Risk Assessment of Non-Uniformity in Irrigation and Fertilization for a Furrow Set Under Climate Uncertainties in the Sofia Field

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Abstract

Water distribution could be quite non-uniform along the furrow length under surface irrigation. This "down field" disuniformity is usually combined with "inter-row" non-uniformity of irrigation water and nitrogen fertilizer distribution. Spatial variation of application depth and nitrogen (N) fertilization rate in the furrow plot produces yield, drainage and nitrogen losses. In addition to that, due to year-to-year variability of climate, regional irrigation depths range significantly (from 0 to 360 mm/season in the studied field). The objective of this paper is to study the impact of global nonuniformity of irrigation water and N fertilizer distribution within a furrow plot on yield, water and nitrogen losses when climate variability is taken into account. Six maize vegetation seasons with contrastive probability of exceedence of irrigation depth P_I are considered. Irrigation water is distributed according to six scenarios for "downfield" and "inter-row" non-uniformity by using the validated FURMOD model (Popova, 1990; 1992; Popova and Kuncheva, 1996). Nitrogen fertilization broadcast corresponds to two scenarios of lateral non-uniformity. The validated CERES-maize model (Jones and Kiniry, 1986;Gabrielle et al, 1995; Popova et al.1999; 2001-b; Popova and Kercheva, 2005) is applied with the different "climate-irrigation nonuniformity-fertilization nonuniformity" scenarios to simulate water&nitrogen cycle and crop growth on a daily basis in 30 representative points along "median", "high intake" and "low intake" furrows of the set. It is established that yield, water and nitrogen losses vary over uniformity scenarios and studied 30-year period. Combination of non-uniform irrigation/N-fertilization with the high irrigation demand seasons (having probability of exceedance P_I<11%) causes losses of yield by 2 to 14.5 % of potential maize productivity, irrigation water (up to 40-45% of applied depth) and nitrogen (up to 10-12% of N-rate). Model runs show that poor distribution uniformity of irrigation water and N fertilizer should be maintained especially in the case of high irrigation requirements. Different strategies aiming at reduction of heterogeneity sources of "inter-row" and "down-field" uniformity of water distribution and fertilizer broadcast are recommended.

Key words: Climate variability, Furrow irrigation model, Nonuniformity of Water, Nonuniformity of Nitrogen, CERES-maize model, Environmentally oriented strategies, Scenario analyses, N-leach, Crop production.

Introduction

Furrow irrigation has been a most wide–spread irrigation method in Bulgaria. It used to be applied over 70% of the irrigated area in this country, i.e. on 0.56 mil. ha in the 80-ies. Nowadays, due to low cost and energy requirements, it is becoming again an economic feasible perspective for irrigation under the conditions of market economy. Non-uniformity of water distribution is one of the basic features for evaluation and improvement of furrow (Varlev, I., 1976; Popova et al., 1998) and sprinkler (Paz et al. 1998) irrigation systems. Well-known fact is that water distribution is quite non-uniform along the furrow length under surface irrigation. This “down field” disuniformity is usually combined with “inter-row” non-uniformity in irrigation water and nitrogen fertilizer distribution (Davidov 1981; Marinov et al.,1985; Popova, 1990; 1991; 1992; Mailhol and Gonzales, 1993; Popova and Kuncheva,1996; Burt et al., 1997; Clemmence et al., 1997; Shahidian et al.,1998; Popova et al.,2005; Crevoisier et al., 2008). References prove that failure to take into account non-uniformity of water&fertiliser distribution should have been related to considerable errors when studding water and nitrogen cycle under furrow irrigation on a cracking soil. Spatial variation of application depth and fertilisation rate in the plot provokes on the other hand non-uniform yield production. There are a number of coefficients that characterise the uniformity of water distribution but not the variability of the resulting yield (Christiansen, 1941). Other numeric characteristics evaluate the impact of irrigation&fertilisation non-uniformity on yield loss by using second-degree polynomial “water/nitrogen-yield” relationships (Howell, 1964; Varlev, 1976; Varlev, 1988; Popova, 2008). Yield losses due to non-uniform irrigation depend also on the wetness of vegetation season and required irrigation depths (Varlev and Popova, 1999; Popova, 2006). Risk of yield losses and environmental pollution associated with climate variability and management practice is analysed by model simulation during the recent decades (Algozin et al., 1988; Popova et al. 1995; Gabrielle et al., 1995; Popova et al., 2001-a; Popova and Kercheva, 2004; 2005; Popova, 2008). Powerful agronomic tools, as CERES (Jones and Kiniry. 1986), WAVE (Vancloster, 1994) and other dynamic models deal in a point scale with the interactions between cropping methods, fertilisers and irrigation in the “ground water-soil-crop-atmosphere” system. One-dimensional models do not take into account though phenomena that are inherent to the plot, as the non-uniformity in applying irrigation water and fertilisers. This paper deals with longitudinal and lateral non-uniformity of irrigation water&nitrogen fertiliser distribution in a furrow set under maize grown on a Chromic Luvisol soil, Chelopechene field, Sofia region. Unlike studies on yield losses due to non-uniform irrigation and fertilisation, which have mostly economical dimensions, this analysis in addition evaluates quantitatively the negative impact of Global non-uniformity on environment and crop productivity in the presence of year-to-year variability&change of climate and maize irrigation requirements. The FURMOD (Popova, 1990; 1991; 1992; Popova and Kuncheva, 1996) and modified CERES-maize (Gabrielle et al., 1995; Popova et al., 1999; 2001-b; Popova and Kercheva, 2005) models, being previously calibrated and validated with data from field observations at plot, parcel and lysimeter scale, are presently used to estimate deep percolation, runoff and yield losses for a set of simultaneously irrigated furrows. The paper compares the consequences of non-uniform distribution of irrigation water and nitrogen fertiliser in a plot scale with the performances of improved surface irrigation technologies with uniform inter-row stream advance and fertiliser broadcast.

Material and Methods

Precise irrigation scheduling of maize grown on a Chromic Luvisol soil in Chelopechene Experimental Field, Sofia region for a long-term 1960-1990 period, as determined by Popova and Kercheva (1999, 2001-a, 2002, 2004, 2010), is used to obtain probability curve of occurrence of an irrigation depth. Data about climate (potential evapotranspiration of grass reference surface and precipitation on a daily basis), crop (duration of growth stages, K_c factors) and soil (total available soil water-***TAW***, that is 140 mm/m, and maximum rain infiltration rate of 150 mm/day) are input for CROPWAT programme (Smith, M. et al 1992). Optimised K_c values under Bulgarian conditions (Popova and Feyen, 1996), respectively 0.3 for initial, 1.1 for mid season and 0.6 for late season growth stages, are constant input for the runs of the program. The irrigation is scheduled whenever the critical soil moisture level, that is 0.4***TAW*** for development and mid season stage and 0.8***TAW*** for late season, is reached. Application depth is set equal to the depleted soil water in the root zone. Seasonal irrigation depths vary from 0 to 359 mm over the studied period. The number of water application is 0-2 in wet irrigation seasons, 3-4 during medium ones and 4-7 in dry ones. Obtained probability curve is validated by comparing it to independent experimentally based estimates of 180, 240 and 300 mm/season for probability of exceedance of the irrigation depth (P_I, %) respectively 50%, 25% and 10% (Zahariev et al, 1986). Six representative maize vegetation seasons with contrastive irrigation requirements (3 %< $\boldsymbol{P_I}$ <97 %) are chosen for the further analyses.

Application depths are distributed over a furrow plot according to six scenarios of irrigation uniformity corresponding to Christiansen coefficient (C_u, %) within the range $53<C_u<90\%$. Spatial mathematical description of intake depth along the non-homogeneous furrows is made by FURMOD model (Popova, 1990; 1991; Popova and Kuncheva, 1996). The model calculates in relative terms water distribution&losses for a wide range of conditions in irrigation practice, as application time and depth, soil infiltration parameters, water deficit in the root zone, “downfield” and “inter-row” non-uniformity of water distribution. It is assumed that equal irrigation streams are simultaneously delivered / stopped at the heads of the furrows. Stream advance L, when arranged in descending order, is approximated by a straight line (Figure 1) with a coefficient K_{nun} (Varlev, 1988), defined as:

$$K_{nun} = (L_{max}-L_{min})/L_{med} \quad (1)$$

, where L_{max}, L_{min} и L_{med} are, respectively, the wetted lengths of the least (No5), most (No1) and median (No3) permeable furrow read from the approximated line of stream advance (Figure 1) and K_{nun} is the coefficient of non-uniformity of stream advance.

The duration of irrigation event is defined as the relative extension of application time I, which represents the additional irrigation time t_{ad} after the irrigation stream has reached the furrow tail in the “median” furrow t_l:

$$I = t_{ad} / t_l \quad (2)$$

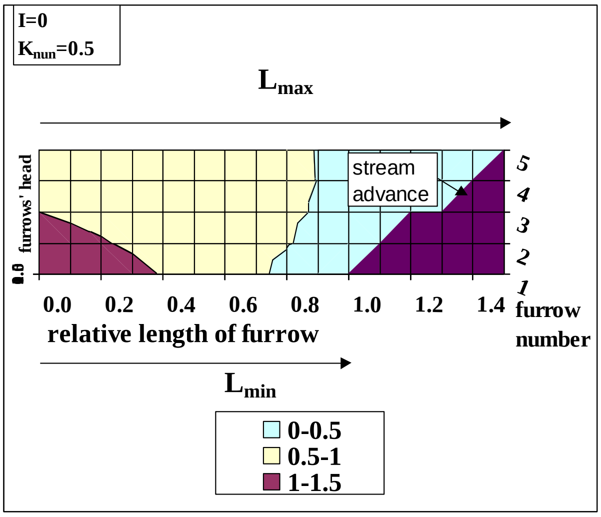


Figure 1. *Distance of advance in high intake (No1), median (No3) and low intake (No5) furrow, arranged in a descending order and lines of equal infiltrated depth for elapsed time t_l (I = 0) and K_{nun} = 0.5 in relative terms.*

The equal volumes of water, delivered at the heads of the furrows, are distributed along the furrow length L as described by the following equation:

$$m_x = 1.5m_{av}\,(1-0.86x/L)^{0.5} \quad (3)$$

,where m_{av} is the average depth of water taken by the soil over the distance of stream advance L.

The furrow length L is the accepted unit of length. The required depth of water for filling up of the root zone to FC - m_{req}, which is retained at the head of the median furrow (No3) for time t_l, is the accepted unit of depth.

Intake depth is calculated using the time based functions of infiltration rate K_t (Kostiakov, 1932):

$$K_t = K_1 / t^{\alpha} \quad (4)$$

and stream advance X in the furrow by Equation (5):

$$X = L_1 \ t_X^{\ n} \quad (5)$$

where K_t is the intake depth after elapsed time t (m/s); K_1 the coefficient (m/s$^{1-\alpha}$); X the advance distance (m); L_1 the distance of stream advance for the first elapsed unit of time (m); t_X the advance time to position X (s); α and n are the empirical exponents.

Despite the fact that exponents α and n (Equations 4 and 5) do not remain the same throughout the irrigation season, in this study it is assumed that they are constant (α = 0.7 and n = 0.8) in the median furrow. Assumed values are within the range of those frequently observed in the field (Popova, 1990; 1992).

The intake depth is calculated along the simultaneously irrigated furrows according to six non-uniformity scenarios. Water distribution is estimated for two values of irrigation duration: one I = 0.8 (Equation 2), when the average intake depth is equal to the required depth m_{req} and another one I = 0, when 70% of required irrigation depth is distributed. Three cases of lateral non-uniformity: K_{nun} = 0; K_{nun} = 0.5 и K_{nun} = 1, provoked by the differences of stream advance, are combined with each irrigation duration.

The treatments of irrigation nonuniformity are studied under different fertilisation application. Nitrogen fertilisation rate (200 kg N/ha) is applied over the furrow plot according to two scenarios: one of ideal N-split and distribution uniformity (coefficient of N variation C_v = 0 %) and another practically oriented one (C_v = 30 %). Total N-dose is split to 1/3 in spring and 2/3 just before the most intensive phases of crop development with the first fertilisation treatment. The second one consists of single N-application in spring with certain inter-row nonuniformity of distribution, as illustrated in Figure 2. The curvilinear diagram in the figure and the range of coefficient of variation of surface N-distribution in practice (C_v = 25-30 %) are established by researchers in the Institute of mechanisation of agriculture (Marinov et al., 1985). The second degree polynomial distribution line is approximated by a step line of three N-rates. The risk assessment analyses are carried out when the representation of each rate over the area of simultaneously irrigated furrows is taken into account.

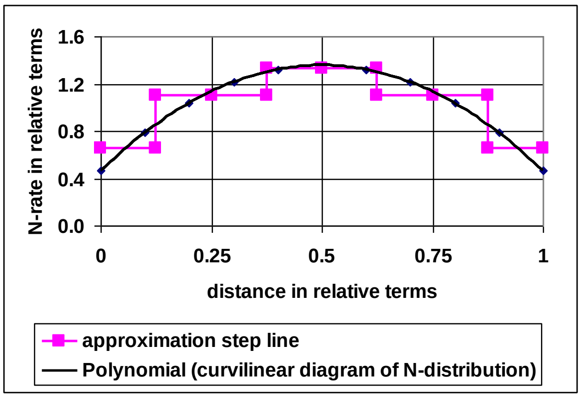
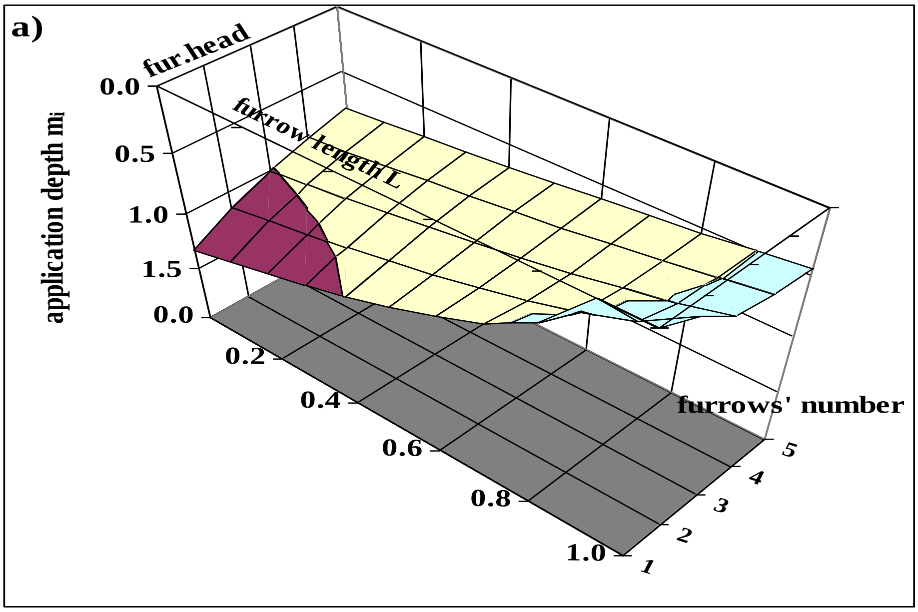


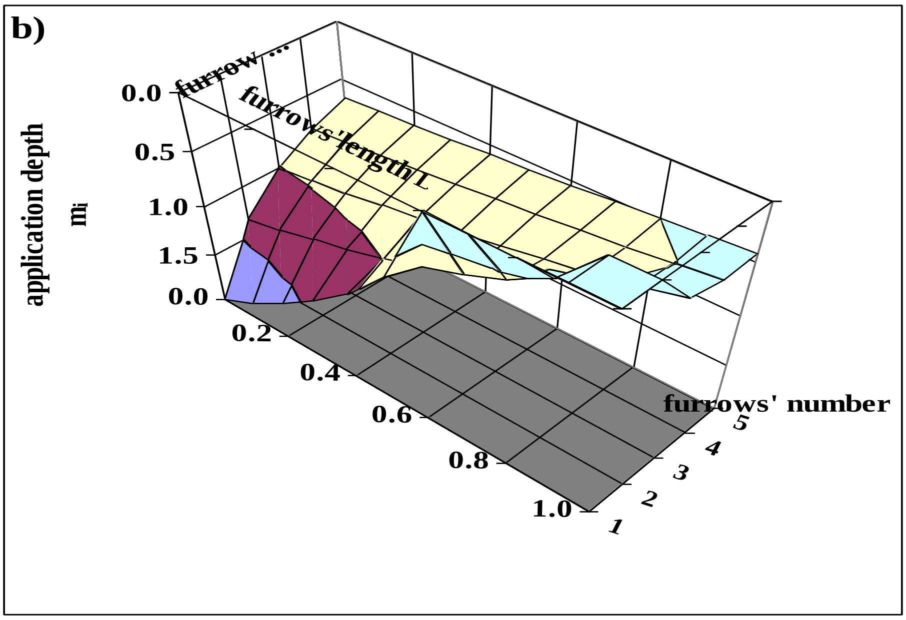
Figure 2. *Inter-row distribution of N-rate over the distance covered by a run of the broadcasting implement in use in Bulgaria.*

Validated CERES-maize model (Jones C.A., J.R. Kiniry. 1986; Gabrielle et al, 1995, Popova et al.1999; Interim and final reports of INCO-COPERNICUS Project 1997-1999; Popova et al. 2001-b; Popova and Kercheva, 2002; 2005) is applied for 30 representative points in the irrigation plot (by 6 along the length L in 5 furrows). Crop growth and fate of water and nitrogen in the non-homogeneous system are simulated for different "climate-irrigation nonuniformity-fertilisation nonuniformity" combinations. The model used to be extensively calibrated and validated previously against three-year data observed in irrigated and rainfed plots and lysimeters in Chelopechene field (Sofia region, Bulgaria). Calibration is carried out for a wide range of water stress and N-split condition at non-limited fertilisation level (200 kg N/ha) and then validated with independently obtained data. As a result the model estimates reliably crop yield (in dry weight of ears), water and nitrogen contents in the soil and crop uptake, water drainage and nitrogen leaching linked to different irrigation and fertilisation treatments and climate. In these analyses it is assumed that crop parameters are constant within the frames of the considered plot, over the years and uniformity scenarios. Yield losses and deviation of drainage and nitrogen leaching within the furrow plot due to nonuniformity of irrigation water&fertiliser distribution is related to probability of exceedance of irrigation depth P_I. The latter characterises the wetness of the irrigation season over a 30-year period (1960-1990).

Results and Discussion

According to the assumptions referred above, distribution of relative intake depth $\mathbf{m_i}$ over the area of furrows' set depends only upon the combination of the parameters of longitudinal (I, Equation 2) and lateral (K_{nun}, Equation 1) nonuniformity. A spatial 3D representation of $\mathbf{m_i}$ distribution for four of the studied nonuniformity scenarios is given in Figure 3. Figure 3-a illustrates the situation from Figure 1 when relative extension of application time I is 0 and coefficient of nonunifomity of stream advance K_{nun} is 0.5. Coefficient of nonuniformity C_u (Christiansen, 1941) is 69%. Figure 3-b presents the distribution of the same quantity of irrigation water (I = 0) but with maximum inter-row disuniformity ($K_{nun} = 1$) corresponding to $C_u = 53$ %. High intake furrow with the shortest stream advance is No1, low intake one with the longest stream advance is No5 and median furrow is No3. Figs.3-c and 3-d illustrate the situations of the same lateral nonuniformity when 50 % more water is applied by extension of application time to I = 0.8 and thus improving the uniformity coefficient to C_u =83 % and C_u =67 %. The area of insufficient water supply ($m_i < m_{req}$) is presented in light yellow and blue colours while the remaining part of the plot, coloured in darker brown and purple, signifies deep percolation losses.





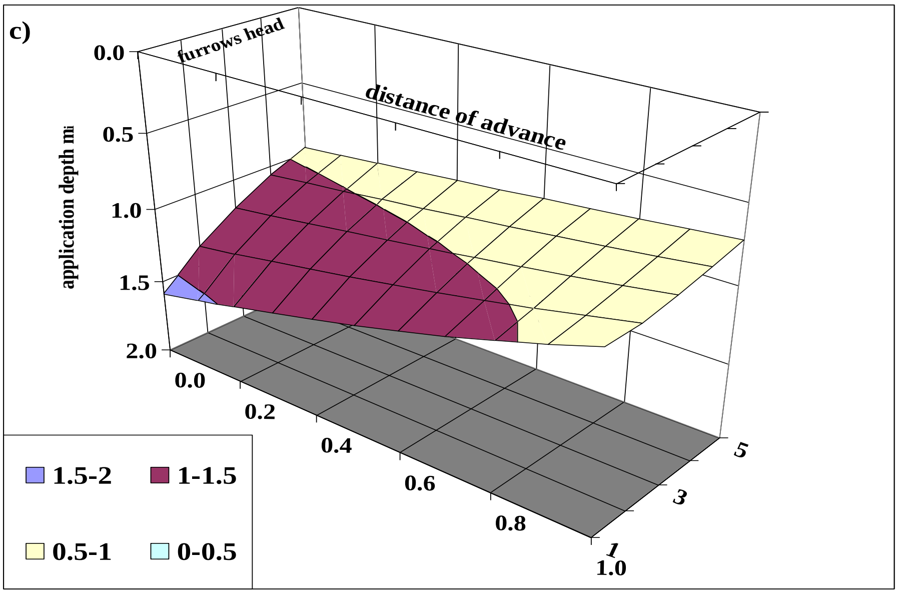


Figure 3. *Intake depth in relative terms m_i along median (No3), high intake (No1), low intake (No5) furrow for different scenarios of nonuniformity of irrigation water distribution: a) I = 0 (Eq.2), K_{nun} = 0,5 (Eq.1), C_u = 69%; b) I = 0, K_{nun} = 1, C_u=53% ; c) I=0.8, K_{nun}= 0,5, C_u = 83% ; d) I = 0.8, K_{nun} = 1, C_u = 67%.*

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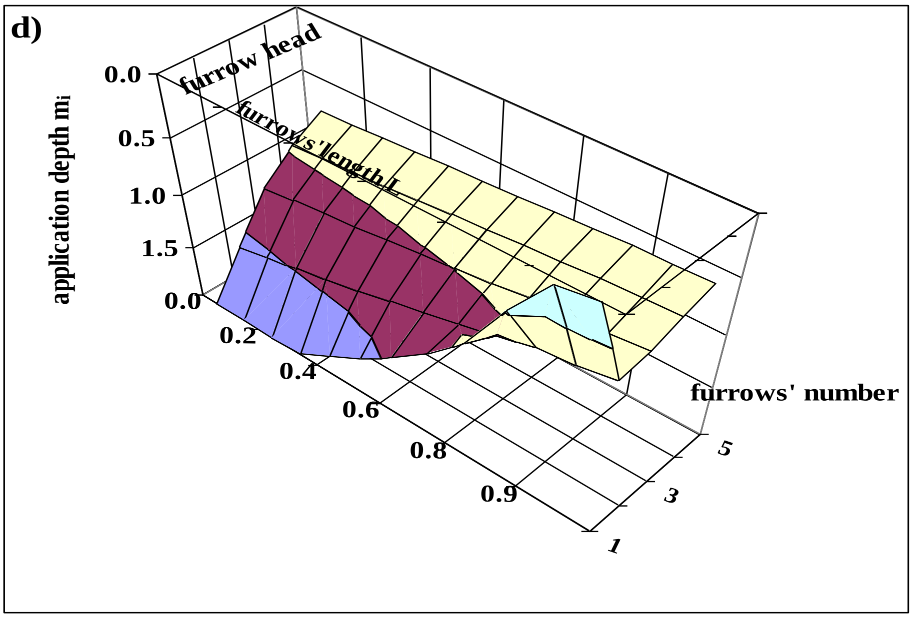

Figure 3. (Continued)

Scenarios of nonuniformity in irrigation water distribution (Figure 3) are combined with the different climate and N fertilisation uniformity treatments (Figure 2). Impact of "low uniformity" irrigation ($I = 0$, $K_{nun} = 1$, $C_u = 53$ % in Figure 3-b) under split uniform fertilisation ($C_v = 0$) on yield, water and nitrogen losses is different over the years. This scenario presupposes that irrigation streams do not reach the tail of "high intake" furrows No1 and No2 and some part of the plot remains rainfed. It means that nitrogen use efficiency is low there in dry irrigation season ($P_I = 3$-11%). As a result the yield is uniform within the area of the plot only after wet irrigation period ($P_I = 77$ %), it varies moderately ($C_v = 4$-8 %) when $P_I = 48$-60% (Figure 4-a) and essentially ($C_v = 19$-26%) after dry seasons with $P_I = 3$-11 % (Figure 4-b).

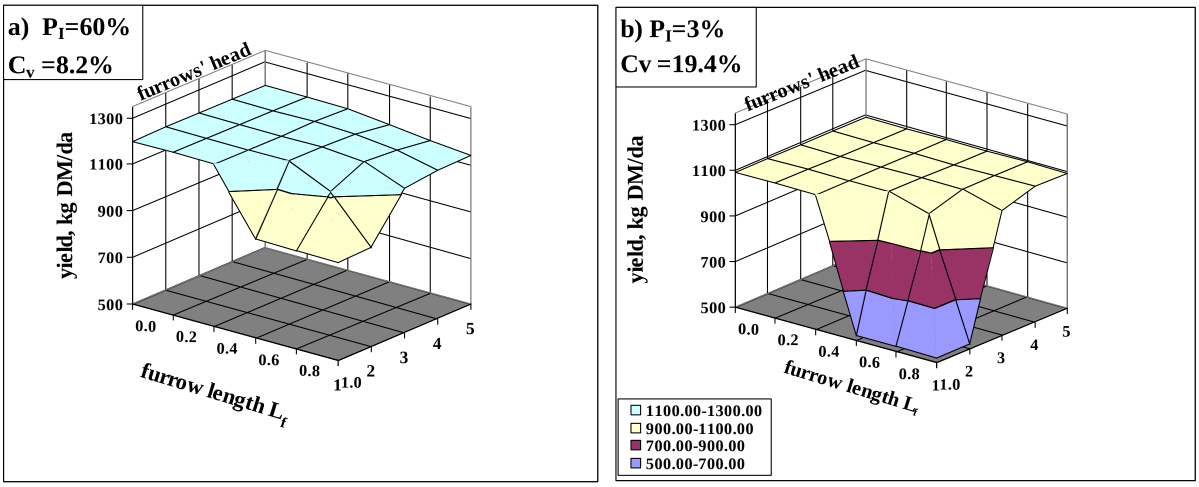

Figure 4. *Yield distribution along median (No3), high intake (No1), low intake (No5) furrow under "low uniformity" furrow irrigation scenario (I=0, K_{nun}=1,Cu=53%) and split uniform fertilisation (C_v=0) in case of: a) average irrigation season (P_I=60%) and b) dry irrigation season (P_I=3%) .*

Figure 5 represents production losses due to nonuniformity of irrigation water distribution dependent upon required irrigation depth and its probability of exceedance P_I.

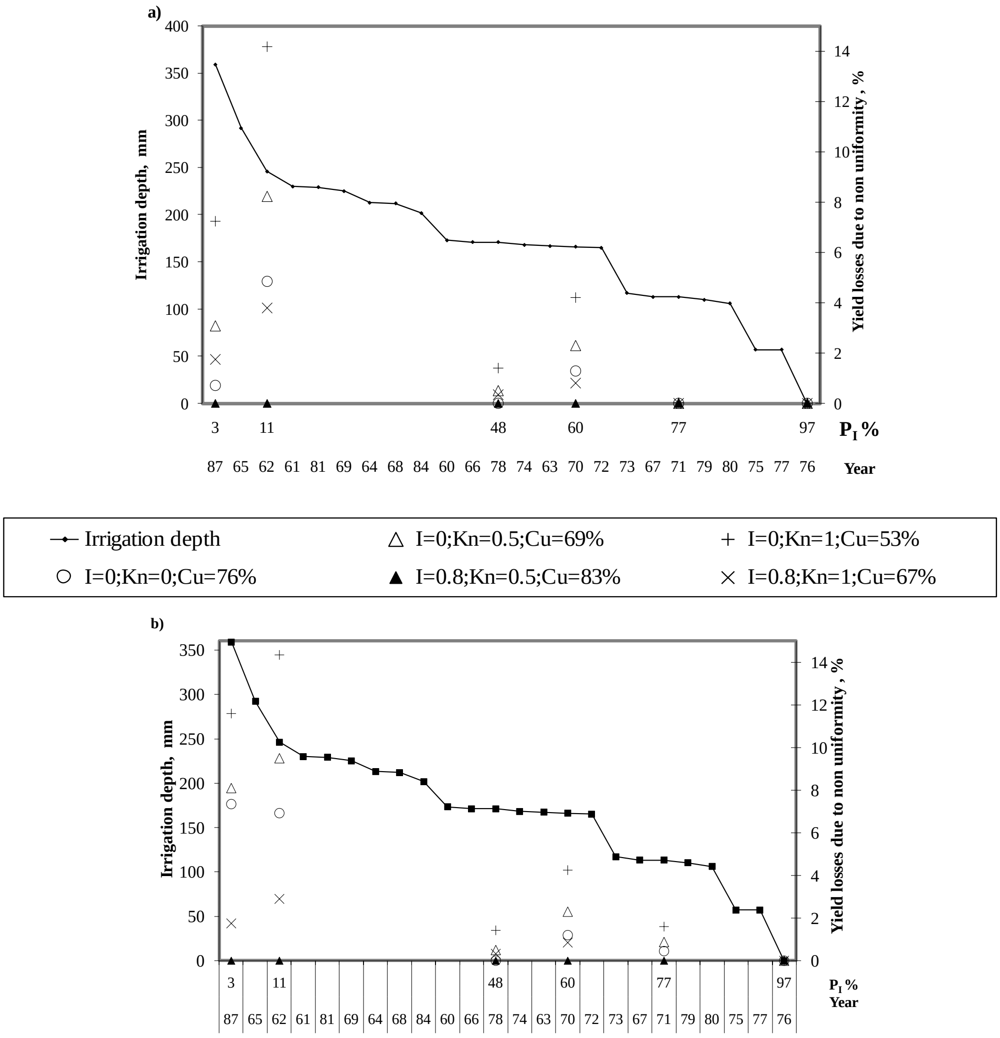

Figure 5. *Yield losses due to irrigation water nonuniformity dependent on probability of occurrence of an irrigation depth P_I, Chromic Luvisol soil, Sofia region under: a) split uniform (C_v=0 %) fertiliser application and b) single nonuniform (C_v=30 %) fertiliser spring broadcasting, 1960-1990.*

Figure 5-a illustrates the results obtained under split uniform (C_v = 0%) N-application and Figure 5-b those valid for single nonuniform (C_v = 30%) fertilisation broadcast according to the diagram in Figure 2. As a consequence of irrigation "low uniformity" treatment of I = 0; K_{nun} = 1 and C_u = 53% (the water distribution situation in Figure 3-b), yield losses in % of the yield, which should have been harvested with uniform irrigation/fertilisation, are practically 0-2 % after wet vegetation periods (P_I = 77 %), they reach 1.8-4.2 % over average (P_I = 48-60%) and augment up to 7.3-14.6 % in the very high and high irrigation demand years of P_I = 3-11 % ("+"-symbols plotted in the secondary Y-axis in Figure 5). The concrete years involved in these analyses are superposed to the probability P_I of irrigation depth plotted in the X-axis. Yield losses could be reduced up to two folds (open "Δ" symbols in Figure 5-a) at the same level of areal average water (I = 0) and nitrogen (200 kg N/ha) supply by improving the "inter-row" uniformity of stream advance to K_{nun} = 0.5 (the situation in Figure 3-a) and fertiliser broadcast to C_v = 0 %. When distances of stream advance along the simultaneously irrigated furrows are completely equal (K_{nun} = 0), as well as the fertilisation

rates distributed across the plot, maximum yield is produced with minimum irrigation water supply (open “o”-symbols, Figure 5-a).

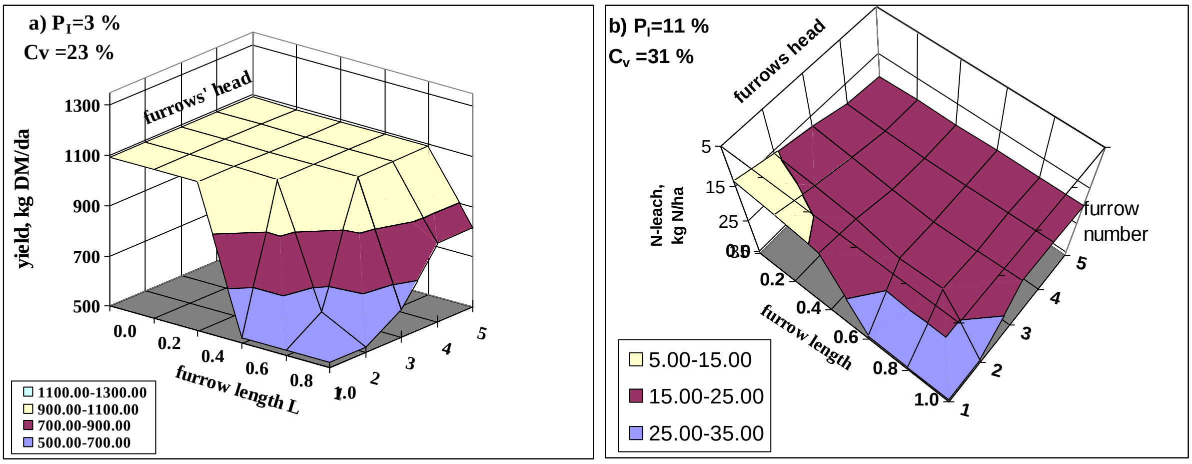

Figure.6. *Consequences of combined “low uniform” furrow irrigation (I=0, Кнер=1,Cu=53%) and fertilisation (Cv=30%) scenarios for maize plot with a dry irrigation season (P_I=3-11%) for : a) Yield distribution b) Variation of N-leach totals for “Oct-Apr” fallow state period.*

Combination of nonuniform fertilisation (C_v = 30%) and irrigation (C_u = 53 %) with the very dry irrigation season of 1987 (P_I = 3 %) leads to additional yield losses (Figure 5-b) due to the reduction of crop productivity along the tail of all furrows (Figure 6-a).

The drier is the irrigation season the higher is also the potential environmental risk due to irrigation&fertilisation nonuniformity. As a result of high residual soil N-NO_3 after a dry season (1962, P_I = 11 %), hazardous N-leaching may arise in case of precipitation extremes in fallow state especially over the rainfed part of the “high intake” furrows No1 and No2 (Figure 6-b).

Figure 7 illustrates the overall environmental impacts of the “low uniformity” irrigation treatment (I = 0; K_{nun} = 1; C_u = 53%) under uniform (“o”-symbols) and nonuniform (“x”-symbols) fertilisation scenarios related to the probability of occurrence of an irrigation depth P_I. Mean and standard deviation (STDEV) bars of drainage and N-leaching totals for May-September period (Figure 7-a) coincide for both fertilisation scenarios except for the N-leach in the extremely wet rainfed vegetation period for 1976 (P_I = 97%). It is obvious that STDEVs in Figure 7-a depend upon the wetness of the irrigation season. In moderately wet 1971 (P_I = 77%) drainage and N-leaching are uniform across the plot. STDEV bars augment when the season in getting drier and reach 98 mm for the drainage and 4 kg N/ha for the leaching in 1987 when P_I = 3%. The same tendencies hold true for the deviation of residual N-NO_3 in the soil, which ranges from 10 kg N-NO_3/ha (1971, P_I = 77%) up to 50-60 kg N-NO_3/ha in the dry irrigation seasons of 1987 and 1962 (P_I = 3-11%) (Figure 7-b). The drier is the irrigation season the higher is the mean residual soil N-NO_3. Nonuniformity in fertilisation produces additional threat to environment since values of mean residual soil nitrate in the furrow set are 10-15 kg N-NO3/ha higher than those associated with uniform fertilisation scenario.

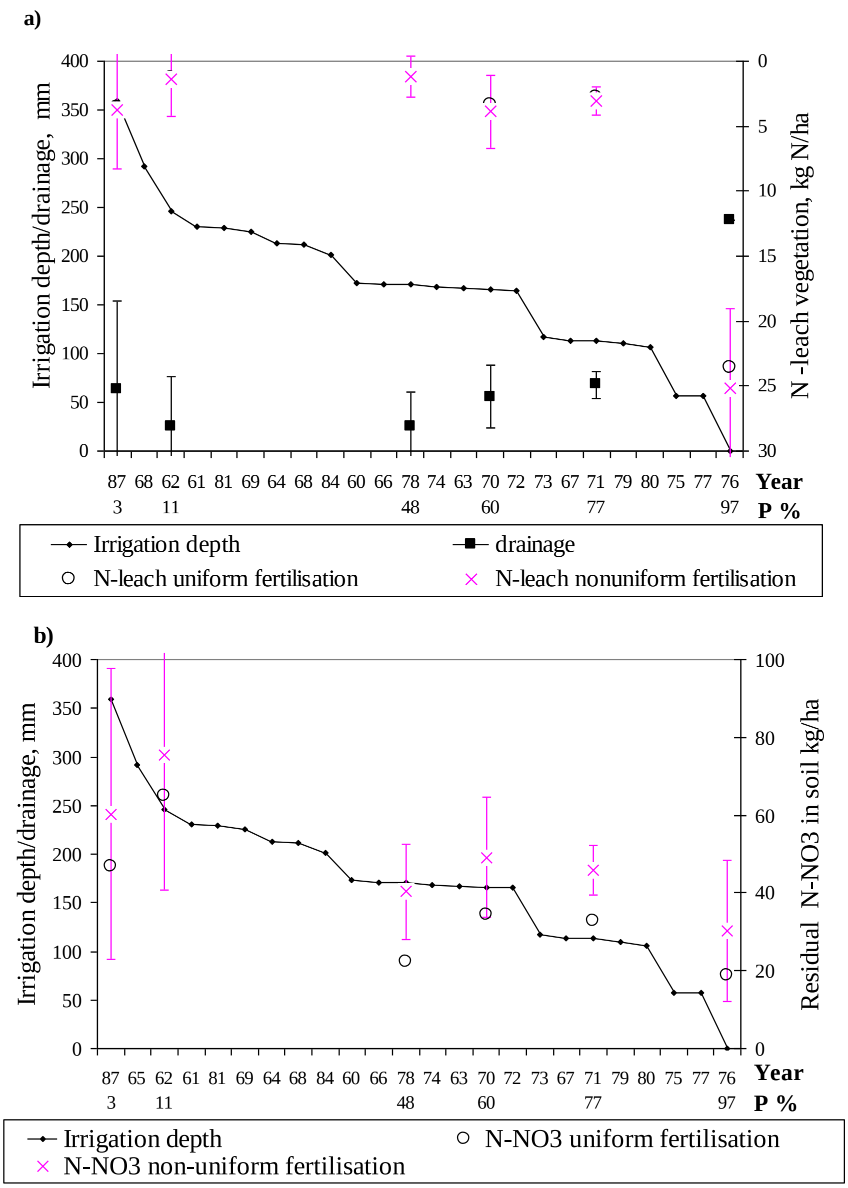

Figure 7. *Impact of irrigation "low uniformity" treatment (I=0 K_{nun}=1 C_u=53%), nonuniformity in fertilisation and probability of occurrence of an irrigation depth (P_I) upon mean and STDEV relative to: (a) drainage and N-leaching totals for May-September period; (b) residual N-NO_3 in the soil, 1960-1990.*

Adverse impact of furrow irrigation on ecology is mitigated at the same level of irrigation water supply (I = 0) in the case of ideal lateral uniformity in irrigation (K_{nun} = 0) and fertilisation (C_v = 0) according to the results plotted in Figure 8. STDEVs of drainage&N-leaching (Figure 8-a) and residual soil N-NO_3 (Figure 8-b) are substantially reduced (2-3 folds) if compared with the respective graphs in Figure 7. The consequences of nonuniformity (C_v = 30%) in N-broadcasting on mean residual N-NO_3 in the soil under improved irrigation uniformity (C_u = 76 %) (Figure 8-b) is similar to those in Figure 7.

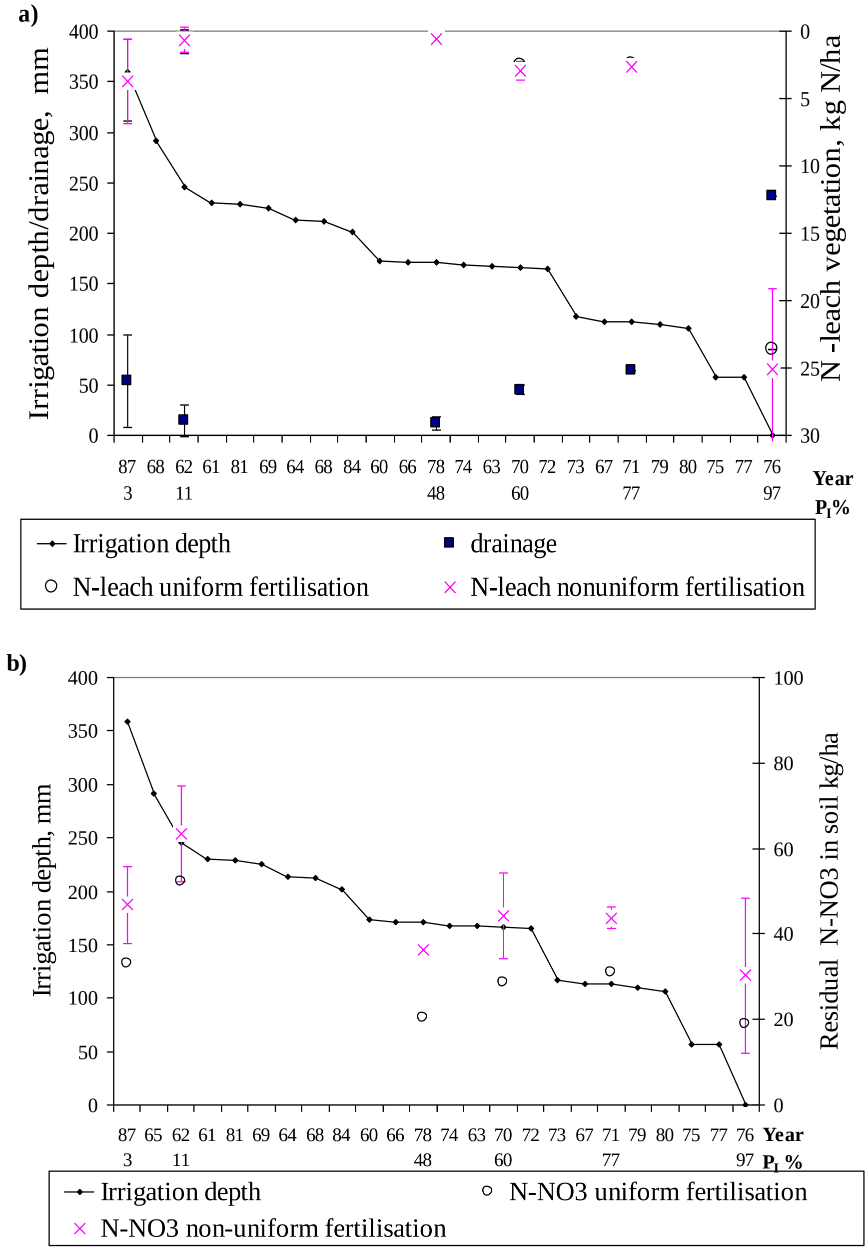

Figure 8. *Impact of irrigation "high- uniformity" treatment (I=0 Knun=0 Cu=76 %), nonuniformity in fertilisation and probability of occurrence of an irrigation depth (P_I) upon mean and STDEV relative to: (a) drainage and N-leaching totals for May-September period and (b) residual N-NO3 in the soil, 1960-1990.*

Regarding surface irrigation practice, the coefficient for non-uniformity of stream advance K_{nun} (Eq.1) ranges within the limits 0.4 - 1.0 (Popova, 1991; 1992; Popova and Kuncheva, 1996; Varlev et al., 1998). The situations of ideal lateral uniformity of stream advance ($K_{nun} = 0$) and N broadcasting ($C_v = 0$) are exceptional. These scenarios are only used as a basis of comparison in the study.

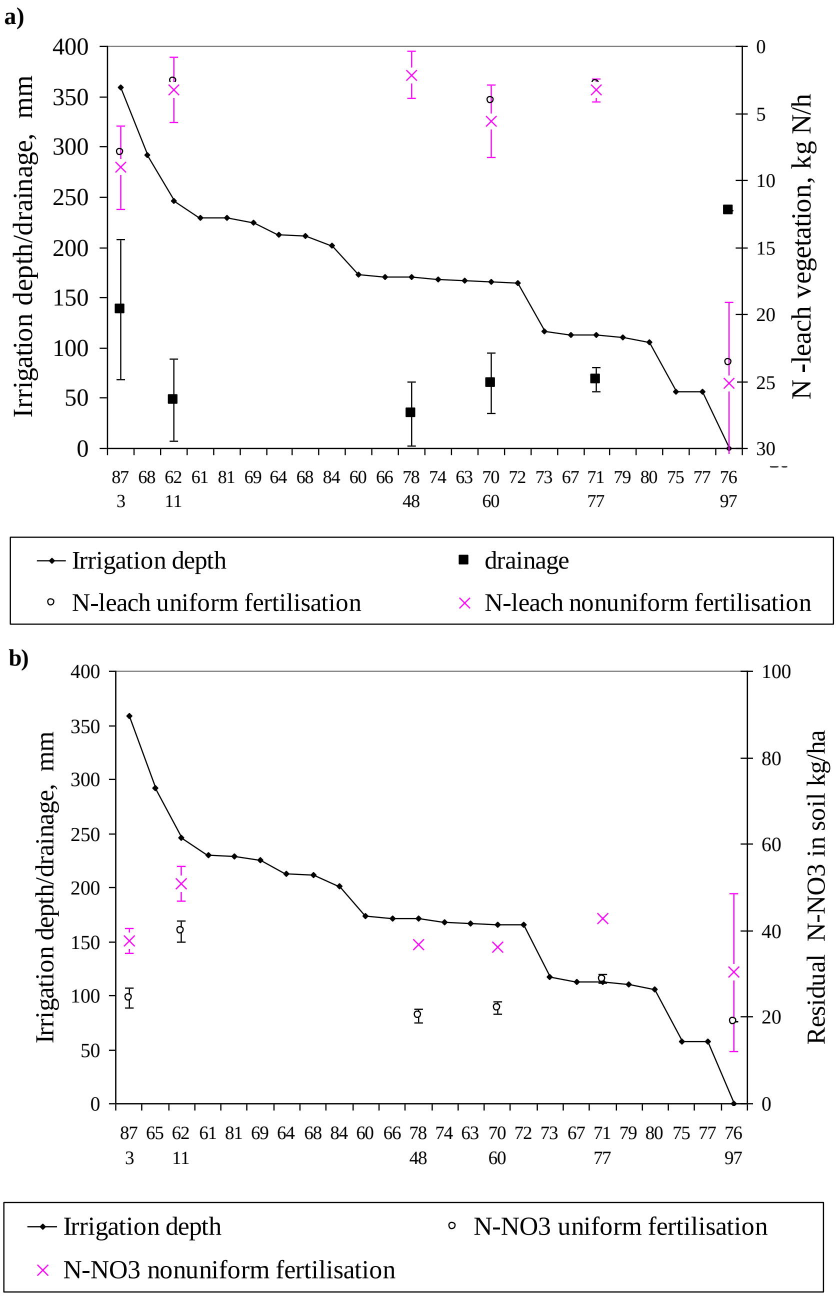

Figure 9. *Impact of irrigation "high-uniformity" treatment (I=0.8 K_{nun}=0.5 C_u=83 %) , nonuniformity in fertilisation and probability of occurrence of an irrigation depth (P_I) upon mean and STDEV relative to: (a) drainage and N-leaching totals for May-September and (b) consequent residual N-NO_3 in the soil, 1960-1990 .*

Yield loss due to non-uniformity of irrigation water distribution drops from 14.2% to 0 % by extending the application time to I = 0.8, i.e. by applying 50 % more irrigation water, and combining it with a real world 'inter-row" nonuniformity of K_{nun} = 0.5 (▲- symbols in Figure 5). Such choice however is possible if the price of water is relatively low and/or if runoff is reused. Figure 9 shows however that this practically oriented irrigation scenario is associated with environmental hazards due to double deep percolation (37-45% of the applied irrigation water) and N-leach (up to 10-12% of the applied N) in dry and average irrigation seasons of P_I < 77 % when compared to the results in Figure 8-a.

Total drainage over "May-September" is 70 mm on the average in 1970 (P_I = 60%) and reaches 130 mm in the driest irrigation season of 1987 having P_I = 3 % (Figure 9-a). When I = 0.8 (Eq. 2), residual soil N-NO_3 is the least and practically constant over the plot and analyzed years: 20-35 kg $N\text{-}NO_3$/ha for split uniform fertilization scenario and between 35-45 kg N/ha for single nonuniform broadcast of the N-rate (Figure 9-b).

In the case of extreme seasonal precipitation events (1976, P_I = 97%), 23 and 25 kg N/ha are leached respectively under uniform and nonuniform fertilization scenarios. N-leach does not vary under uniform fertilisation and it deviates by 6 kg N/ha due to nonuniform fertilisation treatment nevertheless that the drainage is completely uniform across the plot in this season (Figures 7a, 8a and 9a).

Surface irrigation performances are improved in Bulgaria during the last decades. Modernised equipment for uniform stream delivery at the furrows' head, as flexible gated pipelines, has been disseminated. The new method of surge irrigation has been studied and practised in this country for 45 years (Varlev, 1971, Popova et al., 1994, Varlev et al., 1998 and 2011). In addition to water saving effect, it mitigates the variability of infiltration characteristics across the field and reduces substantially lateral non-uniformity of stream advance. Another surface irrigation practice is the cutback of streams delivered in the "low intake" furrows (No4 and No5 in Figures 1 and 3) or compaction of the "high intake" furrows (No1 and No2). Better distribution of nitrogen fertiliser is achieved by optimising the distance between two adjacent runs of the broadcasting implement used that could range between 6 and 30 m depending on the grown crop in Bulgaria (Marinov et al.1985).

Conclusions

The impact of nonuniformity in irrigation and fertilisation on yield, water and nitrogen losses is studied for maize grown on a Chromic Luvisol soil in six vegetation seasons of contrastive irrigation requirements, which are representative over a thirty-year period in Sofia field. Application depths are distributed over a furrow plot according to six scenarios of irrigation uniformity corresponding to Christiansen coefficient (C_u, %) within the range 53 % <C_u< 90 %, three of which are discussed in details. Description of intake depth along the non-homogeneous furrows is made by FURMOD model (Popova, 1990; 1991; Popova and Kuncheva, 1996), which calculates in relative terms water distribution for a wide range of conditions in irrigation practice, as application time and depth, soil infiltration parameters, water deficit in the root zone, "downfield" and "inter-row" non-uniformity of water distribution. Each treatment of irrigation nonuniformity is combined with two scenarios of nitrogen fertilisation: one of ideal N-split and uniformity of distribution (C_v=0) and another one reflecting the real world nonuniformity of N-broadcast (C_v=30%). Crop growth and fate of water and nitrogen over the furrow set are simulated in 30 representative points by the validated CERES-maize model. Analyses of the risk due to non-uniform irrigation and fertilization in the context of climate uncertainties are organized in three aspects:

1. **Yield losses:**

Yield losses in % of the yield, which should have been harvested under uniform irrigation, depend significantly on water distribution nonuniformity and wetness of the irrigation season. In case of "low uniform" irrigation (I=0; K_{nun}=1; C_u=53 %) and split uniform N fertilisation (C_v=0), they are practically 0 % after moderately wet irrigation periods (P_I=77 %) and augment up to 7.3-14.2 % after dry seasons (P_I=3%-11 %) (Figure 5-a). Yield losses could be reduced up to two folds at the same level of mean water and nitrogen supply by improving the lateral nonuniformity of stream advance from K_{nun}=1 to K_{nun}=0.5. When applying 50% more irrigation water (I=0.8) with a sufficient stream advance uniformity (K_{nun}<0.5) yield losses do not depend upon climate variability. Such irrigation practice however is economically feasible only if the price of the water is relatively low and/or if the runoff is reused.

Combining nonuniform fertilisation (C_v=30%) and irrigation (C_u=53 %) with dry irrigation season leads to maximum yield losses (Figure 5-b) due to reduced crop productivity over the furrows' tail (Figure 6-a). When I=0 yield losses are minimal (less than 4 %) if K_{nun}=0 and C_v=0.

2. **Pollution of ground water:**

Variation of irrigation depth and fertilisation rate across the furrow set might provoke pollution of ground water. Drainage and N-leaching relative to May-September period are uniform and harmless for environment in case of moderately wet irrigation season (P_I = 77%) under any of the studied irrigation/fertilisation treatments (Figures 7, 8 and 9). Mean N-leach is between 1 and 4 kg N/ha in average and dry irrigation seasons under "low uniform" irrigation scenario (I = 0; K_{nun} = 1; C_u = 53 %) (Figure 7-a). The drier is the irrigation season the higher is risk to environment due to nonuniformity in irrigation water distribution and N-broadcast. Standard deviation bars (STDEV) augment and reach 100 mm for the drainage and 4-5 kg N/ha for the leaching in the very dry 1987 of P_I = 3%. The same holds true for the residual N-NO_3 in the soil (Figure 7-b) when STDEV reaches 50-60 kg N-NO_3/ha after dry irrigation seasons (P_I = 3-11%).

Nonuniformity in fertilisation produces additional threat to environment when combined with the studied irrigation scenarios. Mean residual soil N-NO_3/ha reaches the maximum of 70-80 N-NO_3/ha due to the integral effect of non-uniformity in irrigation (C_u = 53 %) and fertilization (C_v = 30 %) and dry irrigation season (Figure 7-b) that is 10-15 kg N-NO_3/ha higher that that relative to the uniform scenario (C_v = 0 %). As a consequence, pick N-leaching could occur in case of precipitation extremes in fallow state (Figure 6-b). Nonuniform fertilisation results also in variable and higher N-leach in wet vegetation season (P_I = 97 %) when rainfed maize is grown.

3. **Mitigation of adverse impact on environment**

Adverse impact of furrow irrigation on productivity and environment is mitigated by improving "inter-row" nonuniformity both of stream advance (to K_{nun} < 0.5) and N-broadcast (to Cv < 10%) while maintaining soil moisture above the soil cracking threshold on a regular basis. For that purpose application of environmentally sound water saving irrigation technologies, such as "surge" and "cut-back" irrigation or pre-seasonal compaction of the "high intake" furrows, are recommended. That reduces 2-3 folds STDEV bars of drainage, N-leaching and residual N-NO_3 in the soil when I = 0 (Figure 8). Application of 50 % more irrigation water (I = 0.8), that minimises yield losses, is not sustainable option for environment (Figure 9). In that case 37-45 % of irrigation water and 10-12% of applied nitrogen fertiliser are lost by deep percolation.

Developed scenarios of nonuniformity of irrigation water and nitrogen fertiliser distribution over a furrow set are applicable for any soil. Obtained results about yield losses due to irrigation and fertilisation nonuniformity and climate variability as well as associated environmental impacts are valid for a precise irrigation scheduling relative to the soils of medium water holding capacity and permeability in Sofia field. Adverse impacts to environment and yield losses in irrigation practice could be even more profound than those simulated in this study.

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