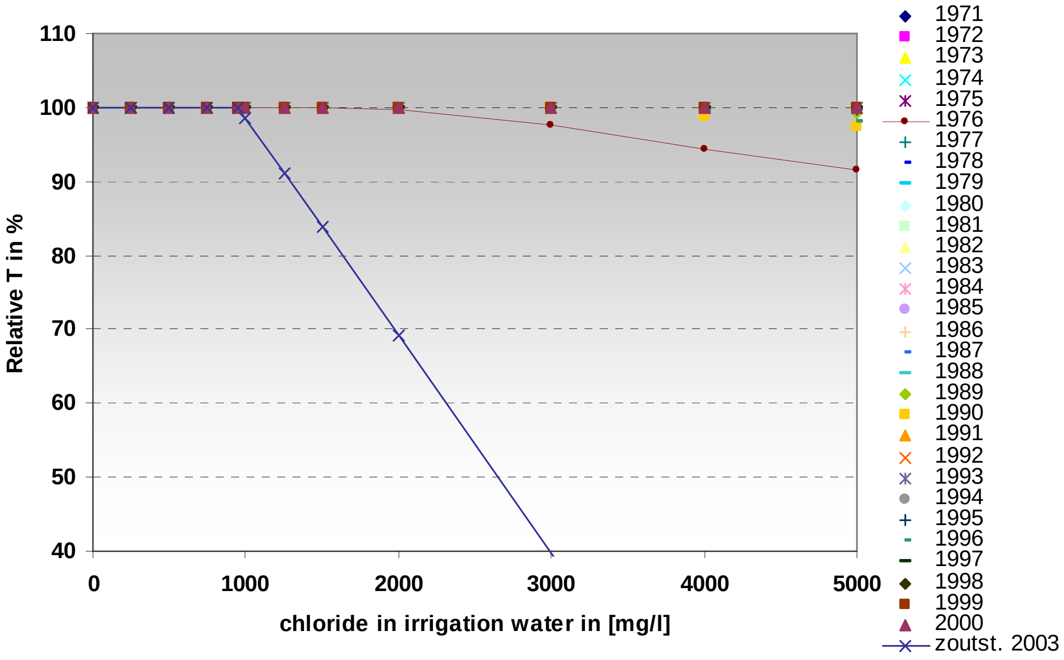

Fig. 31 Relative crop transpiration (relative to irrigation with zero salinity water for 30 consecutive hydrological years and chloride concentrations in the irrigation water up to 5000 mg/l. ***Grass on loam.***

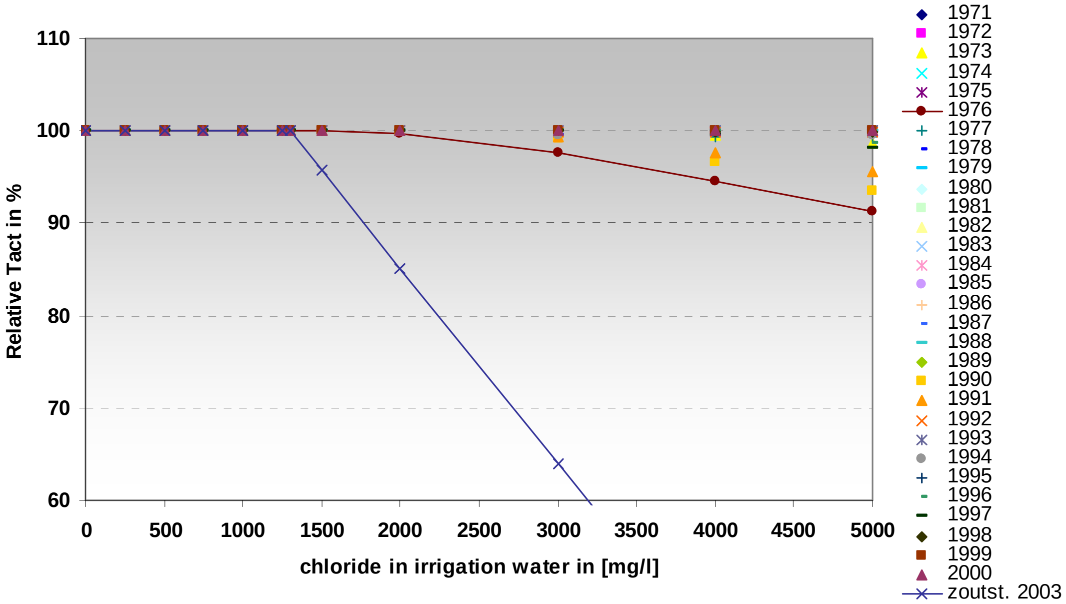

Fig. 32 Relative crop transpiration (relative to irrigation with zero salinity water for 30 consecutive hydrological years and chloride concentrations in the irrigation water up to 5000 mg/l. ***Sugar beet on sand.***

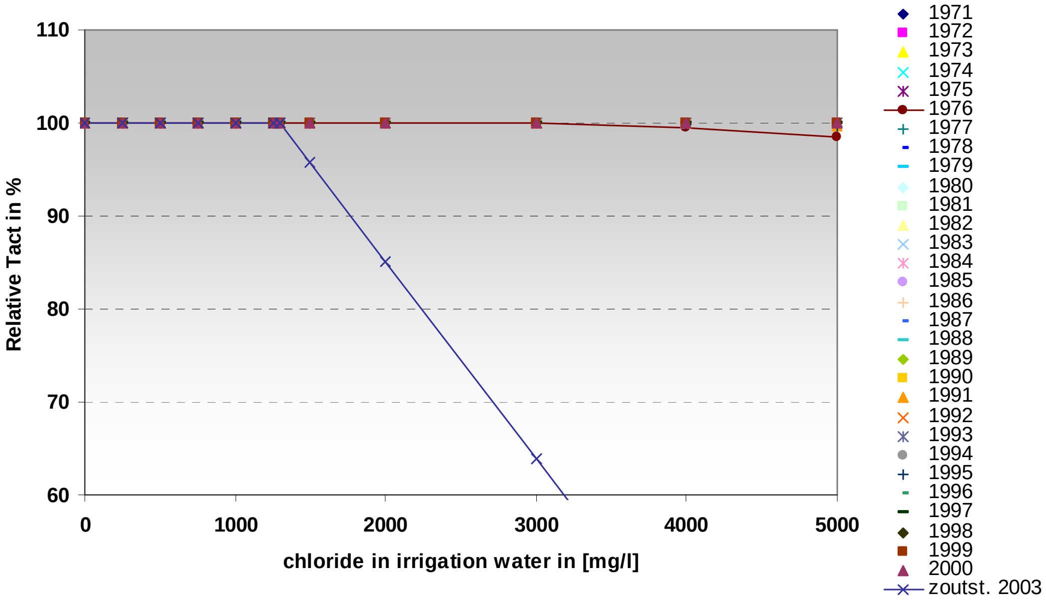

Fig. 33 Relative crop transpiration (relative to irrigation with zero salinity water for 30 consecutive hydrological years and chloride concentrations in the irrigation water up to 5000 mg/l. ***Sugar beet on clay.***

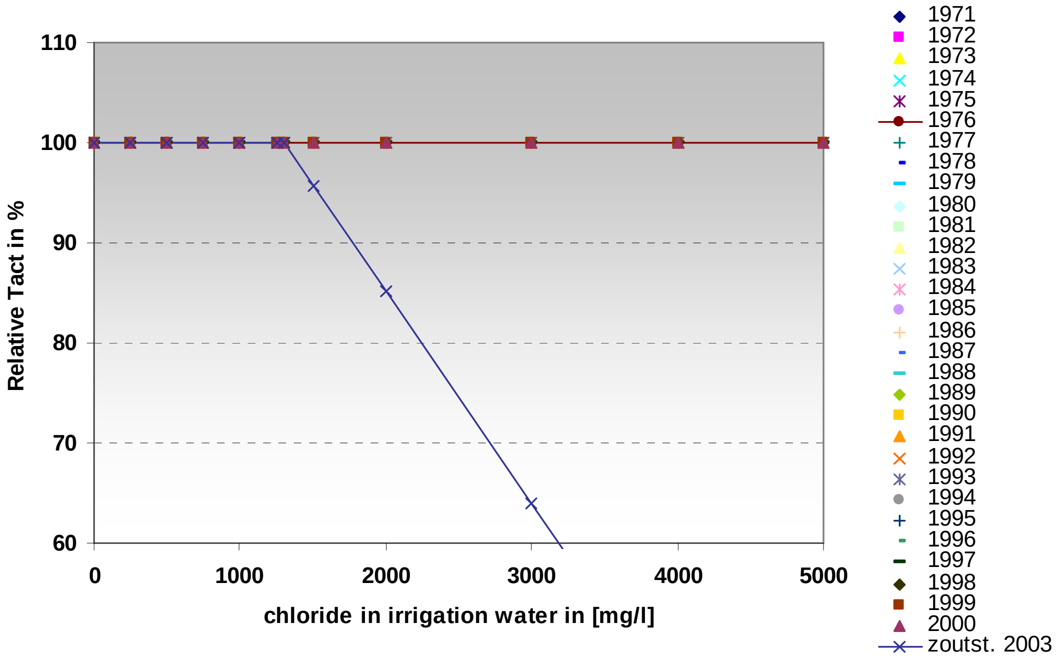

Fig. 34 Relative crop transpiration (relative to irrigation with zero salinity water for 30 consecutive hydrological years and chloride concentrations in the irrigation water up to 5000 mg/l. ***Sugar beet on loam.***

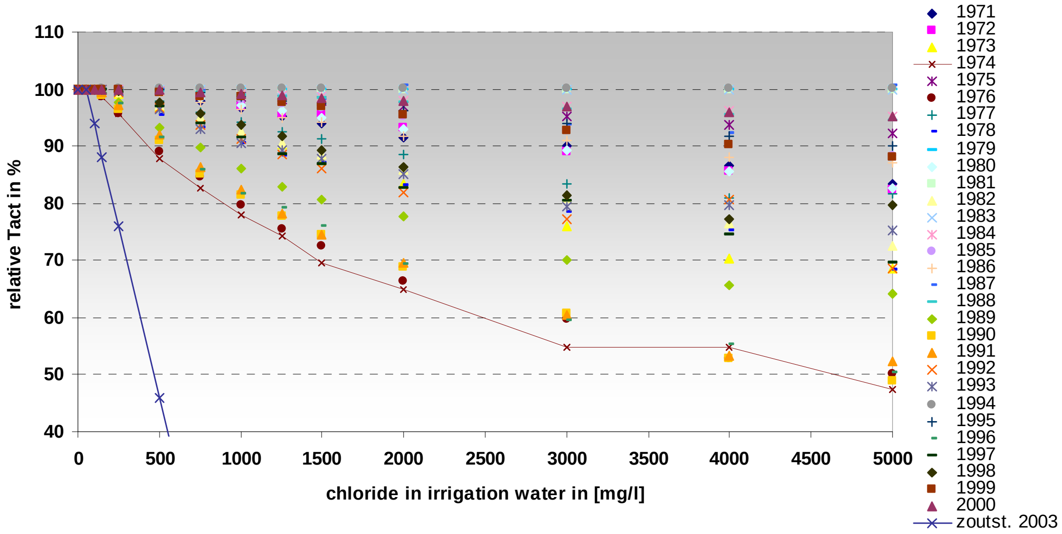

Fig. 35 Relative crop transpiration (relative to irrigation with zero salinity water for 30 consecutive hydrological years and chloride concentrations in the irrigation water up to 5000 mg/l. ***Tulips on sand.***

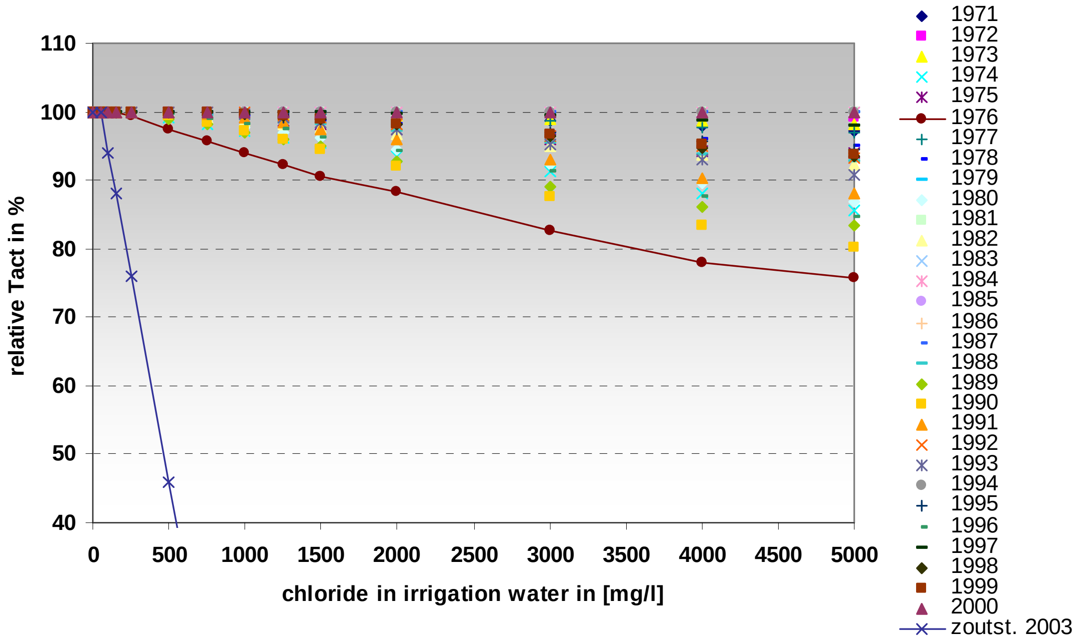

Fig. 36 Relative crop transpiration (relative to irrigation with zero salinity water for 30 consecutive hydrological years and chloride concentrations in the irrigation water up to 5000 mg/l. ***Tulips on loam.***

Appendix 1.6 Simulated relative (relative to not irrigated) crop transpiration as response to an irrigation salinity up to 5000 mg/l.

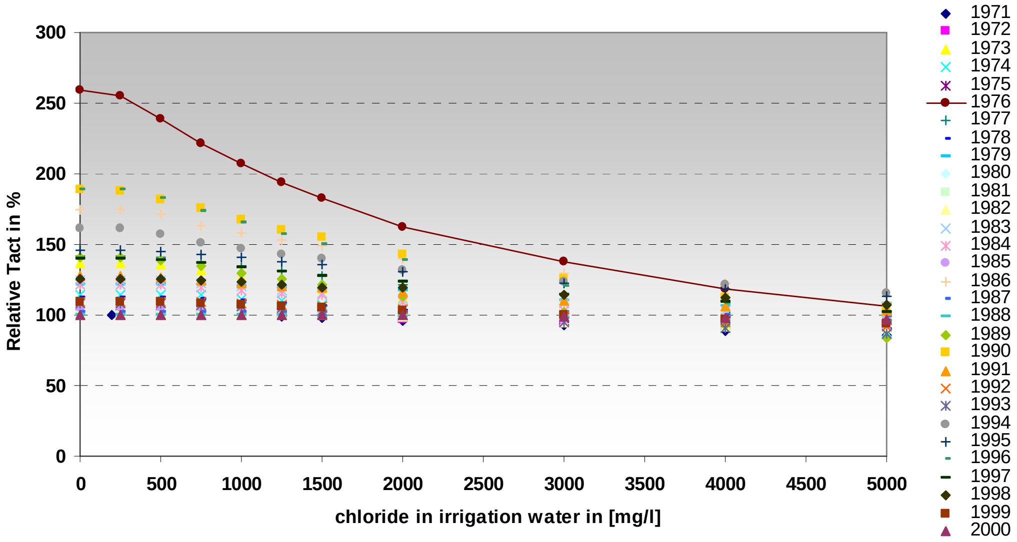

Fig. 37 Relative crop transpiration (relative to non-irrigated) for 30 consecutive hydrological years and several chloride concentrations in the irrigation water. ***Potatoes on sand.***

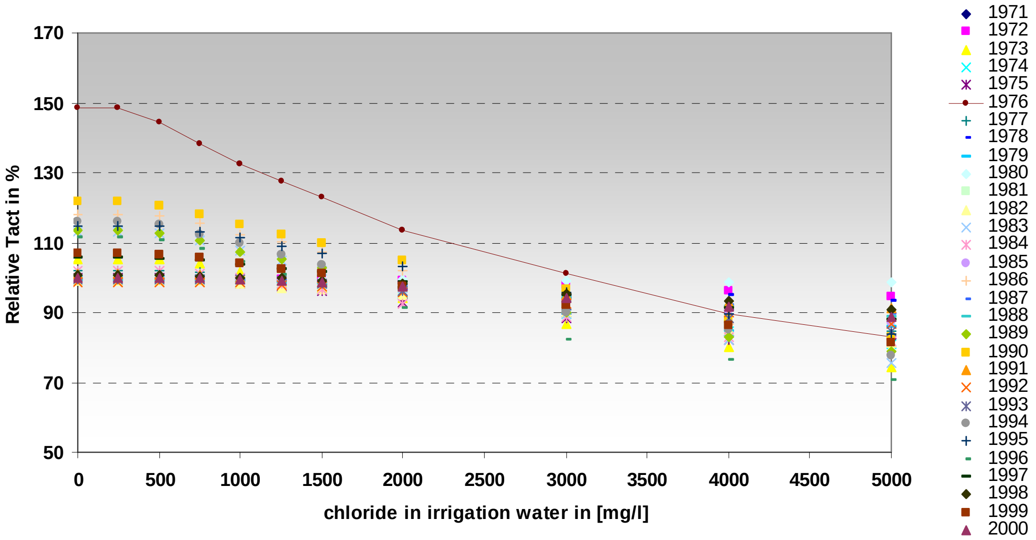

Fig. 38 Relative crop transpiration (relative to non-irrigated) for 30 consecutive hydrological years and several chloride concentrations in the irrigation water. ***Potatoes on clay.***

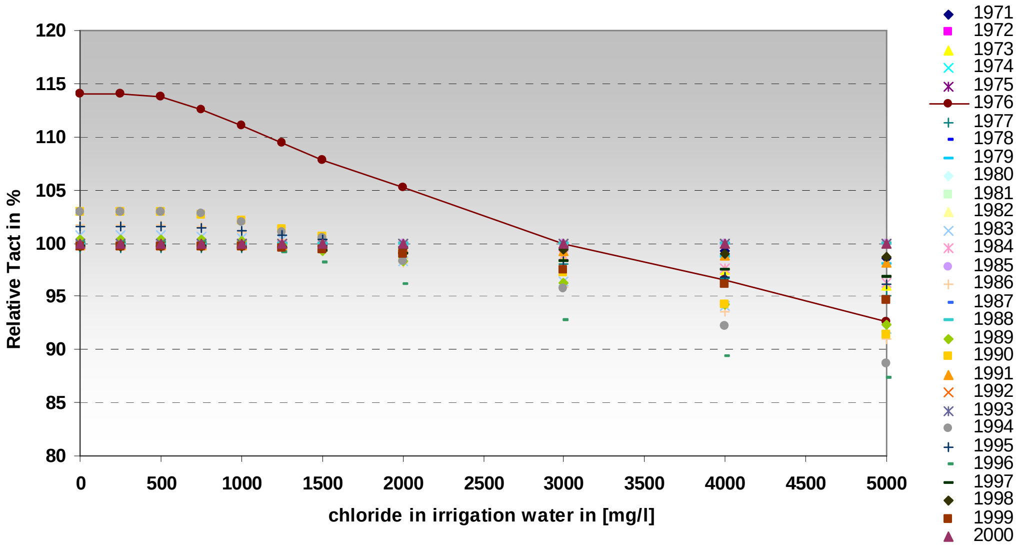

Fig. 39 Relative crop transpiration (relative to non-irrigated) for 30 consecutive hydrological years and several chloride concentrations in the irrigation water. ***Potatoes on loam.***

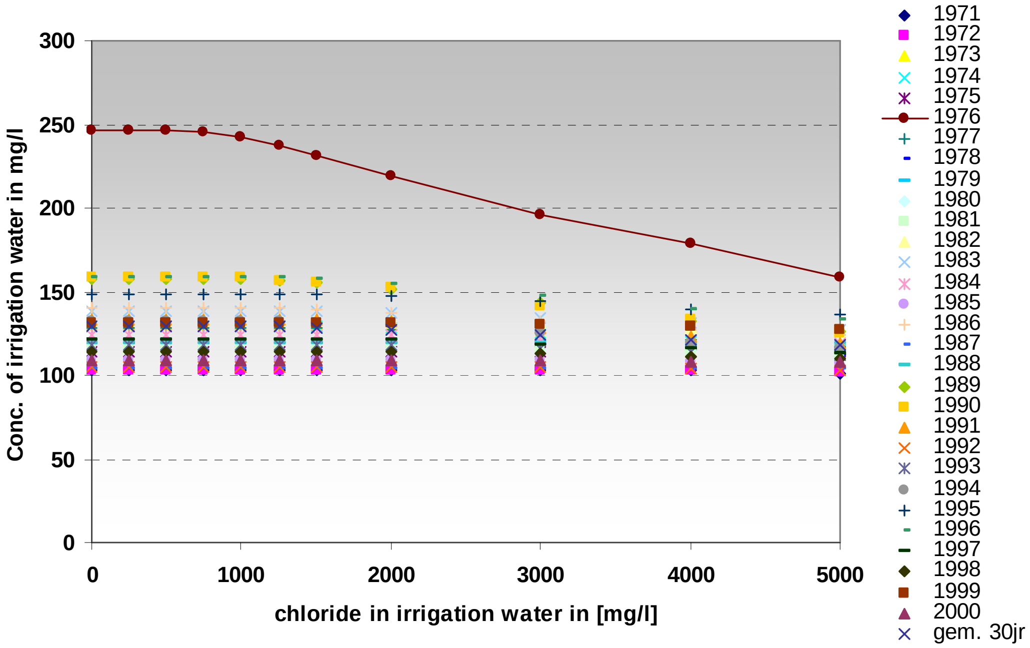

Fig. 40 Relative crop transpiration (relative to non-irrigated) for 30 consecutive hydrological years and several chloride concentrations in the irrigation water. ***Grass on sand.***

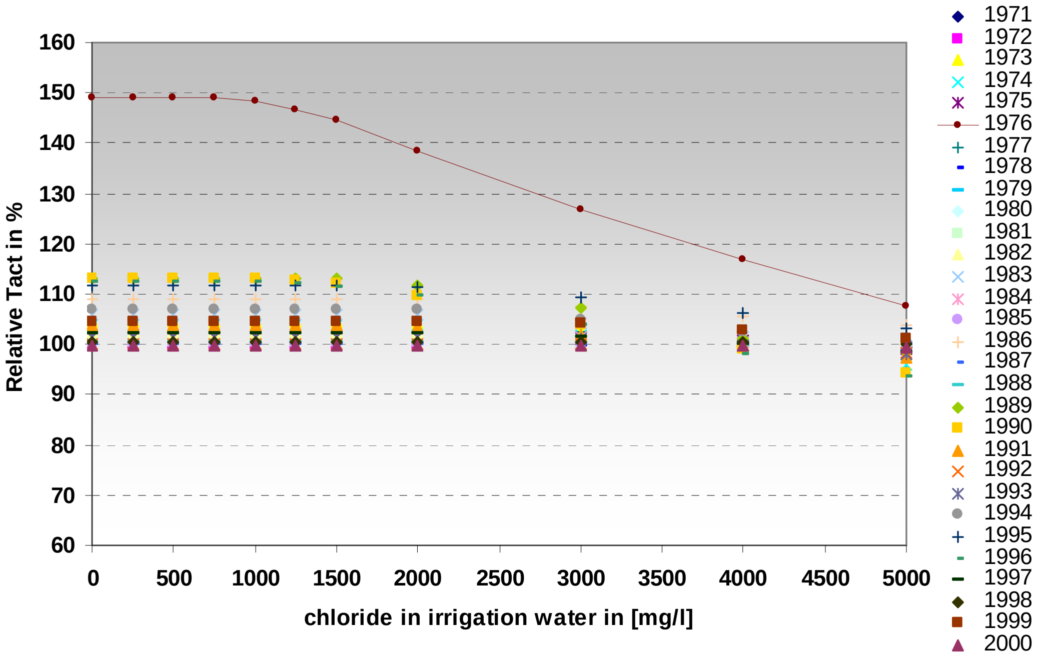

Fig. 41 Relative crop transpiration (relative to non-irrigated) for 30 consecutive hydrological years and several chloride concentrations in the irrigation water. ***Grass on clay.***

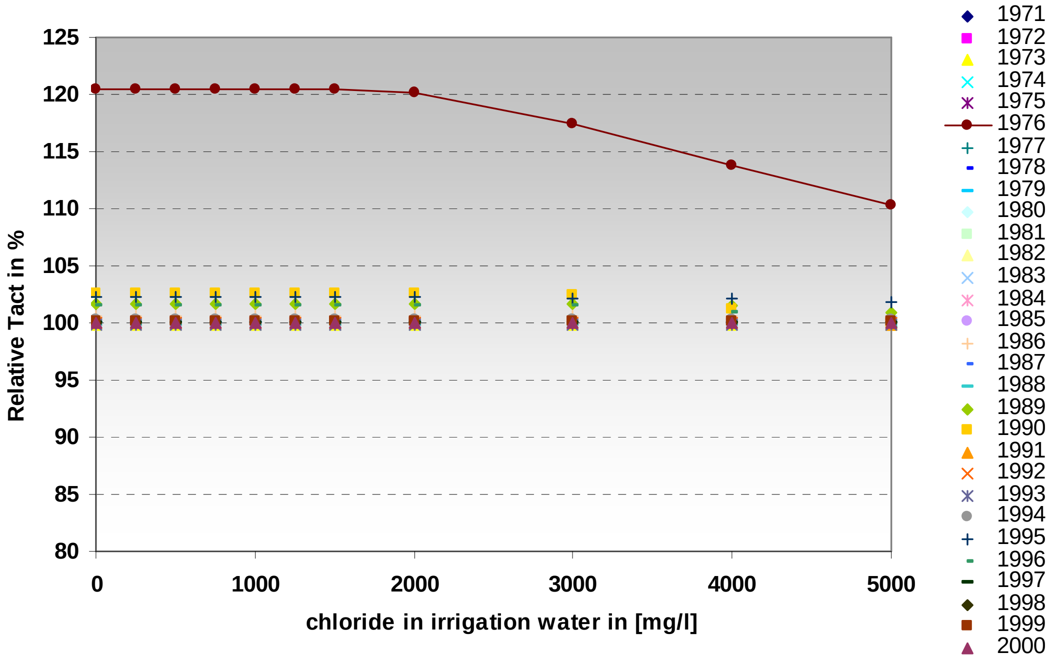

Fig. 42 Relative crop transpiration (relative to non-irrigated) for 30 consecutive hydrological years and several chloride concentrations in the irrigation water. ***Grass on loam.***

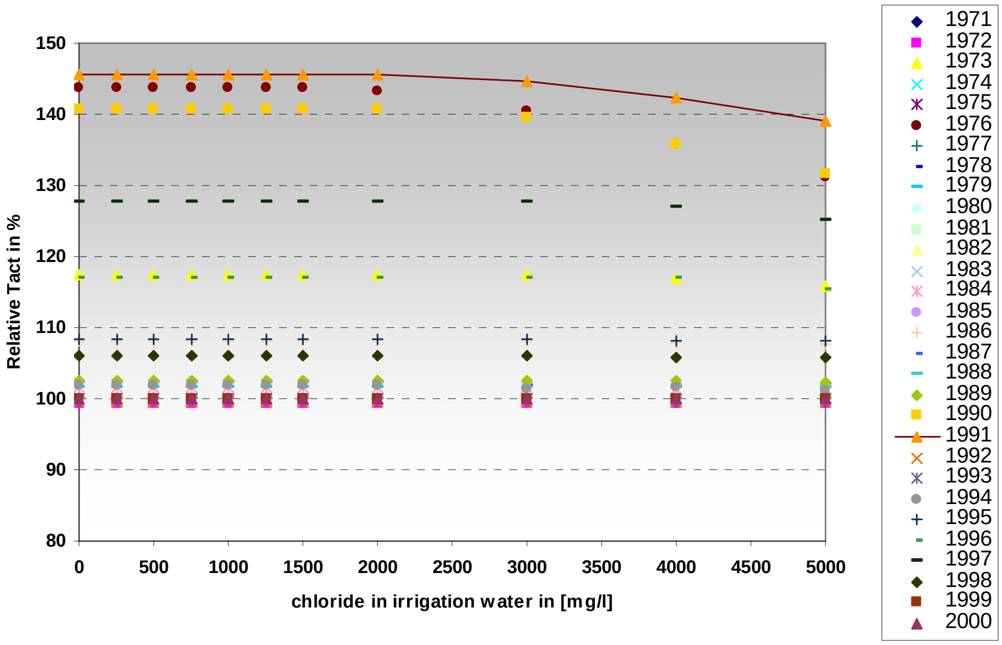

Fig. 43 Relative crop transpiration (relative to non-irrigated) for 30 consecutive hydrological years and several chloride concentrations in the irrigation water. ***Sugar beet on sand.***

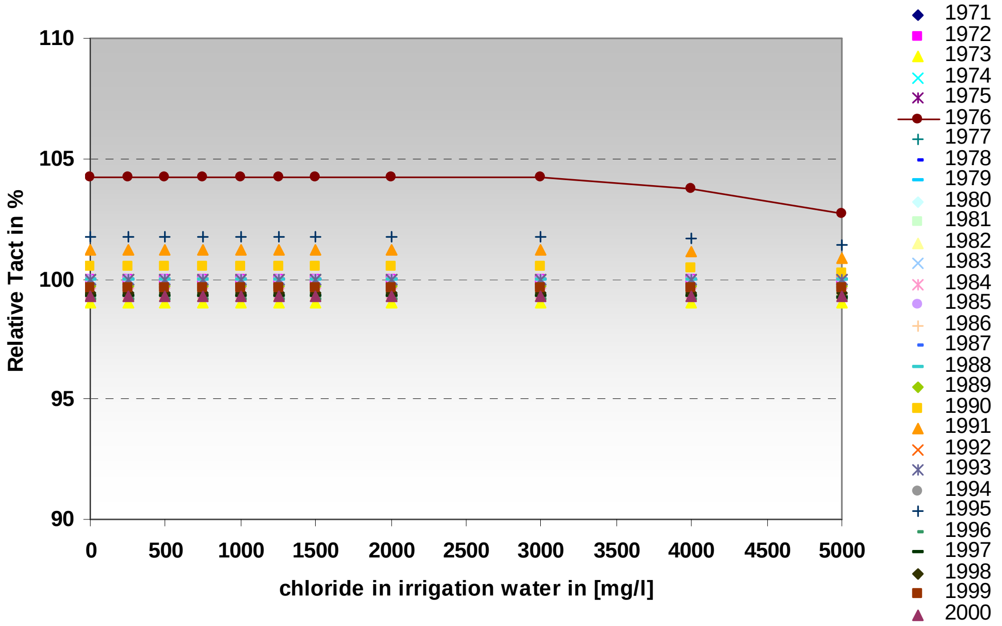

Fig. 44 Relative crop transpiration (relative to non-irrigated) for 30 consecutive hydrological years and several chloride concentrations in the irrigation water. ***Sugar beet on clay.***

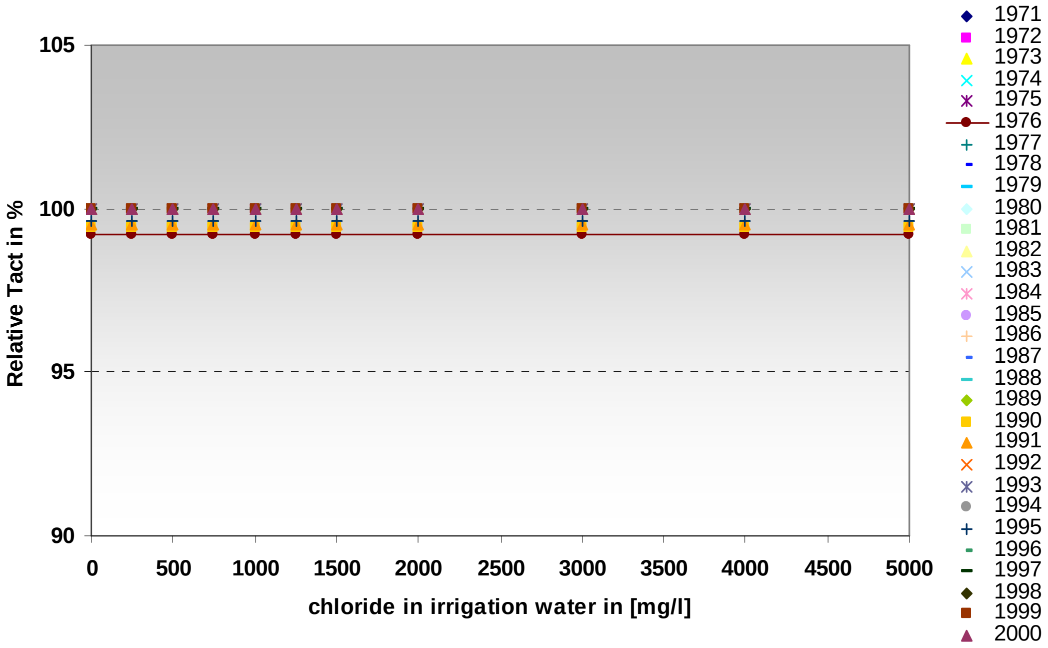

Fig. 45 Relative crop transpiration (relative to non-irrigated) for 30 consecutive hydrological years and several chloride concentrations in the irrigation water. ***Sugar beet on loam.***

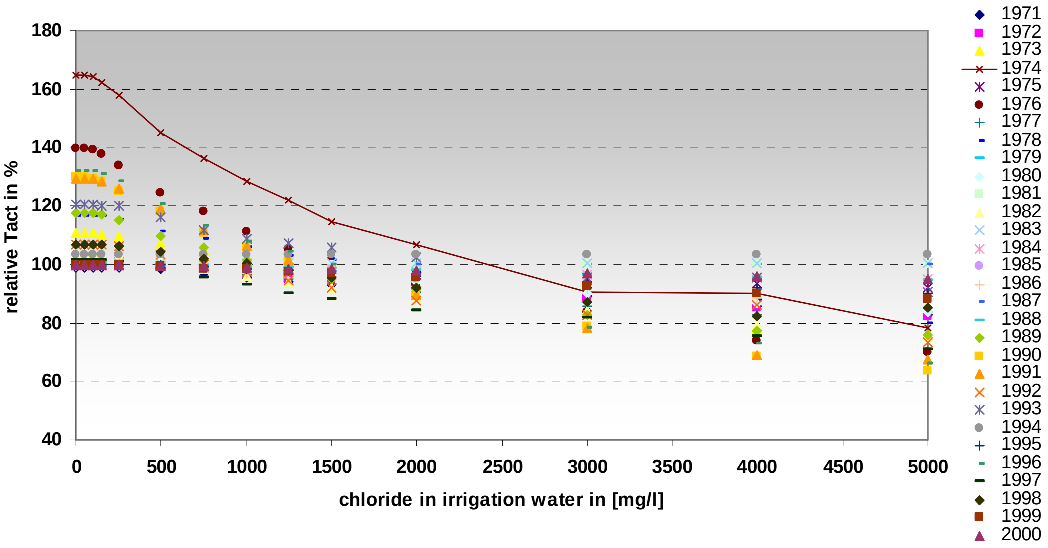

Fig. 46 Relative crop transpiration (relative to non-irrigated) for 30 consecutive hydrological years and several chloride concentrations in the irrigation water. ***Tulips on sand.***

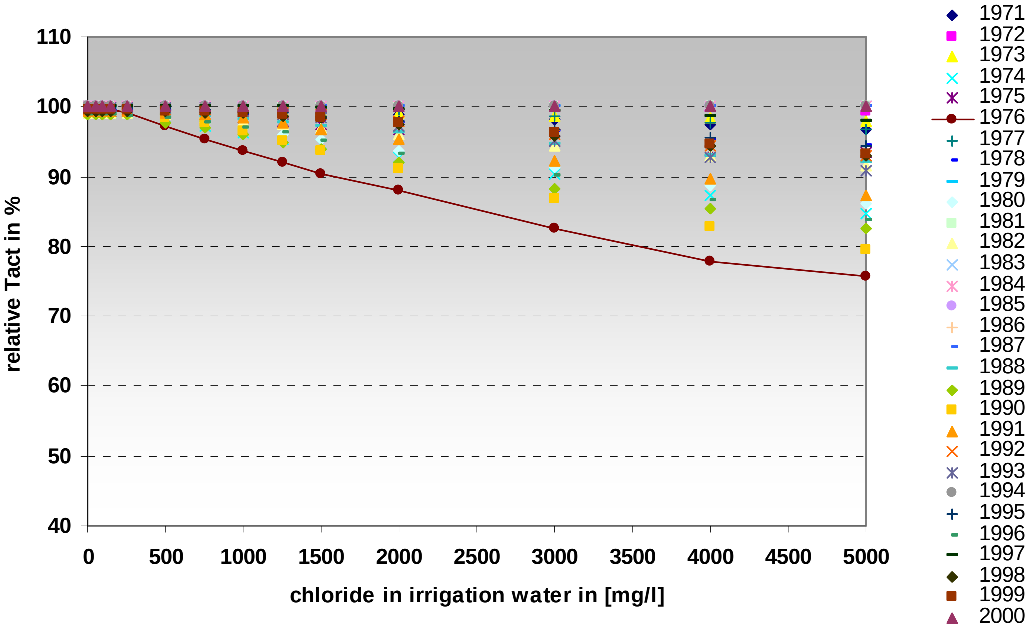

Fig. 47 Relative crop transpiration (relative to non-irrigated) for 30 consecutive hydrological years and several chloride concentrations in the irrigation water. ***Tulip on loam.***

Appendix 1.7 Simulated frequency distributions of relative crop transpiration.

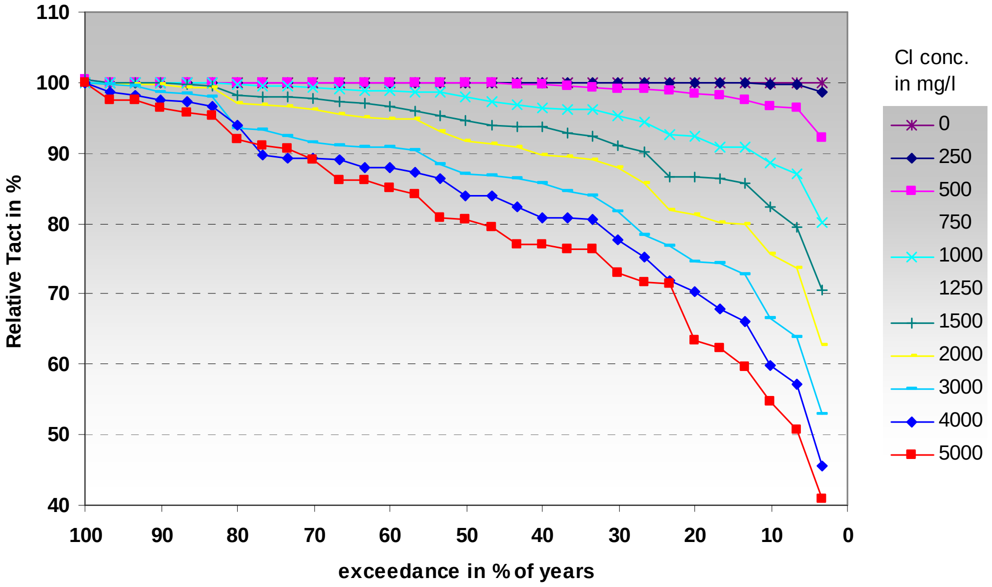

Fig. 48 Frequency distribution of relative crop transpiration during the 30 consecutive hydrological years and several chloride concentrations in the irrigation water. ***Potato on sand.***

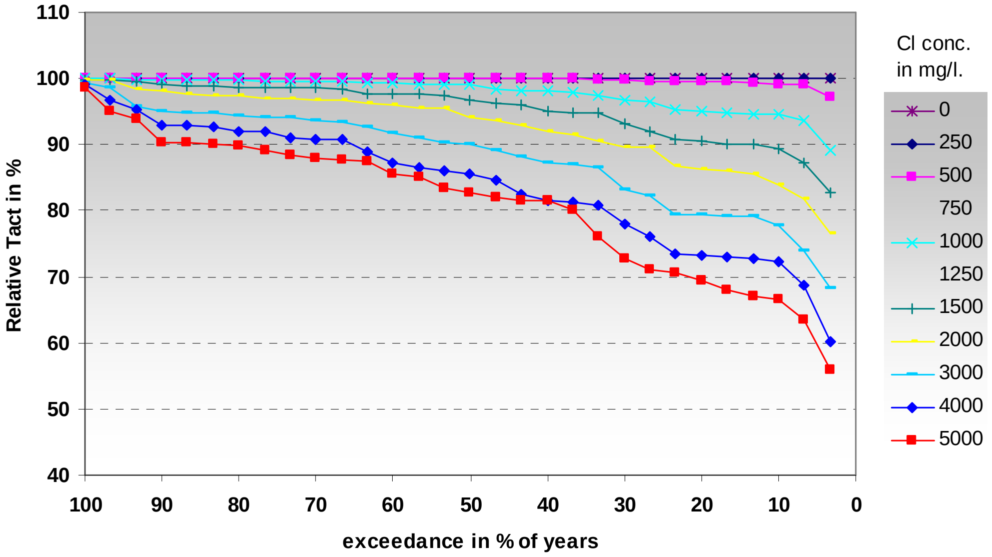

Fig. 49 Frequency distribution of relative crop transpiration during the 30 consecutive hydrological years and several chloride concentrations in the irrigation water. ***Potato on clay.***

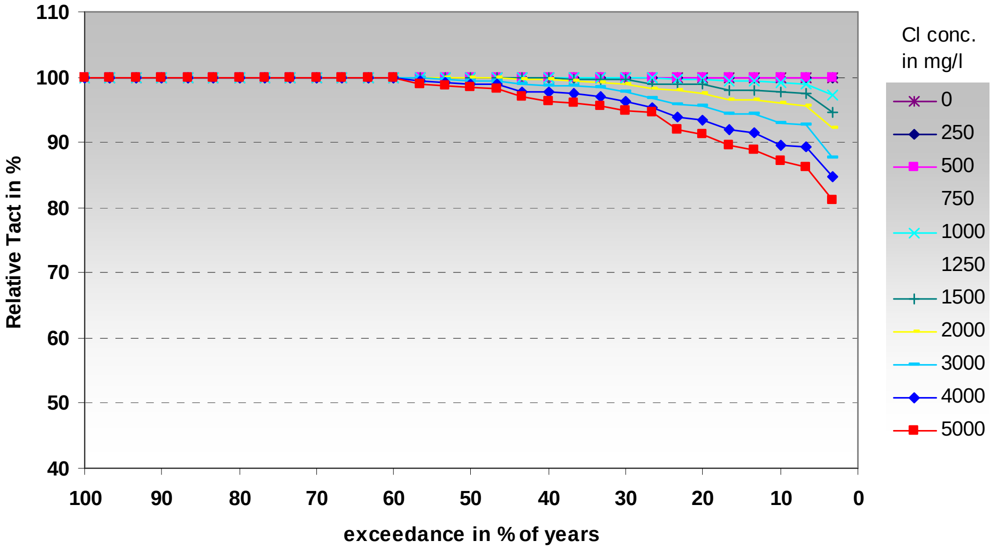

Fig. 50 Frequency distribution of relative crop transpiration during the 30 consecutive hydrological years and several chloride concentrations in the irrigation water. ***Potato on loam.***

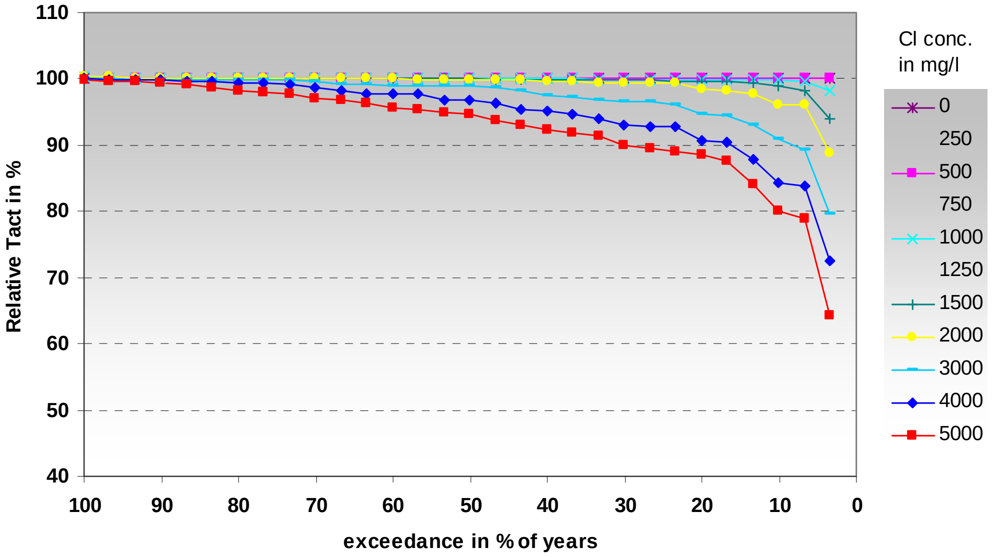

Fig. 51 Frequency distribution of relative crop transpiration during the 30 consecutive hydrological years and several chloride concentrations in the irrigation water. ***Grass on sand.***

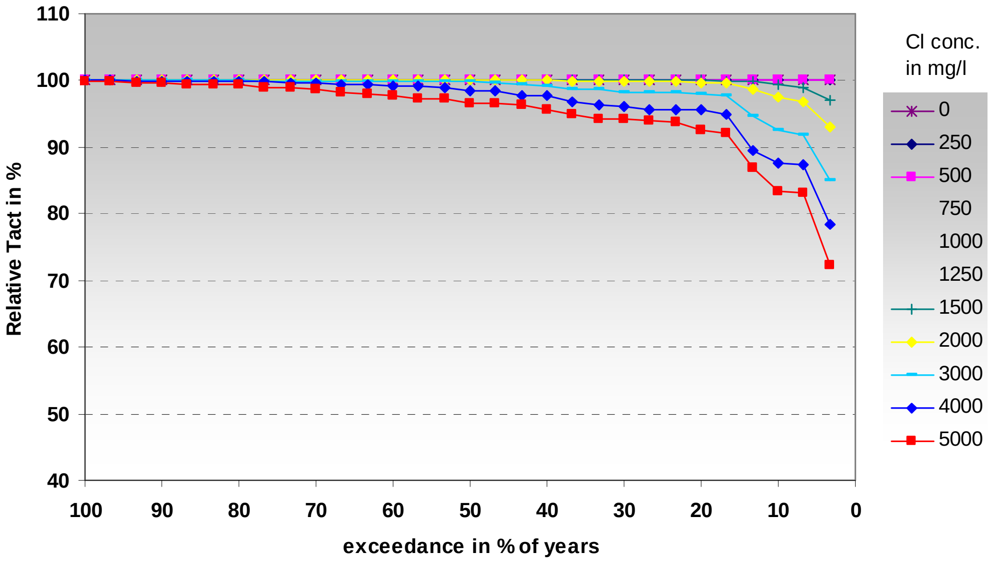

Fig. 52 Frequency distribution of relative crop transpiration during the 30 consecutive hydrological years and several chloride concentrations in the irrigation water. ***Grass on clay.***

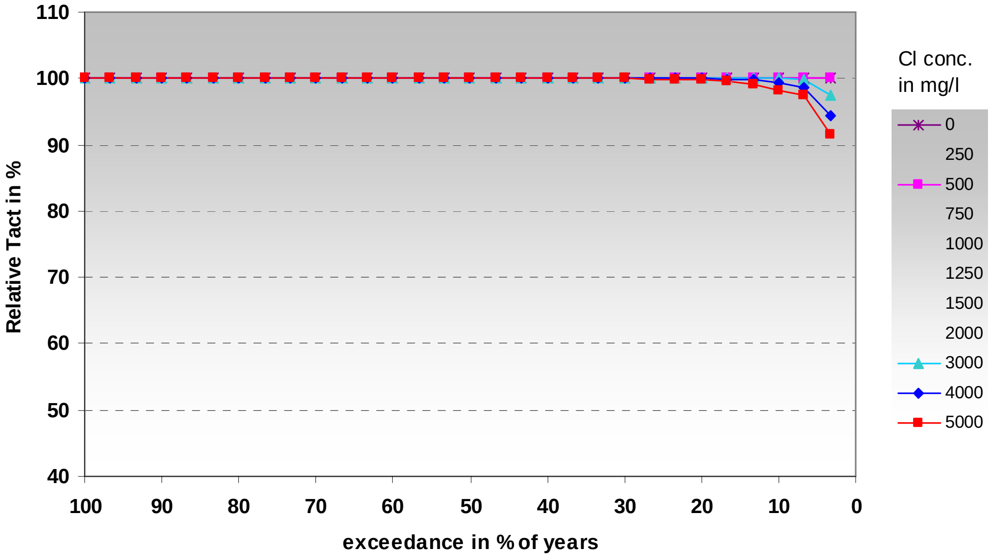

Fig. 53 Frequency distribution of relative crop transpiration during the 30 consecutive hydrological years and several chloride concentrations in the irrigation water. ***Grass on loam.***

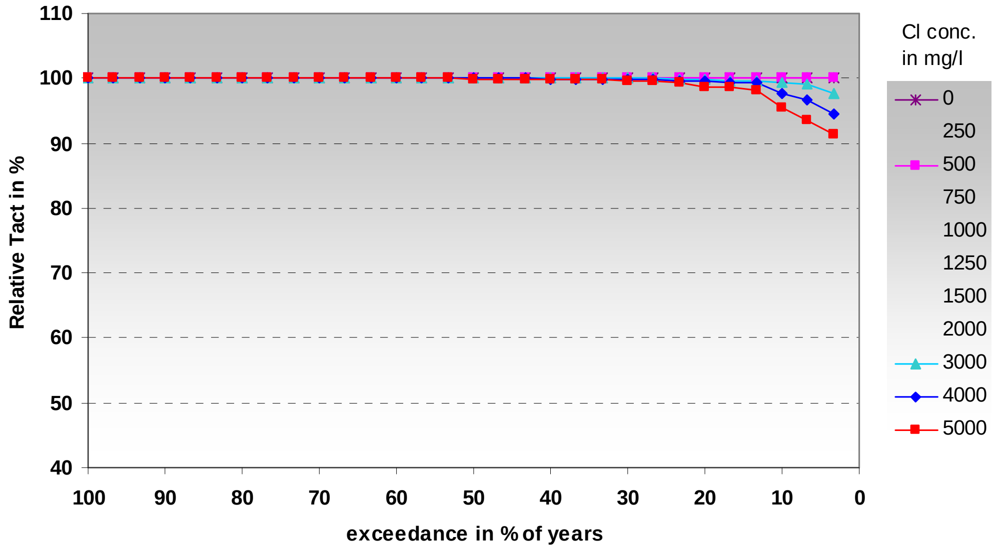

Fig. 54 Frequency distribution of relative crop transpiration during the 30 consecutive hydrological years and several chloride concentrations in the irrigation water. ***Sugar beet on sand.***

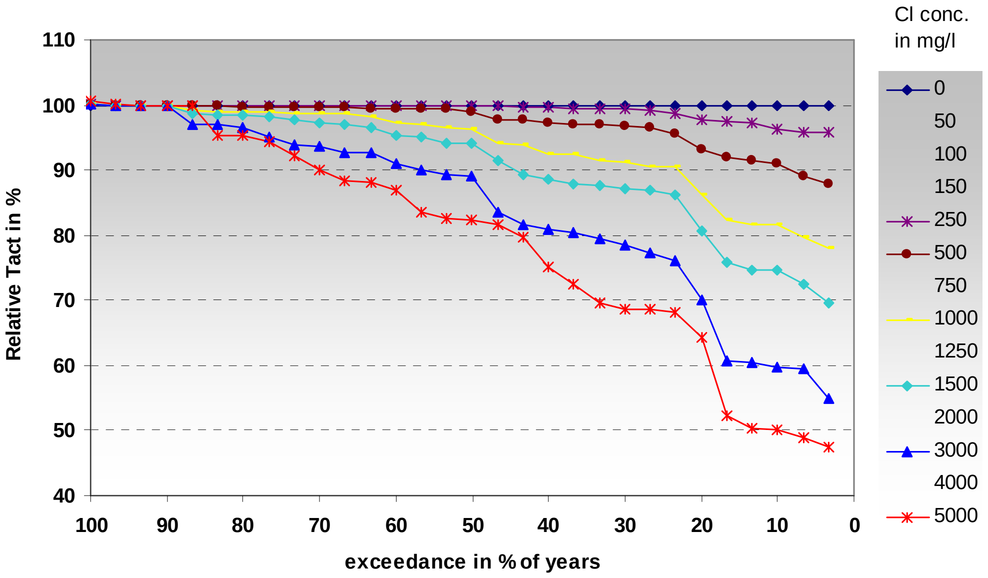

Fig. 55 Frequency distribution of relative crop transpiration during the 30 consecutive hydrological years and several chloride concentrations in the irrigation water. ***Tulip on sand.***

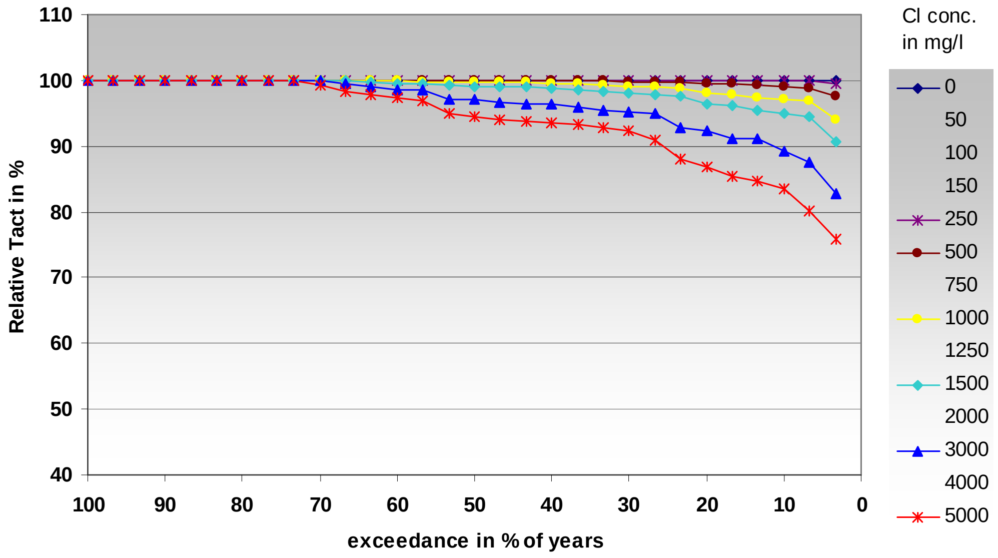

Fig. 56 Frequency distribution of relative crop transpiration during the 30 consecutive hydrological years and several chloride concentrations in the irrigation water. ***Tulip on loam.***

Appendix 2 Translated draft note Roest et al. (2003)

Updating of salt tolerance parameters of field and horticultural crops for the computation of salt damage in The Netherlands with the RIZA modeling instruments (Draft)

C.W.J. Roest
P.J.T van Bakel
A.A.M.F.R. Smit

1. Introduction

As a result of the agreement on WB21 (Water management in the 21st century) at this moment (2003 and 2004) the drought management study for The Netherlands is under implementation. Based on the existing salt tolerance data in The Netherlands, the conclusion is drafted in the report on the first phase of this study that the Total salt damage in agriculture is about 10% of the drought damage. In phase 2 of the drought study the salt damage will be based on better data. The recent drought of 2003 however has accelerated the study and RIZA has been requested to compute the drought and salt damage already during the year 2003. As a consequence the previously known data for crop salt tolerance as used for the PAWN study (Abrahamse e.a. 1982) had to be used. Especially in horticulture many developments took place since that time (soilless cultures) and the related use of irrigation water. The threshold values and salt sensitivity have been adjusted initially by RIZA. As a next step these adjusted values were commented by a number of external experts. Their comments were such that Alterra received the assignment to update the salt tolerance data of field and horticultural crops on very short notice. This report provides the results of this assignment. In chapter 2 the approach and results are described. In chapter 3 the results are commented and conclusions are formulated.

2. Approach and results

Salt damage to crops can have several reasons. The dominant and best known mechanism of salt damage to crops is the osmotic effect. Because salt increases the osmotic potential of the soil solution it diminishes the availability of soil water to crops. In addition to the dominant osmotic effect of salt in the crop root zone, certain elements scan also cause toxic effects for some crops. Toxic effects have been proven for sodium, for Chloride and for bore for instance. A third type of damage can be caused by an excess of sodium ions in the soil solution. Especially for clay soils excess sodium can cause swelling of the soil causing oxygen shortages in the crop root zone. This effect is an indirect effect of the composition of the water and not a crop damage that is directly related to salt. Finally, when saline water is used for sprinkling under certain weather conditions it can cause leaf burn. In summary crop damage due to saline water can be caused by:

- The osmotic effect of salts in the soil;
- The toxicity of certain elements (Na, Cl, B);
- The swelling of (clay) soils;
- Leaf burn by sprinkling.

In this report we only account for the osmotic effects of salts. We consider crop transpiration as flow of water from the soil to the crop roots, through the crop towards the stomata and through the stomata to the atmosphere:

$$E = \frac{\psi_l - (\psi_s + \psi_o)}{r_p + r_s} \qquad (1)$$

Here E is the crop transpiration, ψ_l the negative water pressure in the crop leaf, ψ_s en ψ_o de water matrix potential in the soil and osmotic potential in the soil solution respectively and r_p en r_s are the resistances against water flow in the crop and in the soil. Adopting this concept results amongst others to the following conclusions:

- With an increasing water demand for transpiration (high temperature, low humidity), the leaf water potential must increase to realize a sufficient gradient for this increased transpiration demand;
- With an increasing osmotic potential (higher salt concentrations) in the crop root zone the available hydraulic gradient for water flow will decrease and reduction of crop transpiration will occur at higher soil moisture contents.

In this mechanism of crop transpiration the stomata play a crucial role. Until a certain (crop dependent) water pressure in the crop leaf the stomata have sufficient turgor to keep the stomata open. With further reduction of the leaf water pressure (by high atmospheric demand, low soil moisture contents or high salt concentrations in the soil) the stomata will close. This causes an increase of the resistance for water flow in the crop and transpiration will be reduced. In addition to their crucial role for transpiration, stomata also play a crucial role in crop development. As long as stomata are open, they absorb CO_2 from the atmosphere and produce dry matter. With the closing of stomata, crop transpiration will reduce and under unfavorable conditions (high temperature and large solar radiation) the leaf temperature can increase to a degree that irreversible damage occurs. Finally the crop will die under conditions of increasing drought (or salinity).

Water stress and salt both have a negative effect on the increase of gross dry matter. During certain crop growth stages this is more serious than during other periods. Generally, the period of elongation of just emerged seedlings, the tillering of grain crops, flowering and fruit development are sensitive stages. If dry matter production is reduced during these periods, essential organs do not develop properly and a more than proportional damage to crop yields can occur. Finally, there are crops that respond to stress (drought and or salt) by changing the proportional distribution of total dry matter and harvestable fraction in favor of the latter. Only with increasing drought or salt stress the crop yield (harvestable fraction) is seriously damaged. Wheat is a typical example of such a crop.

Despite the above mentioned non-linear effects, climate and soil dependencies, specific toxicities and potential soil problems, in the literature salt tolerance data are reported based on empirical research in the form of a threshold value for soil salinity below which no damage occurs and above which the damage increases linearly with increasing soil salinity. This means that empirical data in the form of scattered data pairs (crop yields and salinities) where the above disturbing effects are included. Due to this interpretation the threshold value and slope is sometimes somewhat arbitrary. Differences in values between different experiments and different authors can therefore be considerable (Fig 1).

As mentioned before, the crop responds to soil salinity, or more specific: to the osmotic pressure in the soil water solution. This means that a high salinity in the irrigation water will be buffered (through mixing) in the soil water. Farmers can further anticipate on high salinity irrigation water by applying leaching of the soil water. Through proper leaching the soil water salinity can be managed to an acceptable level. A disadvantage of increased leaching is that more fertilizers are needed, because also crop nutrients will be leached beyond the crop root zone. This implies additional costs for farmers. In addition, also negative effects on the environment are caused: not only nutrients, but also possibly applied pesticides and herbicides may end up increasingly in the natural environment.

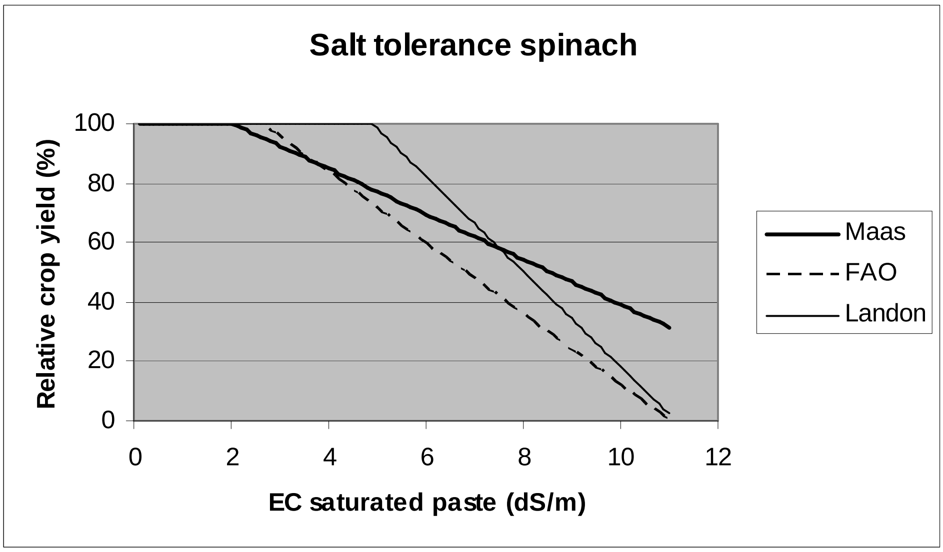

Figure 1 *The salt tolerance of spinach as reported by three authors. The shift to the right in the threshold value as compared to FAO is compensated by a steeper slope of the relation.*

For the interpretation and mutual comparison of the available literature, a number of interpretations are needed, because the different reports and interpretations are based on different approaches:

- In the Mozart-modeling instrument of RIZA the Chloride concentrations at average soil moisture content are needed (Mozart computes the damage based on actual concentrations of Chloride in the soil solution);
- In some (Dutch) experiments crop yields have been plotted against chloride concentrations in the soil solution at field capacity;
- In the majority of the reported experiments the salinity is expressed as the electrical conductivity in the (super) saturated soil moisture extract (saturated paste. For Dutch conditions the electrical conductivity can be transformed to chloride concentration using the following relation:

$$c = 151 EC^{1,31} \tag{1}$$

  With c as the Chloride concentration expressed in mg/l en *EC* the electrical conductivity dS/m. The relation is valid for the range of EC between 0 and 10 (Cultuurtechnisch Vademecum, 1988);
- In the Dutch literature, finally, the irrigation water norms for salinity are expressed as Chloride concentration.

We used the following factors and relations tot transform the concentrations in the saturated paste to the concentrations in the crop root zone (what the Mozart model uses for estimating crop damage):

$$c_{fc} = 2c_{sp} \tag{2}$$

With c_{fc} as the concentration of Chloride in the soil solution at field capacity and c_{sp} the concentration in the saturated paste. The factor 2 used should be considered as a rough estimate of the average. Depending on soil type the real factor may vary between 1.5 and 2.5.

$$c_m = 1,25 c_{fc} \tag{3}$$

With c_m the Chloride concentration in the Mozart computations ands c_{fc} the concentration at field capacity. The implicit assumption used in this relation is that the average soil moisture content on irrigated fields is about 20% below field capacity. The relation between irrigation water concentration and soil water concentration at field capacity is given by the following relation:

$$c_g = \frac{c_{fc}}{3} \qquad (4)$$

With c_g the irrigation water concentration. With an average assumed leaching of 20%, a salinity profile in the soil is generated with an average factor of about 3. In practice this factor of course strongly depends on the irrigation regime.

The results of the literature study have been translated to the crop clusters as used in Mozart for the drought and salt stress. For each individual crop the different literature sources have been compared and a choice has been made for the most probable appropriate values for Dutch circumstances. As a next step the threshold values and slope for the individual crops have been averaged for each crop cluster. Finally, the data have been normalized to the moisture content as used by the Mozart model (Table 1). The corresponding irrigation water quality thresholds and slopes have also been included in this table (see for details the annexes).

Table 1 Average threshold value and slope for crop damage per Mozart crop cluster derived from the literature survey.

	Soil solution		Irrigation water	
	Chloride concentration		Chloride concentration	
	Threshold	slope	Threshold	slope
Crop cluster	mg/l Cl	%/mg/l Cl	mg/l Cl	%/mg/l Cl
Potato	756	0.0163	202	0.0610
Grass	3606	0.0078	962	0.0294
Sugar beet	4831	0.0057	1288	0.0212
Fodder maize	815	0.0091	217	0.0343
Grain crops	4831	0.0058	1288	0.0218
Fruit trees	642	0.0264	171	0.0991
Horticulture	378	0.1890	101	0.7086
Vegetables	917	0.0158	245	0.0591
Greenhouses[6]	1337	0.0141	356	0.0527
Flower bulbs	153	0.0182	41	0.0683

It could be argued that the arithmetic averages for salt tolerance are being used. It would be better to weigh the average based on the occurrence of the different crops. For establishing norms it would be better to look at the most sensitive crop in each crop cluster. If we accept salinity damage in maximum 10% of the crops in the Mozart crop clusters, the values given in table 2 are found:

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[6] This concerns soil based greenhouse culture. The most important crops are grown on substrate. The allowed irrigation water qualities for substrate cultures should be about a factor 4 more restrictive.

Table 2 Threshold values and slope for salt damage per Mozart crop cluster. For each crop cluster the values are base don salt damage in less than 10% of the crops belonging to the crop cluster.

	Soil solution		Irrigation water	
	Threshold	Slope	Threshold	Slope
Crop cluster	mg/l Cl	%/mg/l Cl	mg/l Cl	%/mg/l Cl
Potato	756	0.0163	202	0.0610
Grass	3606	0.0078	962	0.0294
Sugar beet	4831	0.0057	1288	0.0212
Fodder maize	815	0.0091	217	0.0343
Grain crops	3947	0.0072	1053	0.0269
Fruit trees	642	0.0264	171	0.0991
Horticulture	259	0.2754	69	1.0327
Vegetables	378	0.0300	101	0.1125
Greenhouses	532	0.0185	142	0.0696
Flower bulbs	125	0.0320	33	0.1200

3. Evaluation and discussion

3.1. Introduction

De values on salt tolerance of crops presented in the previous paragraph have been established as objectively and verifiable as possible base done the available literature and interpretation of the results found. These values will first be compared with the previous PAWN values used up till now for the evaluation of crop salt damage. Next, the irrigation water salinities will be compared to previous recommended values. Finally, the results and the comparison will be discussed.

3.2. Evaluation

Comparison of the previously used PAWN salt damage values and the established values in the present study.

For a proper comparison of the values used for the estimation of salt sensitivity of crops both the threshold value as well as the slope of the crop yield salinity relation should be considered. Both values determine how crop damage develops upon increasing salinity. We will limit ourselves here to the threshold values for the Chloride concentration in the soil solution (at the assumed soil moisture content of 20% below field capacity) (Table 1).

Table 3 Comparison of the previously used threshold values for salinity damage in the PAWN study with the newly derived values (averages per crop cluster).

	Threshold value for the Chloride concentration in the soil solution above which salt damage starts becomes manifest (mg/l)	
Crop cluster	Pawn (1983)	This study (rounded to values of 50 mg/l Cl)
Potato	700	750
Grass	1000	3600
Sugar beet	700	4800
Fodder maize	1000	800
Grain crops	1000	4800
Fruit trees	1000	650
Horticulture	200	350
Vegetables	500	900
Greenhouses	200	1300 (150)[7]
Flower bulbs	200	150

Only for three crops the new value are close to the previously used numbers: potatoes, fodder maize and flower bulbs. For grass, sugar beet and grain crops the old values used in PAWN were too restrictive: higher soil salinity values can be tolerated according to the international literature scanned. For horticultural crops and vegetables the new salinity damage threshold values are slightly higher than the previously used values. For fruit trees and flower bulbs the new values are lower than the values used before and the computed damage due to salt stress will increase.

Comparison of the chloride concentration norms and recommendations in irrigation water as found in the Dutch literature and the values estimated in the present study.

In the present study we used the 10% sensitive crop per crop cluster (see annexes for details) (Table 4).

Table 4 Comparison of the commonly used irrigation water norms for Chloride concentration in tThe Netherlands and the threshold values derived in the present study.

	Recommended irrigation water quality – Chloride concentration (mg/l)			
Crop cluster	Cultuurtechnisch Vademecum (1988)	Huinink (1994)	PR (1997)	This study (rounded to values of 50 mg/l Cl)
Potato	600			200
Grass	600	600	800-1150	950
Sugar beet	600	600		1250
Fodder maize	600			200
Grain crops	600	600		1050
Fruit trees	300	300		150
Horticulture	300			75
Vegetables	300	300		100
Greenhouses	200	200		150
Flower bulbs	300			50
Substrate culture	50	50		

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[7] The value in between brackets is the value for the 10% sensitive crop.

Comparison of the norms in this study with those from the “Cultuurtechnisch Vademecum” reveals that the norm for irrigation water salinity should be decreased with a factor six for flower bulb production. For potatoes, fodder maize, horticulture and vegetables the norm should become stricter with a factor three and for fruit trees with a factor two. For greenhouses the old norm was more or less right. For grasss the irrigation water salinity (expressed as Chloride concentration) can go up with about 50% and for sugar beets with a factor two. These are not minor changes. It should be recommended therefore to check these new values in practice on farmers’ fields.

3.3. Discussion

Due to the high commercial value of the production in greenhouses, we think it would be wise to base the norm, not on averages per crop cluster but on the 10% sensitive crop. Moreover, the more important crops (tomato, cucumber, sweet pepper) are almost always grown on substrate. These facts suggest that it would be better to use the values for the 10% sensitive crop for irrigation water (Table 2 and 3) who resemble better the earlier recommendations mentioned in the Dutch literature.

In practice salinity damage in Dutch greenhouses will not be common. Greenhouse growers ensure the water supply to their greenhouses by rainwater harvesting and concluding contracts with drinking water supply companies. Even desalination through reverse osmosis would be a relatively low cost item compared to the production value of intensive greenhouse agriculture and the crop damage that could occur. Therefore salt damage in the greenhouse sector (and for the horticultural sector as well) should not be computed on the basis of crop damage, but based on additional investment and operation cost needed to guarantee the supply of good quality water. Only in case of calamities (growers who have no timely information on high salinity water supply), salt damage could occur.

Comparison of the values found per crop cluster with the international literature results in an inconsistent picture of crop salt damage. It is therefore recommended for phase 2 of the drought study in The Netherlands tor re-evaluate the clustering of crops and the associated acreages.

Also the interpretation of (field) research results is debatable because the field conditions under which these experiments have been implemented are unknown. It is therefore recommended to use process oriented approaches using crop physiologic background knowledge tor re-interpret these experiments and / or to implement new research.

Appendix Literature research

Annex A: Overview

	Maas&Hofman 1977		Maas 1990		FAO 1998		Landon 1984		Aendekerk 2000		Sonneveld 1988		Ploegman	
	Threshold	slope	Threshold	slope	Threshold	slope	Threshold	slope	Threshold	slope	Threshold	slope	Threshold	slope
Crop	dS/m	%/dS/m	dS/m	%/dS/m	dS/m	%/dS/m	dS/m	%/dS/m	dS/m	%/dS/m	dS/m	%/dS/m	dS/m	%/dS/m
potato	1.7	12.0	1.7	12.0	1.7	12.0	1.4	11.4						
meadow	5.6	7.6	5.6	7.6	5.6	7.6								
sugar beet	7.0	5.9	7.0	5.9	7.0	5.9	8.5	6.7						
fodder maize	1.8	7.4	1.8	7.4	1.8	7.4	4.5	20.0						
grain crops	7.0	6.1	6.5	4.6	6.6	5.6	7.9	6.2						
fruit trees	1.5	18.0	1.5	18.0	1.5	18.0								
horticulture									1.0	100.0				
vegetables	1.3	16.9	1.6	13.8	2.0	11.7	2.2	16.2						
greenhouses	1.6	13.7	1.5	12.1	1.5	12.7	2.6	16.1			4.2	9.9	0.7	14.4
flower bulbs													0.5	11.8

	Based on averages per crop cluster							
	Saturated Paste		Saturated paste		**Soil solution**		Irrigation water	
	Sensitivity		Chloride mg/l		**Chloride mg/l**		Chloride mg/l	
	Threshold	slope	Threshold	slope	**Threshold**	**slope**	Threshold	slope
Crop	dS/m	%/dS/m	mg/l	%/mg/l	**mg/l**	**%/mg/l**	mg/l	%/mg/l
potato	1.7	12.0	303	0.0406	**756**	**0.0163**	202	0.0610
meadow	5.6	7.6	1442	0.0196	**3606**	**0.0078**	962	0.0294
sugar beet	7.0	5.9	1932	0.0142	**4831**	**0.0057**	1288	0.0212
fodder maize	1.8	7.4	326	0.0229	**815**	**0.0091**	217	0.0343
grain crops	7.0	6.1	1932	0.0146	**4831**	**0.0058**	1288	0.0218
fruit trees	1.5	18.0	257	0.0661	**642**	**0.0264**	171	0.0991
horticulture	1.0	100.0	151	0.4724	**378**	**0.1890**	101	0.7086
vegetables	2.0	11.9	367	0.0394	**917**	**0.0158**	245	0.0591
greenhouses	2.6	11.3	535	0.0352	**1337**	**0.0141**	356	0.0527
flower bulbs	0.5	11.8	61	0.0455	**153**	**0.0182**	41	0.0683

	Gebaseerd op het 10% gevoeligste gewas							
	Saturated Paste		Saturated paste		**Soil solution**		Irrigation water	
	Gevoeligheid		Chloride mg/l		**Chloride mg/l**		Chloride mg/l	
	Threshold	slope	Threshold	slope	**Threshold**	**slope**	Threshold	slope
Crop	dS/m	%/dS/m	mg/l	%/mg/l	**mg/l**	**%/mg/l**	mg/l	%/mg/l
potato	1.7	12.0	303	0.0406	**756**	**0.0163**	202	0.0610
meadow	5.6	7.6	1442	0.0196	**3606**	**0.0078**	962	0.0294
sugar beet	7.0	5.9	1932	0.0142	**4831**	**0.0057**	1288	0.0212
fodder maize	1.8	7.4	326	0.0229	**815**	**0.0091**	217	0.0343
grain crops	6.0	7.1	1579	0.0179	**3947**	**0.0072**	1053	0.0269
fruit trees	1.5	18.0	257	0.0661	**642**	**0.0264**	171	0.0991
horticulture	0.8	133.3	104	0.6885	**259**	**0.2754**	69	1.0327
vegetables	1.0	19.0	151	0.0750	**378**	**0.0300**	101	0.1125
greenhouses	1.3	13.0	213	0.0464	**532**	**0.0185**	142	0.0696
flower bulbs	0.4	18.5	50	0.0800	**125**	**0.0320**	33	0.1200

Annex B: Grain crops

Crop	Maas&Hofman 1977		Maas 1990		FAO 1998		Landon 1984		Choice	
	Threshold dS/m	slope %/dS/m	Threshold dS/m	slope %/dS/m	Threshold dS/m	slope %/dS/m	Threshold dS/m	slope %/dS/m	Threshold dS/m	slope %/dS/m
barley	8.0	5.0	8.0	5.0	8.0	5.0	10.5	6.7	8.0	5.0
wheat	6.0	7.1	6.0	7.1	6.0	7.1	5.3	5.7	6.0	7.1
triticale			6.1	2.5						
wheat durum			5.9	3.8	5.8	4.7				

Annex C: Fruit trees

Crop	Maas&Hofman 1977		Maas 1990		FAO 1998		Choice	
	Threshold dS/m	slope %/dS/m	Threshold dS/m	slope %/dS/m	Threshold dS/m	slope %/dS/m	Threshold dS/m	slope %/dS/m
plums	1.5	18.0	1.5	18.0	1.5	18.0	1.5	18.0

Annex D: Horticulture

Crop	Maas&Hofman 1977		Maas 1990		FAO 1998		Aendenkerk 2000	
	Threshold dS/m	Slope %/dS/m	Threshold dS/m	slope %/dS/m	Threshold dS/m	slope %/dS/m	Threshold dS/m	slope %/dS/m
sensitive (37 spp)							0.75	133.3
moderately sensitive (237 spp)							1	100
moderately tolerant (65 spp)							2	50

Annex E: Vegetables

	Maas&Hofman 1977		Maas 1990		FAO 1998		Landon 1984		Choice		25% damage
Crop	Threshold dS/m	slope %/dS/m	Threshold dS/m	slope %/dS/m	Threshold dS/m	slope %/dS/m	Threshold dS/m	slope %/dS/m	Threshold dS/m	slope %/dS/m	
strawberry	1.0	33.0	1.0	33.0	1.3	22.0			1.0	33.0	1.8
green beans	1.0	19.0	1.0	19.0	1.0	19.0	1.1	25.0	1.0	19.0	2.3
onions	1.2	16.0	1.2	16.0	1.2	16.0	1.5	20.0	1.2	16.0	2.8
carrots	1.0	14.0	1.0	14.0	1.0	14.0	1.0	20.0	1.0	14.0	2.8
peas					1.5	14.0			1.5	14.0	3.3
broad beans	1.6	9.6	1.6	9.6	1.6	9.6	2.8	13.3	1.6	9.6	4.2
cabbage	1.8	9.7	1.8	9.7	1.4	11.9	1.4	8.9	1.8	9.7	4.4
chicory					1.8	9.7			1.8	9.7	4.4
celery			1.8	6.2	2.2	9.6			2.0	7.9	5.1
spinach	2.0	7.6	2.0	7.6	2.6	11.9	4.9	16.0	2.0	7.6	5.3
broccoli	2.8	9.2	2.8	9.2	2.8	9.2	3.0	10.0	2.8	9.2	5.5
cauliflower					1.8	6.2			1.8	6.2	5.8
red beets	4.0	9.0	4.0	9.0	4.0	9.0			4.0	9.0	6.8
asparagus			4.1	2.0	4.1	2.0			4.1	2.0	16.6

Annex F: Greenhouse

Crop	Maas&Hofman 1977		Maas 1990		FAO 1998		Landon 1984		Ploegman		Sonneveld 1988		Choice		25% damage
	Threshold dS/m	slope %/dS/m	Threshold dS/m	slope %/dS/m	Threshold dS/m	slope %/dS/m	Threshold dS/m	slope %/dS/m	Threshold dS/m	slope %/dS/m	Threshold dS/m	slope %/dS/m	Threshold dS/m	slope %/dS/m	
green beans	1.0	19.0	1.0	19.0	1.0	19.0	1.1	25.0			4.5	18.5	1.0	19.0	2.3
lettuce	1.3	13.0	1.3	13.0	1.5	12.0	1.3	13.3			4.5	3.8	1.3	13.0	3.2
pepper	1.5	14.0	1.5	14.0	1.6	13.0					4.5	11.9	1.5	14.0	3.3
grapes	1.5	9.6	1.5	9.6	1.5	9.6							1.5	9.6	4.1
cucumber	2.5	13.0	2.5	13.0	1.8	10.0			0.3	16.3	4.5	10.3	2.5	13.0	4.4
cherry tomato			1.7	9.1									1.7	9.1	4.4
anthurium											3.4	21.1	3.4	21.1	4.6
aubergine			1.1	6.9							4.5	8.4	1.1	6.9	4.7
cellery			1.8	6.2	2.2	9.6					4.5	7.7	2.2	9.6	4.8
tomato	2.5	9.9	2.5	9.9	1.7	9.0	3.0	10.0	1.1	12.5	4.9	6.5	2.5	9.9	5.0
gerbera											3.4	14.1	3.4	14.1	5.2
hippeastrum											3.4	13.3	3.4	13.3	5.3
spinach	2.0	7.6	2.0	7.6	2.6	11.9	4.9	16.0			4.5	1.2	2.0	7.6	5.3
alstroemeria											3.4	11.3	3.4	11.3	5.6
chrysant											3.4	8.5	3.4	8.5	6.3
sweet pepper											4.5	13.5	4.5	13.5	6.4
carnation											4.0	4.7	4.0	4.7	9.3
endive											4.5	4.4	4.5	4.4	10.2

Annex G: Flower bulbs

Crop	Maas&Hofman 1977		Maas 1990		FAO 1998		Saturated paste Ploegman		25% damage
	Threshold dS/m	slope %/dS/m	Threshold dS/m	slope %/dS/m	Threshold dS/m	slope %/dS/m	Threshold mg/l	slope %/mg/l	
gladiolus							50	0.0800	363
tulip							65	0.0500	565
lily							80	0.0260	1042
rose							50	0.0260	1012

Annex H: Additional notes on calculation and interpretation procedures

Explanation

The international and national literature has been reviewed on experimental results on salt tolerance of crops. To this purpose the crop clusters as used by RIZA has been used. In the international literature crop salt tolerance is reported as the threshold of the electrical conductivity and the percentage damage per full increase of this EC value (in dS/m). **Both are determined in the saturated paste extract and presented as such in the literature.** For the transformation of the salinity in the saturated paste to the salinity in the soil solution at field capacity (**soil type dependent**) the standard factor 2.0 has been used.

The salinity damage in Mozart is computed based on the actual salt concentration in the soil solution at the end of each 10-day period. The soil moisture content in the root zone is then estimated at about 20% below field capacity (**soil type dependent**). For this we used a factor 1.25.

RIZA uses the chloride concentration in the model simulations. Tor the transformation of the electrical conductivity (EC) to CL concentration the relation given in the Cultuurtechnisch Vademecum has been used. For the range until an EC of 10 dS/m the following relation is valid: Cl = 151 EC ** 1,31. Here the chloride concentration is given in mg/liter.

For the transformation of the slope of the yield - salinity curve, the above given formula has been used to transform the EC value at 50% crop damage to the equivalent Cl concentration at 50% damage. Both the threshold and 50% damage CL concentrations are then used to compute the Cl concentration - crop damage slope.

Finally, in the overview table, the irrigation water quality is also included. Here we used the most pessimistic scenario, with a constant high irrigation water salinity and average leaching. In the international literature a factor 3 is generally used (irrigation water salinity multiplied with this factor results in the salinity at field capacity.

In a number of steps we derived the overview tables (Annex A) for the different crop clusters (a Mozart crop may be composed from a number of different agricultural crops). On individual crop kevel a choice has been made from the different literature data of the most probable correct salt tolerance data. These have subsequently been averaged (threshold and slope) for the crop clusters to be used for the damage computations in Mozart. In a separate table, finally, the numbers for the 10% sensitive crops from the crop cluster have been given (this table is therefore more directed towards norms). For the computation of the 10% sensitive crop we selected the damage level of 25%

Notes per crop cluster

Grain crops: For the average salinity damage response of grain crops, we ignored triticale and wheat durum, because these crops are almost non-existent in The Netherlands

Fruit trees: For the Dutch common fruit trees we found data for plums only. It is known that apples and berries are also sensitive (same category as plums)

Horticulture: In horticulture a lot of Dutch research has been done into salinity damage. A yield reduction per unit increase in salinity does not make much sense, because a lower product quality quickly disqualifies the product in the shops. For this reason we used the threshold value per sensitivity class and assumed that at double the threshold the product value will be zero.

Vegetables. These are the open field cultures. No Dutch data known.

Greenhouses: From the international literature data on the crops which are also grown in Dutch greenhouses have been selected. A review of Dutch literature (Sonneveld) reveals that the tolerance to salinity of vegetables in Dutch greenhouses is much higher than in arid regions (where the majority of the international literature has been generated). The data of Ploegman deviate from this and have been ignored.

Flower bulbs: The only data found and used are the results of Ploegman. Possibly, at PPO more data are available, but time and funds are not available to check this out.