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To cite this version:

Laurent Bruckler, Francois Lafolie, Stephane Ruy, Jean Marc Granier, D. Baudequin. Modelling the agricultural and environmental consequences of non-uniform irrigation on a maize crop. 1. Water balance and yield. Agronomie, 2000, 20 (6), pp.609-624. hal-02699087

HAL Id: hal-02699087
https://hal.inrae.fr/hal-02699087v1

Submitted on 1 Jun 2020

Agronomie 20 (2000) 609–624

Original article

Modelling the agricultural and environmental consequences of non-uniform irrigation on a maize crop. 1. Water balance and yield

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(Received 26 November 1999; revised 19 May 2000; accepted 31 May 2000)

Abstract – Among cropping systems, intensive irrigation probably represents one of the greatest threats to groundwater quality. Irrigation uniformity is a key factor for obtaining more efficient water use by crops and for limiting percolation. The objective of this study is to predict plant growth and water fluxes under non-uniform irrigation conditions. Simulations were applied to a maize crop irrigated with a moving gun. The spatial coefficients of variation for 21 years did not exceed 18, 9, 20, and 36% for irrigation depth, actual evapotranspiration, drainage below the root zone and yield, respectively. Temporal effects due to natural climatic variability dominated, and spatial effects only increased the variance of the fluxes and biomass without strongly modifying the mean patterns. Other sources of variation such as soil type, soil hydrodynamic properties or irrigation strategies must also be analysed to provide more general conclusions.

irrigation / non-uniformity / water balance / modelling / maize

Résumé – Modélisation des conséquences agronomiques et environnementales d'une irrigation non uniforme sur une culture de maïs. I. Bilan hydrique et rendement. Les systèmes de culture ayant recours à une irrigation intensive présentent probablement le plus grand risque pour la qualité des eaux. L'homogénéité de l'irrigation est déterminante pour améliorer l'efficience de l'eau et limiter le drainage. Le but de cet article est de simuler la croissance d'une culture de maïs et les flux hydriques associés avec une irrigation hétérogène appliquée par un canon mobile. Les coefficients de variation spatiaux calculés pour 21 années sont inférieurs à 18 %, 9 %, 20 %, et 36 %, pour la dose d'irrigation reçue, l'évapotranspiration réelle, le drainage, et le rendement. Les effets liés à la variabilité climatique interannuelle

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Communicated by Gérard Guyot (Avignon, France)

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dominent, ceux liés à la variabilité spatiale ne font qu'augmenter la variance spatiale des flux et de la biomasse sans affecter considérablement les comportements moyens. Les effets liés au type de sol, aux propriétés hydrodynamiques, aux stratégies d'irrigation seraient à analyser avant de tirer des conclusions plus générales.

irrigation / hétérogénéité / bilan hydrique / modèle / maïs

1. Introduction

A major challenge in agriculture is developing management techniques that ensure high crop production while saving environmental quality. Intensive crops with high irrigation input probably represent one of the greatest threats to the quality of groundwater [34,35]. One of the most efficient means of minimising contamination of groundwater resources is through guidelines on water and fertiliser use. Although it is possible to determine the mean irrigation depth to be provided to a crop and for given climatic conditions [9,26], the uniformity of irrigation depth at the field scale must still be improved. Indeed, the uniformity of water distribution is one of the key factors for obtaining more efficient use of water by crops and limiting percolation below the root zone [6, 7, 14]. To increase the irrigation uniformity coefficient [12,31,39], methods for designing irrigation systems [19,22] or comparisons between nozzle performances [16, 18] have been provided. Nevertheless, variability in water depth in the field remains one of the most important characteristics of irrigation practices [1,30]. This is due to several factors such as local topography, pressure loss along the laterals, nozzle characteristics, or wind velocity during irrigation [30].

The impact of non-uniform irrigation on crop yield and environmental damage has been explored in different ways: (i) theoretical analyses on irrigation non-uniformity as related to crop production functions or to drainage [6, 13, 17, 33, 36]; (ii) numerical simulations generally based on Monte-Carlo approaches analysing the influence of both soil properties and irrigation or rain non-uniformity on the water budget have shown significant effects of spatial heterogeneity of soil hydraulic properties or non-uniform irrigation on the annual water balance [20,21,28]; (iii) spatial variability of crop yield as related to non-uniform irrigation has been explored using numerical models comparing actual crop yield to potential yield for a given irrigation distribution [8, 14, 37, 38]. Warrick and Gardner [38] have shown that variation in either irrigation or soil uniformity has an impact on crop yield, but irrigation is probably more important especially for surface systems. Among the large number of parameters determining crop yield non-uniformity, Dagan and Bresler [14] found that six had a significant impact on yield variability: two plant parameters had an average relative contribution of 23% to yield variability, three soil hydraulic parameters had a relative impact of 47%, and one irrigation non-uniformity parameter had an average contribution of 30%. For a Christiansen coefficient of 0.8, they estimated coefficients of variation for maize of 0.31 close to the line source, and of 0.94 close to the margins of the irrigated field.

Experimental data generally have confirmed the negative impact of non-uniform irrigation on both crop yield and drainage loss [4, 5, 7, 14, 29, 32]. Theoretical approaches have been partially validated by experimental data showing that the amount of water that moves below the root zone increases as the uniformity coefficient decreases, and have provided evidence of a smoothing effect by plant root systems within the soil profile [7]. As a consequence, soil water, crop height and crop yield variability exhibited spatial structures similar to the applied-irrigation non-uniformity, but with crop yield variability lower than that of the irrigation [32].

Some points have not been sufficiently analysed by the previously mentioned studies. First, most of the studies deal with individual or regularly distributed sprinklers, while data for moving guns are scarce. Second, the linkage between water and nitrogen is not fully described, although it is one of the most important issues [11]. Third, only simplified approaches such as crop production functions or actual to potential yield ratio are used to describe crop growth and biomass production. Indeed, models giving a realistic representation of physical and biological processes occurring in the soil-plant system are necessary to provide consistent responses [26]. Such models must be able to take into account agricultural practices such as sowing and harvest dates, soil temperature, root growth, cultivar, and organic matter management and fertilisation practice. Consequently, the main objective of these papers is to link irrigation non-uniformity for an irrigation system (moving gun) with a crop model constructed as a simulation tool capable of working under agricultural conditions and of providing outputs relative to both yield and the environment.

2. Materials and methods

2.1. Scenario approach

The soil used for the simulations was a loamy clay soil with a bulk density of 1450 kg·m^{-3}, 22% clay content, a field capacity of 0.22 kg·kg^{-1} and a permanent wilting point of 0.12 kg·kg^{-1}. Initial water content at sowing was field capacity. The soil was divided into five layers (0–0.30 m; 0.30–0.50 m; 0.50–0.65 m; 0.65–0.80 m; 0.80–0.95 m). The first layer initially contained 50 kg N·ha^{-1}, the second layer 20, and no mineral N in the three deepest layers. Organic N content in the first layer was set to 1.0 g·kg^{-1} soil. Crop development was described by successive stages (germination, emergence, maximum leaf area index, beginning of grain filling, senescence, end of grain filling, ripeness and harvest), each characterised by a given thermal time calculated with a 6 °C thermal base. Maize (cv Cecilia) was assumed to be sown on April 20th (day 111) and harvested no later than December 1st (day 335). Crop residues were assumed to be incorporated in the soil on December 3rd (day 337). Irrigation occurred between June 7th (day 158) and September 24th (day 267), corresponding to the 500–1800 °Cd day interval, with a travelling gun in a 300 m long and 350 m wide field, oriented 340° North. Because the spacing between two consecutive waterings with the travelling gun was 70 m (1.4 lag distance of the gun) with one passage per day, the irrigation period for the entire field was 5 days, and an 8 day irrigation frequency was chosen. Each dose of irrigation was 40 mm, irrigation was postponed to the next day if it rained at least 15 mm, and cancelled if it rained more than 35 mm. The first irrigation began when the amount of water in the soil was reduced by more than 45 mm. Of course, we selected here a specific irrigation scheduling strategy, but many other strategies are possible and the results of the analysis would be different for each case. As an example, an irrigation strategy setting water supply when the allowable depletion in the soil is reached would provide different results.

The climatic database comes from the experimental site of L'Etoile (Drôme, France), covering the period January 1, 1975 to December 31, 1995, corresponding to 21 crop cycles and 20 intercropping periods. The parameterisation described above corresponds to the "reference" scenario. For comparison, a scenario with a different gun spacing (77 m, 1.6 lag distance of the gun) was simulated. Generally, spacing between two passages with the travelling gun is recommended to be 1.5 the lag distance of the gun. In this paper, we considered the [1.4–1.6] lag distance interval to more precisely analyse the sensitivity of crop yield and water balance to this parameter. For graphic outputs versus space, a transect was chosen perpendicular to the direction in which the gun travelled and located at 100 m from the border of the field (Fig. 1). The transect was divided into 70 elementary sections of 5 or 5.5 m for the 70 m or 77 m spacing, respectively, each considered uniform for irrigation dose and crop growth. We also define a relative value for each term of the water budget or for yield at the field scale, defined as the dimensionless ratio of the actual spatial mean to the calculated value at a virtual location for which the target irrigation dose is assumed to be truly and uniformly applied. Consequently, relative values may be greater or smaller than 1, and are 1 if the entire field has a similar pattern to the location receiving the target

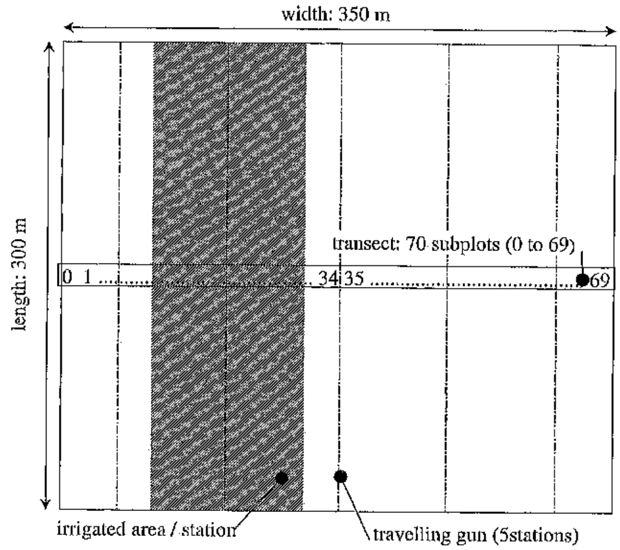

Figure 1. Irrigation set-up used in the simulations.

dose. The scenarios will be analysed for the 21 year simulation period.

2.2. The NIWASAVE model

The NIWASAVE ("Nitrate Water Saving") model links an irrigation water distribution model, that calculates irrigation rates for given, spatially distributed locations in the field, with the STICS ("Simulateur mulTIdisciplinaire pour les Cultures Standard") model that runs at the same locations and simulates the crop-soil system. The model provides daily and cumulative output variables for crop and soil.

First, the model computes the irrigation distribution at field scale as a function of equipment and climatic conditions. The irrigation equipment is characterised by the operating water pressure determining the water flow, type and orientation of nozzle, and grid-layout for sprinklers, or distance between successive passages in the field for guns [2]. The water distribution at the soil surface is measured under field conditions in the absence of wind and simulated by using drop trajectory calculations. Wind direction and velocity then modify the water distribution at the soil surface [23]. Evaporation during drop trajectory is not considered [3], but the overlap of the water distribution over the whole field is calculated. Predicted water distribution in the field is validated by standard field experiments [23]. The NIWASAVE model uses a database which numerically describes the water distribution for any given irrigation equipment (guns in our case) and for various wind directions (10° angle step) and speeds ($1 \text{m} \cdot \text{s}^{-1}$ velocity step).

Crop development and growth, yield components, water and nitrogen balance are computed using the STICS model [10]. STICS is a dynamic model with a daily time step that simulates the soil-crop system within a year or for a succession of years. The climate is characterised by standard data (solar radiation, minimum and maximum temperature, rainfall, potential evapotranspiration) and the crop is characterised by its above ground biomass, leaf area index, the number of grains and the biomass of harvested crop organs. Root length distribution in the soil profile is calculated every day in dependence of shoot growth. A phenological model calculates the development stages. Water and/or nitrogen stress are calculated using three indices that can reduce the leaf area index and radiation-use efficiency. The soil is considered as a succession of horizontal layers in which water and nitrate transport and uptake are simulated, whereas production of nitrate by mineralization occurs mainly in the plough layer. Since the nitrogen balance partly depends on the carbon balance, both are calculated simultaneously. Although the model computes the carbon, water and nitrogen balances, some specific processes like ammonia volatilisation and denitrification are not treated.

3. Results

3.1. Spatial and temporal variability of water fluxes

Annual climatic conditions showed high variability (Fig. 2). Global radiation, Penman potential

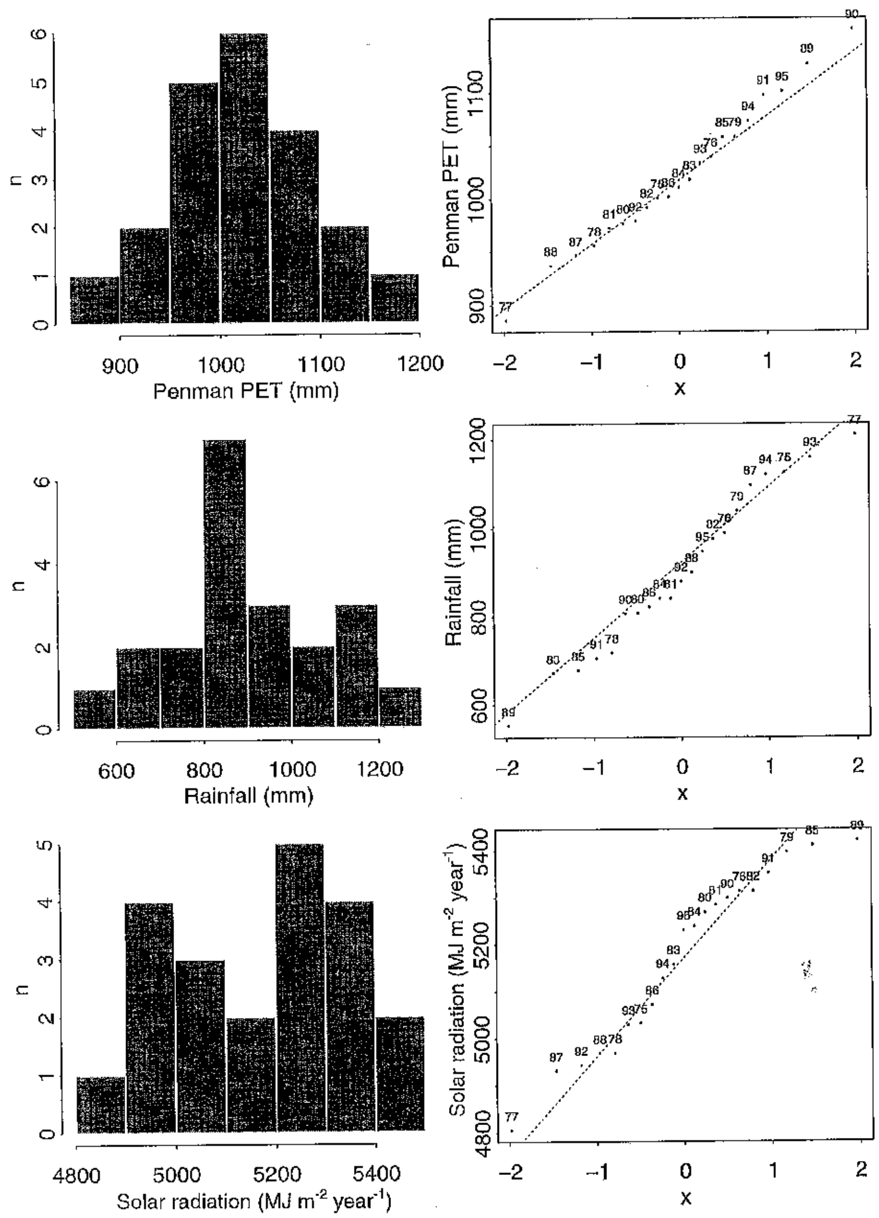

Figure 2. Statistics of the annual potential evapotranspiration (PET), rain and global radiation for the 21 year period: (a) Frequency distribution; (b) Normality tests.

evapotranspiration and rain were located in the [4800–5400 MJ·m^{-2}·y^{-1}], [850–1200 mm], and [500–1300 mm] range, respectively. Mean rainfall was 888 mm and the standard deviation 215 mm for the overall period (CV = 24%). Both, normal or non-normal distributions of climatic data were observed. During the cropping period, values for the relative irrigation, evapotranspiration and drainage as defined above vary from 0.87 to 0.98 (mean of 0.93), 0.95 to 1.00 (mean of 0.96), and 0.86 to 1.16 (mean of 1.00), respectively (Tab. I). Hence, although spatial variability of water fluxes induced by non-uniform irrigation exists, the spatial mean at the scale of the field is close to the value representing a uniform irrigation depth. Of course, these results cannot be generalised for all irrigation practices and would have been different for other irrigation scheduling strategies. For

Table I. Statistics of relative irrigation, evapotranspiration and drainage in the cropping period during the 21 years simulated (the ratio is 1 if the entire field has a similar pattern to the location receiving the target dose).

Period	Irrigation	Evapo-transpiration	Drainage
1975-1976	0.87	0.96	0.96
1976-1977	0.98	0.96	1.04
1977-1978	0.88	1.00	0.91
1978-1979	0.93	0.98	0.86
1979-1980	0.91	0.96	1.00
1980-1981	0.93	0.98	0.93
1981-1982	0.97	0.98	1.05
1982-1983	0.98	0.97	1.05
1983-1984	0.95	0.97	0.98
1984-1985	0.90	0.95	1.01
1985-1986	0.99	0.98	1.00
1986-1987	0.93	0.96	1.00
1987-1988	0.95	0.96	1.04
1988-1989	0.90	0.96	0.99
1989-1990	0.96	0.91	1.16
1990-1991	0.93	0.96	1.03
1991-1992	0.90	0.95	1.01
1992-1993	0.94	0.99	0.99
1993-1994	0.91	0.97	0.98
1994-1995	0.91	0.96	1.01
1995-1996	0.89	0.95	1.00
Min	0.87	0.91	0.91
Max	0.99	1.00	1.16
Median	0.93	0.96	1.00
Mean	0.93	0.96	1.00
Standard deviation	0.03	0.02	0.06
CV (%)	7	2	6

irrigation, the ratio is always below 1 due to water losses and border effects, i.e. dry zones due to the uncompleted irrigation. For evapotranspiration, the same applies, and "dry" zones created by non-uniform irrigation, directly generate zones where plant water uptake is lower than for uniform irrigation. Nevertheless, the calculated ratio for evaporation (0.96) exceeds that for irrigation (0.93), indicating the effect of the soil operating as a reservoir. For drainage (Tab. I), variability among years (standard deviation 0.06) was higher than for irrigation and evapotranspiration (standard deviation of 0.03 and 0.02, respectively). The ratio may be higher or lower than 1, depending on the relative areas where over- or under-irrigation dominates.

Standard deviations and coefficients of variation of irrigation for the 21 years are in the [24–46 mm] and [10–18%] range, respectively (Tab. II). Points in Figure 3 with low irrigation depth correspond to locations on the border of the field that are under-irrigated. This is evident in Figure 4, illustrating dry zones on the border of the field, and overlapping zones at regular intervals according to the passage of the gun. Nevertheless, the spatial variability of irrigation is regarded as moderate (coefficient of variation on an annual basis less than or equal to 18% for the 21 years). While spatial variability may be quite large for one particular irrigation, successive irrigations have compensatory effects, finally resulting in moderate spatial variability: one zone may be relatively "dry" for one irrigation, "wet" for another, depending on wind velocity or direction for example (Fig. 5).

Seasonal evapotranspiration also shows significant temporal variability (Fig. 3), depending on both the level of global radiation and water availability in the soil. Crop uptake not only depends on irrigation depth, but also on climatic demand and on the ability of the root system to extract water. Standard deviations and coefficients of variation are in the range [2–44 mm] and [0.3–9%], respectively, i.e. spatial variability of evapotranspiration is lower than for irrigation (Fig. 4), evapotranspiration depends not only on irrigation, but also on water present in the soil and on rain.

Standard deviations of drainage vary from 1 to 36 mm and coefficients of variation from 1 to 20% among years (Tab. II). Spatial variability of drainage appears moderate (Fig. 4), and temporal effects dominate (Fig. 3), because drainage depends on both rain and irrigation distribution in time, while in the model only irrigation is able to generate spatial variability. Spatial variability of drainage depends on the partitioning between under- and over-irrigated zones in the field, such as overlapping zones (Fig. 4), and on compensatory effects in water uptake by the crop: an over-irrigated zone corresponds to a wet zone where water uptake by plants is higher than from drier zones,

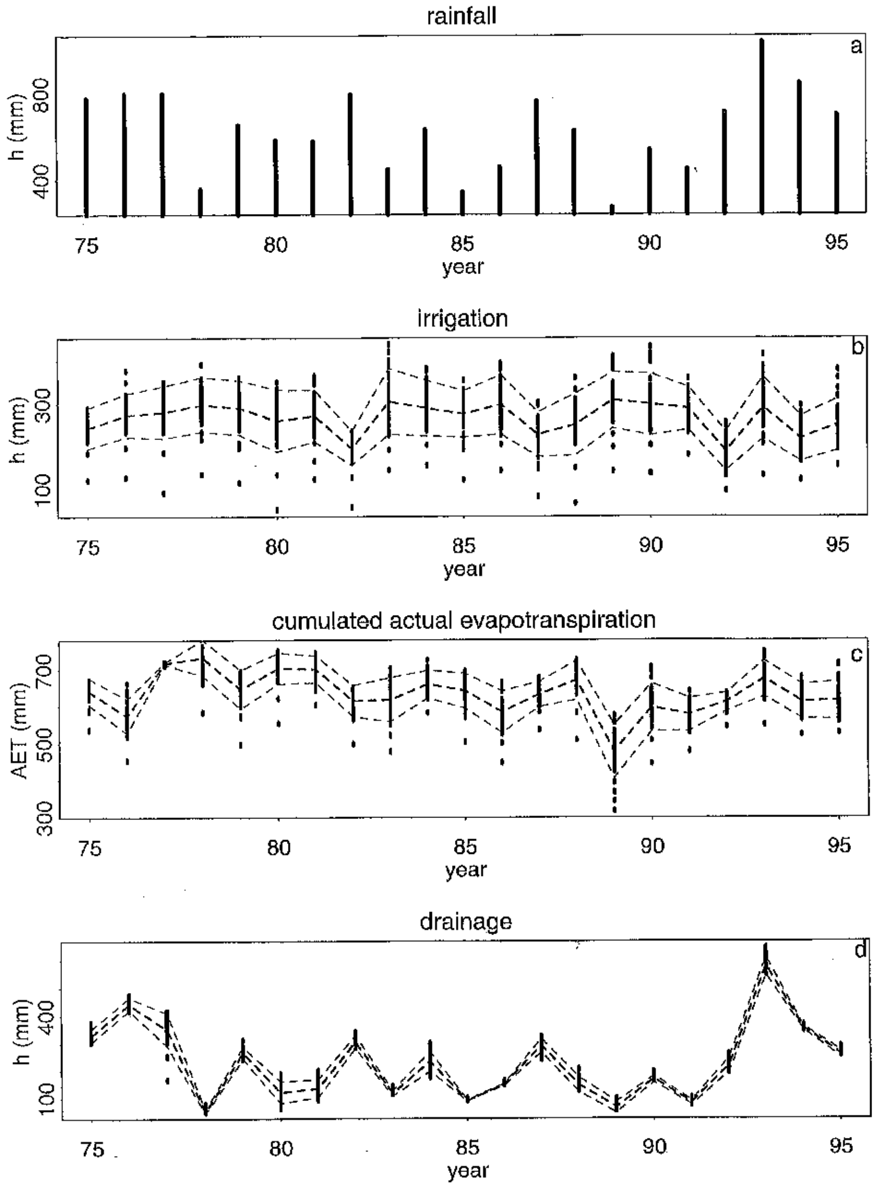

Figure 3. Rain (a) and simulated variations in (b) irrigation, (c) actual evapotranspiration, and (d) drainage in the cropping period during the 21 years simulated. The intermediate line represents the mean, the dashed lines represent the confidence interval. Each point corresponds to a 5 m plot located along a transect perpendicular to the direction in which the gun moves.

thus limiting drainage. If the whole field is over-irrigated, drainage exists at each point and there is a trend for low spatial variability. When under-irrigation dominates at field level, generally no drainage appears at any location and the spatial variability is still low. Between these two extremes a domain probably exists where spatial variability is maximal.

No direct relationship exists between irrigation and drainage, because in some cases no drainage occurs whatever the spatial variability of irrigation. In our simulations, drainage becomes significant (typically exceeding 100 mm) when rain exceeds 400 mm (Fig. 6a) or when rain plus irrigation exceeds 700 mm (Fig. 6b). Points corresponding to each location and for all years, summarising both

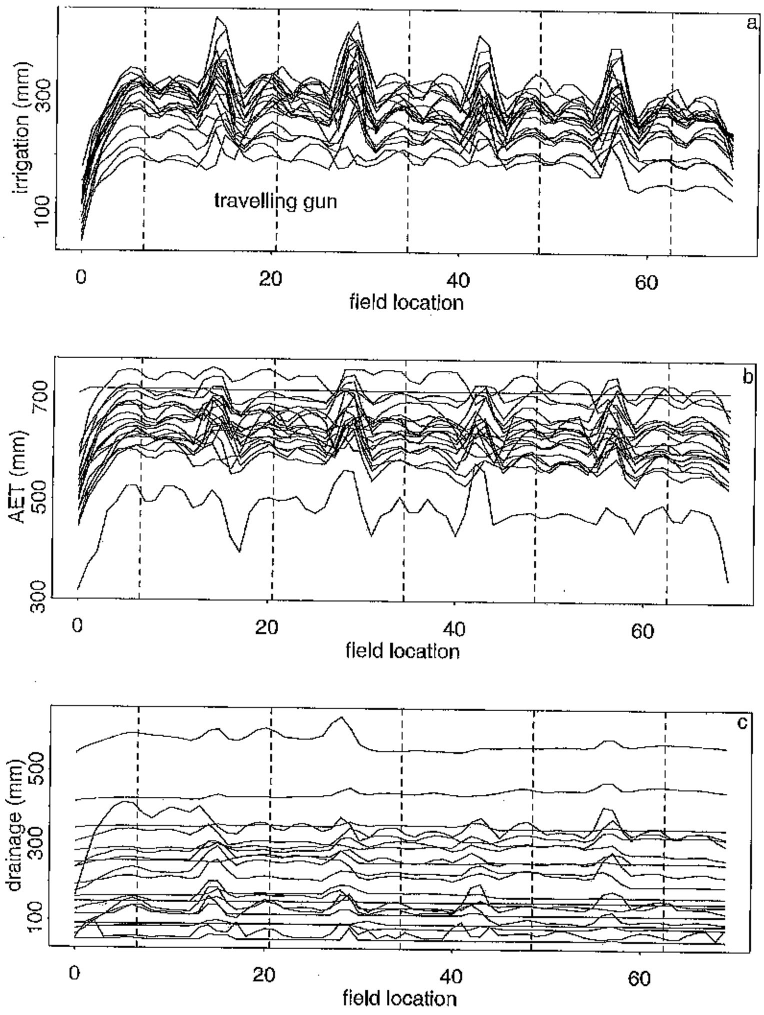

Figure 4. Spatial distribution along a transect of (a) irrigation, (b) actual evapotranspiration, (c) drainage in the cropping period during the 21 years simulated. Each line corresponds to one year, the dashed lines indicate the position in which the gun travels.

the temporal and spatial effects, are organised in a unique pattern (Fig. 6b).

3.2. Biomass and yield

In agreement with the results for both irrigation and evapotranspiration, the mean calculated ratio of yield (Tab. III) is near 1 (0.93 compared to 0.96 for evapotranspiration). Spatial variability appears moderate (standard deviation between 0.1 and 1.4 $t \cdot ha^{-1}$, and coefficient of variation between 1 and 13%, except 36% for one year). Spatial and temporal variability are both significant (Fig. 7), but temporal effects due to natural climate

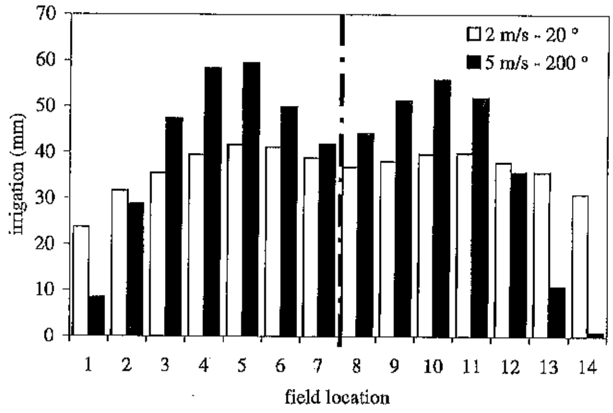

Figure 5. Simulated irrigation distribution right and left of the moving gun axis for the 2 $m \cdot s^{-1}$ and 5 $m \cdot s^{-1}$ wind velocity and two wind directions (20° and 200°).

Table II. Spatial statistics (mean, standard deviation σ, coefficient of variation CV) of irrigation, evapotranspiration and drainage in the cropping period for the whole field during the 21 years simulated.

	Irrigation			Evapotranspiration			Drainage		
	Mean (mm)	σ (mm)	CV (%)	Mean (mm)	σ (mm)	CV (%)	Mean (mm)	σ (mm)	CV (%)
Min	188	24	10	477	2	0.3	49	1	1
Max	307	46	18	732	44	9	580	36	20
Median	276	37	13	632	28	5	218	14	5
Mean	267	36	14	634	27	4	226	13	7

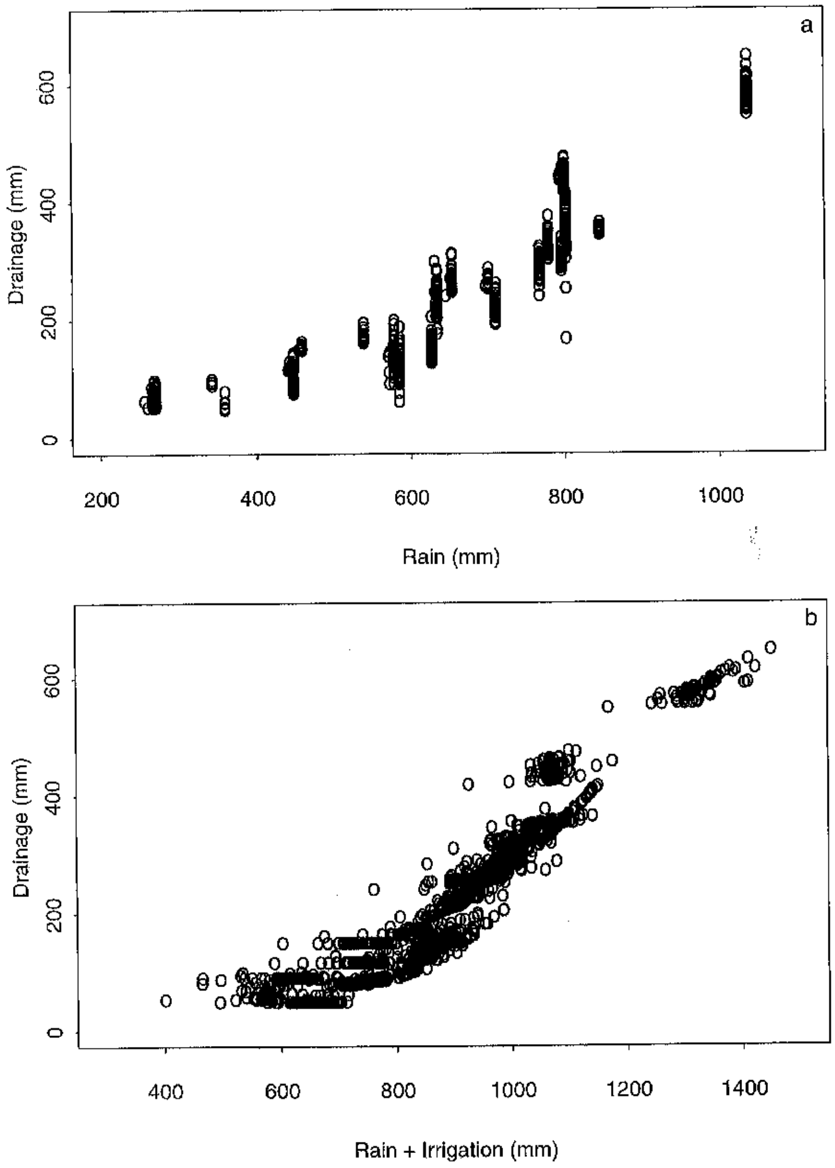

Figure 6. Relationship between (a) drainage and rain, and (b) drainage and rain plus irrigation during the 21 years simulated (each point in the figures corresponds to one individual plot in the field for one given year).

Table III. Statistics (mean, standard deviation σ, coefficient of variation CV) of yield in the cropping period for the whole field during the 21 years simulated.

Period	Yield				
	Uniform irrigation	Non-uniform irrigation			
	Mean (1) t·ha^{-1}	Mean (2) t·ha^{-1}	σ t·ha^{-1}	CV (%)	Ratio (2)/(1)
1975-1976	12.1	11.3	0.7	6	0.93
1976-1977	12.5	11.8	1.0	8	0.94
1977-1978	13.6	13.4	0.1	1	0.99
1978-1979	14.6	14.1	0.8	6	0.97
1979-1980	11.6	10.6	1.4	13	0.91
1980-1981	13.6	13.3	0.9	7	0.98
1981-1982	13.6	13.4	0.4	3	0.99
1982-1983	11.3	10.7	0.7	7	0.95
1983-1984	9.5	9.2	0.8	9	0.97
1984-1985	11.6	10.3	1.0	10	0.89
1985-1986	11.2	10.7	0.7	7	0.96
1986-1987	8.9	8.4	0.8	10	0.94
1987-1988	10.4	9.8	0.4	4	0.94
1988-1989	12.5	11.8	0.8	7	0.94
1989-1990	5.5	3.6	1.3	36	0.65
1990-1991	8.6	8.0	0.8	10	0.93
1991-1992	9.2	8.5	0.6	7	0.92
1992-1993	10.9	10.7	0.3	3	0.98
1993-1994	11.7	11.4	0.6	5	0.97
1994-1995	8.2	7.7	0.6	8	0.94
1995-1996	9.4	8.8	0.6	7	0.94
Min	5.5	3.6	0.1	1	0.65
Max	14.6	14.1	1.4	36	0.99
Median	11.6	10.7	0.7	11	0.94
Mean	11.0	10.4	0.7	8	0.93
Standard deviation	2.2	2.4	0.3	7	0.07
CV (%)	20	23	41	83	8

variability dominate (Figs. 7a, 7c). Spatial distribution of yield and dry matter (Figs. 7b, 7d) indicate that both, dry zones located at the border of the field and wet zones where irrigation is overlapping had an effect on dry matter and yield. Because yield and biomass production are generally related to actual evapotranspiration, similarity of the results for yield and dry matter and evapotranspiration are not surprising (Fig. 8). Dry matter and yield were strongly correlated to evapotranspiration, and moderately correlated to irrigation (Fig. 8), because irrigation represents only part of the total available water for plants.

3.3. Impact of lane spacing

Under the 77 m lane spacing, overlapping between successive passages of the gun disappears, leading to zones of water deficit (Fig. 9). However, this has only a moderate impact on the terms of the water balance, as shown in Figure 10 for drainage during the cropping period for the 70 m and 77 m

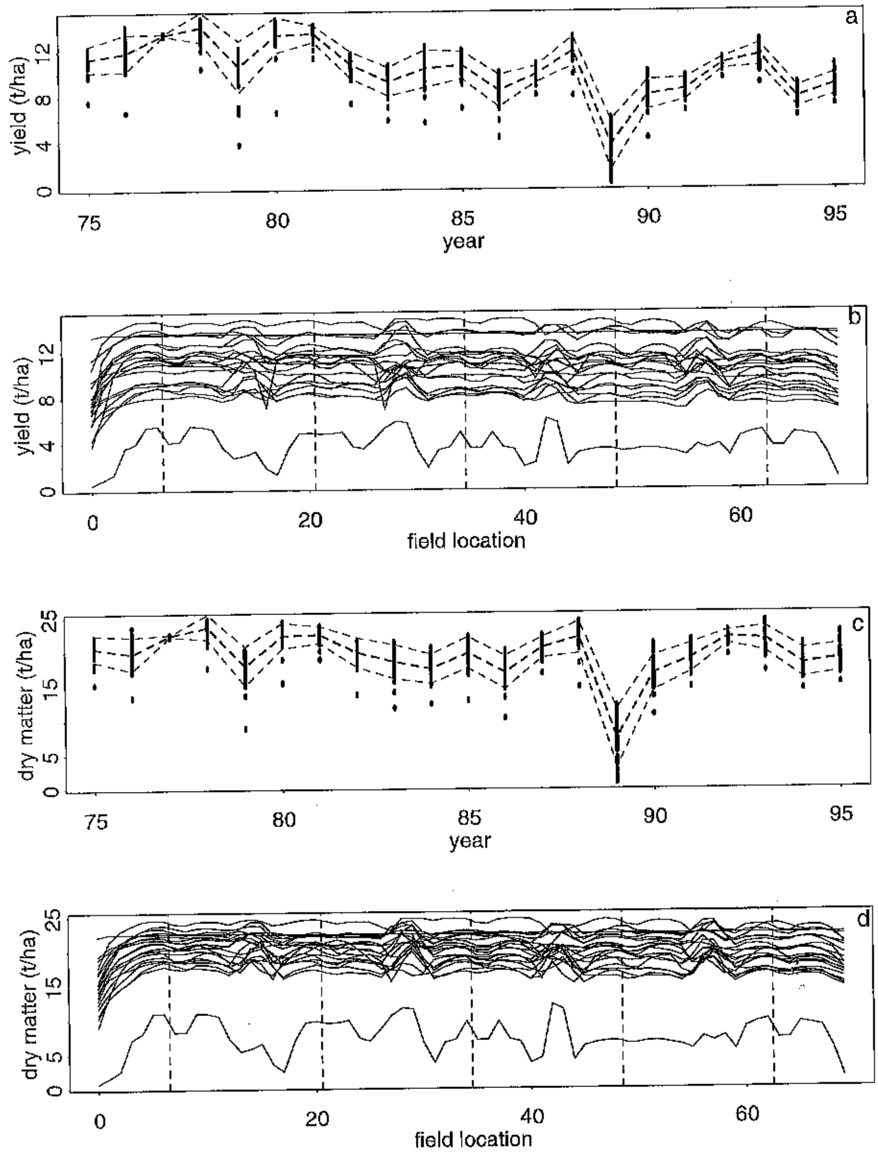

Figure 7. Simulated variations in (a) yield and (c) dry matter in the cropping period during the 21 years simulated (the intermediate line represents the mean, the dashed lines represent the confidence interval, each point corresponds to a 5 m plot located along a transect perpendicular to the direction in which the gun travels), and spatial distribution along a transect of (b) yield and (d) dry matter in the cropping period during the 21 years simulated (each line corresponds to one year, the dashed lines indicate the position in which the gun travels).

treatments. The general trend for drainage is similar, although small differences exist between individual plots.

4. Discussion

Numerous models have been proposed in the literature to simulate water flow, nutrient transport, heat flux, crop uptake for water and nutrients, as well as biological transformations of N in the soil [24, 25]. In this study a link is provided between temporal variability from natural climatic conditions and spatial variability from non-uniform irrigation to predict the impact on crops and environment. Although our results are conditioned by the irrigation scheduling strategy, they show that temporal effects dominate, while the spatial variability appears moderate for annual terms of the water balance. Spatial averages for the different terms relative to water budget or yield at the field scale

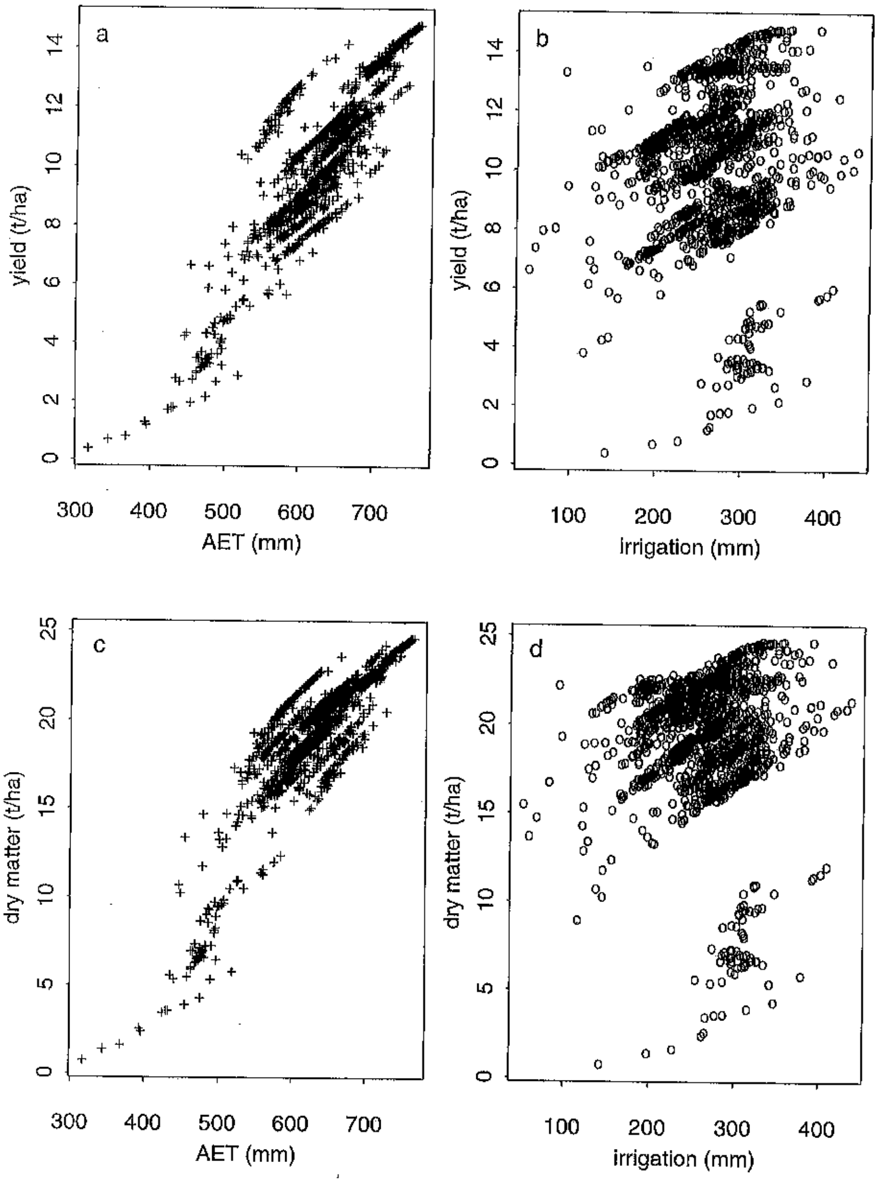

Figure 8. Relationships between (a) yield and cumulative actual evapotranspiration or (b) irrigation, and between (c) dry matter and cumulative actual evapotranspiration or (d) irrigation for the 21 years simulated (each point in the figures corresponds to one individual plot in the field for a given year).

moderately differ from the entirely uniform situation. These results confirm those of previous studies that show for example that irrigation non-uniformity was only one component of total yield variability [20, 21, 38]. Nevertheless, some points in the NIWASAVE have to be further discussed.

First, the model implies that the field surface consists of parallel and independent soil columns without interactions. We assumed that water distribution in the 5.0 or 5.5 m plots (depending on the lane spacing between the passages of the gun) was uniform, thus neglecting local interception by plants or micro-scale infiltration heterogeneity. Disregarding this micro-scale heterogeneity may underestimate water flux variability. Homogeneous lateral expanse of the root system was assumed for each soil depth, which is probably acceptable for maize with a distance between rows of 0.80 m. Many results have indicated that plants tend to

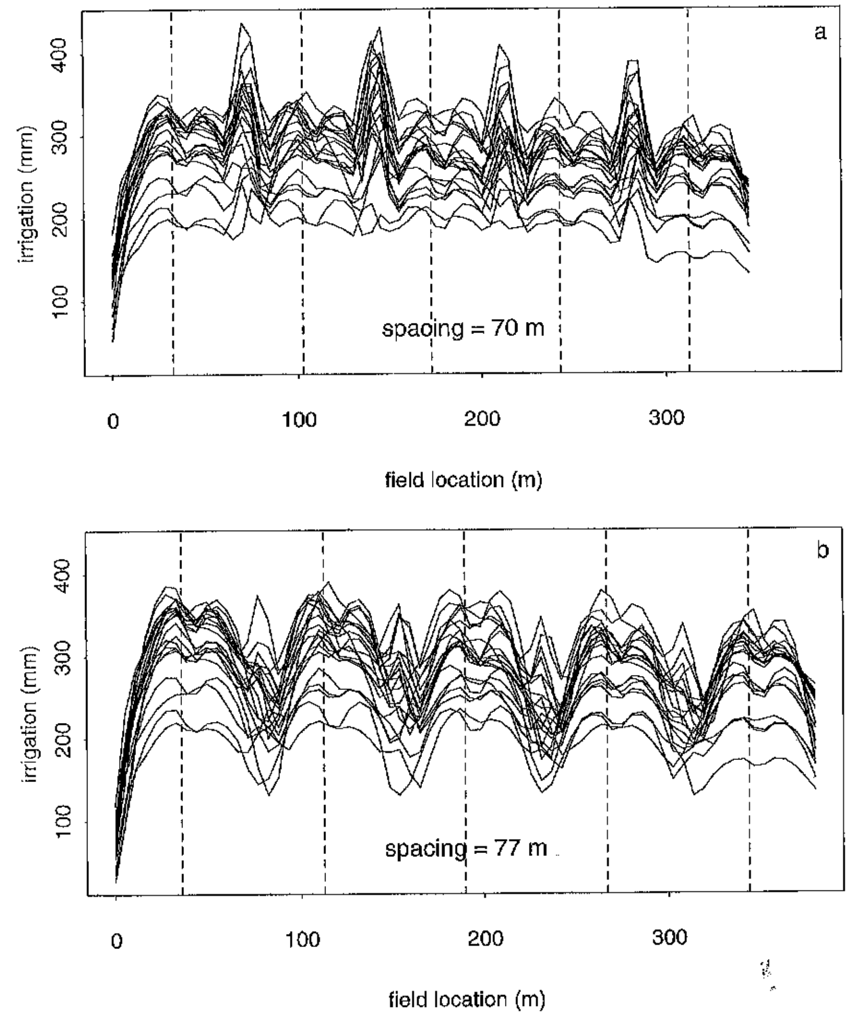

Figure 9. Spatial distribution along a transect of irrigation for (a) 70 m and (b) 77 m lane spacing in the cropping period during the 21 years simulated (each line corresponds to one year, the dashed lines indicate the position in which the gun travels).

integrate and smooth the effects of variable soil water potential within the root zone [5], that lateral movements of water smoothed the spatial variation in the wetting front during infiltration, or that redistribution of water caused crop yield to be more uniform than irrigation [37]. Consequently, some non-uniformity in water distribution within the root zone can be tolerated without strongly modifying crop growth and yield [6, 7, 13, 27, 33].

Secondly, we assumed that the soil was spatially uniform, which never is the case [15]. According to Dagan and Bresler [14], with uniform plant parameters and irrigation, soil hydraulic properties were the major parameters determining total yield variability. In highly permeable soils, where evapotranspiration is limited by percolation, soil heterogeneity increases the spatially averaged evapotranspiration relative to the uniform case. In contrast, for less permeable soils, the lower infiltration rates due to soil heterogeneity limit evaporation because surface runoff may dominate [20, 21]. Nevertheless, low spatial non-uniformity of soil hydrodynamic properties may be partly smoothed by root uptake. Additional research is needed to deeply examine the relationships between infiltration non-uniformity, run-off and water use by plants [27].

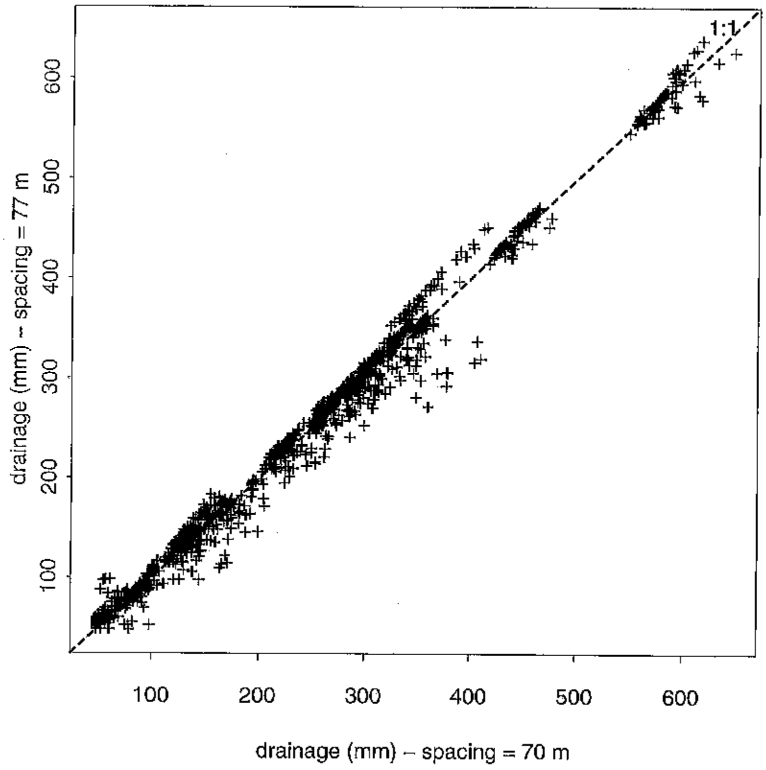

Figure 10. Relationship between the calculated drainage for two lane spacings (70 m and 77 m) during the 21 years simulated.

5. Conclusions

As irrigation distribution, biomass production, and environmental consequences of various agricultural practices strongly interact, it is essential to combine them in a single model to simultaneously analyse the consequences of agricultural management in terms of both yield and environmental quality. In the present study, attention focused on situations with intensive irrigation management. Results indicated that the spatial coefficients of variations for 21 years did not exceed 18, 9, 20, and 36% for irrigation depth, actual evapotranspiration, drainage below the root zone and yield, respectively. These results are in agreement with published data based on other approaches such as crop production functions or stochastic numerical simulations. Spatial variability appeared not to influence strongly the field mean of the water balance, as compared to the perfectly uniform case. Hence, determining the mean irrigation depth remains essential to ensure satisfactory yield without environmental damage. This approach of course does not explore all possible agricultural practices, and many other sources of variation such as type of soil, soil hydrodynamic properties or irrigation strategies must be analysed to arrive at more general conclusions. Nevertheless, this model appears a useful tool in analysing water use by crops under spatially heterogeneous conditions. Moreover, practices such as precision farming need such integrated approaches to link agricultural and environmental guidelines in a realistic way.

Acknowledgements: The research received financial support from the EC (Contract Fair-CT95-0088). We are also indebted to the technical staff at the Institut National de la Recherche Agronomique (INRA) for their assistance, and to C. Young of the Translation Service at INRA for revising the manuscript.

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