CZECH UNIVERSITY OF LIFE SCIENCES PRAGUE

Faculty of Agrobiology Food and Natural Resources

Department of Water Resources

Development of a Fertigation Decision Support System to design and exploit pressurized irrigation systems with water management and fertigation features

PhD THESIS

PhD student: Eng. João Manuel Moreira Barradas

Supervisor: Prof. Ing. Svatopluk Matula, CSc

Co-supervisor: Ing. František Doležal, CSc

Praha, 2013

DECLARATION

I declare that the paperwork for this PhD thesis on the theme “Development of a Fertigation Decision Support System to design and exploit pressurized irrigation systems with water management and fertigation features” was prepared separately and has used only the sources which I quote and mention in the attached bibliography.

Prague, 23.01.2013

Signature: ____

Acknowledgements

This study was partly supported by the research program no. MSM6046070901 ‘‘Sustainable agriculture, quality of agricultural products, sustainable use of natural and landscape resources’’ of the Czech University of Life Sciences in Prague, financed by the Ministry of Education, youth and Sports of the Czech Republic.

I would like to thank my colleagues Ing. Kamila Báťková, Ph.D., Ing. Markéta Miháliková, Ph.D., Getu Mekonnen, MSc. and Ayele Teressa, MSc. for their support and friendship.

A very special thanks to my mentors prof. Ing. Svatopluk Matula, CSc. and Ing. František Doležal, CSc. for their precious support making the publication of this work a reality.

For my father: This is for you. Thank you for all.

Abstract

Irrigation combined with fertigation has produced unquestionable results in the last few decades. It is a rather complicated technology as many factors must be controlled in order to produce good and environmentally safe fertigation practices. The efficiency and uniformity of irrigation, as well as the balance of the nutritive solution used to irrigate are highly ruled by the complex and diverse information (weather, soil, water, and crop data). A tool for irrigation and fertigation management described in this article is a Decision Support System – Fertigation Simulator (DSS-FS). The DSS-FS has been developed to design and optimize irrigation and fertigation systems. The data set to be processed is stored in the DSS database and can be continuously updated according to new development results. Afterwards, the user might handle the input data through a basic and user-friendly interface while allowing the DSS-FS to retrieve default scenarios and thereby reducing the systems user's need for advanced knowledge. An advanced mode of DSS-FS, which adds an increased level of precision in exchange for human support, includes soil sample analysis and other relevant information. Salinity of nutritive solution was related to salt concentration through experimentation and the ideal combination of nutritive salts formulated through an algorithm relating their nutritive content according to an efficiency index.

The software was used by several farmers worldwide and a survey was made in order to collect their results. The use of DSS-FS demonstrated an improvement on farmers performance as opposed to the annual averages from their production region. DSS-FS enhance production and quality results with environmental sustainability.

Table of contents

List of figures

List of Tables

Nomenclature and Abbreviations

Symbols	**Description**	**Unit**
α	Model parameter for Van-Genuchten equation	(-)
a_y	Salinity tolerance treshold in terms of the electrical conductivity of the soil saturation extract	mS cm^{-1}
Δ	Slope of the saturated vapour pressure curve at T	kPa $°C^{-1}$
Δs	Change in the concentration of a given nutritive element after the soil/nutritive solution interaction	kg m^{-3}
ΔH_{dist}	Total distributed energy loss	m
Φw	Soil water potential	m
θ_{fc}	Volumetric soil moisture content at field capacity	%
θ_i	Soil moisture content by volume before fertigation	%
θ_s	Volumetric soil moisture content at saturation	%
θ_t	Volumetric soil moisture content at the limit of RAW	%
θ_{wp}	Volumetric soil moisture content at wilting point	%
η	Pump‘s efficiency	(-)
η_t	Root absorption efficiency for a given element	%
γ	Specific weight of water	N m^{-3}
A_{bulb}	Section area of the wet bulb	m^2
b_y	Rate of decrease in Y_{rel} per unit increase of EC_e.	ton mS^{-1}
C	Buffer capacity	(-)
C_p	Salinity of the nutritive solution	ppm
C_t	Salinity of the mother solution	kg m^{-3}

C_w	Hazen-Williams coefficient	(-)
CEC	Cation Exchange Capacity	meq kg^{-1}
D_i	Internal diameter of the pipe	mm
e_a	Actual vapour pressure at 2 m height	kPa
e_s	Saturation vapour pressure at T	kPa
EC	Electro-Conductivity	mS cm^{-1}
EC_e	EC beyond which a reduction in yield with respect to non saline conditions starts	mS cm^{-1}
ET_a	Actual evapotranspiration	mm day^{-1}
ET_m	Maximum (potential) evapotranspiration	mm day^{-1}
ET_o	Reference crop evapotranspiration	mm day^{-1}
f_{ew}	Wet surface exposed (not covered by vegetation).	%
f_w	Soil surface wetted by irrigation	%
F_r	Christiansen's reduction factor	(-)
F_{rate}	Flow rate in the main conduct	m^3 h^{-1}
G	Soil heat flux density	MJ m^{-2} day^{-1}
h	Pressure head	m
$h(\theta)$	Pressure head at a specific soil moisture content	m
H_t	Total head lift	m
I	Intensity factor	mg L^{-1}
I_f	Intensity factor after equilibrium	mg/L
I_i	Concentration of the soil solution before fertigation	ppm

I_m	Concentration of the soil solution after fertigation	ppm
I_n	Concentration of the nutritive solution	ppm
I_{rate}	Injection rate of mother solution into the irrigation main conduct	m^3 h^{-1}
j	Loss of energy per meter of pipe	m/m
J	Total losses of energy along the irrigation	m
K_a	Acid dissociation constant	(-)
K_{cb}	Basal crop coefficient	(-)
K_e	Soil evaporation coefficient	(-)
K_s	Water stress coefficient	(-)
K_y	Crop sensitivity index to after shortage	(-)
L	Total pipe length	m
m_s	Mass of soil	m^3
m_w	Mass of water	m^3
$M(e)$	molar mass of the element (*e*) to be rated	g mol^{-1}
$M(o)$	Molar mass of the oxide (*o*)	g mol^{-1}
$M(s)$	molar mass of the nutritive salt (*s*) which contains the element (*e*)	g mol^{-1}
n	Model parameter for Van-Genuchten equation	(-)
N_h	Required time of irrigation to restore field capacity	h
N_o	Number of atoms of the element (*e*) present in its oxide (*o*)	(-)

N_s	Number of atoms of the element (*e*) present in a molecule of the nutritive salt (*s*)	(-)
p	Fraction of RAW in TAW	(-)
p[H]	Negative logarithm of the molar concentration of dissolved H_3O^+	(-)
p_o	Outlet required pressure head	m
p_t	Expected production	kg
pK_a	Negative logarithm of K_a	(-)
P	Power	W
q	Emitters flow rate	$m^3\ s^{-1}$
Q	Quantity factor	$mg\ kg^{-1}$
Q_f	Quantity factor after equilibrium	mg/Kg
Q_l	Flow rate	m^3s^{-1}
Q_x	Total flow rate entering the parcel	$m^3\ h^{-1}$
r(e)	Rate of the element (*e*) in the nutritive salt (*s*)	%
r(o)	Element ratio in the nutritive salt expressed as its oxide (*o*)	%
R_n	Net radiation at the crop surface	$MJ\ m^{-2}\ day^{-1}$
RAW	Readily available water	mm
TAW	Total available water	mm
TAW_{adj}	Adjusted total available water	m^3
s	Concentration of a given nutritive element in the nutritive solution	$kg\ m^{-3}$
s_i	Ideal average concentration of a given element in the	

	nutritive solution in a “no losses scenario”	kg m^{-3}
S_t	Ideal concentration of a given nutrient	
	in the nutritive solution	kg m^{-3}
SAR	Sodicity index	(-)
tx	A suitable indicator of soil texture	(-)
t	duration of event	s
T	Mean daily air temperature at 2 m height	°C
u_t	uptake of a given nutritive element	
	per kg of expected production	kg kg^{-1}
U_2	Wind speed at 2 m height	m s^{-1}
V_{cyl}	Volume of hypothetical wet cylinder	m^3
V_{total}	Total volume of soil traditionally considered for	
	estimation of *TAW* at the roots depth *z*	m^3
v_{Tr}	Bulk volume of soil	m^3
v_w	Volume of water	m^3
V_x	Required volume of water to restore field capacity	m^3
y_a	Actual yield	ton
y_m	Potential yield	ton
Y_i	Partial electroconductivity given by one element	
	of the nutritive solution	mS cm^{-1}
Y_{rel}	relative yield	ton ha^{-1}
w	Gravimetric soil moisture content	%

w_t	Estimated total volume of water to be used during the whole crop cycle	m^3
z	Roots depth	mm

Abbreviations

CEC	Cation Exchange Capacity
DSS	Decision Support System
FAO	Food and Agriculture Organization
FEI	Fertigation Efficiency Index
RAW	Readily available water
SAR	Sodicity Index
SWRC	Soil water retention curve
TAW	Total available water
PBC	Potassium Buffering Capacity

1 INTRODUCTION

Water is a scarce resource nowadays, thus it is vital to optimize its use in irrigated agriculture. Water availability varies in time and space, even though in global terms the total amount of water remains constant. Water shortage is made worse by water pollution impact.

Water supply is then limited, in the world where water demand steadily increases. As a consequence, there is a need in developing new technologies to optimize the use of water in all branches of industry and agriculture, especially in the activities related to enhancement of food production needed for the rapidly growing population of the world.

The injection of fertilizers into irrigation water, as opposed to classical soil fertilization, has been a big leap forward in agricultural development during the last century. Irrigation combined with fertigation has already produced unquestionable results over the past few decades. However, what seems to be a quite simple process (the setting up of a fertigation system) is actually a rather difficult task, because one has to control and optimize all characteristics of the fertigated water (nutritive solution), which involves many different and important parameters, each of which might affect both plants and the soil either positively or negatively. Many factors must be controlled in order to produce good and environmentally safe fertigation practices. The efficiency and uniformity of irrigation, as well as the balance of the nutritive solution, depend on the ability of an irrigation manager to properly exploit the complex and diverse information available (weather, soil, water, and crop data). Ultimately, when generating correct fertigation solutions, one saves fertilizers and optimizes the use of water, saving this precious resource and maximizing food production.

1.1 Aims

The aim of this study was to develop a Decision Support System – Fertigation Simulator (DSS-FS). The DSS-FS designs and optimizes the exploitation of irrigation and fertigation systems. The detailed background data are stored in the DSS database and can be continuously updated according to new results. Afterwards, the user may handle the routine input data easily through a basic and user-friendly interface, while allowing the DSS-FS to retrieve default scenarios and thereby reducing the systems user's need for advanced knowledge. An advanced mode of DSS-FS, which adds an increased level of precision in exchange for human support, includes soil sample analysis and other relevant information. This software has been therefore created in two modes, an advanced mode and a basic one, allowing it to serve the two main target groups of users. The software should allow a simple fertigation solution consultancy, making its formulations easy to grasp and apply even in the countries, where very little resources and knowledge are available. It can be seen as one more contribution to the boosting of production and combating against starvation and waste of natural resources in the years to come.

1.2 Hypothesis

It is possible to integrate chemigation, water management and irrigation systems design in one DSS offering a complete solution to manage irrigated crops.

It is possible to collect results from several points worldwide by distributing this application for free in exchange for information on its performance provided by its users

2 LITERATURE REVIEW

2.1 Water management

2.1.1 Soil water retention curves

Soil moister content is usually defined in relation to either the volume of soil

$$\Theta = v_w / v_{Tr} \tag{1}$$

or the mass of the dry soil

$$w = m_w / m_s \tag{2}$$

where v_w is volume of water, v_{Tr} the bulk volume of soil, m_w the mass of water and m_s the mass of dry soil.

It has been demonstrated that the soil water potential Φw (in most cases expressed as the pressure head h) is related to the soil water content θ. The functional relationship $h(\theta)$, referred to as the soil water retention curve (SWRC), is typical for a given soil in its particular state of consolidation, geometrical arrangement of particles and aggregation and other chemical and biological features (Kutílek & Nielsen, 1994).

The definition of the soil moisture retention curve is of great interest for soil agronomic appreciation for irrigation purposes and also in a rain-fed agriculture context. The information on soil water retention curves allows us to define irrigation intervals and volumes in order to make the soil moisture content vary within certain defined boundaries, ensuring maximization of production with minimal use of water.

The function $h(\theta)$, such as those plotted in Fig. 1 represents soil behaviour in what concerns water retention when submitted to a certain negative pressure head. The water which can be extracted from the soil between pF=2.53 (represents -0.33 bar of pressure) and pF=4.18 (–15 bar of pressure) is called Total Available Water (Allen et al, 1998) with its pressure boundary limits designated as the wilting point for pF=4.18 and the field capacity for pF=2.53, with pF defined as log $|h|$ and h being the pressure head [cm]. The water which is retained in the soil at pF below 2.53 is water, which can is easily drained by gravity, while the water retained at pF above 4.18 (below the wilting point), which can only be extracted by high pressure extractors or by physical evaporation, is unavailable to plants.

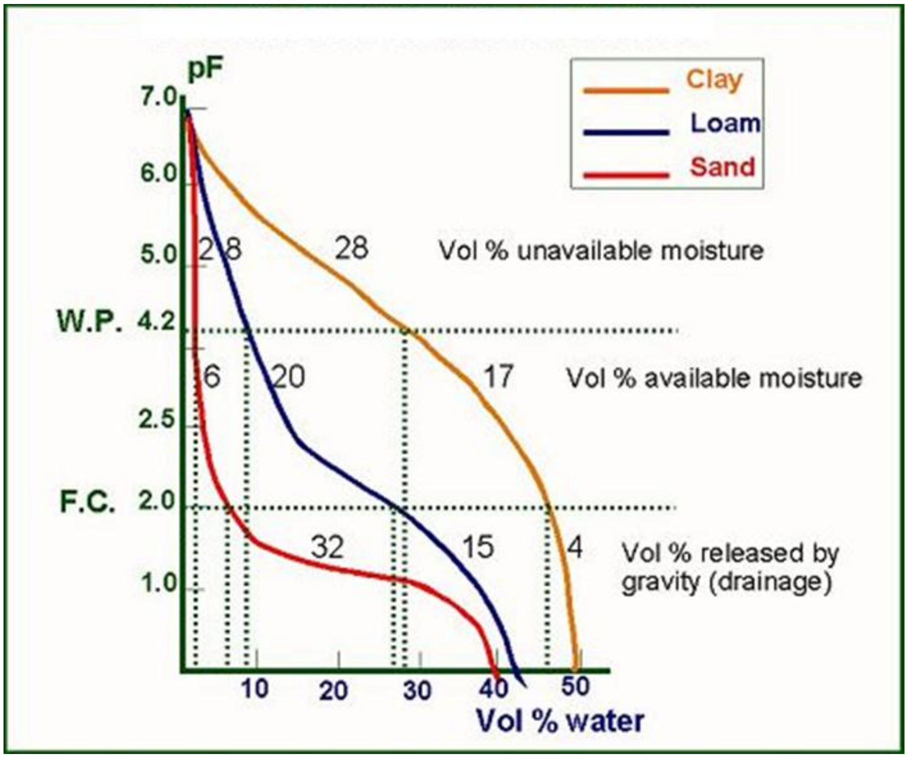


Figure 1. Soil water retention curves.

Source: http://www.aardappelpagina.nl/explorer/pagina/soilwater.htm

According to the same authors, not the whole Total Available Water (TAW) is Readily Available Water (RAW), as some fractions can only be used by plants when the latter find themselves under stress. RAW is defined by the stress coefficient p as a percentage of TAW ($RAW = p \times TAW$).

The soil moisture content at the limit of RAW is designated $\theta_t = \theta_{wp} + (\theta_{fc} - \theta_{wp})p$

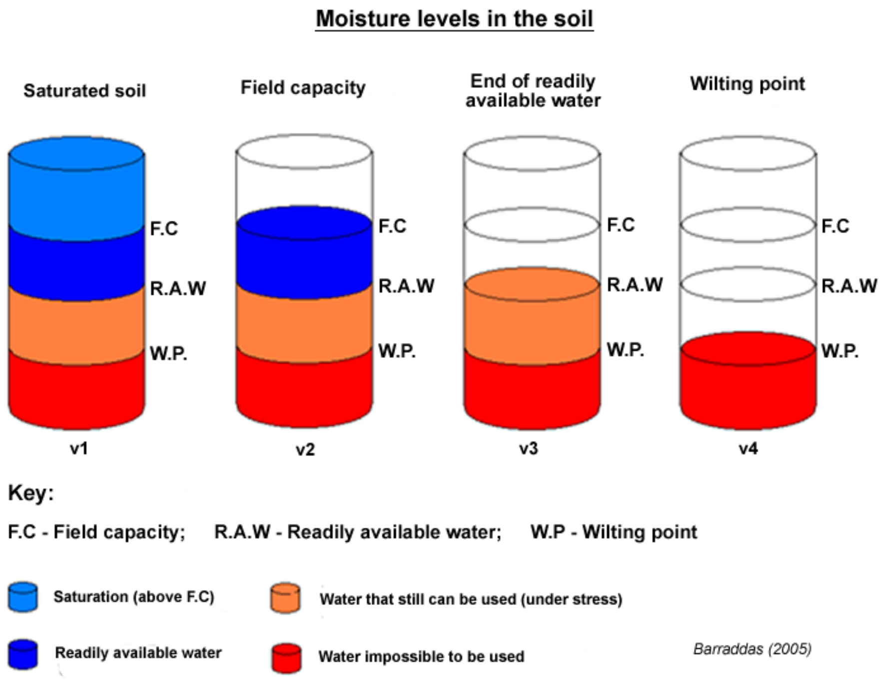
An analytical expression of SWRC

The following four-parameter van Genuchten function can be used to approximate the soil water retention curve (van Genuchten, 1980)

$$\Theta = \frac{\Theta_s - \Theta_r}{[1+(\alpha h)^n]^{(1-\frac{1}{n})}} \qquad (3)$$

where θ is the soil moisture content (m^3/m^3), h is the (positively taken) soil water pressure head (e.g. in cm) and θ_s, θ_r, α (e.g., in cm^{-1}) and n are model parameters.

We may simplify the variable soil water availability to plants by relating it to four distinct levels, as depicted in Fig. 2.



Barraddas (2005)

Figure 2. A schematic representation of the four moisture levels in the soil.

2.1.2 Evapotranspiration

In May 1990, FAO organized a consultation of experts and researchers in collaboration with the International Commission for Irrigation and Drainage and with the World Meteorological Organization, to review the FAO methodologies on crop water requirements and advise on the revision and update of underlying procedures.

The panel of experts recommended the adoption of the Penman-Monteith combination method as a new standard for reference evapotranspiration and advised on procedures for calculating the various parameters. The resulting FAO combination method was developed by defining the reference crop as a hypothetical crop with an assumed constant height of 0.12 m, with a constant surface resistance of 70 s m^{-1} and a constant albedo of 0.23, closely resembling an extensive surface of green grass of uniform height, actively growing and adequately watered. The method overcomes the shortcomings of the previous FAO Penman method and provides values that are more consistent with actual crop water use data worldwide. Furthermore, recommendations have been developed for using the FAO combination method with limited climatic data, thereby largely eliminating the need for any other reference evapotranspiration methods and creating a consistent and transparent basis for a globally valid standard for crop water requirement calculations.

Allen et al (1998) introduced what is now commonly known as the FAO 56 method for predicting crop water requirements.

According to the same authors:

$$ET_a = (K_s K_{cb} + K_e) ET_o \tag{4}$$

where:

ET_a - actual evapotranspiration [mm day^{-1}]

K_s - water stress coefficient [-]

K_{cb} - basal crop coefficient [-]

K_e - soil evaporation coefficient [-]

ET_o - reference crop evapotranspiration [mm day^{-1}], estimated by the FAO 56 combination equation, which is a modified Penman-Monteith equation, as follows:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}U_2(e_a - e_d)}{\Delta + \gamma(1 + 0.34U_2)} \tag{5}$$

where:

R_n - net radiation at the crop surface [MJ m^{-2} day^{-1}],

G - soil heat flux density [MJ m^{-2} day^{-1}],

T - mean daily air temperature at 2 m height [°C],

U_2 - wind speed at 2 m height [m s^{-1}],

e_s - saturation vapour pressure at T [kPa],

e_a - actual vapour pressure at 2 m height [kPa],

e_s-e_a - vapour pressure deficit [kPa],

Δ - slope of the saturated vapour pressure curve at T [kPa °C^{-1}],

γ - psychrometric constant [kPa °C^{-1}].

2.1.3 Calculating the K_s coeficient

When the crop has consumed all the readily available water, it enters a zone where the water extraction is made under stress and, because of this stress, the amount of transpired water is less than what it should be in the absence of the stress. To estimate the decrease in transpiration due to hydric stress of the crop, we will calculate the water stress coefficient K_s as follows:

- If the readily available water *RAW* has not been completely depleted, then

  K_s=1

- If the *RAW* has already been depleted then

$$K_s = \frac{TAW - D_r}{TAW - RAW} \tag{6}$$

where D_r [*mm*] is the actual root zone depletion (mm), i.e. the amount of water needed to restore the soil to its field capacity (it would be equal to *TAW* if the soils were at its wilting point). We can observe the output of this expression in Fig. 3 below:

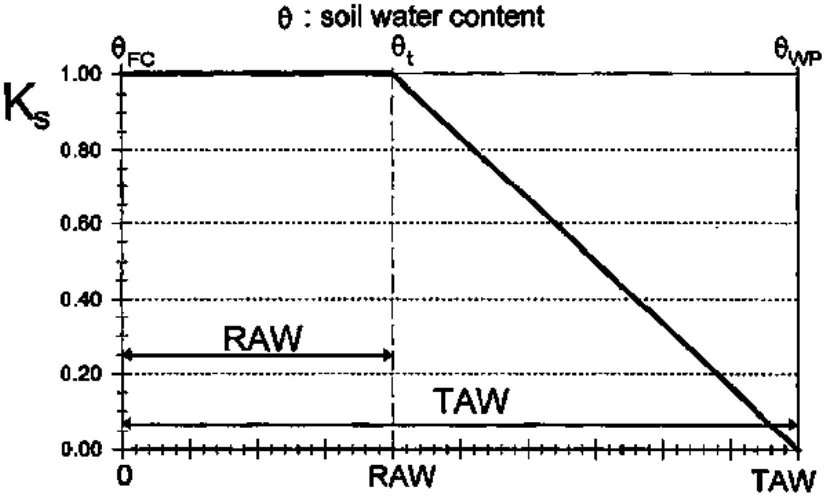


Figure 3. Schematic representation of *RAW*, *TAW* and K_s (Allen et al., 1998)

As long as *RAW* has not been completely depleted, the value of K_s is always unity. Bellow *RAW* the K_s value decreases linearly and becomes zero at wilting point.

2.1.4 Calculating the K_{cb} coeficient

In the same way as K_s is an indicator of the hydric stress, K_{cb} is an indicator of the effective leaf area index *LAI* (which is the one-sided area of leaves divided by the area of soil they occupy) of the crop, the canopy and soil roughness and the plant's genetic ability to transpire water. Thus, the value of K_{cb} (see Fig. 4) is very low at the beginning of the crop season after emergence and reaches its maximum at mid-season, when the crop undergoes its maximum vegetative development. The variation of K_{cb} during the season is expressed by a broken straight line, which can be reconstructed if one knows three typical values of K_{cb} ($K_{cb\ ini}$, $K_{cb\ mid}$ and $K_{cb\ end}$) and the positions of breaking points on the horizontal time scale.

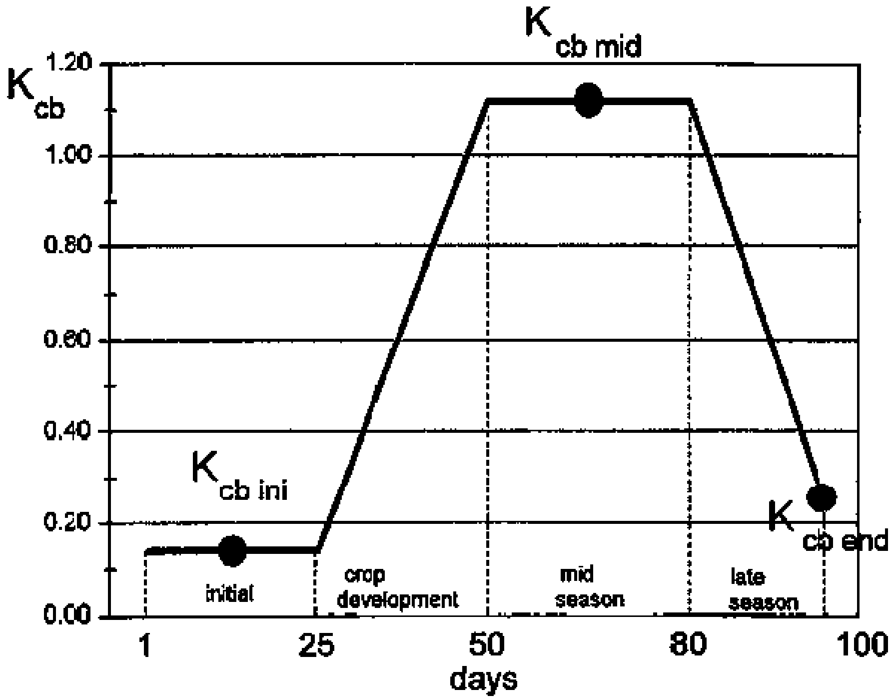


Figure 4. K_{cb} progression along the crop cycle (Allen et al., 1998)

Table 1 K_{cb} and p values according to Allen et al. (1998)

Crop	$K_{cb\ ini}$	$K_{cb\ mid}$	$K_{cb\ end}$	**p (depletion fraction) for $ET_c=ET_o(K_{cb}+K_e)$ =5 mm/day**
sunflower	0.1	1.1	0.25	0.45
corn	0.15	1.1	0.5	0.55
wheat	0.15	1.1	0.15	0.55
tomato	0.15	1.1	0.6	0.4
pepper	0.15	1	0.8	0.3
cabbage	0.15	0.95	0.85	0.45
potato	0.15	1.1	0.65	0.35
citrus	0.65	0.55	0.65	0.5
apples	0.35	0.9	0.65	0.5
plumbs	0.35	0.85	0.6	0.5
grapes	0.15	0.65-0.80	0.4	0.4
olive trees	0.55	0.65	0.65	0.6

The depletion fraction p (from Table 1) can be used to estimate *RAW* from *TAW*.

However, the values from table 1 are only valid for ET_c =5 mm/day. With $\mathrm{ET_c} = ET_o(K_{cb}+K_e)$. If the value of ET_c is different than 5 mm/day, then we can calculate the true value of p as follows:

$$p = p(Table\ 1) + 0.04(5 - ETc) \tag{7}$$

where p is expressed as a fraction and ET_c in mm/day.

2.1.5 Calculating the K_e coeficient

Similarly we can estimate the value of the soil evaporation component of evapotranspiration. The factors directly affecting K_e are:

- Reference crop evapotranspiration ET_o
- n_e = Number of days after a wetting event
- f_w = % soil surface wetted by irrigation
- f_{ew} = % of the wet surface exposed (not covered by vegetation)
- Volume of infiltration during the wetting event

The dependence of K_e on the reference crop evapotranspiration ET_o and on the number of days after wetting is detailed in the following Tables 2 and 3.

Table 2. K_e values in the first 20 days after a wetting event for medium and heavy soils (Allen et al., 1998)

K_e after a wetting event (scenario for medium and heavy soils after an infiltration event with the cumulative infiltration depth above 40mm)

Days	**ET_o (mm d^{-1})**										
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.10	1.05	1.00
2	1.15	1.15	1.15	1.15	1.10	1.00	0.95	0.85	0.80	0.75	0.70
4	1.15	1.15	1.00	0.85	0.70	0.65	0.55	0.50	0.45	0.40	0.35
7	1.15	1.00	0.70	0.55	0.45	0.40	0.35	0.30	0.30	0.25	0.20
10	1.15	0.70	0.50	0.40	0.35	0.30	0.25	0.20	0.20	0.15	0.15
20	1.15	0.35	0.25	0.20	0.15	0.15	0.10	0.10	0.10	0.10	0.10

Table 3. K_e values in the first 20 days after a wetting event for coarse soils (Allen et al., 1998)

K_e after a wetting event (scenario for coarse soils after an infiltration event with the cumulative infiltration depth above 40mm)

Days	**ET_o (mm d^{-1})**										
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1	0.95	0.9
2	1.05	1.05	1.05	1.05	1	0.9	0.85	0.75	0.7	0.65	0.6
4	1.05	1.05	0.9	0.75	0.6	0.55	0.45	0.4	0.35	0.3	0.25
7	1.05	0.9	0.6	0.45	0.35	0.3	0.25	0.2	0.2	0.15	0.1
10	1.05	0.6	0.4	0.3	0.25	0.2	0.15	0.1	0.1	0.05	0.05
20	1.05	0.25	0.15	0.1	0.05	0.05	0	0	0	0	0

Then the actual soil evaporation coefficient K_e is obtained as:

$$K_e = K_e(table) f_w f_{ew} \tag{8}$$

Where

f_w - % soil surface wetted by irrigation,

f_{ew} - % of the wet surface exposed (not covered by vegetation).

Similar tables can be built for infiltration depths <40mm using figure 5

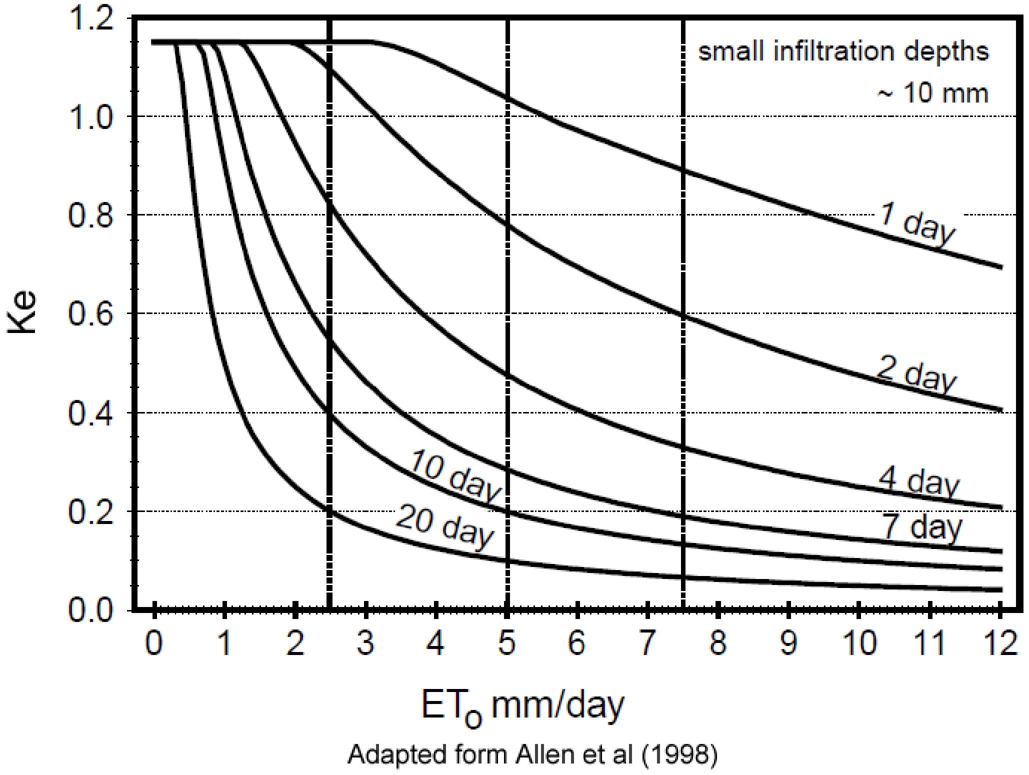
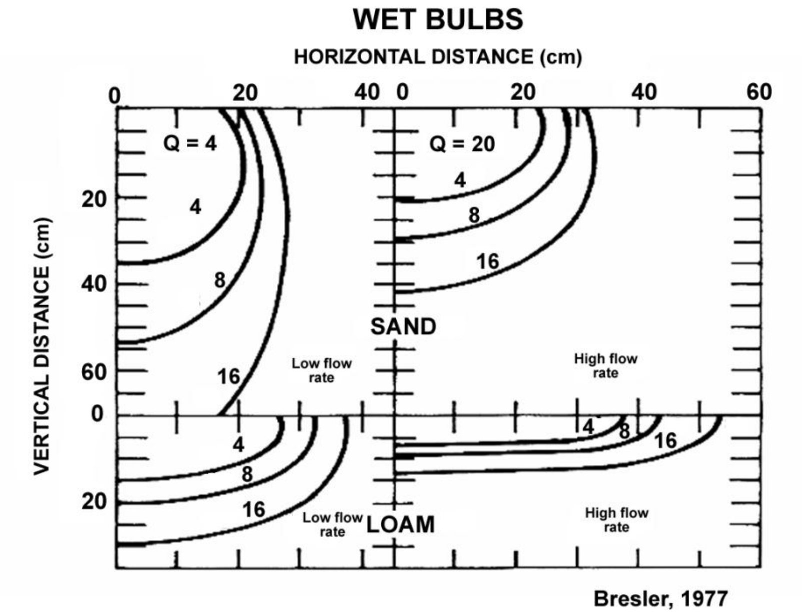


Figure 5 K_e values in the first 20 days after a wetting event for small infiltration depths (all textures)

2.2 Particularities of infiltration under drip irrigation conditions – wet bulbs

According to Bresler (1977), Nogueira et al. (2000) and Gil-Marín (2001) and some other authors, the shape of the wet bulb (the wetted volume of soil under an irrigation dripper) can be estimated from the soil texture, emitters flow rate and duration of the irrigation.



Bresler, 1977

Figure 6. Wet bulbs according to soil texture and flow rate. The labels at particular curves mean infiltration duration in hours.

The results of Bresler's work (Fig. 6) allow us to understand that the horizontal diameter of the wet bulb (with its vertical diameter kept constant) is very well related to the texture of the soil and the flow rate applied through the drippers. The relation between the flow rate, soil texture and the geometry of the wet bulbs will definitely be of great use when designing drip irrigation systems as it conditions the total volume of wet soil after irrigation.

2.3 Irrigation system hydraulics

2.3.1 Estimating energy losses

The loss of energy (loss of head) due to friction is directly related to the liquid flow velocity within the pipe, which gives rise to tangential stress.

This loss is known to be varying linearly with the velocity in the laminar flow, and linearly with the squared velocity in the turbulent flow.

Colebrook and White, already in 1939 proposed the following law, valid for the turbulent flow and based upon theoretical considerations and also upon several experiments with pipes of different materials::

$$\frac{1}{\sqrt{f_r}} = -2\log(\frac{k_r}{3.7D_i} + \frac{2.51}{R_e\sqrt{f}}) \tag{9}$$

where:

k_r – pipe's absolute roughness (m),

R_e – Reynolds number (dimensionless),

f_r – Darcy friction factor (dimensionless), defined by the Darcy-Weisbach equation:

$$f = \frac{J2gD_i}{LU^2} \tag{10}$$

where

D_i – pipe's internal diameter (m),

J – head loss (energy loss) along the pipe (m),

L – length of the pipe (m),

g – acceleration due to gravity (m s^{-2})

U – average flow velocity in the pipe (m s^{-1})

The Colebrook-White equation cannot be solved explicitly for the energy loss. It must be solved iteratively, e.g. by trial and error.

In order to obtain the unit energy loss we have either to solve the equation iteratively or to resort to a graphical solution, e.g. with the Moody Diagram (see Fig. 7), which also includes the laminar flow case.

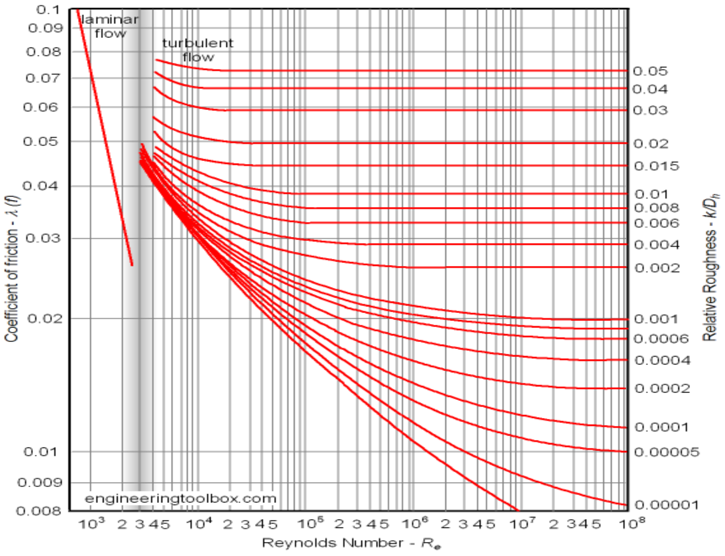


Figure 7. The Moody Diagram.

Source: http://www.engineeringtoolbox.com/moody-diagram-d_618.html

From the diagram (knowing R_e and the relation k/D) we may obtain f, and from f we may obtain the head loss J using the Darcy-Weisbach equation rewritten as follows:

$$J = \frac{LU^{2f}}{D_i 2g} \tag{11}$$

where:

g – gravity acceleration (m/s^2)

L – pipe‘s length (m)

J – head loss (m)

U – average flow velocity (m/s)

D_i – internal diameter of the pipe (m)

The Darcy-Weisbach equation in combination with the Moody diagram are considered to be the most accurate model for estimating frictional head loss in a steady pipe flow. However, as neither the trial-and-error calculation nor the graphical procedure are not so practical for rapid and frequently repeated calculations, an alternative empirical head loss calculations, like the one based on the Hazen-Williams equation given below, may be preferred.

The Hazen-Williams empirical equation reads:

$$j = 1.212\exp(10)(\frac{Q_l}{C_w})^{1.852} D_i{}^{-4.87} \tag{12}$$

where:

j - loss of energy per meter of pipe (m / m);

C_w - Hazen-Williams coeficient, which is about 150 L/s for P.V.C plastic pipes;

Q_l - flow rate (L / s);

D_i - internal diameter of the pipe (mm);

The head loss for the total pipe length is:

$$\varDelta H_{dist} = jL \tag{13}$$

where:

L - total pipe length (m);

ΔH_{dist} - total distributed energy loss (m)

The system's required head is computed as follows:

$$H_t = J + h + P_o \tag{14}$$

where:

H_t – total head lift (m)

h - terrain elevation (m)

p_o – pressure head required by the outlet in order to work properly (m) with:

$J = 1.1\Delta H_{dist}$ *

* assuming 10% of localized losses (connections, filters, curves, etc)

Christiansen, 1942 has simplificated the estimation of energy losses along pipes with more tan one outlet, i.e, drip line or sprinkler laterals by adopting a friction reduction factor due to flow reduction along lines with several outlets

This information is then used to calculate the pump's required power *P* as follows:

$$P = \frac{\gamma . Q_l . H_t}{\eta} \tag{15}$$

where

P – power (W)

η – pump‘s efficiency (-)

Q_l – flow rate (m^3 s^{-1})

H_t – total head lift (m)

γ –specific weight of water (N m^{-3})

2.4 Fertigation

2.4.1. Fertigation principles

The adoption of trickle irrigation methods with only partial wetting of soil surface brought about the concomitant transition in restricting crop root system distribution mainly to the wetted zone. These limited root systems considerably modify classical fertilization management. The shift from a broadcast fertilizer application to banded fertilization or to fertilizer added to the irrigation water was developed in order to meet the nutrient needs of the trickle-irrigated crop. Chronologically, fertigation was an outcome of the localized irrigation. (Kafkafi and Tarchitzky, 2011)

When injecting a fertilizer into the irrigation water, a nutritive solution is generated. The chemical properties of this nutritive solution (such as pH, EC and ionic content) depend on many factors, such as the characteristics of the raw water used and the injection rates of different fertilizers.

The following figure exemplifies the principle of nutritive solution injection into the main irrigation pipe, resorting to a Venturi injector as a part of the system.

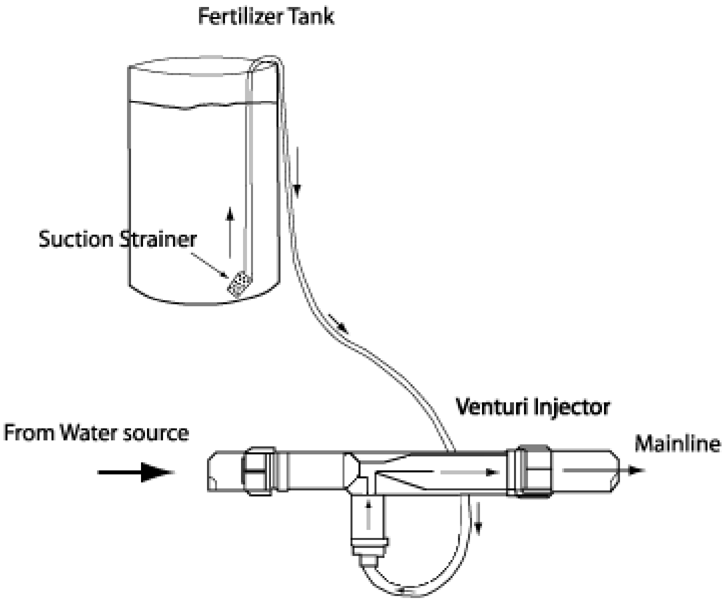


Figure 8. Venturi fertigation injection system

Source: http://ghadvisor.blogspot.com/2008/11/fertilizer-calculations-proportioners.html

Following the Bernoulli theorem (Daniel Bernoulli entry in Encyclopaedia Britannica, 2012), the Venturi effect can be easily explained: Reducing the pipe section, we increase the velocity of the flow as well as its kinetic energy, thus inducing the decrease of hydrostatic pressure in order to maintain the total energy unchanged. When the pressure decreases, the suction effect is produced in the narrower section of the venture pipe.

According to the Law of the Minimum formulated by Liebig (1840), there is only one combination among the infinite number of possible combinations of fertilizers and injection rates into the system that will generate the right pH, EC, [K^+], [Mg^{++}], [NO_3^-], sodicity etc. and maximize the use of all constituents the nutritive solution for one specific crop at one specific development stage.

It is difficult to control nutritive relations in the fertigation solution. For example, if any nutritive acid (such as nitric or phosphoric acid) is added into the fertigation solution in order to correct the water pH, then it might unbalance the contents of nitric or phosphoric ions. If one adds magnesium sulfate in order to correct the magnesium content, then one might automatically exceed the sulfur optimum level (e.g., because potassium sulfate, which also provides sulfur, might have already been added previously in order to correct the potassium level).

Another problem that arises when designing irrigation plans is how to create an irrigation system which, depending on the soil type, crop and weather data, will efficiently apply this optimized water nutritive solution to the crop, providing it with optimal conditions for grow, maximizing good quality food production with minimal input of water and other production factors. Thirdly, there may be a conflict between water requirements and nutrient requirements of the crop. Raw water without nutritive amendment may be supplied by irrigation when there the soil is rich enough in nutrients or, vice versa, it may be desirable to supply nutritive solution to the plants even if they have enough water, e.g., after natural rain. It is still a handicap of DSS-FS to quantify with considerable accuracy the contribution of the soil on the enrichment or impoverishment of the nutritive solution after fertigation application. This makes DSS-FS so far to be more adequate to be used in soils with low Cation Exchange Capacity (CEC).

Just needs to be mentioned that, at the moment this thesis was written, we were working on a way of solving this problem. The progress on this topic has been presented in chapter 3.1.2 of this manuscript.

2.4.2 The nutritive solution

The Hoagland solution is a hydroponic nutrient solution that was developed by Hoagland and Snyder (1933) and is one of the most popular solution compositions for growing plants. The original composition of the solution as proposed by Hoagland and Snyder in 1933 has been modified several times (mainly by adding iron chelates and the like), but the original concentrations for each element as shown below are still used as a general reference in many fertigation systems.

Table 4. Ideal concentration of nutritive elements according to Hoagland and Snyder (1933)

Element	**ppm**	**element/Molybdenum ratio**
N	210	21000
K	235	23500
Ca	200	20000
P	31	3100
S	65	6500
Mg	48	4800
B	0.5	50
Fe	2	200
Mn	0.5	50
Zn	0.05	5
Cu	0.02	2
Mo	0.01	1

The values in Tab. 4 were optimized for tomato and pepper growth (Hoagland and Snyder, 1933). They might be adjusted to fulfill specific requirements of other crops according to their uptake tables. Different authors propose different uptake tables even for the same crop (e.g., tomato), as we can see in Table 5.

Table 5. Tomato nutrient uptake tables according to several authors (Vivancos, 1993)

Author	Target production (ton/ha)	N (kg/ton of product)	P (kg/ton of product)	K (kg/ton of product)
Pérez Melián	120	3.66	4.46	5.8
A. Jacob	40	2.75	0.75	4.0
Besford	80	3.41	0.86	7.53
Serrano	40	2.75	0.63	3.75
Horta	50	5.0	1.60	5.40
Horta	100	3.6	1.2	7.0

Table 6. Crop tolerance limits in terms of pH* and soil solution electrical conductivity EC (Vivancos, 1993)

Crop	min pH	max pH	max soil solution EC_s* (mS/cm)
Tomato	5.0	7.2	4
Lettuce	5.8	8.0	4
Cabbage	5.2	8.0	4
Cucumber	5.5	7.5	4
Vine	5.0	7.3	6
Oats	4.8	7.0	6
Wheat	4.8	7.0	6
Corn	4.8	7.0	6

* measured; using water saturated paste extract.

2.4.3 Crop response to the chemical features of the nutritive solution

Salinity

The crop response to salinity has been extensively investigated over the last few decades (Fig. 9). Empirical observations highlight that the increase in soil salinity (in terms of the saturated paste extract electrical conductivity EC_e) reduces the relative yield (Y_{rel}). The sensitivity of most crops to salinity has been established by relating the increase in salinity to the yield decrease (Maas and Hoffman, 1977; Ayers and Westcot, 1985). This method was also used to classify the salt tolerant and the salt sensitive species at any latitude and in any pedo-climatic conditions (Shalhevet, 1994).

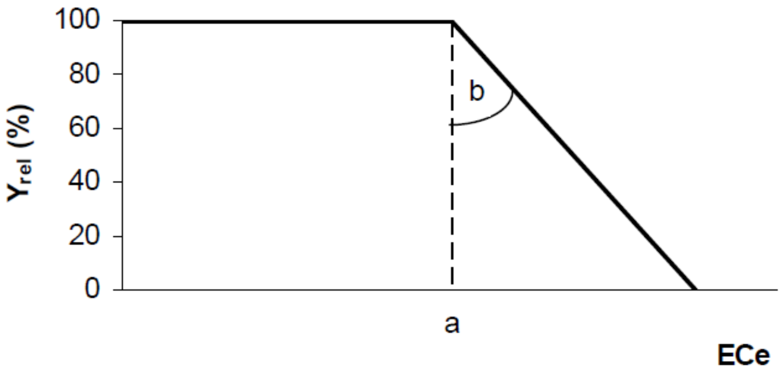


Figure 9. General relationship of relative yield Yrel (%) to salinity, according to Maas and Hoffman equation (1977)

The relation between salinity and relative yield can be expressed by the Maas and Hoffman (1977) equation:

$$Y_{rel} = 100 - b_y\,(EC_e - a_y) \qquad (16)$$

where

a_y - salinity tolerance treshold in terms of the electrical conductivity of the soil saturation extract

EC_e - EC beyond which a reduction in yield with respect to non saline conditions starts

b_y – rate of decrease in Y_{rel} per unit increase of EC_e.

_p[H]_ – value

Considering the nutritive solution as a buffer solution, we can calculate its *pH* after calculating all the species available in the equilibrium, based on the Henderson-Hasselbach equation as described by de Levie (2003):

$$P[H] = pK_a + log\,\frac{[A^-]}{[HA]} \tag{17}$$

where

p[H] - the negative logarithm (base 10) of the molar concentration of dissolved H_3O^+ [-]

$[A^-]$, $[HA]$ - the molar concentrations of the conjugate base and the its respective acid [mol L^{-1}]

pK_a - the negative logarithm (base 10) of K_a, where K_a is the acid dissociation constant [-]

pH defined in terms of activity (measurable by a suitable electrode) is slightly different than *p[H]* defined in terms of concentration. The value of *pH* or *p[H]* is a criterion allowing us to judge whether or not a nutritive solution is suitable for fertigation of a given crop.

Sodicity index (*SAR*)

According to Bohn et al. (1979) and Jurinak (1990), the sodium adsorption ratio (*SAR*) of soil aqueous extracts is a principal tool for diagnosing sodic soils. Hence, the nutritive solution shall also be analyzed according to this indicator, which is defined as:

$$SAR = \frac{[Na^{+}]}{[Ca^{2+}+Mg^{2+}]^{0.5}} \qquad (18)$$

where

$[Na^{+}]$, $[Ca^{2+} + Mg^{2+}]$ - the respective cations concentrations [mmol L^{-1}]

In table 7 is possible to observe some of the SAR limits and their relation to potential problems.

Table 7. SAR limits in irrigation water

Potential Irrigation Problem	**Units**	**Degree of Restriction on Use**		
		None	**Slight to Moderate**	**Severe**
Infiltration*(affects infiltration rate of water into the soil. Evaluate using EC_w and SAR together)*[3]	**mS/cm**			
SAR = 0 – 3 **and EC_w (EC of irrigation water)** =		> 0.7	0.7 – 0.2	< 0.2
= 3 – 6 =		> 1.2	1.2 – 0.3	< 0.3
= 6 – 12 =		> 1.9	1.9 – 0.5	< 0.5
= 12 – 20 =		> 2.9	2.9 – 1.3	< 1.3
= 20 – 40 =		> 5.0	5.0 – 2.9	< 2.9

Source: Modified from R.S. Ayers and D.W. Westcott, "Water Quality for Agricultue," Irrigation and Drainage Paper, 29, FAO, Rome, 1976; rev. 1986.

2.4.4 Water economy

Dorenbos and Kassam (1979) presented a methodology how to quantify the yield response to water through aggregate indicators, which form the "handles" to assess crop yields under both adequate and limited water supply. The method presented in part A of their publication takes into account maximum and actual crop yields as influenced by water deficits, using the yield response functions relating the relative the yield decrease to the evapotranspiration deficit. The part B of the same publication gives an account of water-related crop yield and product quality information for 26 crops. Building on this work, FAO has developed the software AQUACROP (http://www.fao.org/nr/water/infores_databases_aquacrop.html), which will be described further in this chapter.

The Stewart model, presented by Doorenbos and Kassam (1979), assumes:

$$1 - \frac{Y_a}{Y_m} = K_y(1 - \frac{ET_a}{ET_m}) \tag{19}$$

where:

$(1\text{-}y_a/y_m)$ – relative loss of production

$(1 - ET_a/ET_m)$ – relative deficit of evapotranspiration

K_y – crop sensitivity index to after shortage

y_a – actual production

y_m – potential production

ET_a – actual evapotranspiration

ET_m – maximum (potential) evapotranspiration

The same methodology can be applied to the effect of all components and parameters of a nutritive solution, instead of just water, and explore the results.

2.4.5 Soil / Nutritive Solution Interaction

Considerable amount of work has been done on I/Q relationship of soils (Beckett, 1964; Acquaye and Maclean, 1966 ; Acquaye et al, 1967; Mengel and Kirkby, 1978; S.C. Das et al, 1980; Ranjha et al 2001)

Following Mengel and Kirkby (1978), we distinguish two nutrient fractions in the soil: The quantity (Q) represents the amount of a potential available (now adsorbed) nutrient and the intensity (I) is the anount of directly available nutrient, represented by the concentration of the soil solution.

Fig. 10, taken from Mengel and Kirkby (1978), describes the relationship between K^+ intensity (I) and K^+ quantity (Q) for two soils with different cation exchange capacity (CEC). The soil A has a high CEC and the soil B has a low one. The steepness of the curve (dQ/dI) represents the K^+ buffer power or capacity (C) of a particular soil.

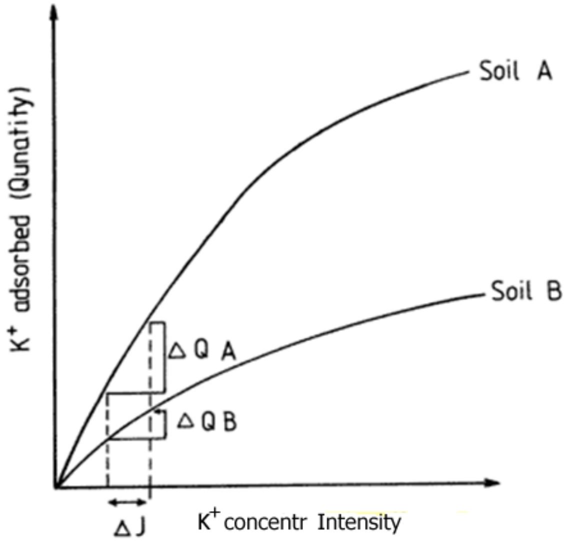


Fig 10 – Quantity to Intensity relation for potassium for two different soils (Mengel and Kirkby, 1978)

A laboratory study has been conducted by Ranjha et al (2001) to observe the effect of lime, K fertilization and soil texture on K availability, i.e. the intensity (I), quantity (Q) and buffering capacity (expressed as Q/I) in soils by using the wet and dry potassium fixation method.

The methodology described by Ranjha et al (2001) involves application of 3 levels of $CaCO_3$ (as lime) and four rates of K (as K_2SO_4) following a completely randomized design with 3 replications. The soil samples were submitted afterwards to three alternate wetting and drying cycles. After this, the samples were analyzed for water soluble K, Ca + Mg and ammonium acetate - extractable K. The analyses were done according to the methods described by U.S Salinity Lab Staff (1954) and Moodie et al. (1959).

The intensity was calculated as an activity ratio by using the expression $\frac{aK}{(aCa+aMg)^{1/2}}$

The activity coefficients of K and Ca + Mg were determined by applying the Debye–Hückel 2nd approximation. Quantity (Q) was calculated by subtracting the water soluble K from the ammonium acetate extractable K. The potassium buffering capacity (PBC) was calculated by the formula PBC = Q/I. Data were statistically analyzed according to the completely randomized design (Steel and Torrie, 1980).

The effects of texture, $CaCO_3$ application and K fertilization on K intensity, K quantity and K buffer capacity were then determined.

Table 8 shows the determined values of Q, I and PBC according to the methodologie mentioned above and related to 3 soil textures

Table 8. Q,I and PBC in 3 different soil textures

Soil series	**Quantity (mmol/kg)**	**Intensity (mmol/kg)**	**Buffering Capacity**
Kotli (fine)	5.292	3.506	152.294
Pindorian (medium)	2.500	3.983	40.745
Wazirabad (coarse)	1.404	6.917	19.511

According to results in table.. the quantity of K increased but the intensity decreased by increasing clay contents

The electro-ultrafiltration technique also provides an avenue for simultaneous measurement of the intensity, quantity, and buffer capacity (Nemeth, 1979) to give indications of the adsorption of nutrient ions on the soil colloids. Anderson and Wu (2001) obtained phosphorus quantity-intensity relationships. Fig. 2 shows the Q/I relationship describing a phosphorus adsorption isotherm after a fertilization treatment (200 kg N + 32 kg P + 160 kg K per ha). This treatment is further on referred to as FERT. Fig. 11 relates the adsorbed phosphorus (P_{ads}) to the phosphorus in solution (P_{sol}).

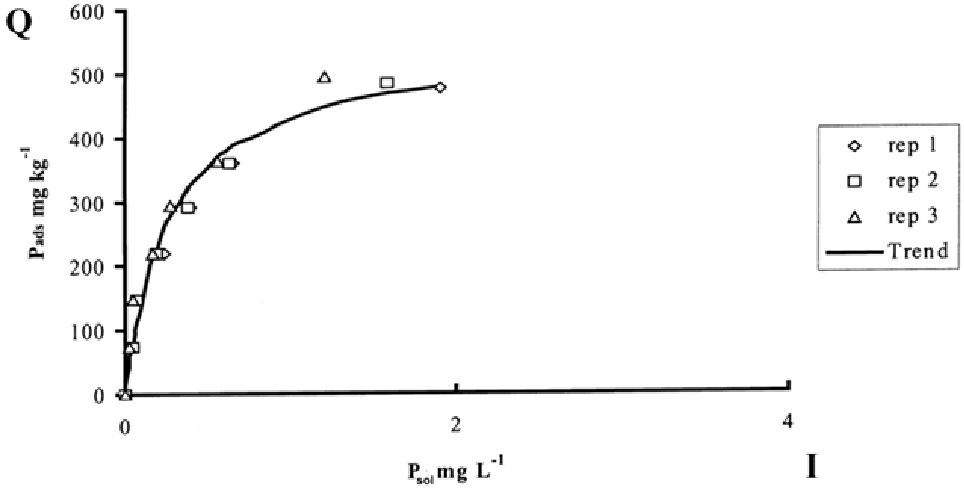


Fig 11 - Phosphorus adsorption isotherm for the FERT treatment (Anderson and Wu, 2001) with 3 replications.

The curve relating I to Q (notwithstanding the mildly non-isothermal conditions in the soil) can be described in both cases discussed above (for potassium and phosphorus) by the Freundlich adsorption isotherm:

$$Q = k.I^{\beta} \tag{20}$$

where:

k and β – empirical constants

Q – quantity [mg/Kg]

I – intensity [mg/L]

With the choice of convenient parameters, the measured Q/I realtion might also fit to the Langmuir adsorption isotherm:

$$Q = \frac{k.I}{1+\eta.I} \qquad (21)$$

where:

k and η – empirical constants
Q – quantity [mg/Kg]

I – intensity [mg/L]

Another known adsorption isotherm which might fit this purpose is the Freundlich adsorption isotherm:

$$Q = k.I^{\beta} \qquad (22)$$

where k, η and β are empirical constants, the units of which depend on the formula used.

One can also use a simple linear or a square-root adsorption isotherm as detailed in Chapter 3

2.5 Other existing models

2.5.1 SIGIRA

Teixeira (1995) developed a model SIGIRA which works with satisfactory results for sprinkler irrigation. It is a water manager with no references to fertigation.

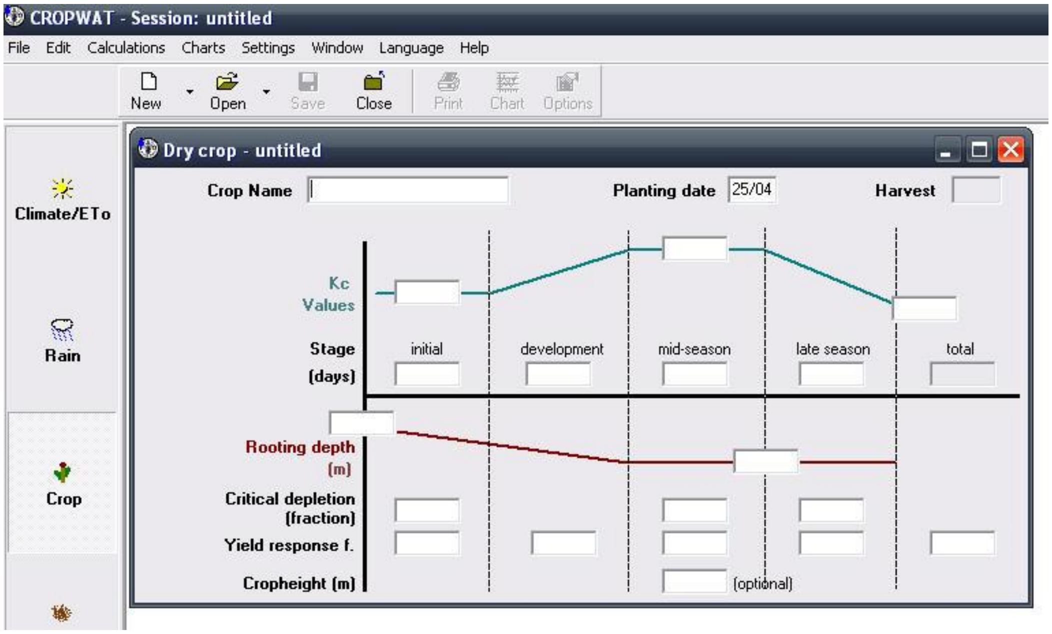
The objective of the SIGIRA project was to create an integrating system that would contribute to better management of irrigation water both at the level of irrigation project and at the on-farm level in the Alentejo region, Southern Portugal, which does not have a tradition in irrigated farming. Teixeira's paper cited above presents an Irrigation Scheduling Service that is a part of the mentioned SIGIRA project. The system has four main components: WWW engine, database, GIS, and computer models, which, as a whole, provide a decision support system for farmers and managers. The system is accessed through a common browser and a low-bandwidth connection to the Internet. Farmers can define their own irrigation systems and enter irrigation data as time goes. The system provides guidance through graphics of soil water content, irrigation management indicators and irrigation advice. The system makes use of a simulation model that estimates the water content in the soil using a simplified reservoir water balance. However, this model does not include drip irrigation scenarios. It is also very incomplete in what concerns transpiration reduction when the plants experience hydric stress. The bare soil evaporation, when the crops do not cover the whole field (the crops in rows, like vineyards), is not considered, either. The model does not consider transpiration reduction due to salinized water.

Bar-Yosef et al. (1999) describe good examples of fertigation solutions and theoretical principles of fertigation. However, in reality the way the chemical parameters of water change by adding soluble fertilizers depend on the source water chemical features. Applying the same recipe to different kinds of raw water may result in completely different nutritive solutions, as pH, salinity-EC and even the nutritive balance may vary, depending on the raw water chemical features. That is why a simulator considering the raw water analysis and simulating fertilizer addition into raw waters of different properties might be needed. An ideal simulator should also analyse the productive potential of the simulated solution (making suggestions on the chemical features observed, allowing changes and improving the results). These aspects were not treated by Bar-Yosef et al. (1999).

2.5.2 CROPWAT

Smith et al. (2000) developed a complex model of what concerns the sprinkler irrigation management - CROPWAT. However, the user's interface is very complicated. A more user-friendly system that would train its users while being used, might be of particular interest to non academics, such as farmers. The CROPWAT system does not provide good support for intervals shorter than 30 days; it rather assumes averages for long term periods. Thus it does not provide enough tools for avoiding management failures, as the irrigation management in dry warm regions and on shallow soils (or crops with shallow root systems) requires several irrigation applications every week.

CROPWAT (see Fig. 12) does not include either drip irrigation or fertigation features.



Planting date 25/04

Figure 12. CROPWAT interface. Smith et al. (2000)

2.5.3 RELREG

The RELREG model is a Windows application to manage irrigation in real time, resorting to the information on soil water content collected by soil sensors and crossing it with soil water retention parameters in order to obtain soil hydric balance and estimate irrigation requirements (Teixeira et al., 1995).

Fortes, Pereira, and Platonov introduced in 2005 the GISAREG model which incorporated geographic information systems into the RELREG model (Teixeira et al., 1995), thereby improving the visuals and graphics and providing a good GIS support (see Fig. 13). However, neither the fertigation features nor the drip irrigation scenarios are included.

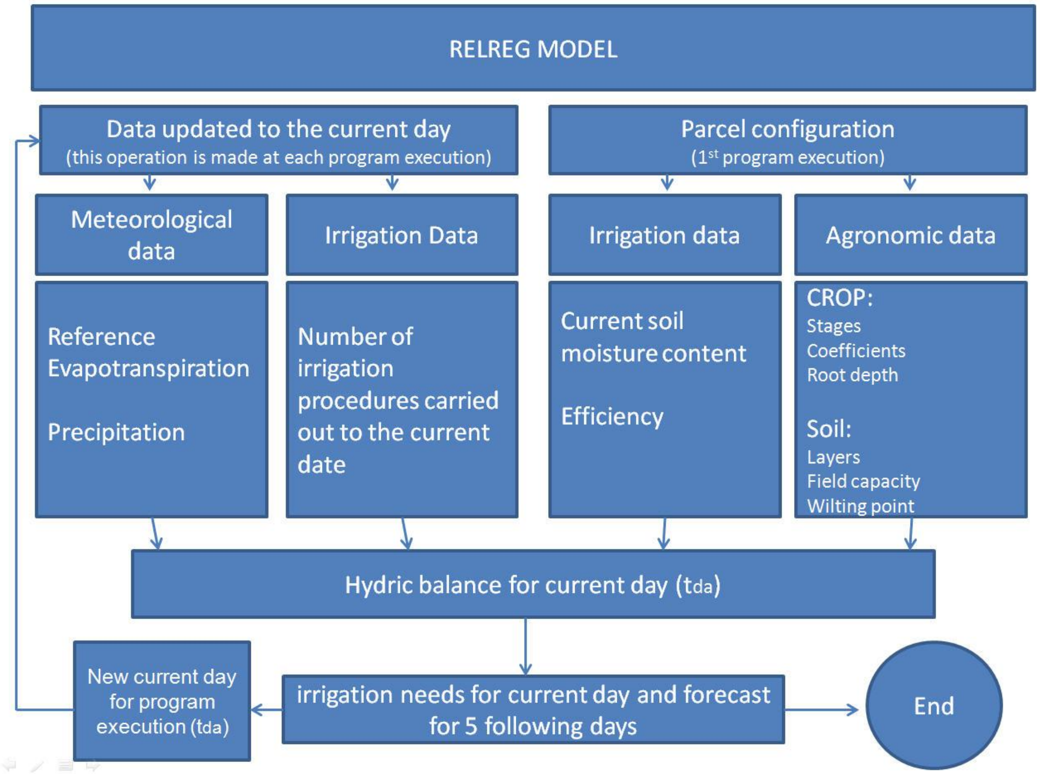


Figure 13. Flowchart of RELREG model. Teixeira et al. (1995).

2.5.4 AQUACROP

AquaCrop is a crop water productivity model developed by the Land and Water Division of FAO. It simulates the yield response to water of herbaceous crops and is particularly suited to address conditions where water is a key limiting factor in crop production.

AquaCrop is mainly intended for practitioners such as those working for extension services, governmental agencies, NGOs, and various kinds of farmers associations. It is also of interest to scientists and for teaching purposes as a training and education tool related to the role of water in determining crop productivity.

Being based on the crop sensitivity index *Ky* (Dorenbos and Kassam, 1979) approach, AquaCrop is water-driven, meaning that the crop growth and production are determined by the amount of water transpired. However, AquaCrop focuses on the fundamental relation between biomass and water transpired rather than yield and evapotranspiration, relying on the conservative behaviour of water productivity (WP). A schematic representation of these steps is reported in the figure below.

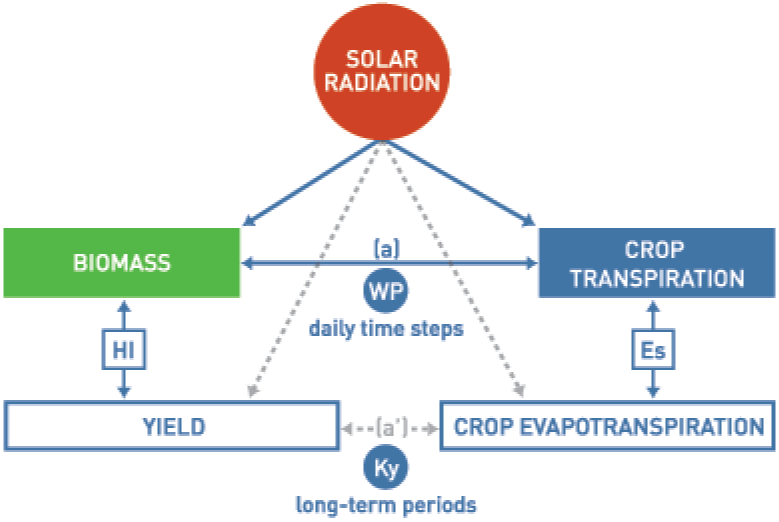


Figure 14. AquaCrop Schematic representation,. where HI represents the harvest index and Es the soil evaporation with the dash lines indicating feedback and continuous lines as direct links. The remaining symbols have been explained before.

Source: http://www.fao.org/nr/water/infores_databases_aquacrop.html

AquaCrop includes the following sub-model components: the soil, with its water balance; the crop, with its development, growth and yield; the atmosphere, with its radiation and thermal regime, rainfall, evaporative demand and CO_2 concentration; and the management, which includes major agronomic practices such as irrigation and fertilization. AquaCrop flowchart is shown in fig. 15

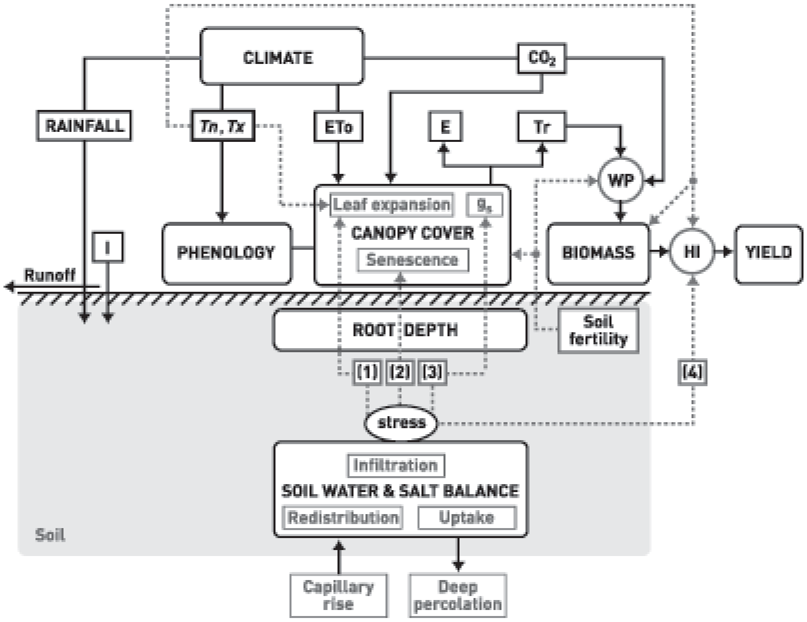


Figure 15. AquaCrop flow chart

Source: http://www.fao.org/nr/water/infores_databases_aquacrop.html

Figure 15 indicates the main components of the soil-plant-atmosphere continuum and the parameters driving phenology, canopy cover, transpiration, biomass production, and final Yield. [*I*, irrigation; T_n, minimum air temperature; T_x, maximum air temperature; ET_o, reference evapotranspiration; *E*, soil evaporation; T_r, canopy transpiration; *gs*, stomatal conductance; *WP*, water productivity; *HI*, harvest index; CO_2, atmospheric carbon dioxide concentration]. Continuous lines indicate direct links between variables and processes. Dashed lines indicate feedbacks.

2.5.5 FertOrgaNic

In the FertOrgaNic EU project and in some parallel projects (Zavadil et al., 2004; Doležal et al., 2005; Heidmann et al., 2008; Battilani et al., 2008a,b,c; www.fertorganic.org), field experiments with drip irrigation and fertigation were carried out at six different sites across Europe, involving seven different varieties of potato. As a result, a FertOrgaNic-DSS was produced and verified, allowing optimizing water and nitrogen use. FertOrgaNic (Fig. 16) has 3 user profiles and output levels. In a basic mode it offers only a weekly fertigation schema based on static strategy calculated from simple forecasted values of crop yield and nutrient uptake and rough empirical estimate of soil nutrient release. The static output level is focused on those technicians that could have direct access to daily meteorological data but don't have a complete feedback from the growers. Irrigation is managed applying a dynamic strategy while fertigation remain on a forecast basis. Using the dynamic output level, a daily feedback to the DSS is required. For this level of input, both irrigation and fertigation are calculated daily by means of plant growth models.

Figure 16 FertOrgaNic model (user interface)

Source: http://www.fertorganic.org/FertOrgaNic.asp

The Daisy model (see Fig 17), which simulates plant growth together with water and nitrogen dynamics, was also used to simulate and extrapolate these field experiments. This work can be extended to crops other than potato and nutrients other than nitrogen, such as phosphorus, magnesium, potassium, sulphur and microelements in organic or inorganic forms.

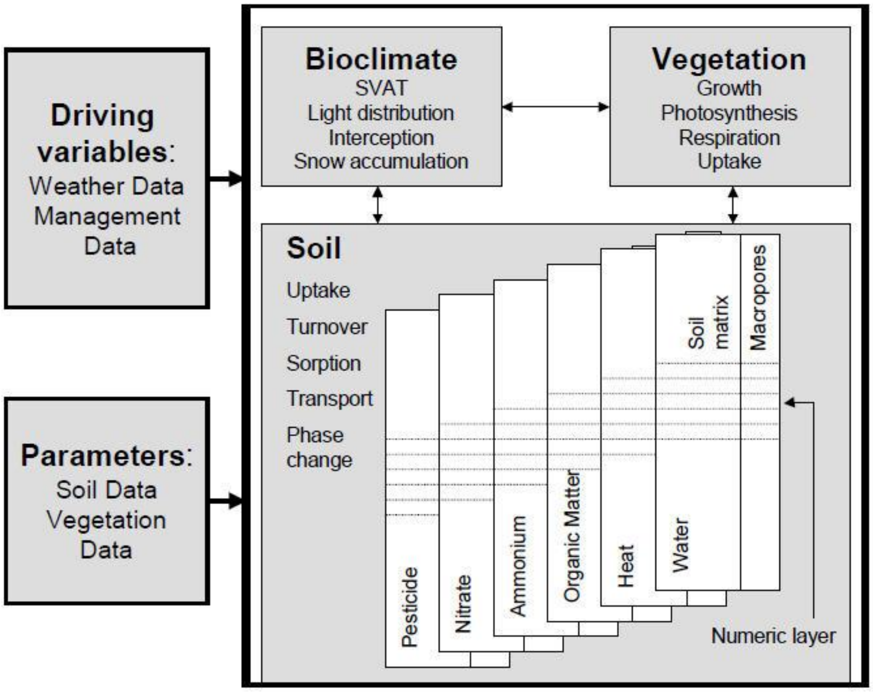
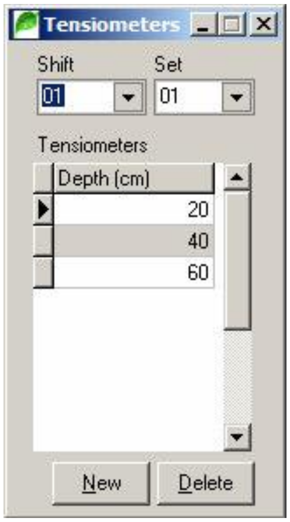


Figure 17. Schematic representation of the agro-ecosystem model Daisy. (Hansen et al., 1991)

2.5.6 FertiNet

FERTINET was developed by NETAFIM Company as an auxiliary tool for irrigation & fertigation management in trickle-irrigated crops. It is a computer program which aims to simplify the necessary calculations like the recommended irrigation cycle time & volume, the fertigation program, the quantity and types of fertilizers needed and specific injection recommendations.

It doesn’t include plant uptake tables database, basing its calculation procedures on real time foliar analysis. The volumes of irrigation and its intervals depend on the readings of existing instruments such as tensiometers, TDR probes, etc (see fig. 18).



Shift: 01
Set: 01

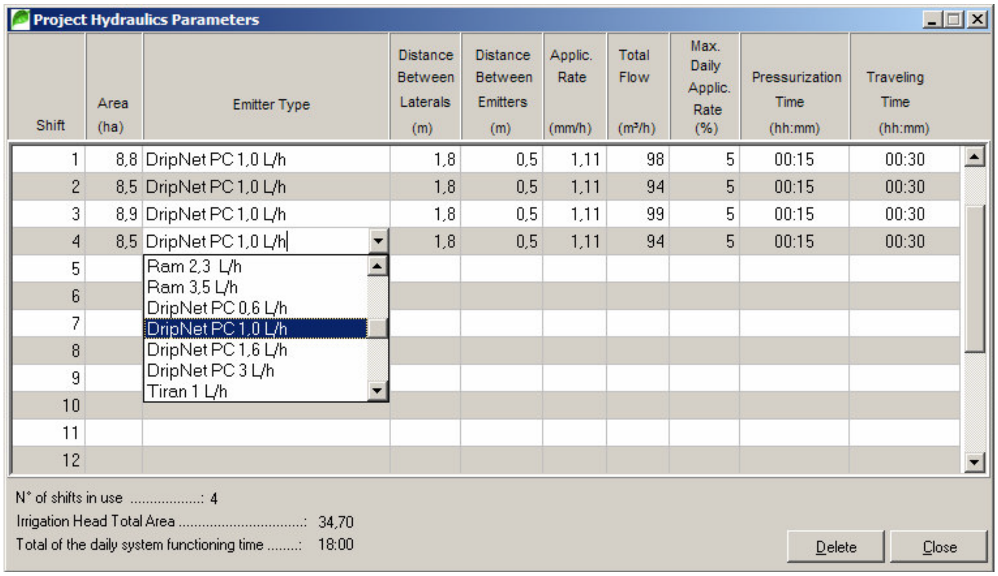
Tensiometers

Depth (cm)
20
40
60

Figure 18. Fertinet tensiometers set interface.

Source: NETAFIM

FERTINET is a project focused on the design of fertigation systems composed of existing products as supplied by NETAFIM Company (see fig. 17)



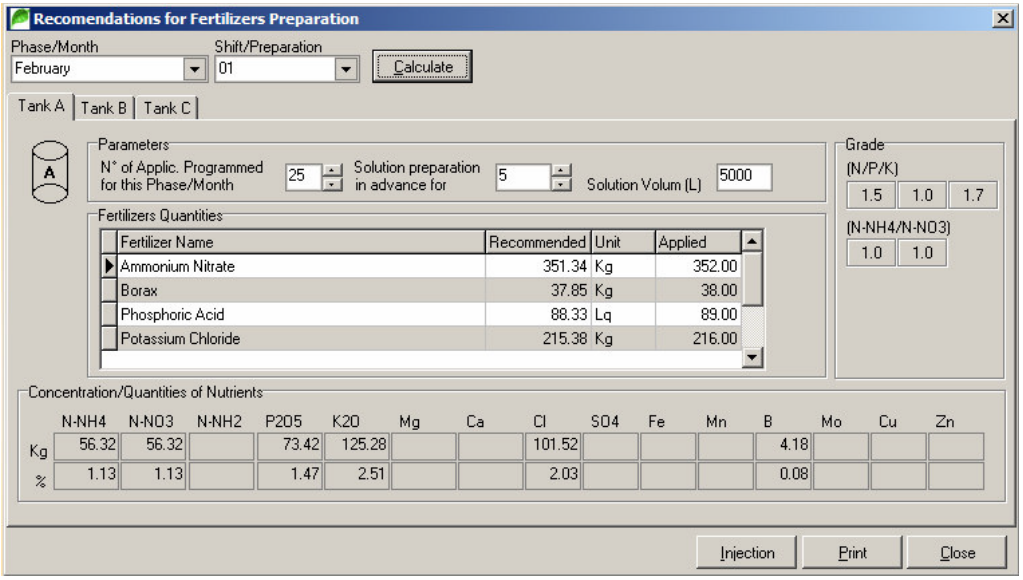
Shift	Area (ha)	Emitter Type	Distance Between Laterals (m)	Distance Between Emitters (m)	Applic. Rate (mm/h)	Total Flow (m^3/h)	Max. Daily Applic. Rate (%)	Pressurization Time (hh:mm)	Traveling Time (hh:mm)
1	8,8	DripNet PC 1,0 L/h	1,8	0,5	1,11	98	5	00:15	00:30
2	8,5	DripNet PC 1,0 L/h	1,8	0,5	1,11	94	5	00:15	00:30
3	8,9	DripNet PC 1,0 L/h	1,8	0,5	1,11	99	5	00:15	00:30
4	8,5	DripNet PC 1,0 L/h	1,8	0,5	1,11	94	5	00:15	00:30
5									
6									
7									
8									
9									
10									
11									
12									

N° of shifts in use ....: 4
Irrigation Head Total Area ....: 34,70
Total of the daily system functioning time ....: 18:00

Figure 19. FERTINET interface showing emitters by reference.

Source: NETAFIM

This software also brings a tool to convert the information on injected fertilizers and injection rates into the final nutrient availability in the nutritive solution (see fig. 19)



Phase/Month: February
Shift/Preparation: 01

Parameters
N° of Applic. Programmed for this Phase/Month: 25
Solution preparation in advance for: 5
Solution Volum (L): 5000

Grade
(N/P/K): 1.5 1.0 1.7
(N-NH4/N-NO3): 1.0 1.0

Fertilizers Quantities

Fertilizer Name	Recommended	Unit	Applied
Ammonium Nitrate	351.34	Kg	352.00
Borax	37.85	Kg	38.00
Phosphoric Acid	88.33	Lq	89.00
Potassium Chloride	215.38	Kg	216.00

Concentration/Quantities of Nutrients

	N-NH4	N-NO3	N-NH2	P205	K20	Mg	Ca	Cl	S04	Fe	Mn	B	Mo	Cu	Zn
Kg	56.32	56.32		73.42	125.28			101.52				4.18			
%	1.13	1.13		1.47	2.51			2.03				0.08			

Figure 20. Fertigation interface for FERTINET

Source: http://www.fertinet.com.br/en/index.htm

2.5.7 DSIRR

The Decision Support System for Irrigation DSIRR (Bazzani, 2004) is a DSS for the economic-environmental assessment of agricultural activity focusing on irrigation, designed to answer both public and private needs. The program simulates the economically driven decision processes of farmers, permitting an accurate description of production and irrigation in terms of technology and agronomics. Distinct farm models can be constructed to describe the relevant production systems in the catchment. Short and long term analyses can be conducted, the latter with endogenous investment choices. Solutions are found by applying multicriterial mathematical programming techniques. Farm models run under a graphical interface, which allows the user to quantify, by farm type, the utilization of water, labor and machinery, considering different types of soils, irrigation systems, water-yield functions and seasonality. Data are aggregated at the catchment scale. Richness of information produced, flexibility and simplicity of use make DSIRR a useful tool for more sustainable agriculture and the definition of a sound water policy.

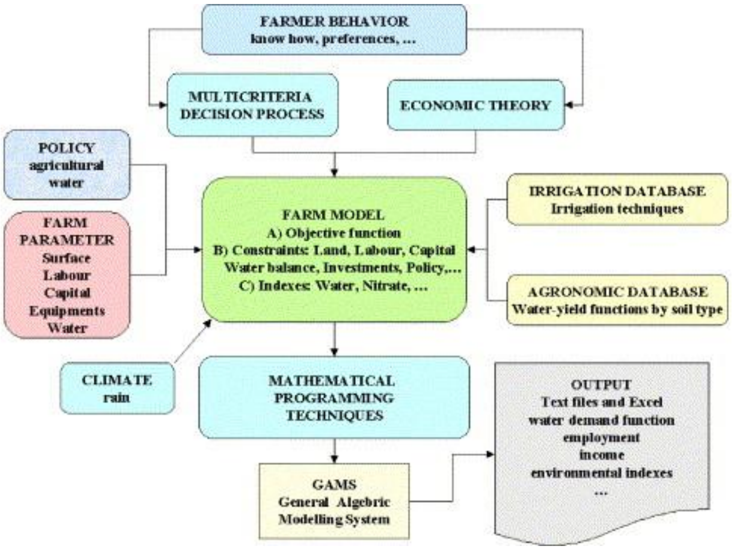


Figure 21 DSIRR flow chart (Bazzani, 2004) .

2.6 Experimental Research

Numerous experiments all over the world have proved the advantages of adequately scheduled fertigation over other management options. This section mentions only few typical studies in order to illustrate the matter. A reader is referred to overviews such as those published by Magen (1995) or Kafkafi and Tarchitzky (2011). Hebbar et al (2003) conducted a field experiment during the summer seasons of 1999–2000 and 2000–2001 at the Main Research Station, University of Agricultural Sciences, Hebbal, Bangalore, to study the effect of fertigation from different sources of nutrients at different levels and methods of fertilizer application on growth, yield and fertilizer use efficiency of hybrid tomato in red sandy loam soil. There were eight treatments including furrow-irrigated and drip-irrigated controls, all replicated three times. The investigations revealed that the total dry matter (TDM) production and the leaf area index (LAI) were significantly higher under drip irrigation (165.8 g and 3.12, respectively) than under furrow irrigation (140.2 g and 2.25, respectively). Water-soluble fertilizer (WSF) fertigation treatment recorded significantly higher total dry matter and LAI (181.9 g and 3.69, respectively) than the drip irrigation control without fertigation. Chlorophyll concentration was significantly higher in fertigation treatments than in the treatments wher the fertilizers were applied on the soil at 90 days after transplanting. The fruit yield of tomato was by 19.9% higher under drip irrigation (71.9 Mg ha^{-1}) than under furrow irrigation (59.50 Mg ha^{-1}). Fertigation with 100% WSF increased the fruit yield significantly (up to 79.2 Mg ha^{-1}) over bothe the furrow-irrigated and the drip irrigation control. Subsurface drip fertigation (76.55 Mg ha^{-1}), nitrogen–potassium fertigation (76.57 Mg ha^{-1}) and 1/2 soil–1/2 fertigation (76.51 Mg ha^{-1}) gave fruit yields similar to the WSF fertigation treatment. Significant yield reduction was recorded with 75% rate fertigation (72.7 Mg ha^{-1}) and 100% rate fertigation (73.27 Mg ha^{-1}), compared to WSF fertigation. WSF fertigation recorded significantly higher number of fruits per plant (56.9) and fertilizer-use efficiency (226.48 kg yield kg^{-1} NPK) compared to drip- and furrow-irrigated controls. Fertigation resulted in less leaching of NO_3-N and K to the deeper layer of the soil. Subsurface drip fertigation caused higher assimilable P content in the deeper soil layer. Root growth and NPK uptake was increased by WSF fertigation.

Zavadil (2007) studied the optimisation of threshold pressure head of soil water on light soils for early potatoes, early cabbage, late cauliflower and celery in a small-plot field experiment with differentiated irrigation regimes. For comparison, the seasonal and individual irrigation depths were determined on the basis of soil water balance, in which the crop evapotranspiration (ET_c) was calculated either according to FAO 56 or using the biological curve (BC) method, based on the water vapour saturation deficit data and on coefficients obtained by local experimentation. The method of biological curve Sláma (1969) is based on the balance of soil moisture according to potential evapotranspiration determined as the product of the sum of actual vapour pressures over the balance period and the coefficient of biological curve. These irrigation depths were substantially different from the really achieved irrigation depths in the treatments where the optimal soil water suction head was maintained based on sensors. For potatoes, the really achieved values of seasonal irrigation depths were nearer to the depths calculated by the BC method, while for the other vegetables (cauliflower, cabbage and celery) they were more similar to the depths calculated by FAO 56 methodology.

Singandhupe, et al (2002) tested the response to urea fertilizer using drip and furrow irrigation systems. The nitrogen supply was provided through 10 equal splits of urea application injected into the irrigation system during the vegetative cycle.

In Fig. 22 we can appreciate the results of different levels of nitrogen applied through irrigation and compare thelevel of nutrient applied to the level of nutrient uptaken. Also it is possible to relate the yield to the level of nutrient applied.

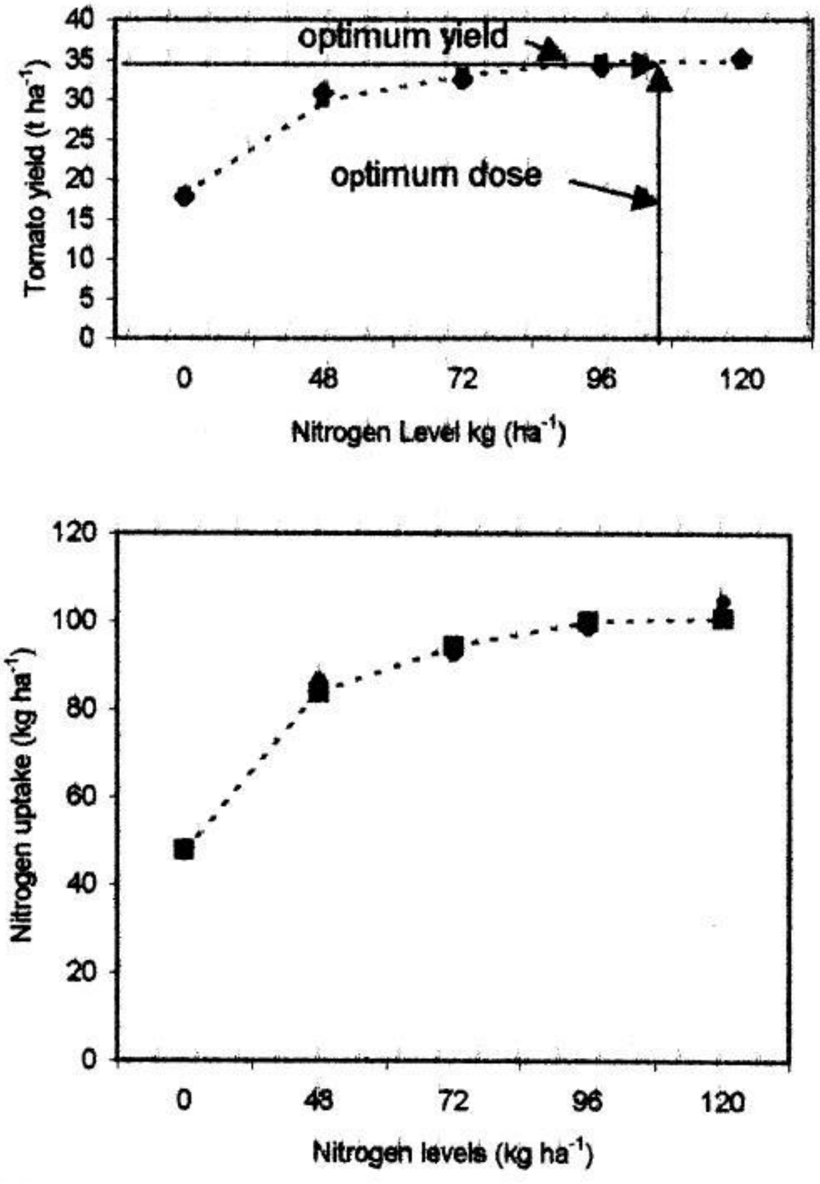


Figure 22. Nitrogen uptake versus nitrogen applied (Singandhupe, et al., 2002)

Andriolo et al. (2009) aimed to compare growth and fruit yield of strawberry plants grown in a closed substrate soilless system under three fertigation methods. The experiment was carried out at the Fitotecnia Department of the Federal University of Santa Maria (Brazil) between May 14th and November 16th, 2007, in a bifactorial 3 x 2 randomised split-plot design with three replications. The growing bed was an organic substrate Plantmax XT®. The control (T1) was a complete nutrient solution (with all necessary nutrients for plant growth included). In T2, the potential uptake amounts of P, K, Ca and Mg were estimated and added to the substrate before planting. Nitrogen was supplied by fertigation during the cropping period. In T3, the quantities of nutrients estimated for T2 were split into fortnight doses and delivered by fertigation, using the same fertilizers employed in the complete nutrient solution. The fruit number and yield over the whole cropping period and the vegetative dry matter at the end of the experiment were determined. The early and total fruit yields were lower in T2. It was concluded that for both clones, the fertigation using a complete nutrient solution can reach similar fruit yield as the treatment based on supplying nutrients in fortnight doses, with a reduction in the consumption of fertilizers in comparison with the complete solution treatment.

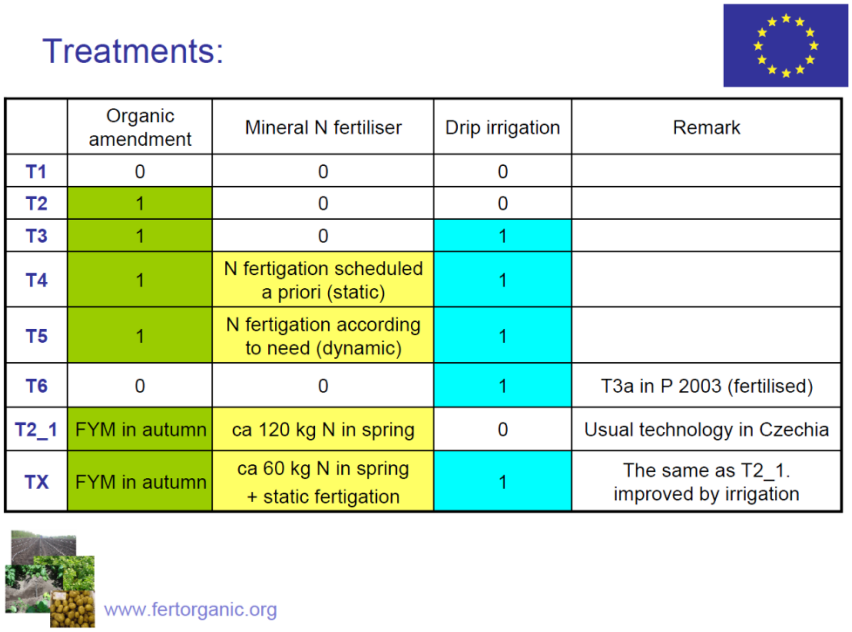
Table 9. Results of Andriolo et al. (2009)

Fertig. Method	Avg. Productivity (g/plant)
T1	427,52
T2	283,62
T3*	449,38

*higher fertilizer consumption

In table 10 we can see the 8 treatments applied within FertOrgaNic project in Europe

Table 10. FertOrgaNic treatments



Treatments:

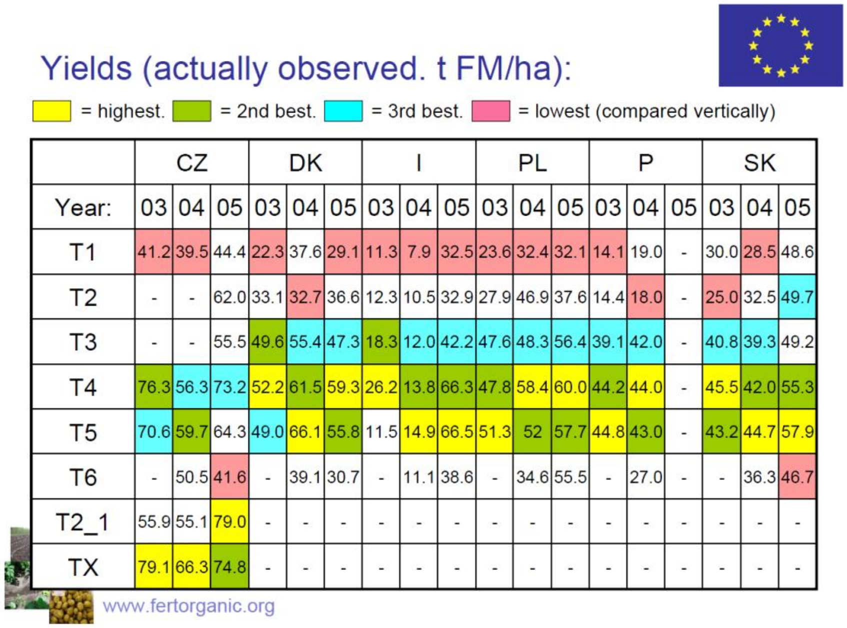
	Organic amendment	Mineral N fertiliser	Drip irrigation	Remark
T1	0	0	0	
T2	1	0	0	
T3	1	0	1	
T4	1	N fertigation scheduled a priori (static)	1	
T5	1	N fertigation according to need (dynamic)	1	
T6	0	0	1	T3a in P 2003 (fertilised)
T2_1	FYM in autumn	ca 120 kg N in spring	0	Usual technology in Czechia
TX	FYM in autumn	ca 60 kg N in spring + static fertigation	1	The same as T2_1. improved by irrigation

www.fertorganic.org

In FertOrgaNic experiments the fertigation was combined with organic manure and both irrigation and nitrogen fertigation were controlled separately, independent of each other.

In table 11 we can see some results of FertOrgaNic in 2003-2005

Table 11. FertOrgaNic results in 2003-2005



Yields (actually observed. t FM/ha):

🟨 = highest. 🟩 = 2nd best. 🟦 = 3rd best. 🟥 = lowest (compared vertically)

	CZ			DK			I			PL			P			SK		
Year:	03	04	05	03	04	05	03	04	05	03	04	05	03	04	05	03	04	05
T1	41.2	39.5	44.4	22.3	37.6	29.1	11.3	7.9	32.5	23.6	32.4	32.1	14.1	19.0	-	30.0	28.5	48.6
T2	-	-	62.0	33.1	32.7	36.6	12.3	10.5	32.9	27.9	46.9	37.6	14.4	18.0	-	25.0	32.5	49.7
T3	-	-	55.5	49.6	55.4	47.3	18.3	12.0	42.2	47.6	48.3	56.4	39.1	42.0	-	40.8	39.3	49.2
T4	76.3	56.3	73.2	52.2	61.5	59.3	26.2	13.8	66.3	47.8	58.4	60.0	44.2	44.0	-	45.5	42.0	55.3
T5	70.6	59.7	64.3	49.0	66.1	55.8	11.5	14.9	66.5	51.3	52	57.7	44.8	43.0	-	43.2	44.7	57.9
T6	-	50.5	41.6	-	39.1	30.7	-	11.1	38.6	-	34.6	55.5	-	27.0	-	-	36.3	46.7
T2_1	55.9	55.1	79.0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
TX	79.1	66.3	74.8	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

www.fertorganic.org

3 MATERIAL AND METHODS

With the primary objective of easily designing irrigation projects with locally tailored features such as hydraulics, agrometeorology, plant nutrition, chemistry and soil properties, the programming language Visual Basic 6 was used to develop a new simulator (DSS-FS) with the characteristics described in subchapter 3.1.

The optimization of fertigation in pressurized irrigation systems (namely, sprinkler and localized irrigation, such as drip) in large surface irrigation projects can be well supported by DSS tools. The aim of the DSS-FS is to assist designers and managers in the process of designing and planning farm irrigation projects. The DSS-FS includes a database, simulation models and user-friendly interfaces. It allows performance ranking and the selection of design alternatives through a multi-criteria decision process.

The optimization of the way in which data are gathered and processed in order to design and exploit irrigation systems responding to crop, soil and weather requirements (and with environmental sustainability) has been achieved in DSS-FS by integrating three main modules in a user-friendly interface which retrieves information from a simple database system. The DSS-FS analyzes the input data, producing electronic consultancy on irrigation system design and management.

The DSS-FS developed consists of three main modules available to the user:

1. Irrimanager
2. Irrisystem
3. Fertigation.

The DSS-FS application scope comprises:

(a) Field analysis: It is related to alternative design options for drip and sprinkler irrigation and permitting the consideration of number of decision variables, such as field slopes, distance between irrigation lines and emitters, crop evapotranspiration, water delivery methods and equipment and the division of fields into irrigation sectors;

(b) Crop water requirements: The DSS-FS is used to compute the reference crop evapotranspiration based on weather information, which can be adjusted afterwards according to crop coefficients and soil composition in order to obtain the actual evapotranspiration for a particular crop and a particular day (Allen et al., 1998);

(c) Nutrition requirements: Based upon soil fertility information and using crop uptake tables together with pH and EC limits, the DSS-FS is able to regulate the injection rates of several nutritive salts in the system's mother solution tanks, allowing for chemical composition of raw irrigation water.

The DSS-FS is a helpful tool in terms of searching for and analyzing modernization of irrigation design. Designing drip and sprinkler irrigation systems involves selection from a large number of combinations of main factors, which makes them easier to manipulate and rank. In addition, the DSS-FS is conceived in such a manner that the user may learn through the application process.

The possibilities of this application, once it is developed, are huge. It could be afterwards interfaced with an automated irrigation system connected to a computer in order to control it in real time and optimize all aspects of its management.

3.1 DSS-FS Modules

3.1.1 Irrimanager

Based on the FAO methodology described by Allen et al. (1998), the first module *Irrimanager* starts the process by obtaining a reference crop evapotranspiration value, which is afterwards adjusted according to the dual crop coefficient approach.

DSS-FS estimates the maximum volume of available water in the soil according to its field capacity, wilting point and root depth. According to Allen et al. (1998), the water volume that can be stored in the soil and used by the plants is referred to as the Total Available Water (*TAW*):

$$TAW = (\Theta_{fc} - \Theta_{wp})z \tag{23}$$

Where

TAW – total available water [mm]

$\theta_{f.c.}$ - soil moisture content by volume at field capacity [-]

$\theta_{w.p.}$ - soil moisture content by volume at wilting point [-]

z - roots depth [mm]

However, this concept assumes a parallelepiped parcel of soil of area A and height z homogeneously wetted by irrigation.

In fact, it is apparent that this concept might not be valid for drip irrigation conditions, where there might be dry zones between the irrigation lines which should not be included in the water balance. Therefore, a homogeneous distribution of water along the irrigation lines is assumed, but not between the lines. TAW should be the sum of the wet volumes of soil formed by the wet zones under the irrigation lines where the wet bulbs corresponding to each dripper intersect each other and form a sort of wet cylinder under and along the irrigation line. In order to estimate the volume of this wet cylinder, it is necessary to know the geometric characteristics of individual wet bulbs of which it consists.

According to Bresler (1977), Gil-Marín (2001) and Nogueira et al. (2000), the shape and size of the wet bulb can be estimated from the soil texture, emitters flow rate and duration of irrigation. Fig. 23 shows a hypothetical spherical wet bulb used in this work:

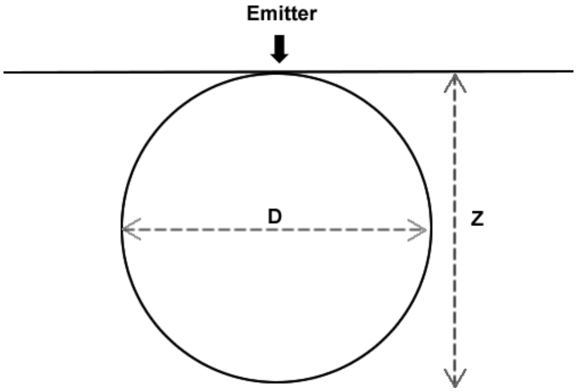


Figure 23. Hypothetical spherical wet bulb (Moreira Barradas et al., 2012)

We can estimate the volume of the corresponding wet cylinder (V_{cyl}) as follows (Moreira Barradas et al., 2012), even if the elementary wet bulbs are not spherical:

$$V_{cyl} = A_{bulb} L \tag{24}$$

where

A_{bulb} - profile area of the wet bulb [m^2]

L - the length of the irrigation line [m]

In the particular case of spherical wet bulbs, these values can be obtained as follows:

$$A_{bulb} = \pi . r^2 \tag{25}$$

$$A_{bulb} = 0.79z^2 \tag{26}$$

and thus

$$V_{cyl} = 0.79z^2 . L \tag{27}$$

More generally (Moreira Barradas et al., 2012):

:

$$V_{cyl} = c . z^2 . L \tag{28}$$

where *c* is an adjustment coefficient.

The value *z* in the equations above is the depth of the hypothetical bulb reaching the roots depth (see Fig 1). The adjustment coefficient $c = 0.79$ expresses a perfectly spherical wet bulb for a typical loam of medium/heavy texture (Moreira Barradas et al., 2012).

For coarser textures (keeping the same depth *z*) the horizontal diameter *D (see Fig. 1)* shrinks, producing a smaller volume and therefore $c < 0.79$.

Generally (Moreira Barradas et al., 2012): $c = f(z, tx, q, t)$ (29)

where

tx - a suitable indicator of soil texture [-]

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

t - duration of irrigation [s]

The total volume of wetted soil V_{adj} within an irrigated field can be calculated as:

$$V_{adj} = V_{cyl} N \tag{30}$$

where

N - total number of wet cylinders in the irrigated area considered (Moreira Barradas et al., 2012)

The adjusted total available water TAW (TAW_{adj}) is then estimated as follows:

$$TAW_{adj} = TAW \frac{V_{adj}}{V_{total}} \tag{31}$$

where

V_{total} – total volume of soil traditionally considered for estimation of TAW for the roots depth z [m^3] and the total area of the irrigated field (Moreira Barradas et al., 2012).

Despite the fact that c is an empirical adjustment factor, this methodology provides a much more flexible approach, simulating more adequately the real conditions of a drip irrigation system, in contrast to the traditional FAO procedure if the latter is applied to all scenarios without any specific adjustment.

Adjusted evapotranspiration

The way the reference crop evapotranspiration is adjusted respects the dual crop coefficient described in the FAO methodology (Allen et al., 1998), in order to estimate the crop water requirements. Details are shown in chapter 2 of this work.

3.1.2 Irrisystem

In order to calculate the optimal number of irrigation sectors, the program starts by requesting data about the spacing of drippers or sprinklers in the field, which allows the computation of the total number of outlets per hectare. According to the flow rate at each outlet, we can then obtain the ideal flow rate per hectare to feed the outlets and so allow them to work at proper pressure according to manufacturer's recommendations.

The number of irrigation hours which are required to restore the soil field capacity at any parcel P_x is estimated as following:

$$N_h = \frac{V_x}{Q_x} \tag{32}$$

where:

N_h – required time of irrigation to restore P_x to its field capacity[h]

V_x – required volume of water to restore P_x to its field capacity [m^3]

Q_x – total flow rate according to the total number of outlets (e.g. drippers) along P_x and their individual flow rates [$m^3\ h^{-1}$] (Moreira Barradas et al., 2012)

Combining this information with the irrigation interval (n in hours) obtained by the Irrimanager, we can then estimate the maximum number of sectors (each of them requiring the volume V) that can complete irrigation before the end of the irrigation interval.

Using the Hazen-Williams equation (Williams and Hazen, 1933), adjusted by the Christiansen reduction factor F (Christiansen, 1942), we can then compute the losses of energy due to friction in the irrigation lines:

$$J = 1.1 L j F_r \tag{33}$$

where

J – total losses of energy along the irrigation pipelines (including laterals and drip/sprinkler lines) [m]

F_r – Christiansen's reduction factor (F=1 in lines with only one outlet at the end of the pipe, and F_r<1 in lines with more than one outlet)

L– length of the pipeline [m]

j - losses of energy per unit length obtained by the Hazen-Williams equation [m m^{-1}]

Combining this information with the irrigation interval (n in hours) obtained by the Irrimanager, we can then estimate the maximum number of sectors that can complete irrigation before the end of the irrigation interval.

Using the Hazen-Williams equation (Williams and Hazen, 1933), adjusted by the Christiansen reduction factor F (Christiansen, 1942), we can then compute the losses of energy due to friction in the irrigation lines as described in chapter 2 and estimate the best water pump to feed the system.

3.1.3 Fertigation

The DSS-FS (fertigation simulator) starts by calculating the system's flow rate of raw water into which mother solutions with known concentrations of each species are to be injected at particular injection rates.

It is then possible to calculate the composition of the resulting nutritive solution in terms of the concentration of each species in equilibrium. The nutritive salt concentration (C_p) in the irrigation water after fertigation injection is calculated as (Moreira Barradas et al., 2012):

$$C_p = \frac{C_t I_{rate}}{F_{rate} + I_{rate}} 1000 \tag{34}$$

where:

C_p – salt concentration of the solution irrigating the field (nutritive solution) [ppm]

C_t - salt concentration in the concentrated (mother) solution in the fertigation tank [kg m^{-3}]

I_{rate} – injection rate of mother solution into the irrigation main pipe [m^3 h^{-1}]

F_{rate} – flow rate in the main pipe [m^3 h^{-1}]

The nutrient rate in each nutritive salt is obtained as follows:

$$r(e) = \frac{M(e)}{M(s)} N_s \tag{35}$$

where:

$r(e)$ – rate of the element (e) in the nutritive salt (s) [%]

$M(e)$ – molar mass of the element (e) to be rated [g mol^{-1}]

$M(s)$ – molar mass of the nutritive salt (s) which contains the element (e) [g mol^{-1}]

N_s - number of atoms of the element (e) present in a molecule of the nutritive salt (s) [-]

When expressing the nutrient content of a salt in terms of its oxide, the conversion is made as follows:

$$r(o) = \frac{\frac{M(e)}{M(s)} N_s}{\frac{M(e)}{M(o)} N_o} \tag{36}$$

where:

r(o) – element ratio in the nutritive salt expressed as its oxide (o) [%]

$M(o)$ - molar mass of the oxide (o) [g mol^{-1}]

N_o – number of atoms of the element (e) present in its oxide (o) [-]

After computing the concentration of individual species in the solution, it is possible to estimate several other chemical parameters of it:

Electrical conductivity (EC)

Fig. 24 presents typical relations between the concentration of various salts and the electrical conductivity of the solution containing the particular (single) salt.

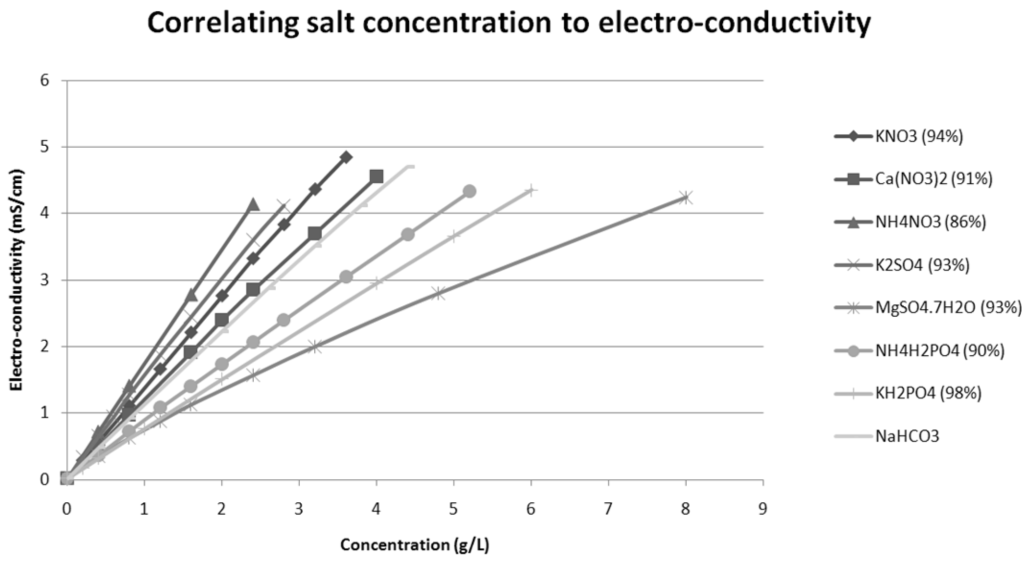


Figure 24. Relation of concentration versus electro-conductivity for various mineral fertilizers. The graph was obtained by the author through experimentation, using common comercial fertigation products, which were not 100% pure (Moreira Barradas et al., 2012).

Relating salt concentration (mg/l) to EC (mS/cm)

In order to obtain the curve relating the combination of salts to its resulting EC [mS/cm] it was proceeded as follows:

Let Y be EC[mS/cm] and X be the concentration [mg/L]

We will relate Y to X with the following general expression:

$$Y_i = aa_i X_i^3 + a_i X_i^2 + b_i X_i + c_i \tag{37}$$

With aa, a, b and c as coefficients obtained from the linear regression equations

In detail:

For KNO_3

$$Y_1 = -0.0174X_1^2 + 1.4114X_1 + 0.0068 \tag{38}$$

For $Ca(NO_3)_2$

$$Y_2 = -0.027X_2^2 + 1.2423X_2 + 0.0118 \tag{39}$$

For NH_4NO_3

$$Y_3 = -0.012X_3^2 + 1.7443X_3 + 0.0217 \tag{40}$$

For K_2SO_4

$$Y_4 = -0.0494X_4^2 + 1.6059X_4 + 0.0177 \tag{41}$$

For $MgSO_4.7H_2O$

$$Y_5 = 0.0028X_5^3 - 0.0506X_5^2 + 0.749X_5 + 0.0436 \quad (42)$$

For $NH_4H_2PO_4$

$$Y_6 = -0.0095X_6^2 + 0.8755X_6 + 0.0281 \quad (43)$$

For $K_2H_2PO_4$

$$Y_7 = -0.0057X_7^2 + 0.7562X_7 + 0.0193 \quad (44)$$

For $NaHCO_3$ (and also for the rest of source water original mixture of soluble solids)

$$Y_8 = 0.00752X_8^2 + 0.45952X_8 + 0.00736 \quad (45)$$

Then the total electro-conductivity Y_f might be estimated as follows:

$$\mathrm{Y_f} = \mathrm{aa_f X_f^3} + \mathrm{a_f X_f^2} + \mathrm{b_f X_f} + \mathrm{c_f} \quad (46)$$

with

$$X_f = \sum_{i=1}^{8} X_i \quad (47)$$

$$aa_f = \frac{\sum_{i=1}^{8} aa_i X_i}{X_f} \quad (48)$$

$$a_f = \frac{\sum_{i=1}^{8} a_i X_i}{X_f} \quad (49)$$

$$b_f = \frac{\sum_{i=1}^{8} b_i X_i}{X_f} \quad (50)$$

$$c_f = \frac{\sum_{i=1}^{8} c_i X_i}{X_f} \quad (51)$$

Fertigation Efficiency Index (*FEI*)

Assuming that the total volume of water to be evapotranspired, as well as the amount of nutritive elements to be uptaken (according to available uptake tables) over the crop cycle, can be estimated, then the ideal average concentrations of these elements in the nutritive solution can be estimated as follows:

After the season or as a part of a modeling scenario, we can estimate the fertigation efficiency index *FEI* as follows (Moreira Barradas et al., 2012):

$$FEI = \frac{[s+\Delta_s]}{s_i} \qquad (52)$$

where:

s - concentration of a given nutritive element in the nutritive solution [kg m^{-3}]

Δs – the change in the concentration of a given nutritive element after the soil/nutritive solution interaction [kg m^{-3}]

s_i – the ideal average concentration of a given element in the nutritive solution in a “no losses scenario” [kg m^{-3}]

S_t – ideal concentration of a given nutrient in the nutritive solution

With:

$$s_i = \frac{u_t p_t}{w_t \eta_t} \qquad (53)$$

where

u_t – uptake of a given nutritive element per kg of expected production [kg kg^{-1}]

p_t – expected production [kg]

w_t – estimated total volume of water to be used during the whole crop cycle [m^3]

η_t – root absorption efficiency for a given element [%]

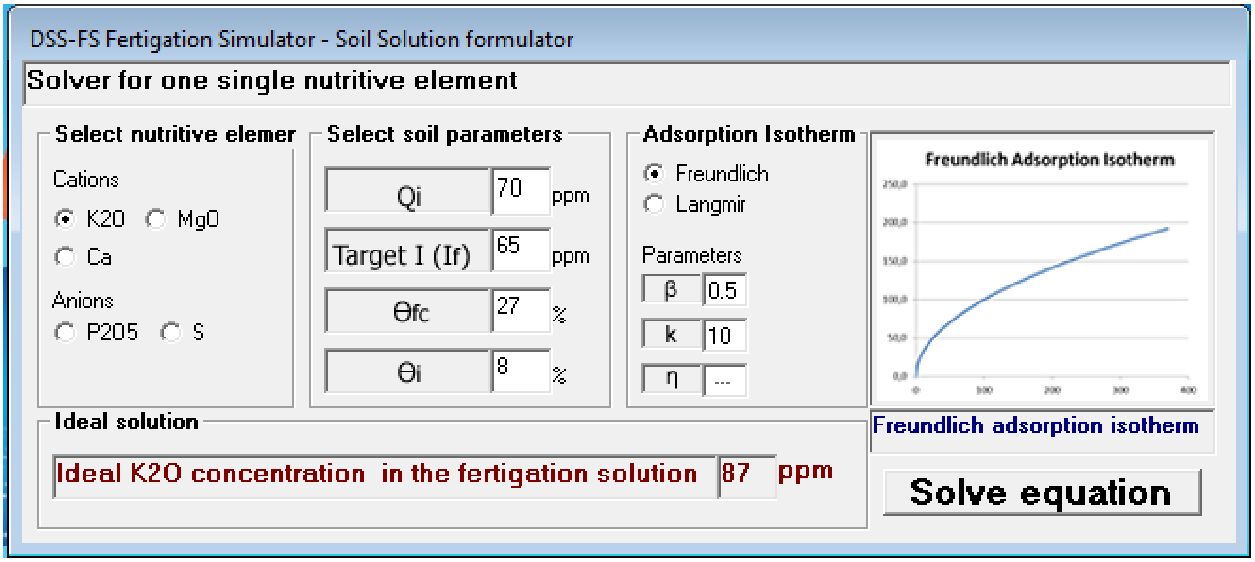
The idea of defining a fertigation efficiency index has been developed by the present author during the creation of the DSS-FS. $\Delta s = 0$ is valid for hydroponic substrates. It is also the default value used in the fertigation simulator; however, it can be adjusted by the user in the advanced mode of simulation, taking into consideration the buffering capacity of the soil for a given element, as described in Fig. 10.

The Hoagland nutritive solution (Hoagland and Snyder, 1933) has been used as a reference in the DSS-FS.this model. However, it needs to be adjusted according to specific uptake requirements (uptake tables), growing cycle stage and production output for each specific crop.The DSS-FS also compares the actual relations between the nutritive elements present in the nutritive solution (if customized by the user) to the required relations between elements in different stages of the crop development. Thus, it can identify the elements in relative shortage or relative excess through an iterative algorithm by observing the Law of the minimum of Liebig. When using raw water with very little salinity, the amount of nutritive salts required reaching the limit of salinity tolerance would be much higher than the plant uptake requirements for metabolizing the maximum possible production. In this case, it would not be enough just to respect the salinity limit. The computer program of the DSS-FS will therefore set a default *FEI* value calculated individually for each nutritive element and will then analyze the deviations from the default for each available element, indicating which elements are in relative shortage or in relative excess in the nutritive solution.

Soil / Nutritive Solution Interaction

Taking the Q/I relations described in chapter 2.4.5 into account, we may think of an optimum concentration of the nutritive element in the fertigation solution (before it enters the soil) as the one which, according to the specific adsorption isotherm for that element and that soil, will generate the ideal concentration s_i of the same element in the soil solution.

By investigating or compiling the Q/I relationships for different soils and different nutritive elements it might be possible to improve our newly developed DSS-FS with a simple user-friendly application that can formulate the optimum composition of the fertigation solution so that an ideal soil solution is generated according to the selected adsorption isotherm and its empirical constants. It is a reasonable simplification to assume for this purpose that the quantity-intensity relation is unique for a given nutrient and a given soil, monotonous and non- hysteretic. Fig. 25 shows the DSS-FS interface of the solver for the optimum fertigation solution.



DSS-FS Fertigation Simulator - Soil Solution formulator

Solver for one single nutritive element

Select nutritive elemer

Cations

● K2O ○ MgO

○ Ca

Anions

○ P2O5 ○ S

Select soil parameters

Qi 70 ppm

Target I (If) 65 ppm

θfc 27 %

θi 8 %

Adsorption Isotherm

● Freundlich

○ Langmir

Parameters

β 0.5

k 10

η ---

Ideal solution

Ideal K2O concentration in the fertigation solution 87 ppm

Figure 25. DSS-FS solver for the soil/nutritive solution interaction

Methodology used in order to find the equilibrium solution after the soil / nutritive solution interaction:

Based on the known Q/I relationships we might be able to estimate the variation of a given element in the nutritive solution after its interaction with the soil (see figure 26).

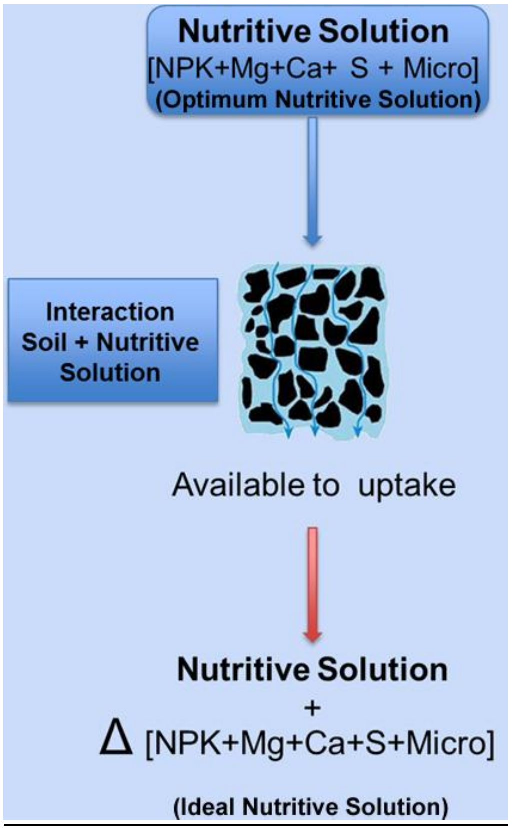


Fig. 26. Soil / Nutritive solution interaction

Fig. 26 expresses the general relation between the availability of a nutrient in the soil solution (I) and its adsorbed quantity (Q) of a given nutritive element in the soil minerals.

It is assumed that the error caused by the variable soil water content is negligible and also that there is no significant soil solution percolation beneath the root zone and no nutrient volatilisation or denitrification into the atmosphere during the process of soil /soil solution equilibration. All processes discussed here take place solely within the root zone.

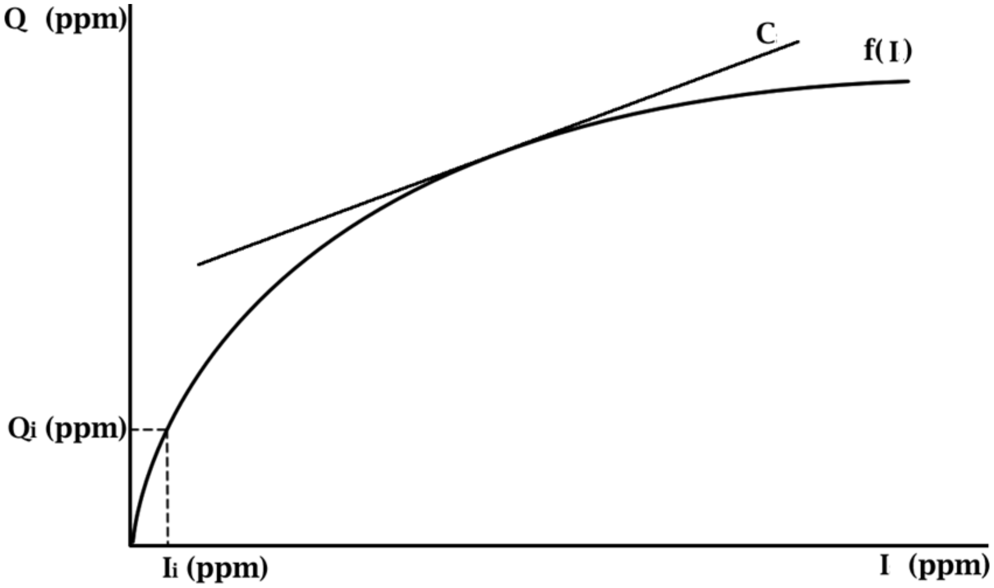


Fig 27. A general Q/I relationships and its derivative (capacity C) at a particular point

I is the concentration of a given element in the nutritive solution and Q = f(I) be the quantity of a given element adsorbed by the soil in equilibrium with I as stated previously in fig. 11.

The capacity factor C (see fig. 27) expresses the derivative of Q with respect to I in the equilibrium for a particular value of I.

$$C = \frac{\partial}{\partial \mathrm{I}} f(I) \qquad (54)$$

After a fertigation application, the intensity I in the soil will change from I_i to I_m,causing an unbalanced situation as shown in fig. 28

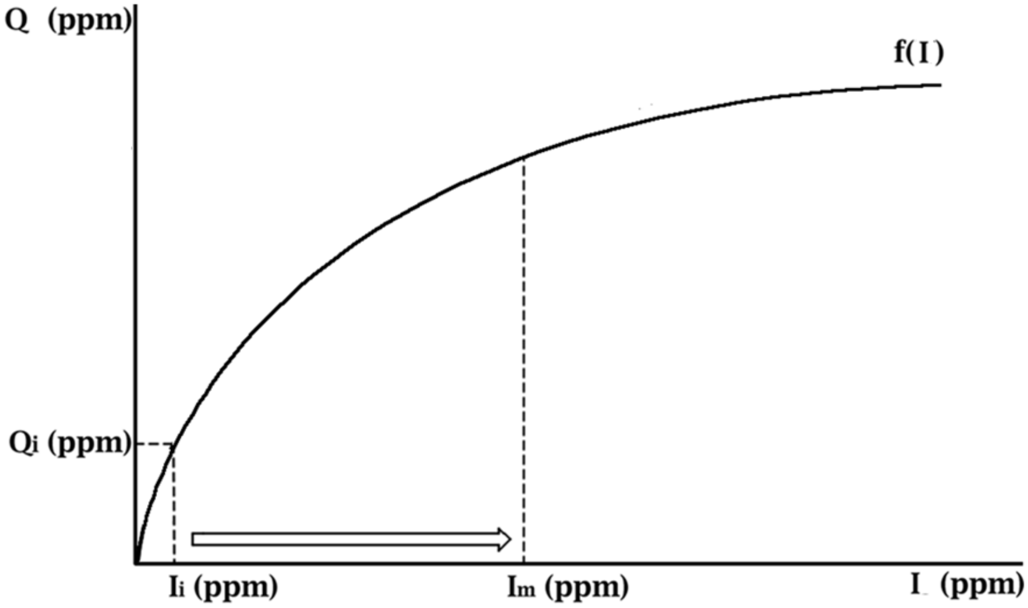


Fig 28. Q/I relationships unbalanced by fertigation, before new equilibration

Let I_m describe the concentration of the soil solution (for a given element) immediately after irrigation with a nutritive solution. The irrigation is assumed to have restored the soil water to the soil's field capacity Θ_{fc}

Assuming the soil solution intensity before irrigation I_i and the nutritive solution concentration I_n, then (assuming no losses by percolation) I_m is given by the following expression:

$$I_m = [I_i\Theta_i + I_n(\Theta_{fc} - \Theta_i)]/\Theta_{fc} \tag{55}$$

where:

I_m[ppm] – concentration of the soil solution after fertigation

I_i[ppm] – concentration of the soil solution before fertigation

I_n[ppm] – concentration of the nutritive solution

Θi [%] - soil moisture content by volume before fertigation

Θ_{fc}[%] – soil moisture content by volume at field capacity

I_m is, however, not in equilibrium with the pre-fertigation soil capacity Qi and, therefore, it is assumed that a rebalance will quickly take place as shown in Fig.29.

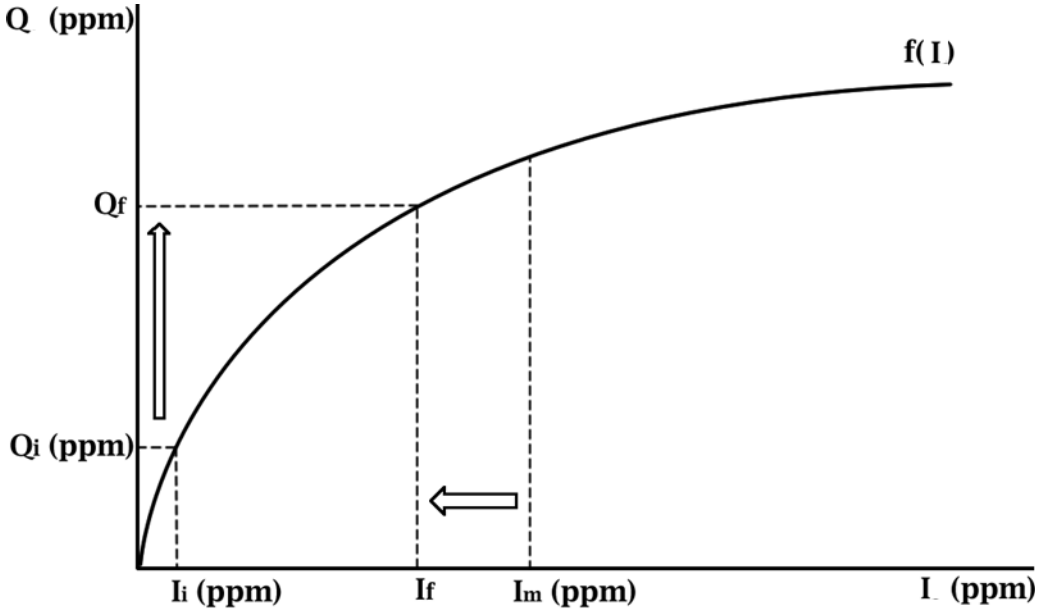


Fig. 29. Q/I relationships – equilibrium restoration

The equilibrium is given by the following expression (after a conversion of the terms to compatible units):

$$Q_f + I_f = I_m + Q_i \tag{56}$$

With

Q_f – quantity factor after equilibrium [mg/Kg]

I_f – intensity factor after equilibrium [mg/L]

As the total amount of a nutritive element within the soil control volume, either adsorbed or in solution, does not change:

$$Q_f + I_f = I_m + Q_i = F \tag{57}$$

with F being a constant for a given case, and *Qi* can be obtained by soil analysis or by simulation in the previous step, it comes:

$$Q_f + I_f = F \tag{58}$$

Assuming:

$$I_f = f(Q_f) \tag{59}$$

Then:

$$f\left(Q_f\right) + Q_f = F \tag{60}$$

The specific solution depends on the specific shape of the generalised adsorption isotherm and on the value of F.

Formulating it for four different algebraic approximations of the adsorption isotherm (and the Q/I relation), we can write:

a) the linear adsorption isotherm:

$$I_f = kQ_f \tag{61}$$

b) the Langmuir adsorption isotherm:

$$I_f = \frac{kQ_f}{1+\eta Q_f} \tag{62}$$

c) the Freundlich adsorption isotherm:

$$Q_f = kI_f^{\beta} \tag{63}$$

where k, η and β are empirical constants, the units of which depend on the formula used.

d) the squared adsorption isotherm, used in this work as a simplification of case c):

$$Q_f = kI_f^2 \tag{64}$$

where k is an empirical constant.

With F as in equation (57), the solutions will be given respectively for the previous cases as follows:

a)

$$kQ_f + Q_f = F \tag{65}$$

$$(k+1)Q_f = F \tag{66}$$

$$Q_f = \frac{F}{k+1} \tag{67}$$

b)

$$\frac{kQ_f}{1+\eta Q_f} = F \tag{68}$$

$$kQ_f = F + F\eta Q_f \tag{69}$$

$$kQ_f - F - F\eta Q_f = 0 \tag{70}$$

c)

$$kI_f^{\beta} + I_f = F \tag{71}$$

$$kI_f^{\beta} + I_f - F = 0 \tag{72}$$

d)

$$I_f + kI_f^2 = F \tag{73}$$

$$I_f + kI_f^2 - F = 0 \tag{74}$$

$$I_f = \frac{-k \pm \sqrt{k^2 + 4F}}{2} \tag{75}$$

In cases b) and c) and d) we might compute *I* using a non-linear optimisation program (e.g. the Excel Solver).

A formal numerical example for the cases a) and d) can be given as follows:

For case a): Let $k = 0.1$, $Q_i = 6$; $I_m = 6$, therefore F = 12 (eq. 57).

$$0.1Q_f + Q_f = 1.1Q_f = 12 \tag{76}$$

$$Q_f = 10.91 \tag{77}$$

(Therefore $I_f = 12 - 10.91 = 1.09$)

For case d): Let $k = 1$, $Q_{initial} = 8$, $I_m = 4$, F = 12 (eq. 57).

$$I_f = \frac{-1 \pm \sqrt{1^2 + 48}}{2} \tag{78}$$

$$I_f = \frac{-1 + \sqrt{49}}{2} = 3 \tag{79}$$

Therefore $Q_f = 12 - 3 = 9$ (see eq. 57)

The Fertigation Efficiency Index– FEI (Moreira Barradas et al, 2012), defined by equation (43) above, can now be calculated as:

$$FEI = \frac{[s + I_f - I_n]}{S_i} \qquad (80)$$

with:

I_f - I_n – *as* the change in the concentration of a given element after the soil/nutritive solution interaction [kg m^{-3}] replacing *Δs* – used in equation (52)

Resorting to a user friendly interface, the DSS-FS can now offer a solution to estimate ideal concentrations of one single element.

The challenge for future is to expand this study to a complete formulation of the whole nutritive solution with all elements by investigating their competition for the sorption sites.

Obtaining the right combination of fertilizers

The fertigation Efficiency Index equation (Moreira Barradas et al, 2012) expresses the ideal relation or ratio between the different nutrients required for plant growth.

Different nutritive salts provide different nutrients into the nutritive solution.

In order to compute the correct amounts of each nutritive salts that should be solved into the nutritive solution, it was proceeded as follows:

DSS-FS resorts to 6 nutritive salts in order to formulate the required nutritive solution (see fig. 23)

The nutritive content of each nutritive salt is the following:

For NS_1: N_NS_1=13% ; K_NS_1=45%

For NS_2: N_NS_2=12%; P_NS_2 = 61%

For NS_3: N_NS_3=15% N; Ca_NS_3=21%

For NS_4: Mg_NS_4=13% ; S_NS_4=18%

For NS_5: K_NS_5=53% ; S_NS_5=18%

For NS_6: N_NS_6=32%

With

NS_i – Nutritive salt of index i

N_NS_i – Nitrogen content of NS_i

P_NS_i – Phosphorous content of NS_i

K_NS_i – Potassium content of NS_i

Ca_NS_i – Calcium content of NS_i

Mg_NS_i – Magnesium content of NS_i

S_NS_i – Sulphur content of NS_i

The optimal quantities of each salt to generate the optimal nutritive solution can be obtained by solving the system of 6 equations with 6 unknown resorting to Cramer rule

A numeric example of this solution is shown below for composing a nutritive solution with the following equilibrium: N=15, P=5, K=30, Ca=10, Mg=5, S=10

Table 12. Applying the Cramer Rule on solving ideal nutritive formulation

%\Salt	**NS1**	**NS2**	**NS3**	**NS4**	**NS5**	**NS6**	**Desired Nutritive relation**	
N	0.13	0.12	0.15	0	0	0.32	**N**	15
P	0	0.61	0	0	0	0	**P**	5
K	0.45	0	0	0	0.53	0	**K**	30
Ca	0	0	0.21	0	0	0	**Ca**	10
Mg	0	0	0	0.13	0	0	**Mg**	5
S	0	0	0	0.18	0.18	0	**S**	10

Determinant0 = 0.000432

Using the Cramer rule:

NS1:

15	0.12	0.15	0	0	0.32
5	0.61	0	0	0	0
30	0	0	0	0.53	0
10	0	0.21	0	0	0
5	0	0	0.13	0	0
10	0	0	0.18	0.18	0

Determinant1= 0.020086

NS2:

0.13	15	0.15	0	0	0.32
0	5	0	0	0	0
0.45	30	0	0	0.53	0
0	10	0.21	0	0	0
0	5	0	0.13	0	0
0	10	0	0.18	0.18	0

Determinant2= 0.003538

NS3:

0.13	0.12	15	0	0	0.32
0	0.61	5	0	0	0
0.45	0	30	0	0.53	0
0	0	10	0	0	0
0	0	5	0.13	0	0
0	0	10	0.18	0.18	0

Determinant3= 0.020555

NS4:

0.13	0.12	0.15	15	0	0.32
0	0.61	0	5	0	0
0.45	0	0	30	0.53	0
0	0	0.21	10	0	0
0	0	0	5	0	0
0	0	0	10	0.18	0

Determinant4= 0.016602

NS5:

$$\begin{matrix} 0.13 & 0.12 & 0.15 & 0 & 15 & 0.32 \\ 0 & 0.61 & 0 & 0 & 5 & 0 \\ 0.45 & 0 & 0 & 0 & 30 & 0 \\ 0 & 0 & 0.21 & 0 & 10 & 0 \\ 0 & 0 & 0 & 0.13 & 5 & 0 \\ 0 & 0 & 0 & 0.18 & 10 & 0 \end{matrix}$$

Determinant5= 0.007379

NS6:

$$\begin{matrix} 0.13 & 0.12 & 0.15 & 0 & 0 & 15 \\ 0 & 0.61 & 0 & 0 & 0 & 5 \\ 0.45 & 0 & 0 & 0 & 0.53 & 30 \\ 0 & 0 & 0.21 & 0 & 0 & 10 \\ 0 & 0 & 0 & 0.13 & 0 & 5 \\ 0 & 0 & 0 & 0.18 & 0.18 & 10 \end{matrix}$$

Determinant6= 0.001112

Potassium Nitrate	**NS1=**	46.53371
Mono Ammon. Phosph.	**NS2=**	8.196721
Calcium Nitrate	**NS3=**	47.61905
Magnesium Sulphate	**NS4=**	38.46154
Potassium Sulphate	**NS5=**	17.09402
Ammonium Nitrate	**NS6=**	2.57548

With NSi = Determinant (i) / Determinant 0

3.2 Description of the DSS-FS software package

The algorithm for processing information in order to produce design features and consultancy on several irrigation scenarios is named Adonis Prototype 2. Utilizing a collection of data stored in four database tables, the DSS-FS generates a set of output results, providing consultancy on the irrigation systems design (Figure 30).

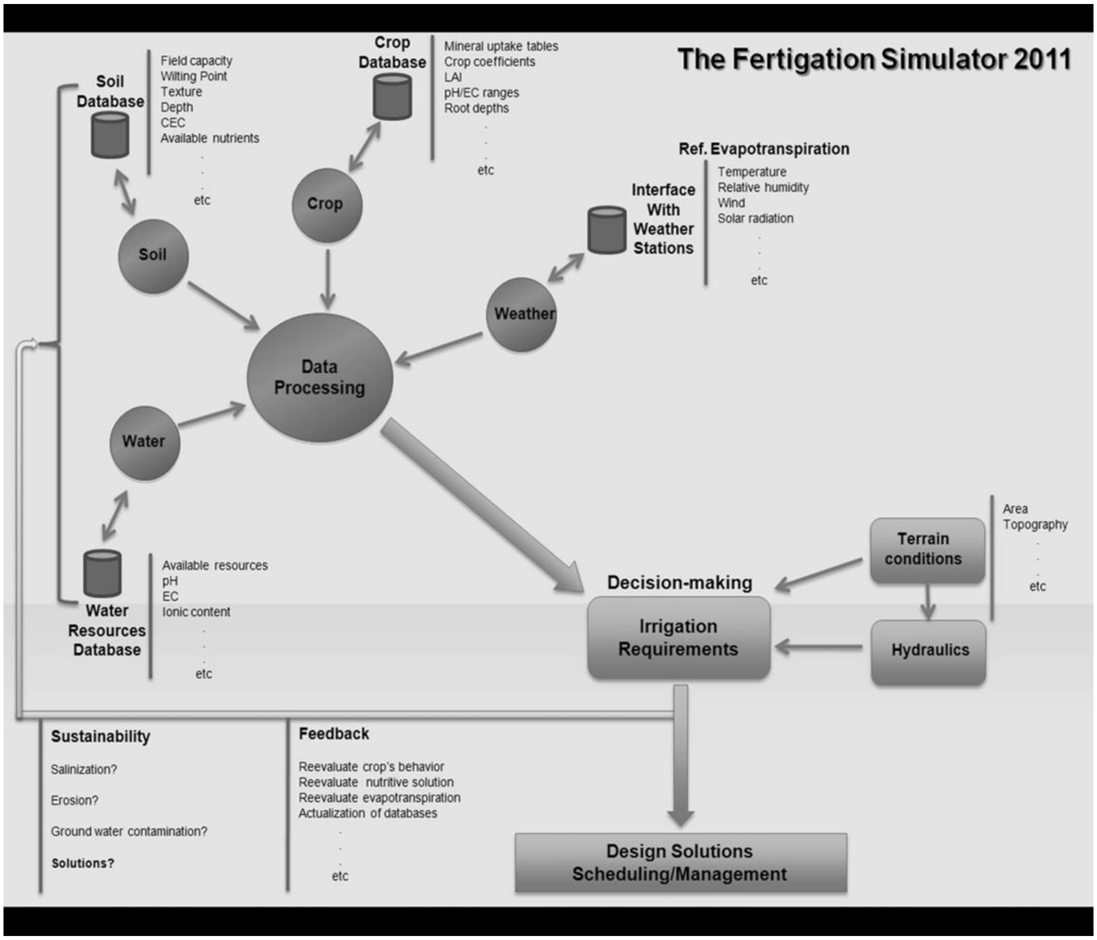


Figure 30. A schematic representation of DSS-FS (Moreira Barradas et al., 2012)

The schematic representation of DSS-FS (Figure 30) shows how it gathers information from the database in order to process the soil, water, crop, and weather data, producing design solutions as an output. The databases are dynamic, allowing (according to the interpretation of the results) their further updating. One of the most innovative features of DSS-FS is the way the users interact with the program's interface.

3.2.1 Entry points

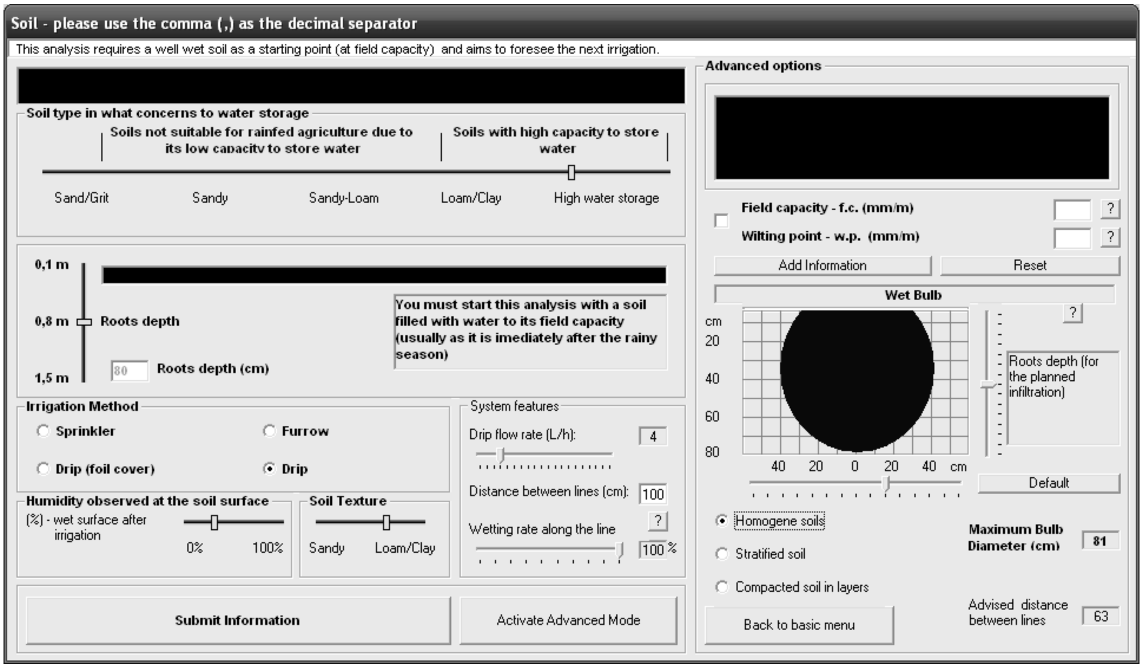
The user's interaction with the program has two entry points:

Advanced mode

In the advanced mode, the user provides input of precise values for each scenario (thus adding an increased level of precision to the output results).

Basic mode

It is targeted at the users who have less knowledge and experience in soil science and fertigation techniques. It takes into account the databases and correlates the empiric scenario selection (which is selected through the interface) to the corresponding values in the database in the process of computing the output results (see Fig. 31).


Soil - please use the comma (,) as the decimal separator

This analysis requires a well wet soil as a starting point (at field capacity) and aims to foresee the next irrigation.

You must start this analysis with a soil filled with water to its field capacity (usually as it is imediately after the rainy season)

Roots depth (cm): 80

Irrigation Method: ● Drip

Drip flow rate (L/h): 4

Distance between lines (cm): 100

Wetting rate along the line: 100 %

● Homogene soils

Maximum Bulb Diameter (cm): 81

Advised distance between lines: 63

Figure 31. Inputting soil data by empirical selection (left side of the interface) or as accurate values (right side of the interface) (Moreira Barradas et al., 2012).

3.2.2 Irrimanager: Scheduling irrigation intervals and volumes

Following the FAO methodology (Allen et al., 1998), the system will retrieve information in order to compute crop water requirements, establishing an irrigation interval after which new irrigation. The volume of which is estimated by DSS-FS, must be applied, in order to fulfill crop water requirements and avoid its hydric stress and production losses. In addition, the system represents these results as a graph; showing the evolution of the available soil water and allowing the user to observe the estimated soil moisture content within the irrigation interval (see Fig 32.)

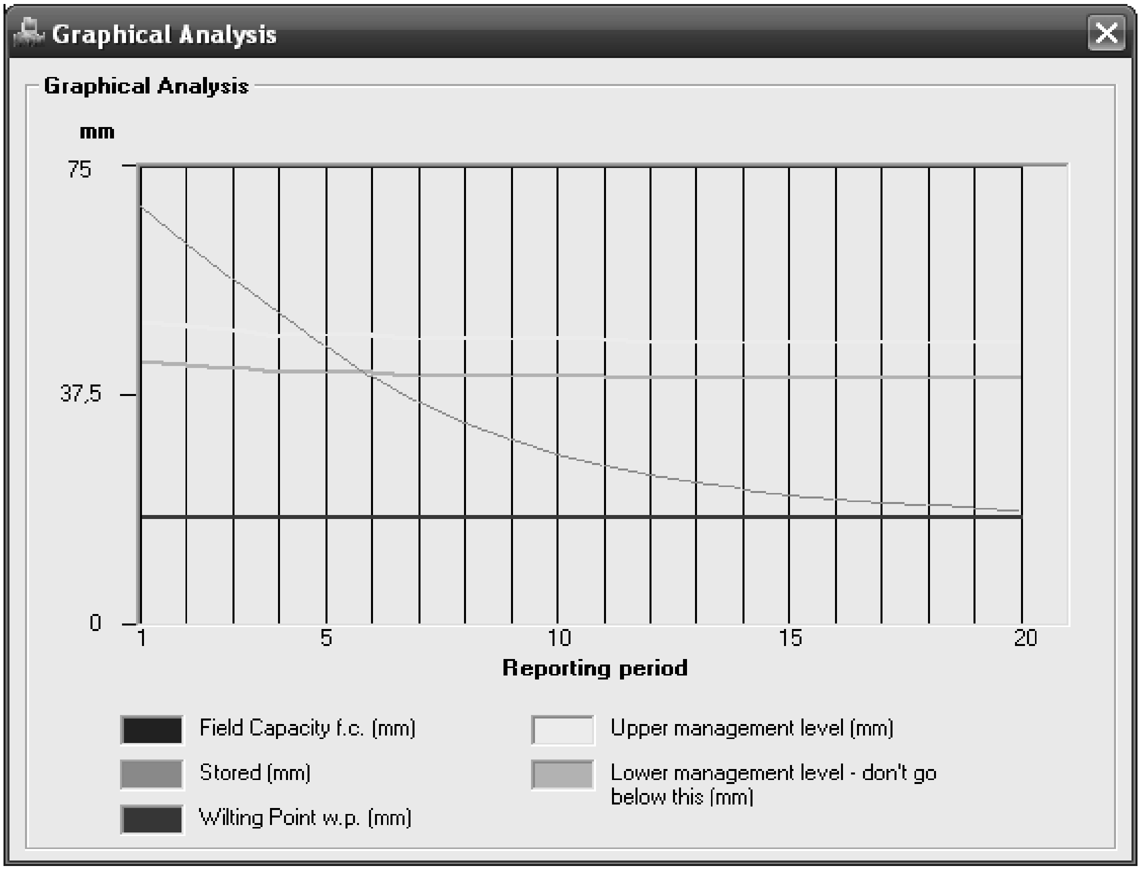


Figure 32. Graphical analysis of the soil water scenario produced by *Irrimanager* (Moreira Barradas et al., 2012).

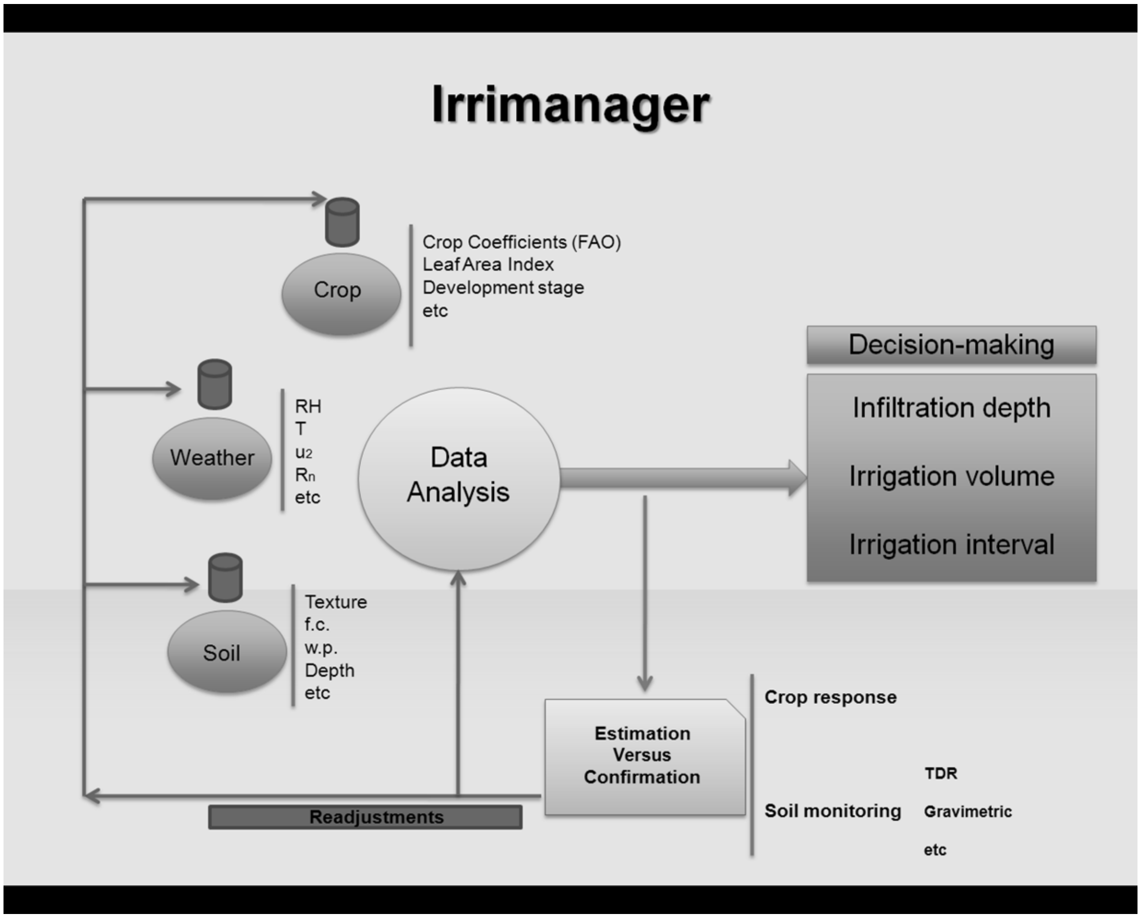


Figure 33. Schematic representation of the 1st module (*Irrimanager*) (Moreira Barradas et al., 2012).

The first module of the DSS-FS, called Irrimanager (see Fig. 33), is responsible for determining the correct interval between successive irrigations and the required volume of water to be supplied. It is worth discussing what is gained and lost (envisaging possible serious errors resulting from sensor calibration and installation problems, but also considering e.g. the results by Zavadil, 2007) when we use this type of estimation, instead of using soil moisture sensors for defining correct application volumes and irrigation intervals.

The output results of this module are then used as input for *Irrisystem* (the 2nd module) to calculate the design features allowing efficient hydraulic dimensioning of the irrigation system.

3.2.3 Irrisystem: Estimating the ideal hydraulic design features

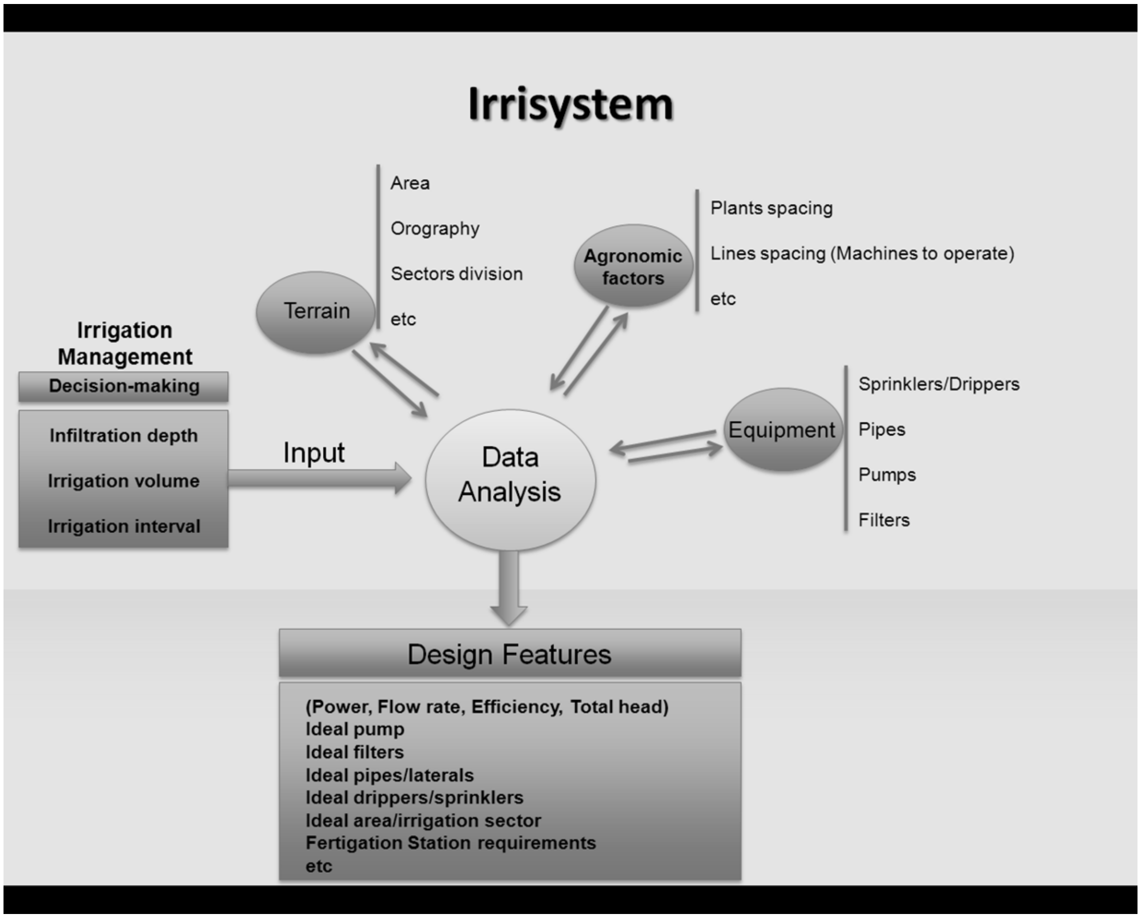
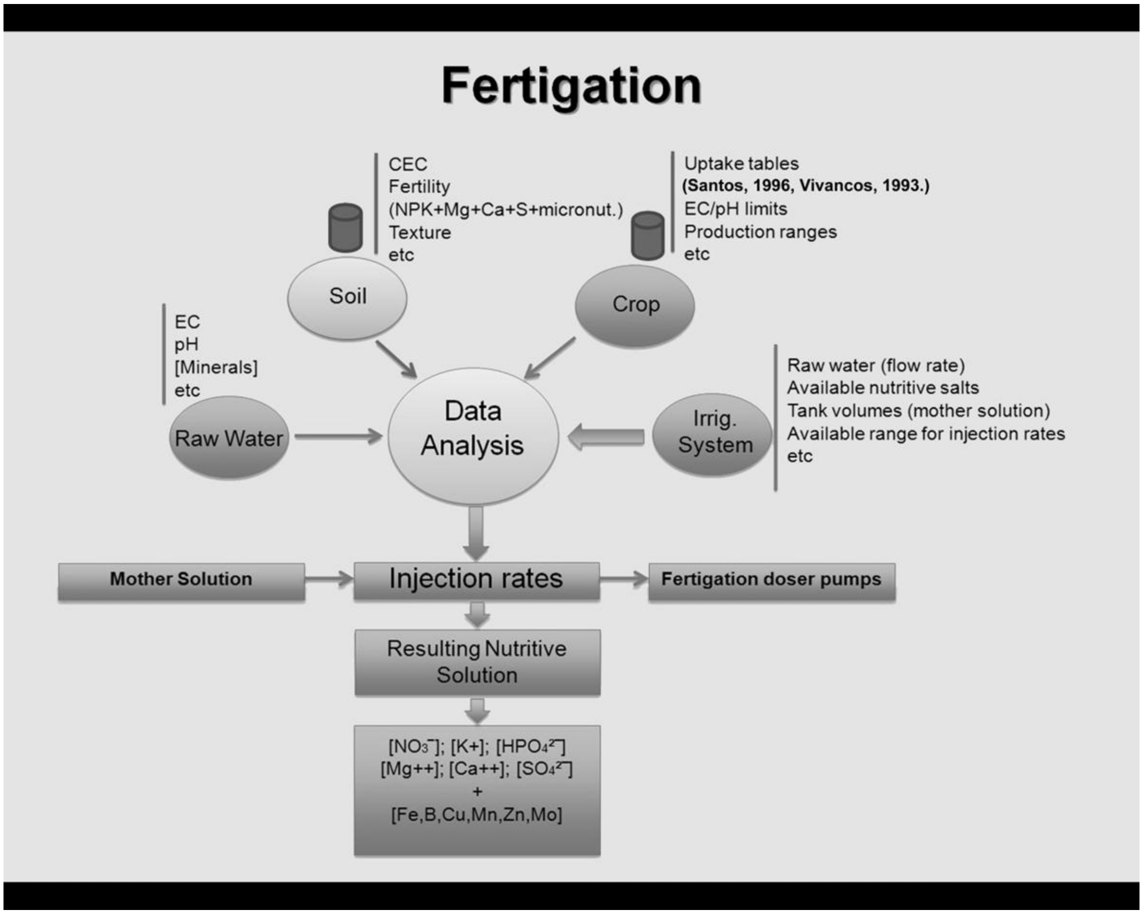


Figure 34. Schematic representation of the 2nd module (*Irrisystem*) (Moreira Barradas et al., 2012).

Irrisystem (see Fig. 34) works as a system designer, estimating ideal dimensions and other parameters in order to optimize the hydraulics of the irrigation system and its division into irrigation sectors. The user can try several solutions, such as pipes of different internal diameter and material, different flow rates for the sprinklers and drippers, etc. and automatically observe the system’s consultancy on his/her choices and recommendations for better alternatives.

3.2.4 Fertigation: Formulating ideal nutritive solutions



Fertigation

CEC
Fertility
(NPK+Mg+Ca+S+micronut.)
Texture
etc

Soil

Uptake tables
(Santos, 1996, Vivancos, 1993.)
EC/pH limits
Production ranges
etc

Crop

EC
pH
[Minerals]
etc

Raw Water

Data Analysis

Irrig. System

Raw water (flow rate)
Available nutritive salts
Tank volumes (mother solution)
Available range for injection rates
etc

Mother Solution

Injection rates

Fertigation doser pumps

Resulting Nutritive Solution

$[NO_3^-]$; $[K+]$; $[HPO_4^{2-}]$
$[Mg++]$; $[Ca++]$; $[SO_4^{2-}]$
+
[Fe,B,Cu,Mn,Zn,Mo]

Figure 35. Schematic representation of the 3rd module *Fertigation*

(Moreira Barradas et al., 2012). Uptake tables from Santos (1996) and Vivancos (1993).

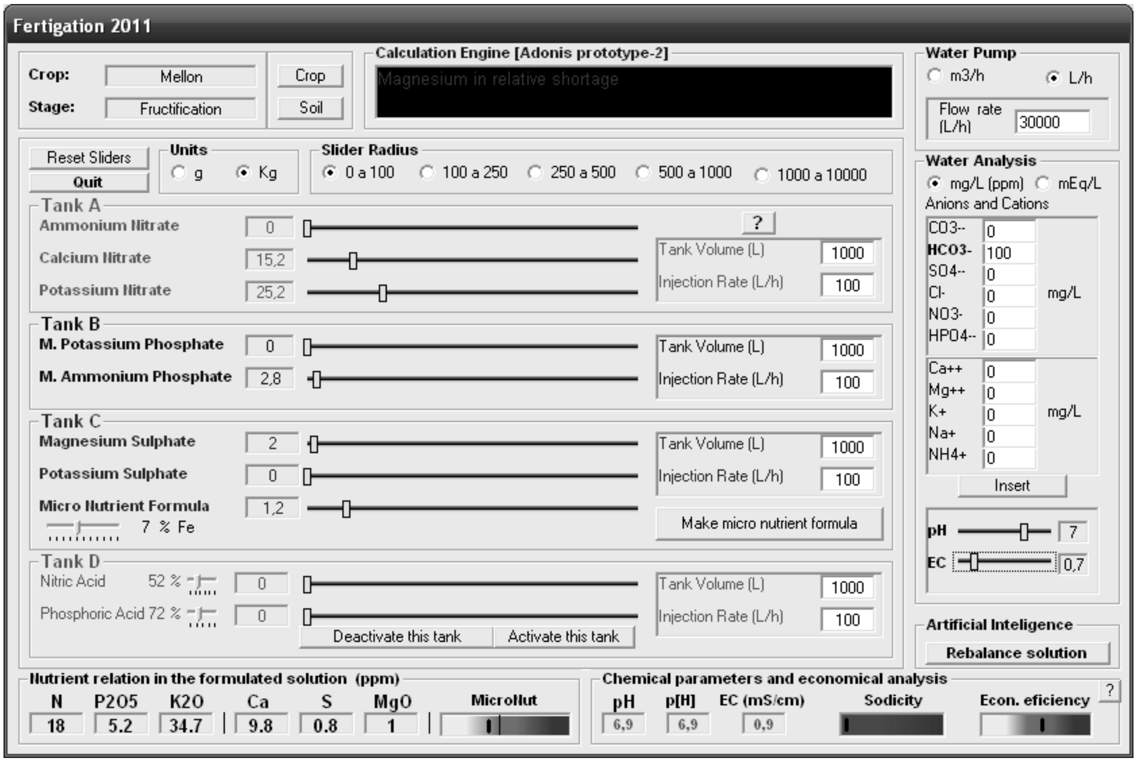
According to crop uptake tables and the available sources of information on fertilizers, the 3rd module of this software package generates information about any simulated scenario of fertilizer injection into the irrigation water, producing also a brief consultancy on its efficiency in terms of several parameters.

This module (Fig. 35) analyzes a typical fertigation system with four fertigation tanks where three mother solutions of different nutritive salts plus one mother solution of two nutritive acids are available and can be injected into the main water pipe which feeds the irrigation system.

The user can then simulate multiple scenarios by way of varying the injection rates of the four fertigation tanks and the amount of different nutritive salts dissolved in each tank, simulating also the chemical features of the raw water used for irrigation (original pH, EC, [ions] etc). These scenarios are then processed and the resulting nutritive solution is presented (resulting pH, EC, [nutrients] etc) and analyzed according to the crop nutritive requirements. The user can make manual adjustments or use a “smart” button to allow the system to automatically rebalance the nutritive solution by readjusting the components of the four mother solutions.

3.2.5 The user interface

An example presenting how the user interacts within the Fertigation module is shown in Fig. 35.



Crop: Mellon

Stage: Fructification

Calculation Engine [Adonis prototype-2]: Magnesium in relative shortage

Units: ○ g ● Kg

Slider Radius: ● 0 a 100 ○ 100 a 250 ○ 250 a 500 ○ 500 a 1000 ○ 1000 a 10000

Tank A			
Ammonium Nitrate	0	Tank Volume (L)	1000
Calcium Nitrate	15,2	Injection Rate (L/h)	100
Potassium Nitrate	25,2		
Tank B			
M. Potassium Phosphate	0	Tank Volume (L)	1000
M. Ammonium Phosphate	2,8	Injection Rate (L/h)	100
Tank C			
Magnesium Sulphate	2	Tank Volume (L)	1000
Potassium Sulphate	0	Injection Rate (L/h)	100
Micro Nutrient Formula (7 % Fe)	1,2		
Tank D			
Nitric Acid 52 %	0	Tank Volume (L)	1000
Phosphoric Acid 72 %	0	Injection Rate (L/h)	100

Water Pump: ○ m3/h ● L/h

Flow rate (L/h): 30000

Water Analysis: ● mg/L (ppm) ○ mEq/L

Anions and Cations

CO3--	0	mg/L
HCO3-	100	
SO4--	0	
Cl-	0	
NO3-	0	
HPO4--	0	
Ca++	0	mg/L
Mg++	0	
K+	0	
Na+	0	
NH4+	0	

pH: 7

EC: 0,7

Nutrient relation in the formulated solution (ppm)

N	P2O5	K2O	Ca	S	MgO
18	5.2	34.7	9.8	0.8	1

Chemical parameters and economical analysis

pH	p[H]	EC (mS/cm)
6,9	6,9	0,9

Figure 36. The 3rd module (*Fertigation*) and its user friendly interface.

(Moreira Barradas et al., 2012).

4 Experimental site description and results of practical application of DSS-FS in olives and grapes production

4.1 Experimental site

The experimental application took place in the Monte dos Aleixos farm, sited in the Alentejo Region – Portugal 38°15'49.05"N, 7°14'47.86"W (see Fig. 36) during the years 2009/2010 and 2010/2011. The conclusions below are lso be based on the history of the farm production in previous years.

The experimental field was divided into 4 parcels (2 parcels for each crop). The olive field consisted of 3.5 ha of olive orchards submitted to DSS-FS fertigation management and another 3.5 ha submitted to classical irrigation. In both parcels, the tree spacing was 7 m x 7 m (variety Picual, 10 years after plantation). The vineyard was divided into 2 parcels of 3 ha each with the spacing 2.8 m x 1.5 m (variety Dona Maria, 25 years after plantation) with the same experimental conditions as the olive orchards. The same quantity of fertilizer was applied in both parcels (kg/ha) but the fertilizers nutritive content (the balance of nutrients) was different.

In the parcels submitted to classical irrigation, the fertilization was made resorting to top and basal dressing fertilizers (with 2 different nutritive balances) split into 3 applications during the crop cycle. In the parcels submitted to DSS-FS fertigation, the management resulted in a different nutritive balance for each phenological stage of the plants. The nutritive balance of the nutritive solution as well as the irrigation volumes and intervals were defined, resorting to the prototype DSS-FS system consultancy.

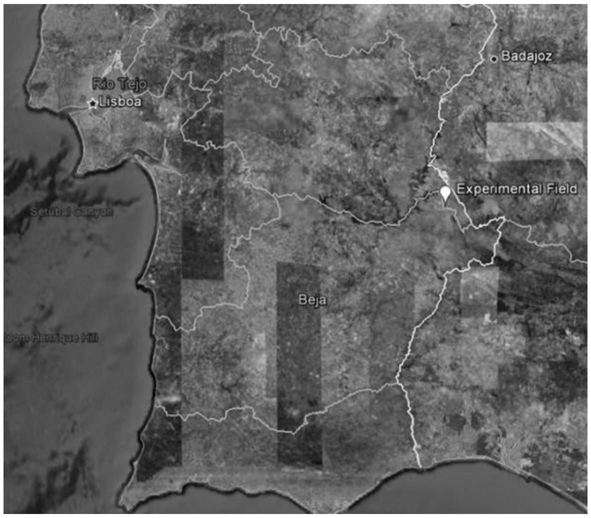


Figure 37. The experimental field in the Monte dos Aleixos farm.

4.1.1 The experimental field

Figure 38. The parcels of olive orchards (top) and vineyard (bottom)

Figure 39. Fertigation station and vineyard.

5 DSS FS Input/Output Data

5.1 Water analysis

Table 13. Irrigation water analysis used as input for DSS FS (year 2009)

Source of water	Barragem	Furos Aleixos
	mg/L	mg/L
Calcium	15.7	98.3
Potassium	3.6	0.8
Magnesium	8.27	55.9
Sodium	10.7	30.4
Phosphorus	0	0
Sulfur	1.4	3.2
Nitrates	2	9
Bicarbonates	80	455
pH	8.2	6.8

5.2 Climatic data

The average air temperature, relative humidity, wind speed and solar radiation data for the region are given in Figs. 39 to 42.

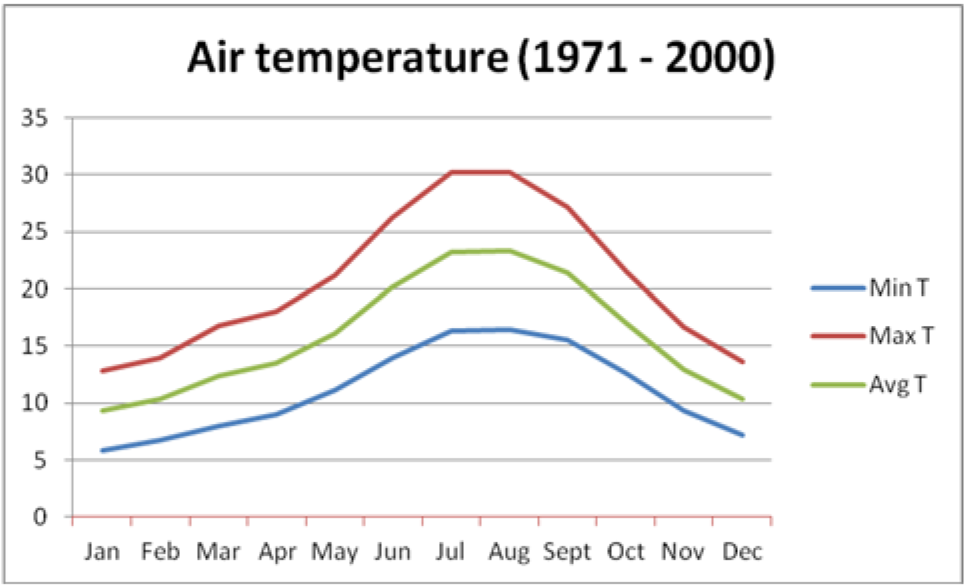


Figure 40. Air temperature averages (2 m) in Évora, 1971-2000 (Source: Portuguese Meteorological Institute IM, I.P.)

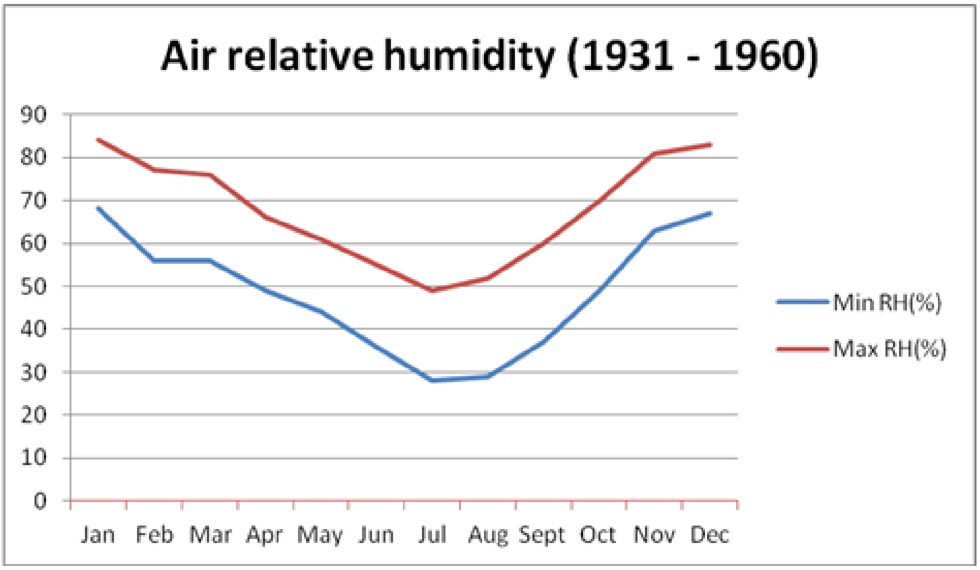


Figure 41. Air relative humidity averages (2 m) in Évora, 1931-1960 (Source: Portuguese Meteorological Institute IM, I.P.)

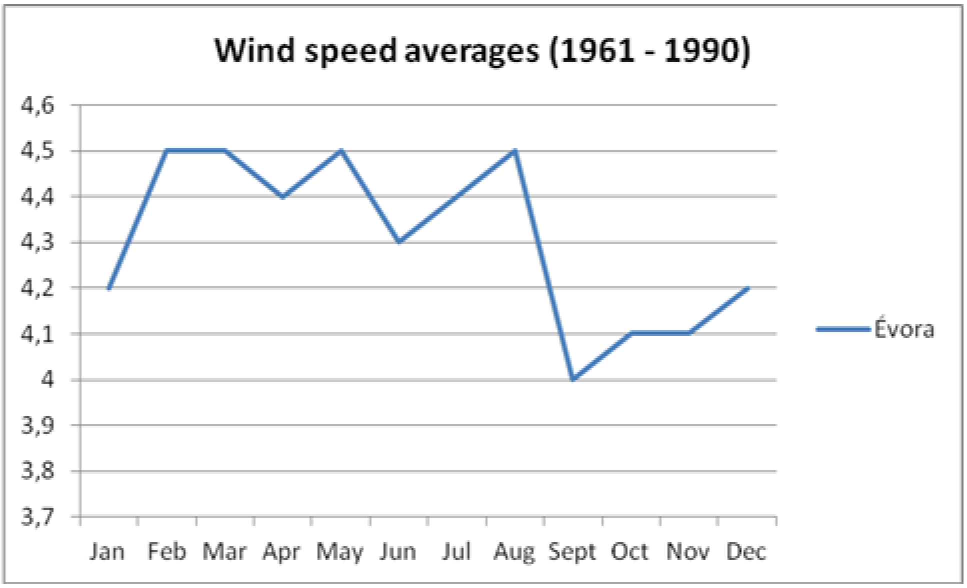


Figure 42. Wind speed averages (2 m) in Évora, 1961-1990 (Source: Portuguese Meteorological Institute IM, I.P.)

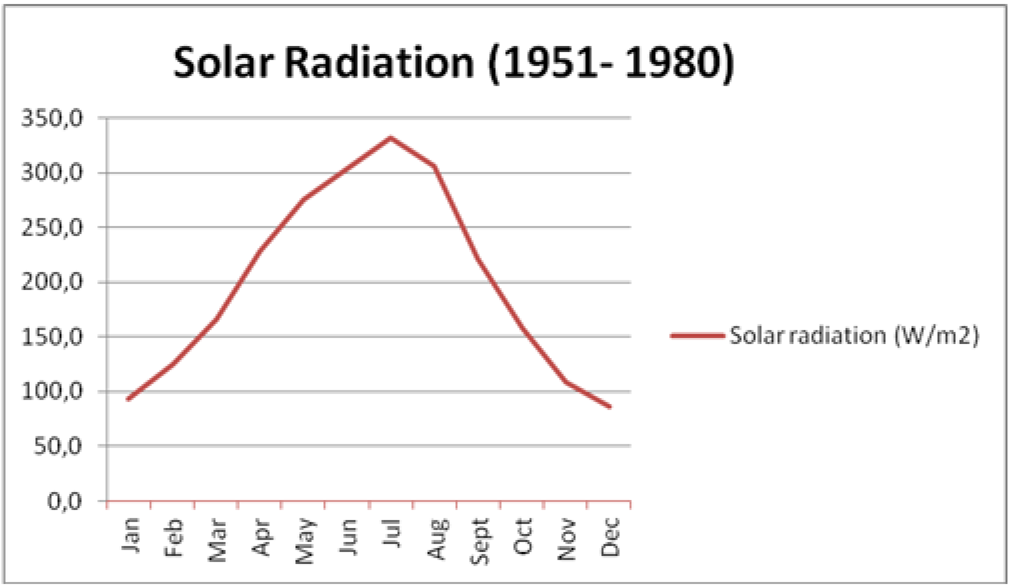


Figure 43. Solar radiation averages in Évora, 1951-1980 (Source: Portuguese Meteorological Institute IM, I.P.)

5.3 Soil data

Soil available data

Table 14. Soil texture and available phosphorus and potassium

Soil	
Texture	Coarse
Fertility	
P (Mehlich 3 - ppm)	45
K (Mehlich 3 - ppm)	10

5.4 Crop data

Table 15. Some agronomic parameters of vineyard and olive orchard in use

Vine	
Vegetative development	70%
Root depth	81 cm
Olives	
Vegetative development	70%
Root depth	81 cm

Other relevant input data: Check Attachment A1

5.5 Preliminary Results

The preliminary results of the production were significantly better for the scenario using DSS-FS as we can observe in the graph below. However, several years of application are needed to eliminate the climatic and other natural random influence on the production.

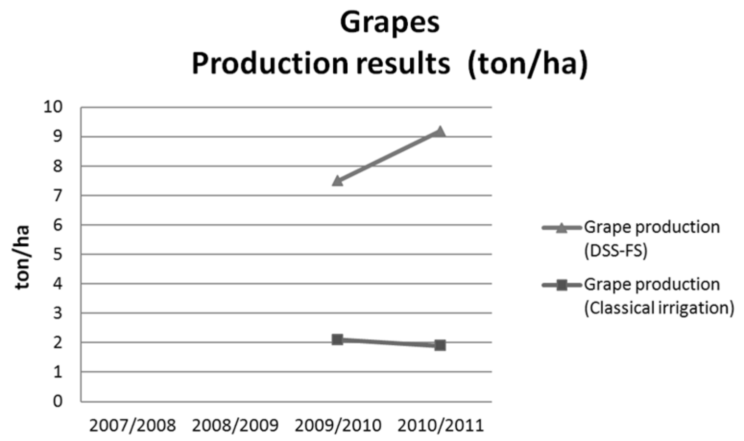


Figure 44. Grapes – Production results.

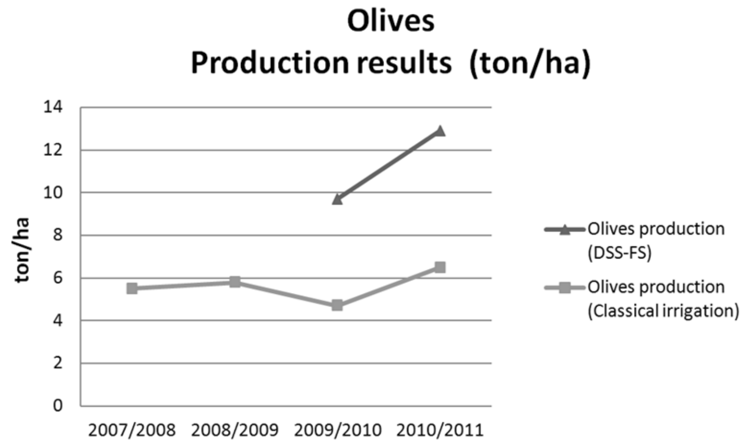


Figure 45. Olives– Production results.

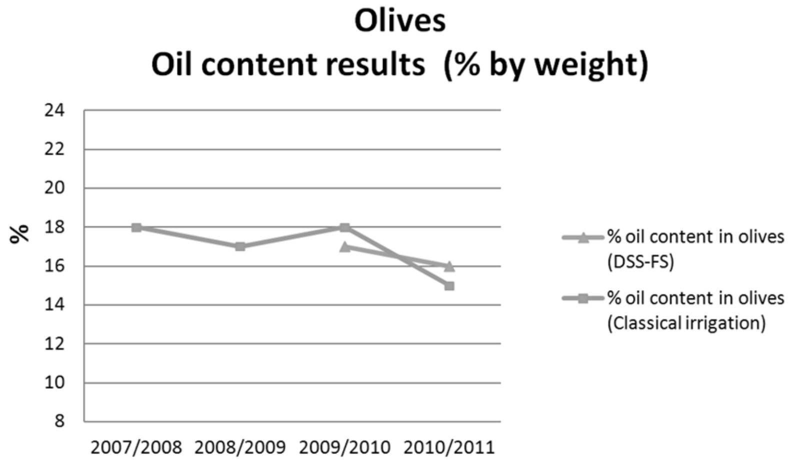


Figure 46. Oil content - Results.

6 DSS-FS application world wide

The fields where DSS-FS was used as a reference for decision making are sited in 4 main regions: North America, Central America, South America and Europe (see Fig. 47). The following crops have been produced: tomato, pepper, lettuce, grapes, citrus fruit, cherries, strawberries and raspberries. These crops, produced under DSS-FS guidance, were analyzed considering the yield (which was compared to the averages reported by FAO for the same region and year) and quality indicators (brix, Gay Lussac degree - °GL) as well as other relevant information: The results are presented in Table 2.

It is a great encouragement to consider the future developments of the DSS-FS system and its potential impact in a world where demographic and socio-economic factors are generating a higher demand – quantity-wise - for food products, without sacrificing quality. This constitutes a particular challenge for agricultural production. Furthermore, rising concerns regarding sustainable farming practices further add to the necessity of exercising judicious management of natural resources. The DSS-FS aspires to address both issues, meeting the needs of producers and consumers around the world whilst implementing good practices that are environmentally sound.

The complete software has been made available as a freeware in its final version since 2010. It has been downloaded by more than 1200 users worldwide who report to be mostly agricultural entrepreneurs, students and technicians in the field of agriculture production.

In Figure 47 the regions where DSS-FS data were produced and are analyzed in this article are marked.

Fig. 47. The regions where the DSS-FS data (presented in this article) were obtained are pin pointed in figure above.

Taking advantage on the information provided by the users when requesting a free serial number to activate the DSS-FS on their computers (namely the users e-mail), it was possible to investigate (through a questionnaire placed online) the purpose for which 1230 registered users downloaded the system and also to investigate their results while they were using DSS-FS as a consulting tool.

A questionnaire was submitted to all the users registered as agricultural entrepreneurs in order to obtain credible results on the performance of the DSS-FS.

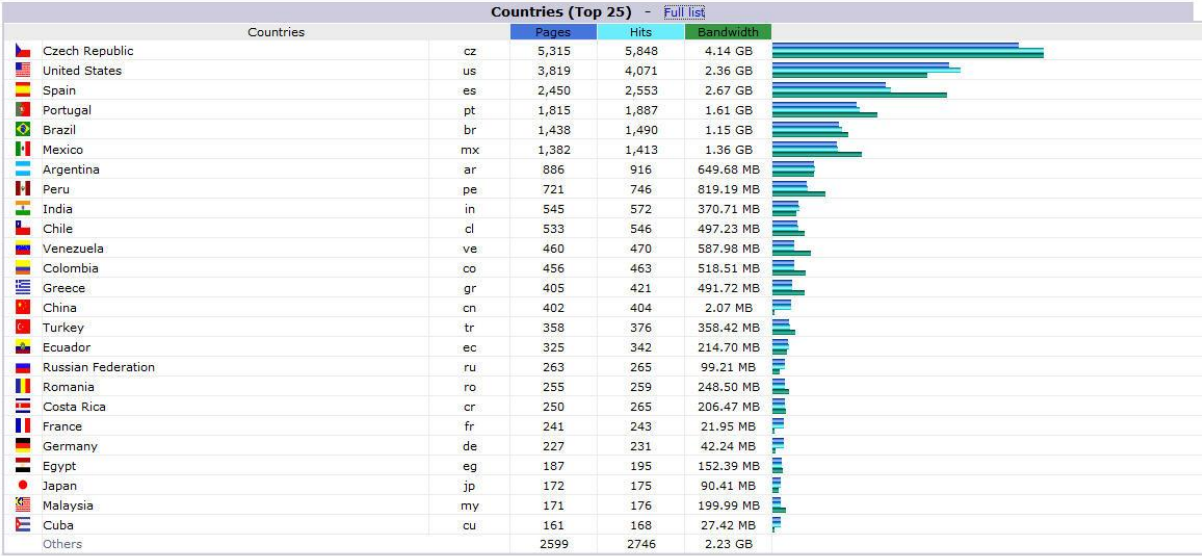
The elements requested through the questionnaire involved information on the following parameters:

1. Production area and region; year of production
2. Crop and its yield; quality indicators (such as brix and ºGL)
3. Soil texture
4. Water EC and pH
5. Information on fertilizer, energy and water economy using DSS-FS
6. Comments about the users' own experience when using the system.

The results derived from the responses to the questionnaire were compared with the annual averages for the same region as reported by FAO. They are presented in the tables and figures below.

The download center of the DSS-FS web site also records all the traffic, sorting it into several groups according to the accessing IP addresses, volume of download, number of visited pages and other useful information about the visitors.

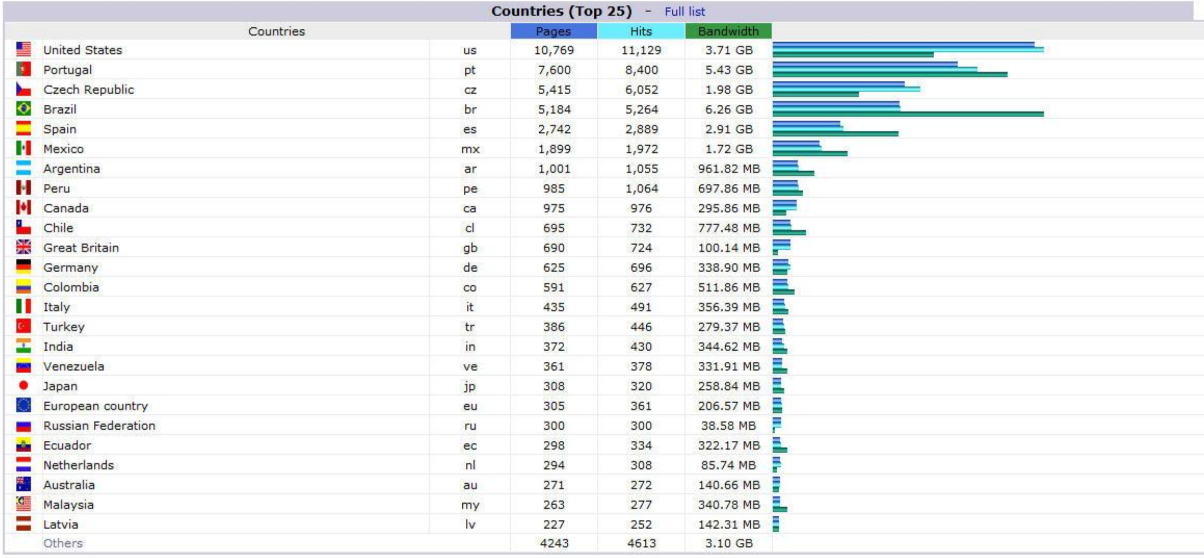
Figures 48 and 49 show the log details of the DSS-FS server during the years 2010 and 2011. The viewed traffic, including the bandwidth for downloads, has been recorded and sorted according to the visitor's IP addresses.



Countries (Top 25) - Full list

Countries		Pages	Hits	Bandwidth
Czech Republic	cz	5,315	5,848	4.14 GB
United States	us	3,819	4,071	2.36 GB
Spain	es	2,450	2,553	2.67 GB
Portugal	pt	1,815	1,887	1.61 GB
Brazil	br	1,438	1,490	1.15 GB
Mexico	mx	1,382	1,413	1.36 GB
Argentina	ar	886	916	649.68 MB
Peru	pe	721	746	819.19 MB
India	in	545	572	370.71 MB
Chile	cl	533	546	497.23 MB
Venezuela	ve	460	470	587.98 MB
Colombia	co	456	463	518.51 MB
Greece	gr	405	421	491.72 MB
China	cn	402	404	2.07 MB
Turkey	tr	358	376	358.42 MB
Ecuador	ec	325	342	214.70 MB
Russian Federation	ru	263	265	99.21 MB
Romania	ro	255	259	248.50 MB
Costa Rica	cr	250	265	206.47 MB
France	fr	241	243	21.95 MB
Germany	de	227	231	42.24 MB
Egypt	eg	187	195	152.39 MB
Japan	jp	172	175	90.41 MB
Malaysia	my	171	176	199.99 MB
Cuba	cu	161	168	27.42 MB
Others		2599	2746	2.23 GB

Fig. 48. DSS-FS website traffic during the year 2010*



Countries (Top 25) - Full list

Countries		Pages	Hits	Bandwidth
United States	us	10,769	11,129	3.71 GB
Portugal	pt	7,600	8,400	5.43 GB
Czech Republic	cz	5,415	6,052	1.98 GB
Brazil	br	5,184	5,264	6.26 GB
Spain	es	2,742	2,889	2.91 GB
Mexico	mx	1,899	1,972	1.72 GB
Argentina	ar	1,001	1,055	961.82 MB
Peru	pe	985	1,064	697.86 MB
Canada	ca	975	976	295.86 MB
Chile	cl	695	732	777.48 MB
Great Britain	gb	690	724	100.14 MB
Germany	de	625	696	338.90 MB
Colombia	co	591	627	511.86 MB
Italy	it	435	491	356.39 MB
Turkey	tr	386	446	279.37 MB
India	in	372	430	344.62 MB
Venezuela	ve	361	378	331.91 MB
Japan	jp	308	320	258.84 MB
European country	eu	305	361	206.57 MB
Russian Federation	ru	300	300	38.58 MB
Ecuador	ec	298	334	322.17 MB
Netherlands	nl	294	308	85.74 MB
Australia	au	271	272	140.66 MB
Malaysia	my	263	277	340.78 MB
Latvia	lv	227	252	142.31 MB
Others		4243	4613	3.10 GB

Fig. 49. DSS-FS website traffic during the year 2011*

*The values regarding the Czech Republic are mostly the result of the project maintenance and management by accessing the website from the CULS, FANFR Department of Water Resources.

6.1 The DSS-FS results worldwide

Since its first release and up to this date, the installation package has been downloaded over 2500 times by more than 1200 registered users, generating total foreign website traffic of more than 50 GB within the last 3 years.

The table 16 provides information on the users registered in our database

Table 16. DSS-FS statistics since January of 2008

DSS-FS statistics	
Number of website visits	19528
Number of DSS-FS instalation packages downloaded	4285
Number of registered users	**1230**
Users registered as students	28%
Users registered as farmers/enterpreneurs	10%
Users registered as consultants	17%
Users registered as other/no info	45%
Users who applied the DSS-FS and answered the questionaire providing results	**1.4%**
Validated answers	82.4%

The data reported from the DSS-FS users were analyzed and are presented in the tables and figures below.

Table 17. Overview of results obtained from the DSS-FS users

Results from					**Using DSS-FS**				**FAO average yields**	**Soil and source water**		
Country	**Region**	**Year**	**Crop**	**Area (ha)**	**Average Yields (ton/ha)**	**Brix or °GL *****	**Production opportunity* (months)**	**Savings:** (energy, water fertilizers)	**Period (2005-2010)** ton/há	**Soil texture**	**water pH**	**water EC (mS/cm)**
Argentina	Tuc.	2011	pepper	4	100	-	10	40%	23.5**	medium	7	0.23
			tomato	4	120	-	10	40%	40	medium	7	0.23
	NW B.A.	2011	lettuce	0.25	38	-	2	-	13.8**	medium	7.1	0.8
Mexico	B. Calif.	2012	lawn	2	4500m^2	-	12	50%	-	coarse	8	2.0 (des. Plant)
		2012	ornam.	4	10000 plants/ ha	-	12	50%	-	coarse	8	2.0 (desaliniz. Plant)
		2011	strawb	4	58	12%	-	-	32.6	-	-	-
	Michoac	2011	strawb	70	92	-	7	-	32.6	medium	6.7	0.6
Brazil	S. Paulo	2011	tomato	10	110	4.9%	-	-	60.8	medium	6.6	0.5
Uruguay	-	2011	citrus fruit	600	20	10.2%	12	15%	15.5	-	7	0.5
Guatemala	A. Vera	2011	tomato	1	65	4.8%	3.5	40%	36.8	medium	7.2	0.38
Portugal	Beira	2011	cherries	2	15	-	12	-	1.8	coarse	-	-
	Alentejo	2012	raspberr.	7	19	-	2x3	20%	5.5**	coarse	7.1	0.6
	Porto	2011	wine	10	7000L /ha	13°	12	-	-	medium	-	-
Spain	Valencia	2011	citrus fruit	4	30.7	-	12	10%	2.9	medium	-	-
Moldova	-	2011	tomato	2	80	-	9	30%	15.4**	medium	7.6	0.3

***** *The Production opportunity in this study refers to the period during which it is possible to cultivate the crop. It is then referred as a multiple of the basic crop cycle. In other words, it indicated the number of months per year during which it is possible to be in a crop cycle. This value is bigger for protected crops or tropical and subtropical climates but smaller in temperate climate conditions.*

*** The FAO averages for Argentina (pepper), Argentina (lettuce), Portugal(raspberries) and Moldova (tomato)have been replaced by the averages from Brazil, Chile, Spain and Romania, respectively, for the same crops, because of the lack of data from the former countries..*

*** *Depending on the crop, one of the following quality indicators was used:*

Brix (%) is an indicator of the dissolved solid gravimetric content (w/w).

ºGL - Gay-Lussac degree (º) is an indicator of the alcoholic volumetric content (v/v).

Figure 50 and figure 51 show the yield results of DSS-FS in tomato and citrus fruit production in Spain and South America. These yields were compared to the averages reported by FAO for the same regions during the previous 5 years (2005-2010). It is evident and expectable that the DSS-FS supports considerably higher results than the FAO averages.

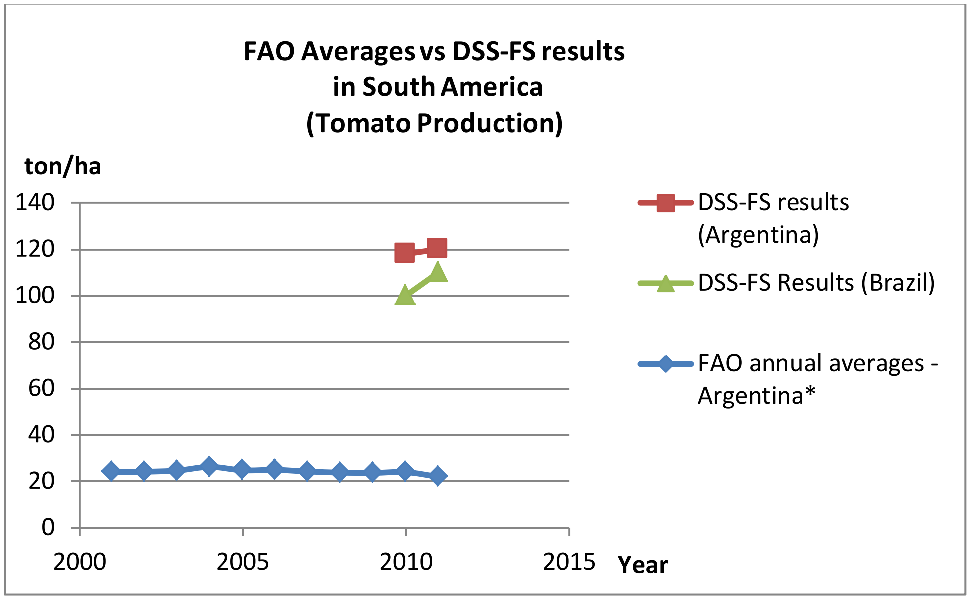


Fig. 50. DSS-FS results for tomato production in South America

**No available data for Brazil averages*

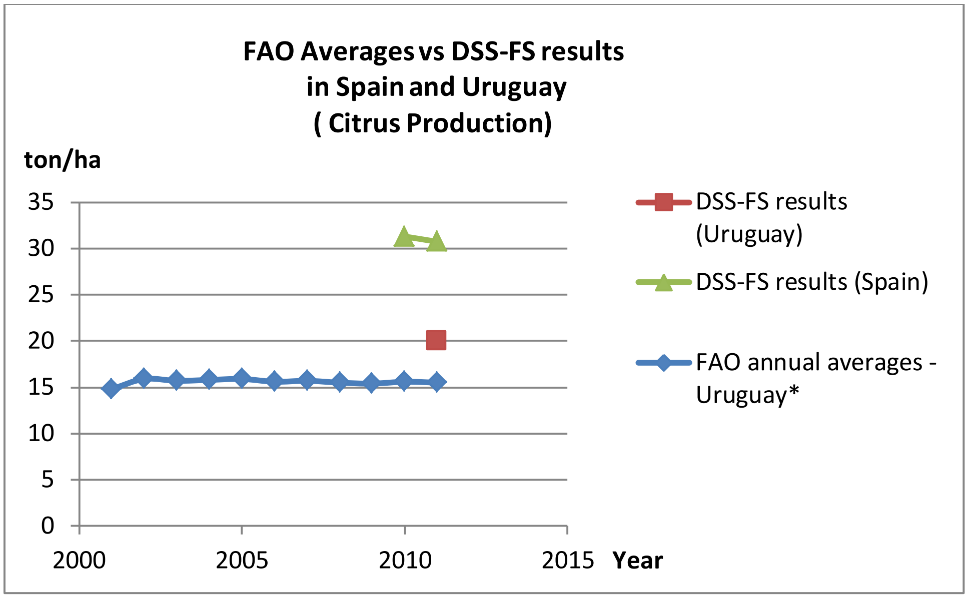


Fig. 51. DSS-FS results for citrus production in Uruguay and Spain

**No available data for Spain averages*

All the users from Mexico, Argentina and Guatemala report savings of water, energy and fertilizers higher than 40% and the remaining users reporting savings varying from 10% to 30% by using DSS-FS as primary consulting system (see table 2).

6.2 A brief discussion on DSS-FS results worldwide

The higher number of users of South America locations (see fig. 1) might be connected to our attempts to broadcast the existence of DSS-FS in fertigation forums online using Spanish as the main conversation language.

Online forums related to fertigation in English language have been more difficult to find and the number of registered users in these forums was also smaller. It is clearly according to our effort to find potential DSS-FS users online that the discussion groups related to fertigation issues are mostly populated by Spanish speaking people.

Among the users' comments, it is important to mention that the majority of the users consider the DSS-FS a very practical and useful application allowing to simplify the decision making process. The percent of users (out of those who actually applied the DSS-FS and answered the questionnaire) declaring being satisfied with the interface interaction and final results was almost 100%.

It is convenient to make a reference to the fact that the high volume of traffic related to the Czech Republic is a consequence of the website being accessed by the author during the software development and management. It is also worth mentioning that a considerable part of the North American traffic is possibly caused by Google and other search engines indexation.

From the list of other countries (see figures 3 and 4) we would like to specifically mention Morocco, United Arab Emirates, Saudi Arabia, Iran and Israel as home countries of some users who have actually installed the software package and requested serial numbers to activate the DSS-FS in their computers. The server logger has grouped these countries into "others" due to low traffic compared to the remaining locations.

These preliminary results were obtained through a simplified questionnaire, requesting easily understandable information and aiming to persuade the highest number of users to provide us with their experience about using the DSS-FS by answering the questionnaire. Nevertheless, the use of DDS-FS is to be analyzed on a higher level of detail in the future in order to better understand the users' its requirements, suggestions for improvement and real expectations.

6.3 Conclusion on DSS-FS results worldwide

From the data gathered and analyzed in this study, we conclude that many users of the DSS–FS system achieved yield results that are significantly above the averages presented by FAO. Although these results might be similar to the ones achieved by other experts in fertigation (not representing the average), it is for non-technology-savvy users that the system was developed, as they are the ones who stand to reap the most benefits from it.

By designing a user-friendly, intuitive system that affords a tailored solution to a basic agriculture production scenario, we are aiming at two distinct goals. On the one hand, to improve efficiency and crop yield, on the other hand, to introduce these users to the wide range of software and technological tools at their disposal, to which the DSS-FS is an easy, free-of-cost, first step.

The future of this applied software considers the development of new modules involving plant pathology, economic analysis and other relevant features, whilst pursuing the continuous improvement of the existing ones.

7 CONCLUSION

The development of the Decision Support System - Fertigation Simulator (DSS-FS) has focused on bringing sustainability wherever irrigation is needed, providing the know-how in a accessible and didactical way, in order to preserve soil and groundwater resources.

The DSS-FS seems to be a helpful tool in terms of searching for and analyzing modernization of irrigation design. Designing drip and sprinkler irrigation systems involves selection from a large number of combinations of main factors, which becomes easier through a DSS-FS tool. In addition, the DSS-FS is conceived in such a manner that the user may learn through the application process.

DSS-FS starts using FAO methodology to estimate crop water requirements; however it presents an innovation allowing the application of this methodology also to drip irrigation scenarios. This was achieved by eliminating the dry zones outside the wet cylinders between irrigation lines in the estimation (Moreira Barradas, 2012).

When computing fertigation requirements, it was possible to estimate the optimum concentration of one single nutritive element resulting in the ideal element concentration in the soil solution after soil interaction. The extension of this study into a complete nutritive solution involving not only one single element but using all the necessary ions for plant growth will be certainly a great step forward on the field of fertigation outside hydroponic scenarios.

From the non-linear regressions correlating Salinity of different commercial fertilizers or nutritive salts (Moreira Barradas, 2012) to electro-conductivity (EC) it was then obtained an expression to relate the final EC to the individual concentrations of each nutritive salt in solution.

After obtaining the ideal relationship between the proportions of N, P, K + Ca + Mg + S in solution according to the FEI (Moreira Barradas et al, 2012), it is then possible by using the Cramer rule to solve a system of 6 equations (6 nutritive salts) with 6 unknowns (N, P, K, Ca, Mg, S) in order to calculate the ideal concentration of each salt in the optimum nutritive solution.

Finally the DSS-FS (Moreira Barradas et al, 2012) uses commonly known methodologies in order to estimate losses of energy along pipes and drip lines, also to estimate required systems power, flow rate, pressure and other requirements producing complete design features for the ideal drip or sprinkler irrigation system willing to respond to each scenario to its irrigation/fertigation needs.

Since 2008, when the first version of the DSS-FS has been released, its web download center has been visited 19567 times and more than 2500 downloads have been made by users from all five continents. The users report to be mostly agricultural entrepreneurs, students and technicians in the field of chemigation who have passed the information of DSS-FS existence from one to another.

Having analyzed the data gathered, we found that many users of the DSS – FS system achieved results that are significantly above the average. Although the average (as reported by FAO) falls somewhat below the initial estimate used in DSS-FS, it reminds us that many users have had limited or no prior experience with computer tools or technology. It is precisely for non-technology-savvy users that the system was developed, as they are the ones who stand to reap the most benefits from it. By designing a user-friendly, intuitive system that affords a tailored solution to a basic agriculture production scenario, we are aiming at two distinct goals.

On the one hand, to improve efficiency and crop yield, on the other hand, to introduce these users to the wide range of software and technological tools at their disposal, to which the DSS-FS is an easy, free-of-cost, first step.

The future of this project considers the development of new modules involving plant pathology, economic analysis and other relevant features, whilst pursuing the continuous improvement of the existing ones.

Acknowledgement

This study was partly supported by the research grant no. MSM6046070901 „Sustainable agriculture, quality of agricultural products, sustainable use of natural and landscape resources“ of the Czech University of Life Sciences in Prague, financed by the Ministry of Education, Youth and Sports of the Czech Republic.

Software availability

Name of software: Fertigation Simulator

Programming language: Visual Basic

Developer: Joao M. M. Barradas - Czech University of Life Sciences Prague, Faculty of Agrobiology, Food and Natural Resources, Department of Water Resources, Czech Republic, EU, barradas@af.czu.cz, suporte@agrolaboratory.com

Availability and online documentation: Download with manual and supporting material at: http://www.fertigationsimulator.com

8 REFERENCES

Acquaye, D.Kkjj., and Maclean, A.J., 1966. Potassium potential of some selected soils. Canadian Journal of Soil Science. Vol 46. 170-184.

Acquaye, D.K., Maclean, A.J., and Rice, H.M., 1967. Potential and capacity of potassium in some representative soils of Ghana. Journal of Soil Science. Vol 103. 79-89.

Allen, R. G., Pereira, L. S., Raes, D. and Smith, M. 1998. Crop evapotranspiration - Guidelines for computing crop water requirements - *FAO Irrigation and drainage paper* 56, FAO, Roma. 328 pp.

Anderson,R. and Wu, Y., 2001. Phosphorus quantity-intensity relationships and agronomic measures of P in surface layers of soil from a long-term slurry experiment. Chemosphere. Vol 42. 161-170.

Andriolo, J., Janisch, D. I., Oliveira, C. S., Cocco, C., Schmitt, O. J., Cardoso, F. L., 2009. Three fertigation methods in soilless production of the strawberry crop. departamento de Fitotecnia, Centro de Ciências Rurais (CCR), Universidade Federal de Santa Maria (UFSM).

Ayers, R.S., and Westcott, D.W., 1976. Water Quality for Agricultue, Irrigation and Drainage Paper, 29, FAO, Rome, 1976; rev. 1986.

Battilani, A., Plauborg, F., Hansen, S., Dolezal, F., Mazurczyk, W., Bizik, J., Coutinho, J., 2008: Nitrogen uptake and nitrogen use efficiency of fertigated potatoes. In: International Symposium on Irrigation of Horticultural Crops, No 5, Mildura, Victoria, Australia, 28/8 – 2/10 2006. Acta Horticulturae 792, p. 61-67. Published by International Society for Horticultural Science.

Battiliani, A., Plauborg F.L., Hansen S., Dolezal F., Mazurczyk W., Bizik J., Coutinho J. 2008: Water use efficiency and dry matter accumulation in fertigated potatoes - Acta Horticulture 792, 77-84

Beckett, P.H.T., 1964. The immediate Q/I relations of labile potassium in the soil. Journal of Soil Science. Vol 15. 9-13.

Bohn, H., McNeal, B., and O'Connor, G. 1979. Soil Chemistry. John Wiley & Sons, Toronto, ON, Canada.

Bresler, E. 1977. Trickle drip irrigation principles and application to soil water management. Advances in Agronomy, Volume **29**, University of Delaware, Newark, pp. 343-393.

Christiansen, J. E. 1942. Irrigation by sprinkling, California Agric. Experiment Station Bull. 670, CA.: Berkeley. 124 pp.

Colebrook, C. F. and White, C. M. 1937. Experiments with Fluid Friction in Roughened Pipes. *Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences, Volume* **161** (906). 367–381

Das, S.C., Sen Gupta, M. and Ghosh, S.K., 1980. Quantity-Intensity (Q/I) relationships of some soil clays of west Bengal in relation to their clay mineralogy. Proceedings of the Indian National Science Academy. Vol 46, A, Nº 5. 499-508.

de Levie, R. 2003. The Henderson–Hasselbalch Equation: Its History and Limitations. Journal of Chemical Education, vol. **80**, p. 146.

Doležal, F., Vacek, J., Zavadil, J., 2005: Problems of potato growing and irrigation in highland regions of Czechia with regard to water resources protection. In: Integrated Land and Water Resources Management: Towards Sustainable Rural Development. Proceedings 21st European Regional Conference ICID, Frankfurt(Oder) and Słubice, 15-19 May 2005, CD

FAOSTAT (2010) http://faostat.fao.org/site/567/default.aspx#ancor

FERTORGANIC (2008) http://www.fertorganic.org

Mengel, K., Kirkby, E.A., 1987. Kosegarten, H., *Appel, T. Principles of plant nutrition*, Kluwer Academic publishers, 5th Ed., Dordrecht. 695 pp.

G.M. Bazzani, 2004. An integrated decision support system for irrigation and water policy design: DSIRR, National Research Council IBIMET, Italy.

Gil-Marín, J. A. 2001. Form and dimensions of wet bulb with the purpose of design of drip irrigation in two typical soils of savanna, *Revista Científica UDO Agrícola* Volumen **1**. Número 1. pp. 42-47

Hoagland, D. R. and Snyder, W. C. 1933. Nutrition of strawberry plants under controlled conditions, Proceedings of the American Society for Horticultural Science. **30** (1933), pp. 288–296

Jurinak, J. J. 1990. The chemistry of salt affected soils and waters. In Tanji, K. K., Ed., Agricultural Salinity Assessment and Management. ASCE, New York, NY, pp. 262-304.

Kafkafi, U., and Tarchitzky, J., 2011: Fertigation: A tool for efficient fertilizer and water management. First Edition, International Fertilizer Industry Association, Paris, France, and International Potash Institute, Horgen, Swizerland. See: www.fertilizer.org/.../2011_ifa_fertigation.pdf, downloaded on 15 February 2013.

Maas, E.V., Hoffman, G.J., 1977. Crop salt tolerance, current assessment. J. Irrig. Drain. Div. ASCE 103, 115-134.

Magen, H., 1995: Fertigation: An overview of some practical aspects. See: http://www.iclfertilizers.com/Fertilizers/Knowledge%20Center/Fertigation_overview_of_practical_aspects.pdf, accessed on 15 February 2013.

Mengel, K., Kirkby, E.A., 1987. Kosegarten, H., Appel, T. Principles of plant nutrition, Kluwer Academic publishers, 5th Ed., Dordrecht. 695 pp.

Moodie, C.D., Smith, H.W., and McCreery, P.R., 1959. Laboratory Manual for Soil Fertility. State College of Washington, Mimeograph, Pullman, Washington, 175pp.

Moreira Barradas, J. M., Matula, S., Dolezal, F., 2012. A Decision Support System-Fertigation Simulator (DSS-FS) for design and optimization of sprinkler and drip irrigation systems. Compututers and Electronics in Agriculture. Vol 86. 111-119.

Nemeth, K., 1979. The availability of nutrients in the soil as determined by electro-ultrafiltration (EUF). Advances in Agronomy. Vol 31. 155-188.

Nogueira, C. S. P., Coelho, E. F., Saraiva, M. C. 2000. Caracteristicas e dimensões do volume de um solo molhado sob gotejamento superficial e subsuperficial, Revista Brasileira de Engenharia Agrícola e Ambiental, v.**4**, n.3, Campina Grande. 315 pp.

Ranjha, A.M., Mehdi, S.M, SAIFULLAH and Mahmood, T., 2001. Quantity intensity relations of K in three alluvial soils. International Journal of Agriculture and Biology Vol 3. Nº 1.

Santos, J. Q. 1996. Fertilização - Fundamentos da Utilização de Adubos e Correctivos, Publicações Europa América, Mem Martins. 394 pp.

Singandhupe, R.B., Rao, G.G.S.N., Patil, N.G., Brahmanand, P.S., 2003. Fertigation studies and irrigation scheduling in drip irrigation system in tomato crop (Lycopersicon esculentum L.), Europ. J. Agronomy 19, p. 327 - 340

S. Hansen, H.E. Jensen, N.E. Nielsen, H. Svendsen. Simulation of nitrogen dynamics in the soil–plant system using the Danish simulation model DAISY. Fertil. Res., 27 (1991), pp. 245–259

Shalhevet, J. 1994. Using water of marginal quality for crop production: major issues, Agricultural Water management, n.25, pp. 233-269

Sláma, V., 1969: Stanovení závlahových režimů zemědělských plodin. (Compiling irrigation schedules of agricultural crops. In Czech.) Part III – Grafická metoda (Graphical method), Metodiky pro zavádění výsledků výzkumu do praxe, No. 1, 1996, Ústav vědeckotechnických informací – Ústředí zemědělského a potravinářského výzkumu, Praha, 79 p. and appendices

Smith, M. CROPWAT. A computer program for irrigation planning and management. In: Irrigation and Drainage, Rome: FAO, 1992, 126p. Paper 46

Steel, R.G.D. and Torrie, J.H, 1980. Principles and Procedures of Statistics. McGraw Hill Book Co. New York, pp. 232-251.

Teixeira, J. L., 1992 RELREG – Programa para Condução da Rega em Tempo Real – Guia do Utilizador. Instituto Superior de Agronomia, Lisboa.

T. Heidmann, C. Tofteng, P. Abrahamsen, F. Plauborg, S. Hansen, A. Battilani, J. Coutinho, F. Dolezal, W. Mazurczyk, J.D.R. Ruiz, J. Takac & J. Vacek. 2008. Calibration procedure for a potato crop growth model using information from across Europe. Ecological Modelling, 211, 209-223.

U.S. Salinity Lab Staff, 1954. Diagnosis and Improvement of Saline and Alkali Soils. USDA Handbook No. 60. Washington, D.C. U.S.A.

van Genuchten, M. Th. 1980. A closed-form equation for pre- dicting the hydraulic conductivity of unsaturated soils. Soil. Sci. Soc. Am. J. 44:892-898.

Vivancos, A. D. 1993. *Fertirrigacion*, Mundi-Prensa, Madrid. 217 pp.

Williams, G. S. and Hazen, A. 1933. Hydraulic Tables, 3rd Ed., Rev. New York, N.Y.: John Wiley & Sons, Inc.

Zavadil, J., Doležal, F., Vacek, J., 2004: Vyplavování dusičnanů z půdy při pěstování brambor. (Leaching of nitrate from the soil in potato growing systems. In Czech.) Soil and Water, VÚMOP Praha, no. 3, p. 163 - 167..

ATTACHMENTS

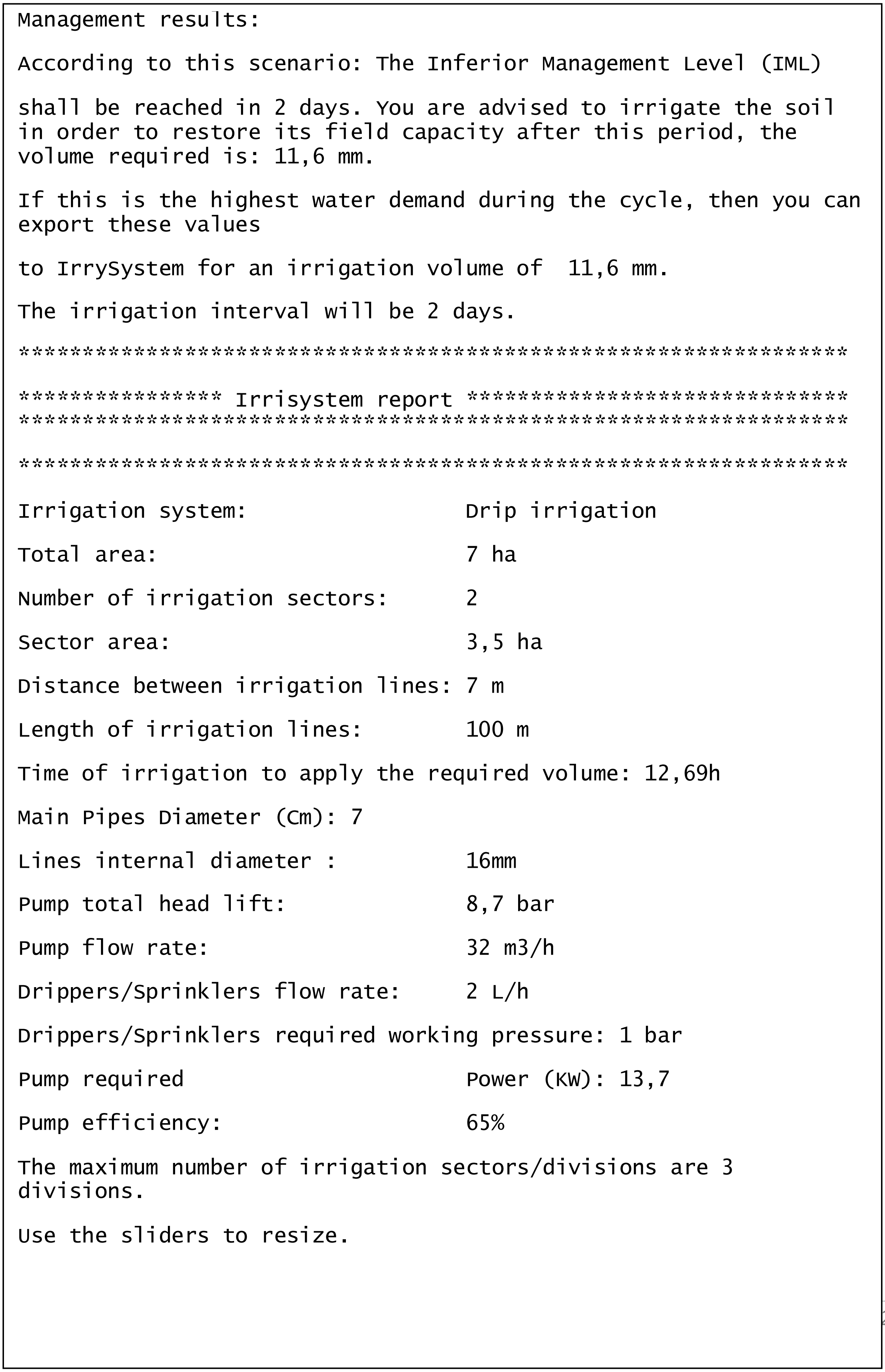
A1 - DSS-FS INPUT/OUTPUT data analysis

The manual and guidelines for DSS-FS are available at

http://www.fertigationsimulator.com

Olives

```
Czech University of Life Sciences Prague

Faculty of Agrobiology, Food and Natural Resources

Department of Water Resources

*****************************************************************

*********** Fertigation Simulator 2011 **************************

***********(By Joao M. Moreira Barradas)*************************

*****************************************************************

***********      Scenario analysis:       ***********************

*****************************************************************


[Not all input/output data is shown]

*****************************************************************

*********** Irrimanager report *********************************

*****************************************************************



Crop:           olives

Root depth:        81 cm

Wet bulb diameter:    52 cm

Average distance between lines (double drip line): 350 cm
```

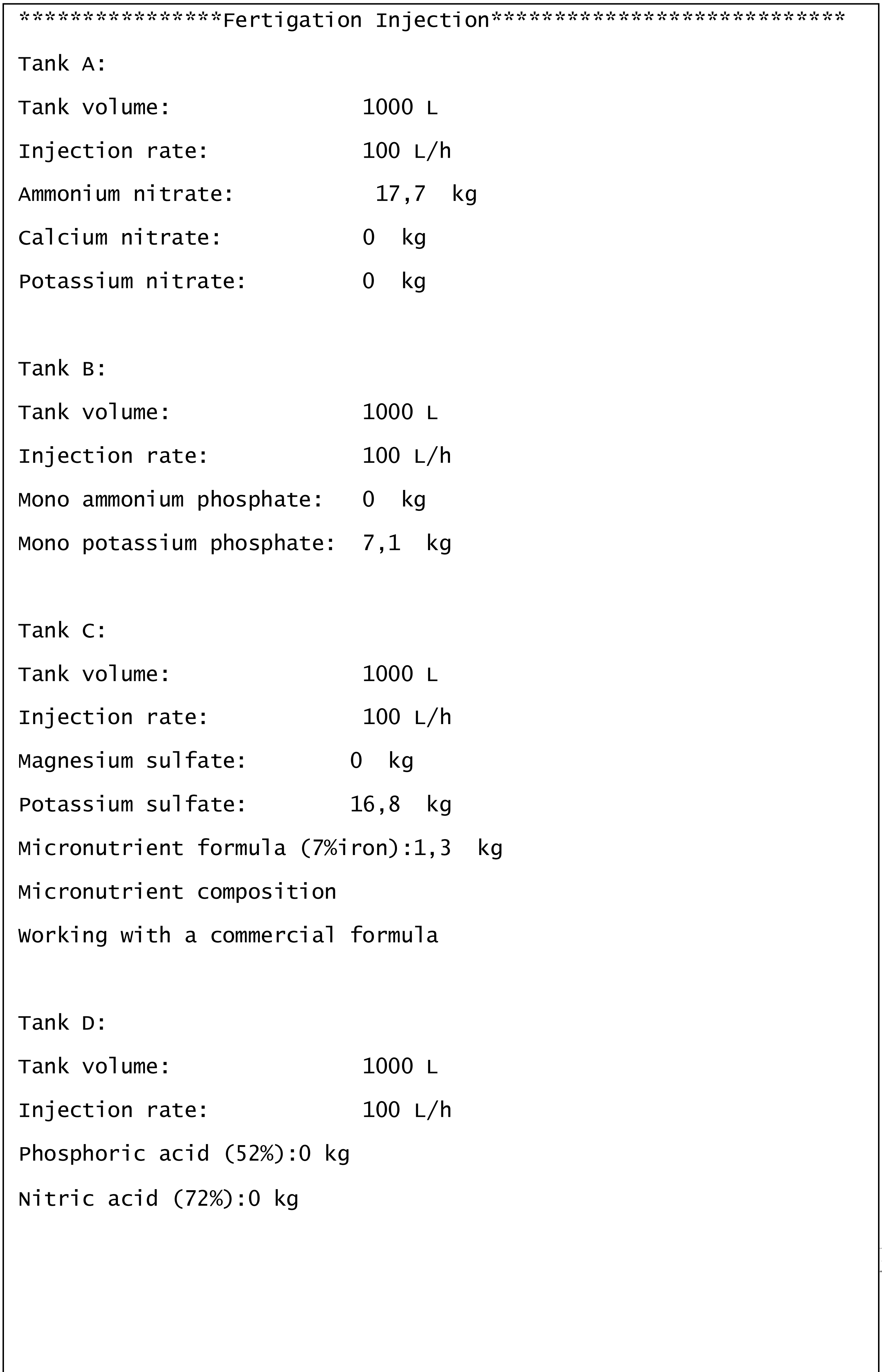


```
Management results:

According to this scenario: The Inferior Management Level (IML)

shall be reached in 2 days. You are advised to irrigate the soil
in order to restore its field capacity after this period, the
volume required is: 11,6 mm.

If this is the highest water demand during the cycle, then you can
export these values

to IrrySystem for an irrigation volume of  11,6 mm.

The irrigation interval will be 2 days.

*****************************************************************

**************** Irrisystem report ******************************
*****************************************************************

*****************************************************************

Irrigation system:                 Drip irrigation

Total area:                        7 ha

Number of irrigation sectors:      2

Sector area:                       3,5 ha

Distance between irrigation lines: 7 m

Length of irrigation lines:        100 m

Time of irrigation to apply the required volume: 12,69h

Main Pipes Diameter (Cm): 7

Lines internal diameter :          16mm

Pump total head lift:              8,7 bar

Pump flow rate:                    32 m3/h

Drippers/Sprinklers flow rate:     2 L/h

Drippers/Sprinklers required working pressure: 1 bar

Pump required                      Power (KW): 13,7

Pump efficiency:                   65%

The maximum number of irrigation sectors/divisions are 3
divisions.

Use the sliders to resize.
```

2013)

```
*****************************************************************

**************** Fertigation report *****************************
*****************************************************************

*****************************************************************

Crop:      Olive

Stage:     General

Flow  rate (L/h)      33000

Raw water characteristics

pH:        7

EC(mS/cm): 0,9


Anions which are present in the raw water

CO3-- :    0 mg/L

HCO3- :    455 mg/L

SO4-- :    3,2 mg/L

Cl- :      0 mg/L

NO3- :     9 mg/L

HPO4-- :   0 mg/L


Cations which are present in the raw water

Ca++       98,3 mg/L

Mg++       55,9 mg/L

K+         0,8 mg/L

Na+        30,4 mg/L

NH4+       0 mg/L
```

```
****************Fertigation Injection****************************
Tank A:
Tank volume:               1000 L
Injection rate:            100 L/h
Ammonium nitrate:           17,7  kg
Calcium nitrate:           0  kg
Potassium nitrate:         0  kg

Tank B:
Tank volume:               1000 L
Injection rate:            100 L/h
Mono ammonium phosphate:   0  kg
Mono potassium phosphate:  7,1  kg

Tank C:
Tank volume:               1000 L
Injection rate:            100 L/h
Magnesium sulfate:        0  kg
Potassium sulfate:        16,8  kg
Micronutrient formula (7%iron):1,3  kg
Micronutrient composition
Working with a commercial formula

Tank D:
Tank volume:               1000 L
Injection rate:            100 L/h
Phosphoric acid (52%):0 kg
Nitric acid (72%):0 kg
```

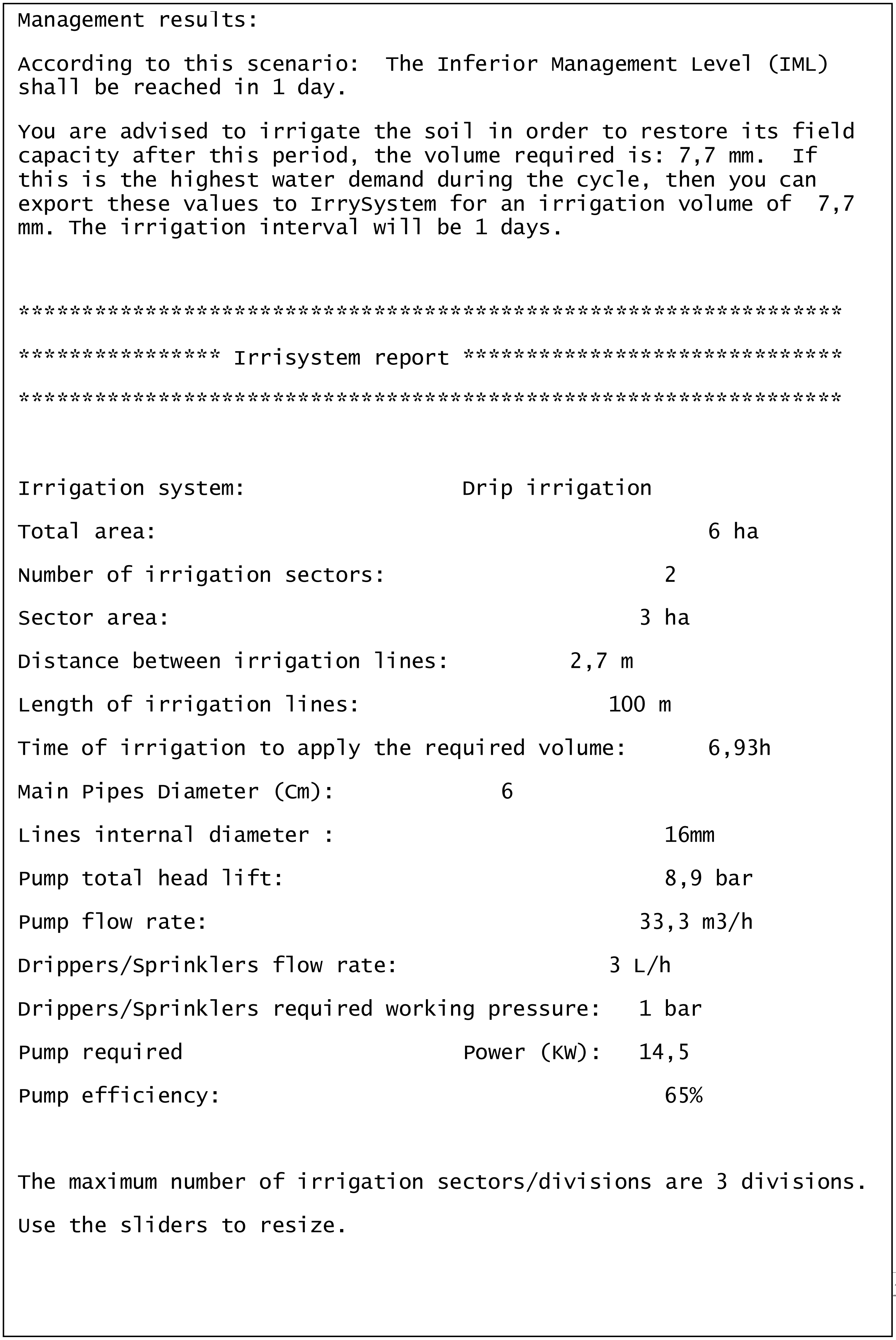


```
***************Fertigation Injection***************************
Tank A:
Tank volume:               1000 L
Injection rate:            100 L/h
Ammonium nitrate:           17,7  kg
Calcium nitrate:           0  kg
Potassium nitrate:         0  kg

Tank B:
Tank volume:               1000 L
Injection rate:            100 L/h
Mono ammonium phosphate:   0  kg
Mono potassium phosphate:  7,1  kg

Tank C:
Tank volume:               1000 L
Injection rate:            100 L/h
Magnesium sulfate:        0  kg
Potassium sulfate:        16,8  kg
Micronutrient formula (7%iron):1,3  kg
Micronutrient composition
Working with a commercial formula

Tank D:
Tank volume:               1000 L
Injection rate:            100 L/h
Phosphoric acid (52%):0 kg
Nitric acid (72%):0 kg
```

```
Resulting fertigation solution

pH:                  6,9

p[H]:                7

EC(mS/cm):           1,1


Nutritive elements(ppm)

N:                   20,1

P2O5:                12,1

K2O:                 25,8

Ca:                  98

S:                   9,4

Mg:                  93


Balance report:

End of report
```

Vine

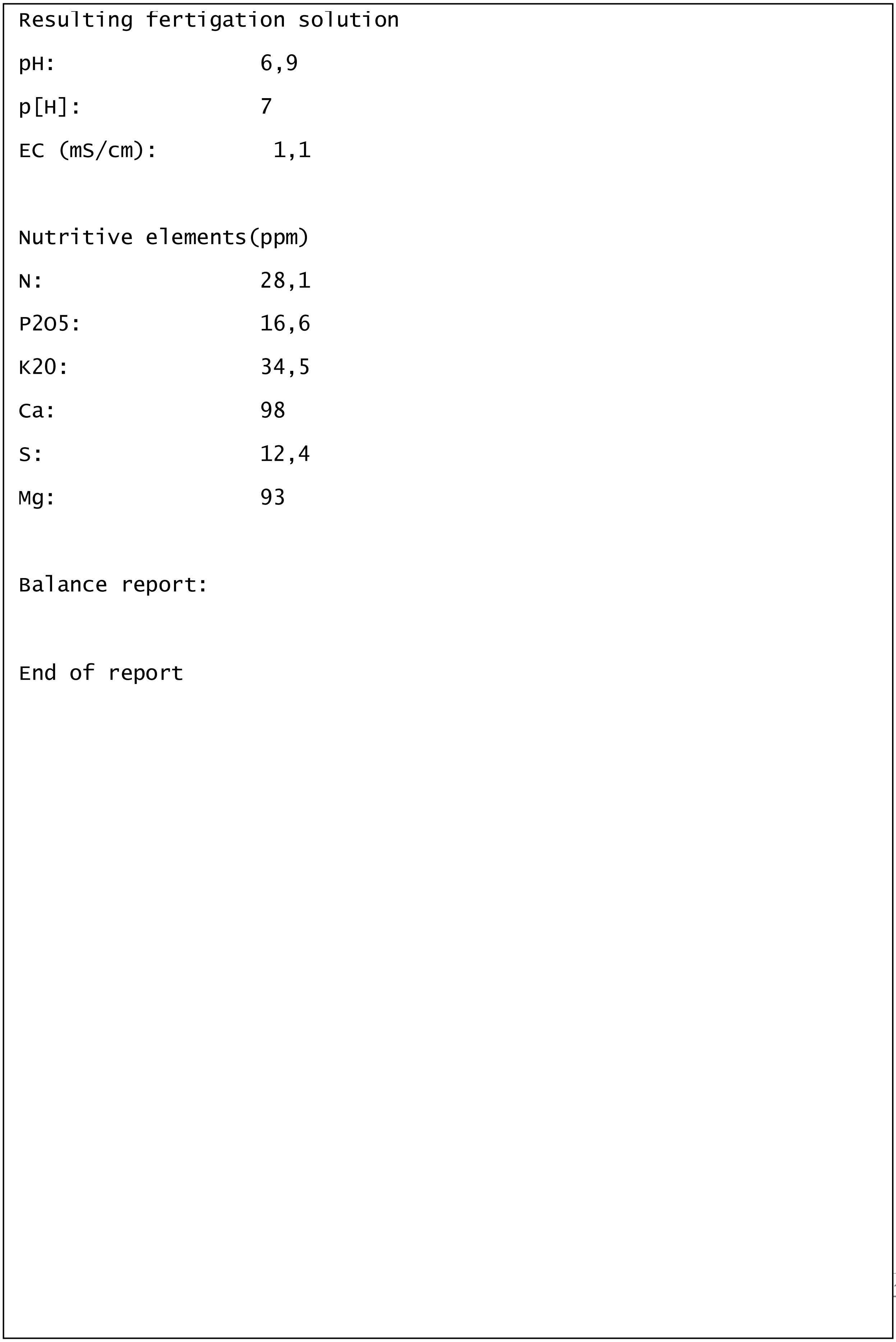
```
Czech University of Life Sciences Prague
Faculty of Agrobiology, Food and Natural Resources
Department of Water Resources
*****************************************************************
*********** Fertigation Simulator 2011 **************************
***********(By Joao M. Moreira Barradas)*************************
*****************************************************************
***********      Scenario analysis:       ***********************
*****************************************************************

[Not all input/output data is shown]
*****************************************************************
*********** Irrimanager report *********************************
*****************************************************************

Crop:                                        vine
Root depth:                            81 cm
Wet bulb diameter:                     52 cm
Average distance between lines:       270 cm
```



```
Management results:

According to this scenario:  The Inferior Management Level (IML)
shall be reached in 1 day.

You are advised to irrigate the soil in order to restore its field
capacity after this period, the volume required is: 7,7 mm.  If
this is the highest water demand during the cycle, then you can
export these values to IrrySystem for an irrigation volume of  7,7
mm. The irrigation interval will be 1 days.



*****************************************************************

**************** Irrisystem report ******************************

*****************************************************************



Irrigation system:                 Drip irrigation

Total area:                                           6 ha

Number of irrigation sectors:                      2

Sector area:                                     3 ha

Distance between irrigation lines:         2,7 m

Length of irrigation lines:                   100 m

Time of irrigation to apply the required volume:      6,93h

Main Pipes Diameter (Cm):             6

Lines internal diameter :                          16mm

Pump total head lift:                              8,9 bar

Pump flow rate:                                  33,3 m3/h

Drippers/Sprinklers flow rate:                3 L/h

Drippers/Sprinklers required working pressure:   1 bar

Pump required                      Power (KW):   14,5

Pump efficiency:                                   65%


The maximum number of irrigation sectors/divisions are 3 divisions.

Use the sliders to resize.
```

```
*****************************************************************
**************** Fertigation report *****************************
*****************************************************************


Crop:      Vine
Stage:     General

Flow  rate (L/h)      33000

Raw water characteristics
pH:        7
EC(mS/cm): 0,9

Anions which are present in the raw water
CO3-- :    0 mg/L
HCO3- :    455 mg/L
SO4-- :    3,2 mg/L
Cl- :      0 mg/L
NO3- :     9 mg/L
HPO4-- :   0 mg/L

Cations which are present in the raw water
Ca++       98,3 mg/L
Mg++       55,9 mg/L
K+         0,8 mg/L
Na+        30,4 mg/L
NH4+       0 mg/L
```

```
****************Fertigation Injection****************************
Tank A:
Tank volume:               1000 L
Injection rate:            100 L/h
Amonium nitrate:           25,6  kg
Calcium nitrate:           0  kg
Potassium nitrate:         0  kg

Tank B:
Tank volume:               1000 L
Injection rate:            100 L/h
Mono ammonium phosphate:   0  kg
Mono potassium phosphate:  9,8  kg

Tank C:
Tank volume:               1000 L
Injection rate:            100 L/h
Magnesium sulfate:        0  kg
Potassium sulfate:        22,7  kg
Micronutrient formula (7%iron):1,8  kg

Micronutrient composition
Working with a commercial formula

Tank D:
Tank volume:               1000 L
Injection rate:            100 L/h
Phosphoric acid (52%):0 kg
Nitric acid (72%):0 kg
```



```
Resulting fertigation solution
pH:                6,9
p[H]:              7
EC (mS/cm):         1,1

Nutritive elements(ppm)
N:                 28,1
P2O5:              16,6
K2O:               34,5
Ca:                98
S:                 12,4
Mg:                93

Balance report:


End of report
```

A2 - DSS-FS Questionnaire - application world wide

The following questionnaire has been submitted to all users registered as agricultural entrepreneurs in order to obtain credible results on the performance of the DSS-FS.

DSS-FS FERTIGATION SIMULATOR – QUESTIONNAIRE

*

1. How did you know about the Agrolaboratory DSS-FS Fertigation Simulator

○ Our publication in the scientific journal Computers and Electronics in Agriculture http://www.sciencedirect.com/science/article/pii/S0168169912000555

○ Google

○ I was informed by colleagues / teachers

○ I saw it in a forum online

Other (specify) ☐

*

2. Some data about the production unit where this software was tested:

User: ☐

Crop: ☐

Total area: ☐

Expected production: ☐

Actual production: ☐

Length of the crop cycle:

Quality indicators: (brix, %oil, % sugar)

Country/Region:

Year:

e-mail:

3. Data from other crops also produced (optional)

Crop:

Area:

Expected production:

Actual production:

Quality indicator (brix, %oil,

%sugar etc)

Cycle length (months)	
Year:	

*

4. Protection System

○ Greenhouse

○ Open field

*

5. Soil texture:

○ Heavy

○ Medium

○ Coarse

○ Hydroponics

○ No information

6. Chemical properties of the water from the source (pH and electroconductivity) before fertigation:

7. How much water, fertilizer and energy have you saved using DSS-FS Fertigation SImulator?

○ >50%

○ 40%-50%

○ 30%-40%

○ 20%-30%

○ 10-20%

○ 0%-10%

○ I didn't save, my costs were even higher

○ I do not have enough information about this

8. Please make any additional comments about this system (DSS-FS Agrolaboratory Fertigation Simulator) Optional

A3

Figure 52 showing 2 years of results with DSS-FS pepper production in Argentina

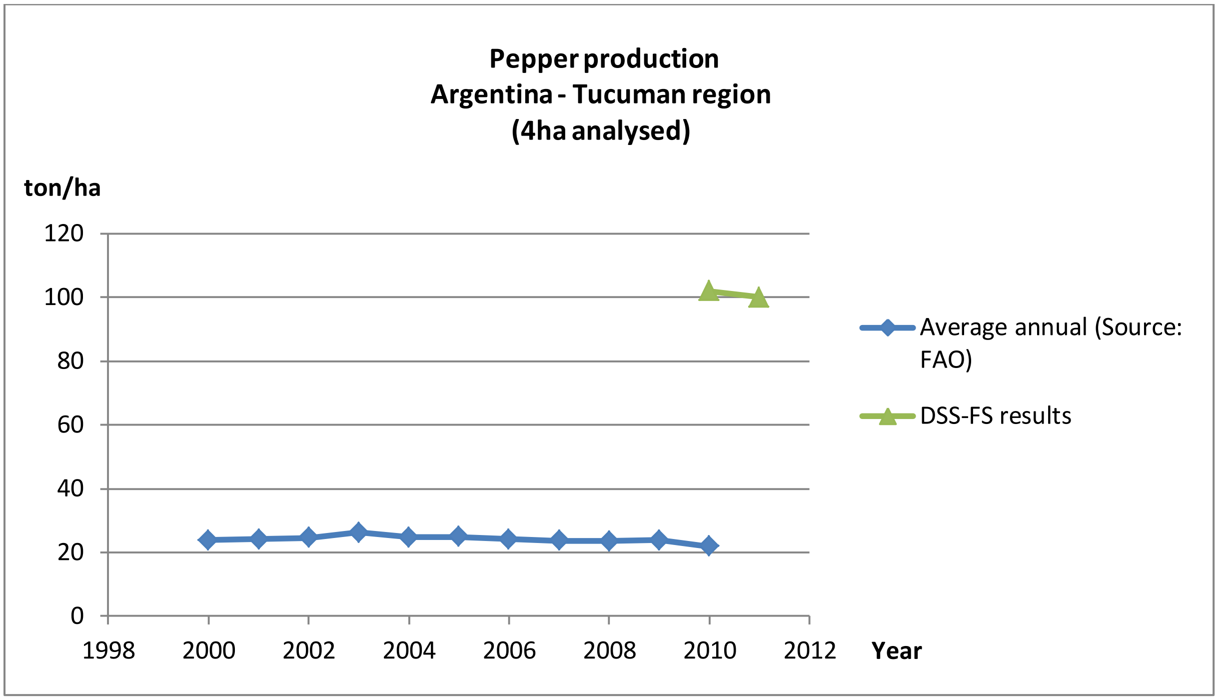


Fig. 52 – DSS-FS Argentina (pepper)

Figure 53 showing 2 years of results with DSS-FS tomato production in Argentina

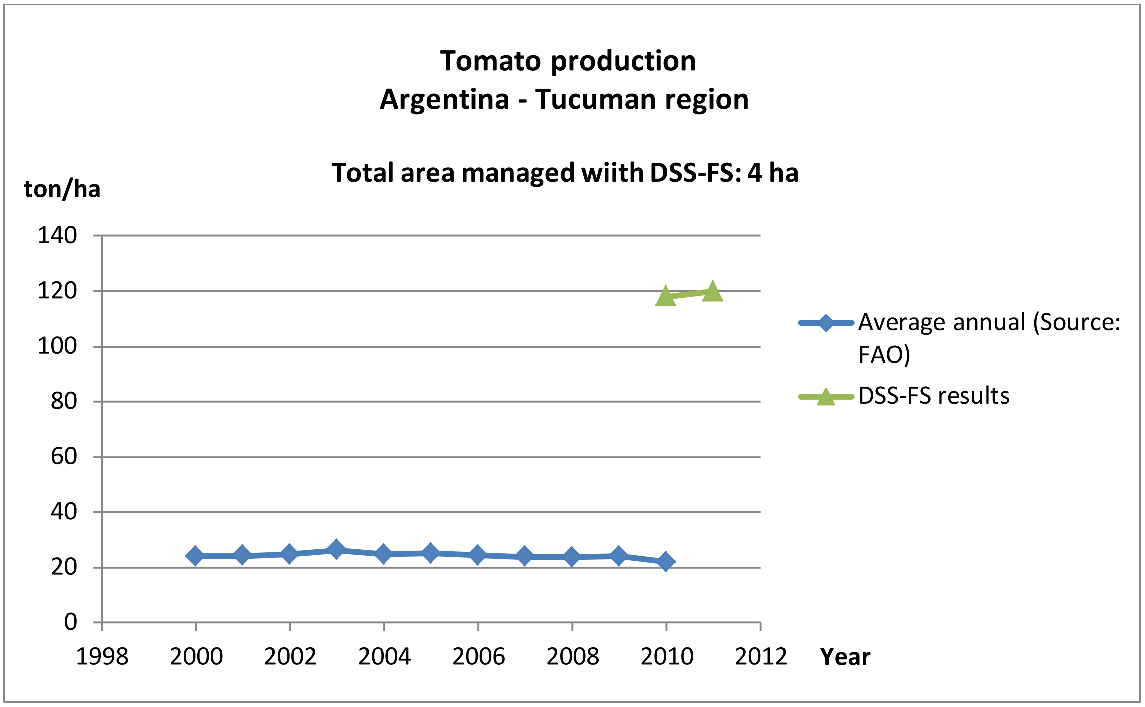


Fig. 53 - DSS-FS Results – Argentina (tomatoes)

Figure 54 showing results with DSS-FS lettuce production in Argentina

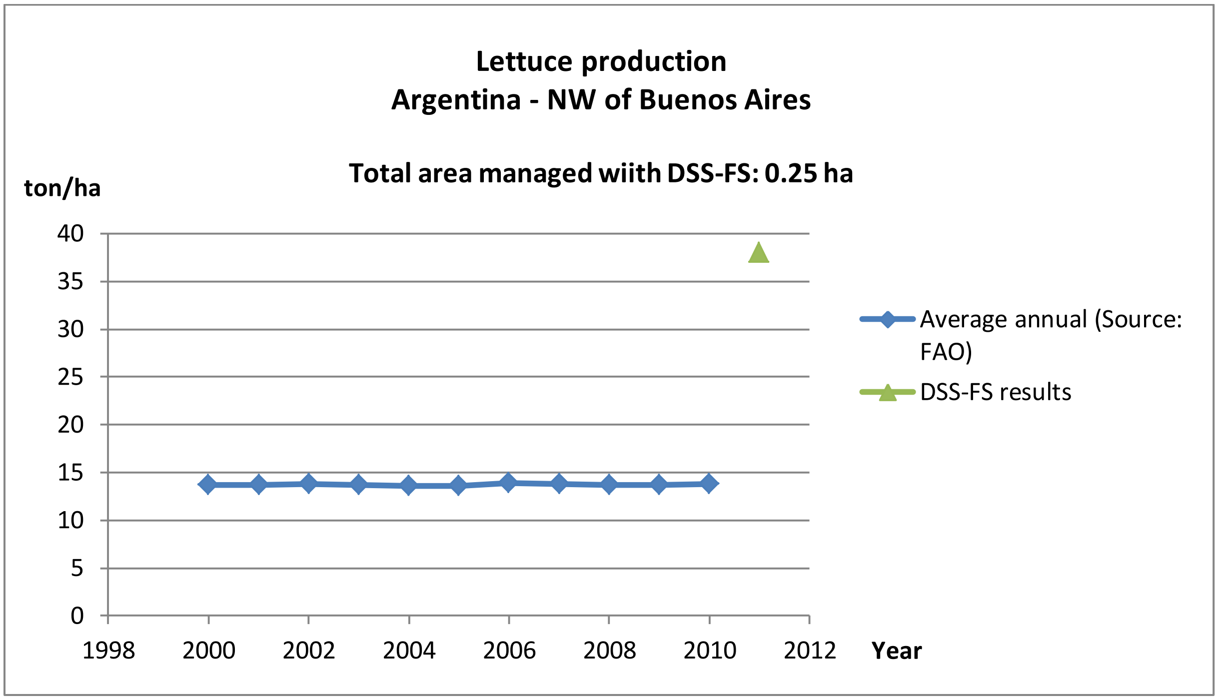


Fig. 54 - DSS-FS Results – Argentina (lettuce)

Figure 55 showing the results with DSS-FS strawberries production in México

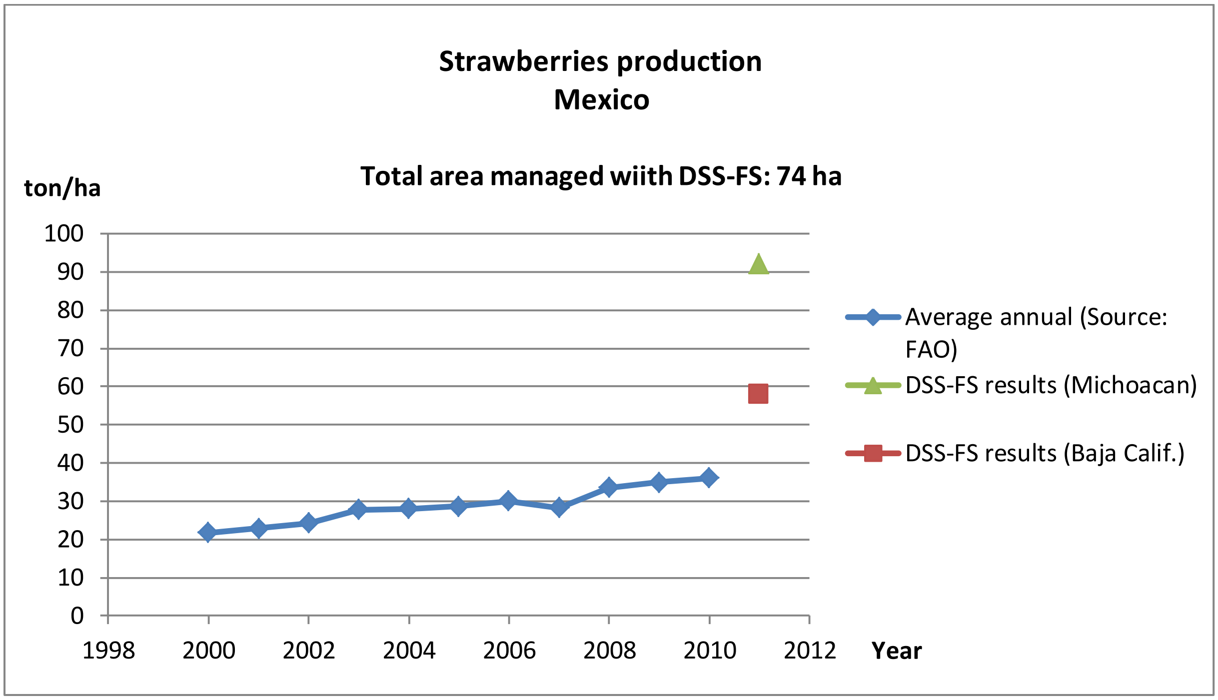


Fig. 55 - DSS-FS Results – México (Strawberries)

Figure 56 showing the results with DSS-FS - tomato production in Brazil

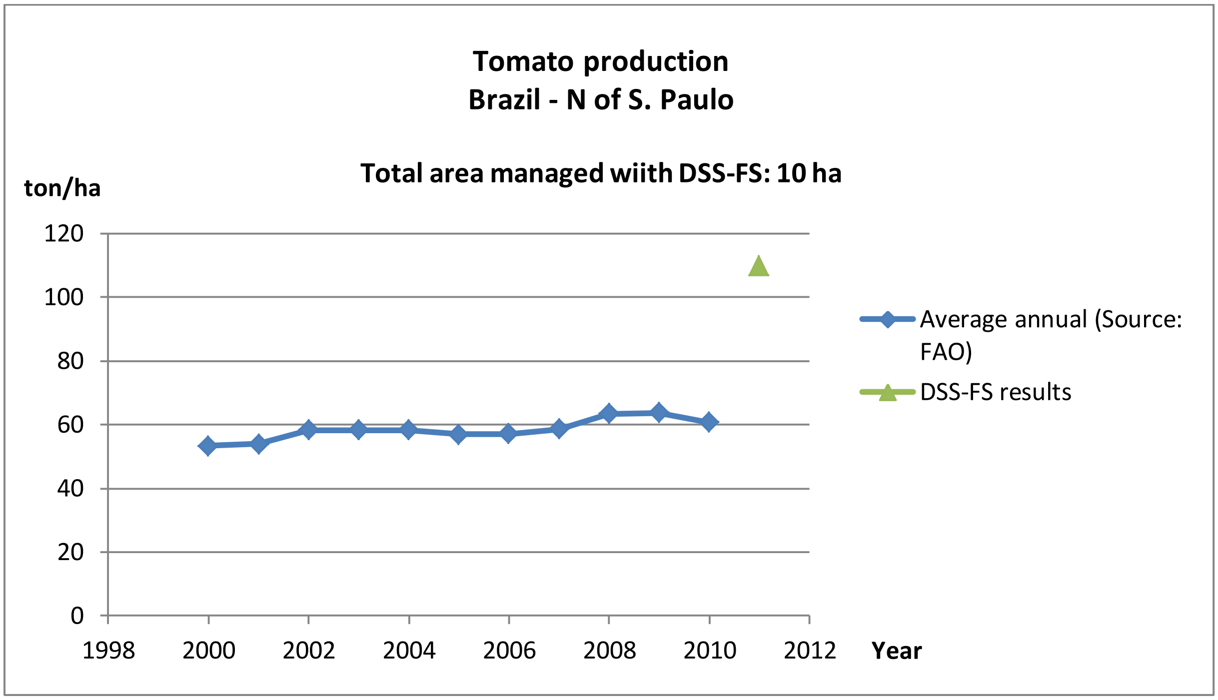


Fig. 56 - DSS-FS Results – Brazil

Figure 57 showing the results with DSS-FS – citrus production in Uruguay

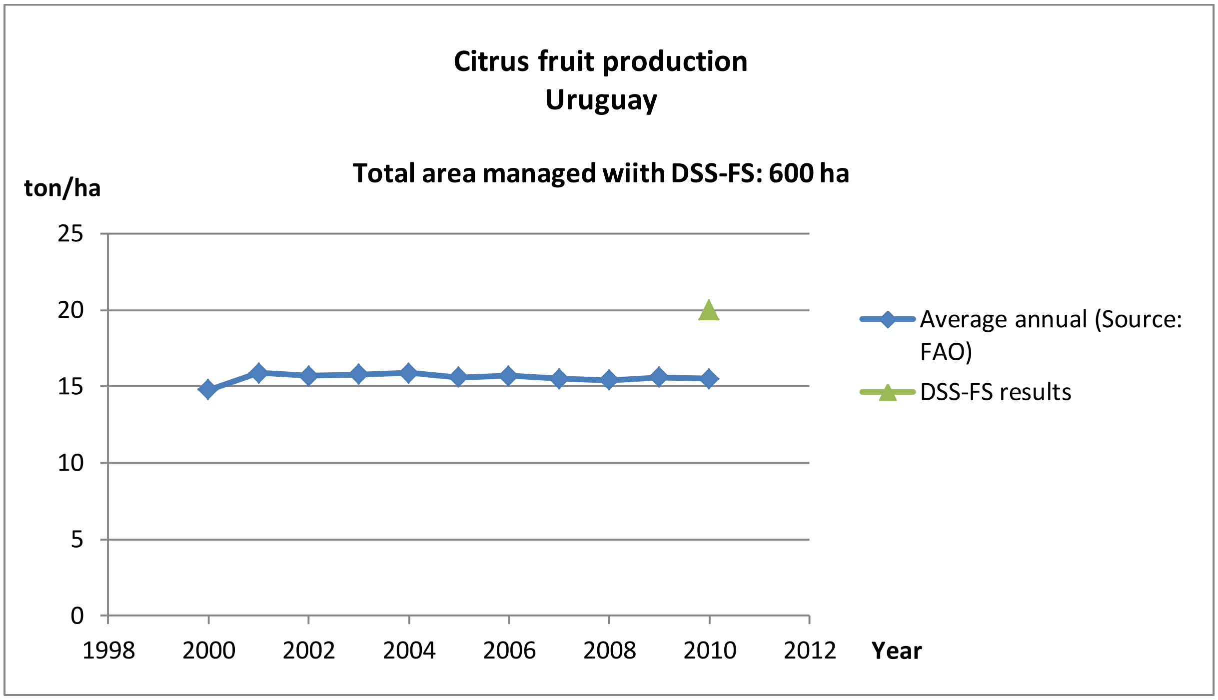


Fig. 57 - DSS-FS Results – Uruguay

Figure 58 showing the results with DSS-FS - tomato production in Guatemala

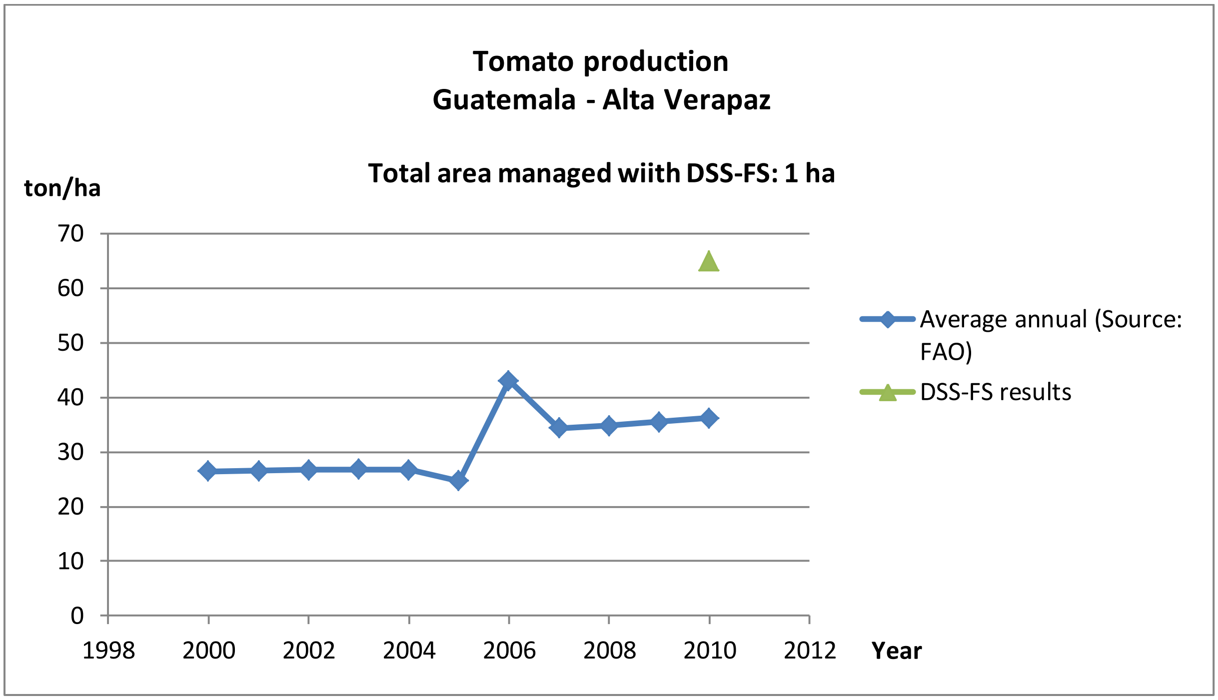


Fig. 58 - DSS-FS Results – Guatemala

Figure 59 showing the results with DSS-FS - reaspberries production in Portugal

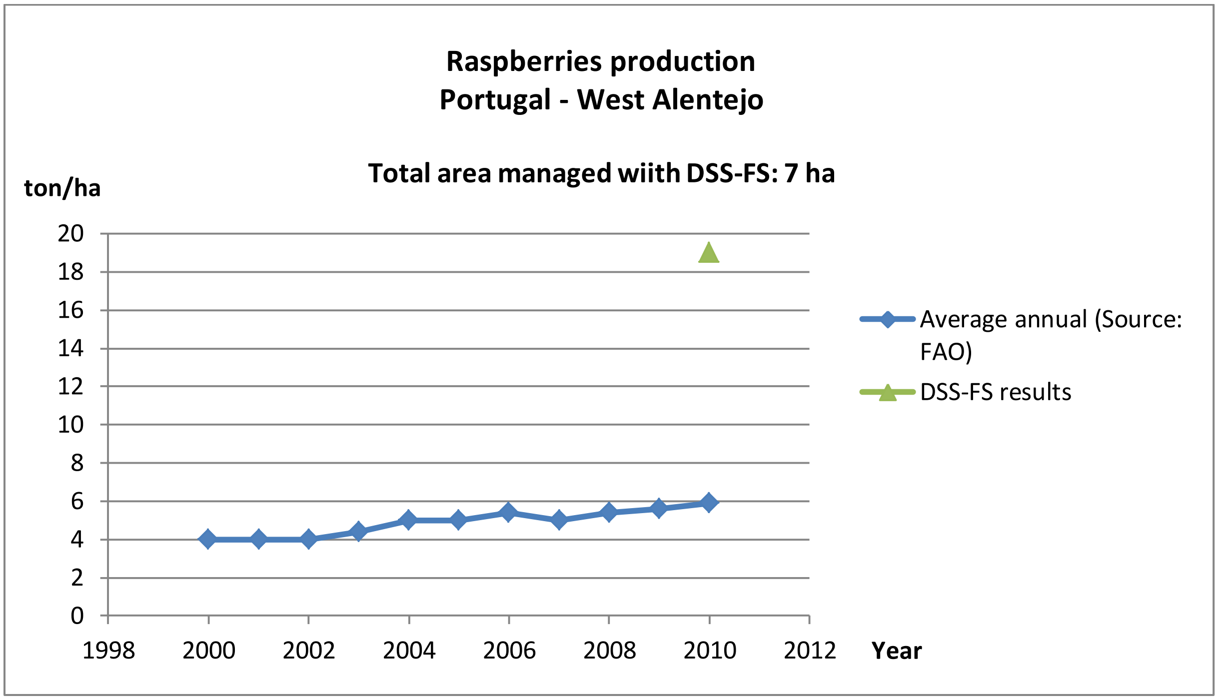


Fig. 59 - DSS-FS Results – Portugal (raspberries)

Figure 60 showing the results with DSS-FS - cherries production in Portugal

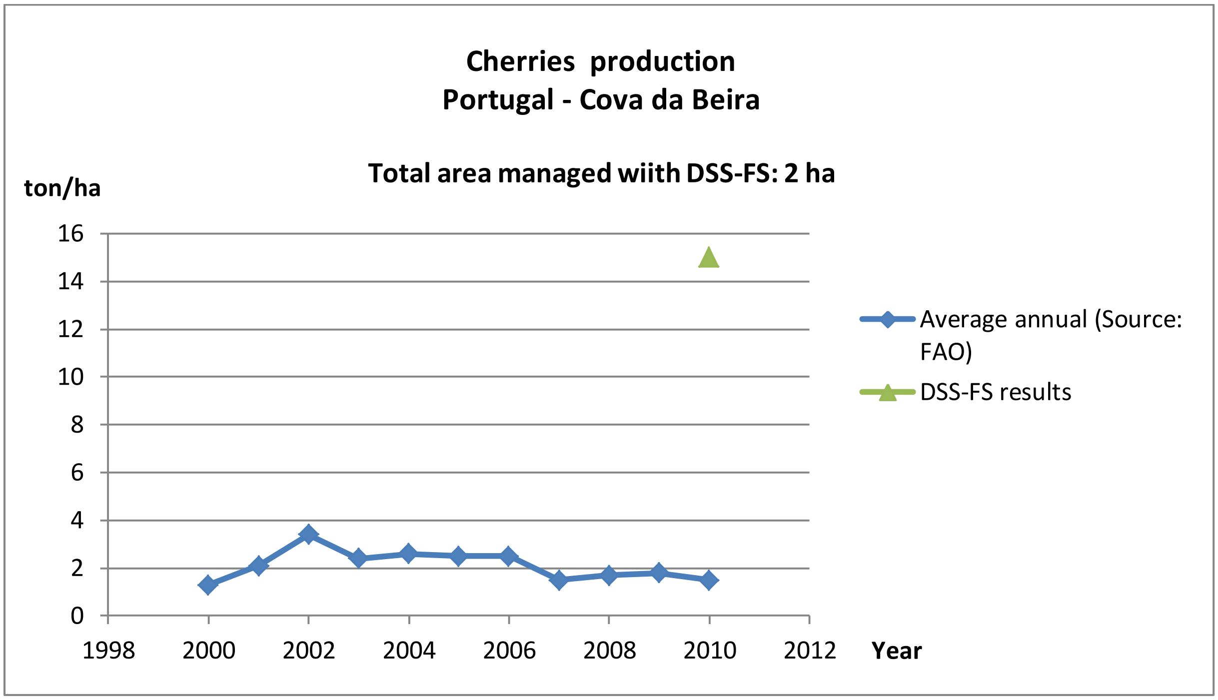


Fig. 60 - DSS-FS Results – Portugal (cherries)

Figure 61 showing the results with DSS-FS - citrus production in Spain

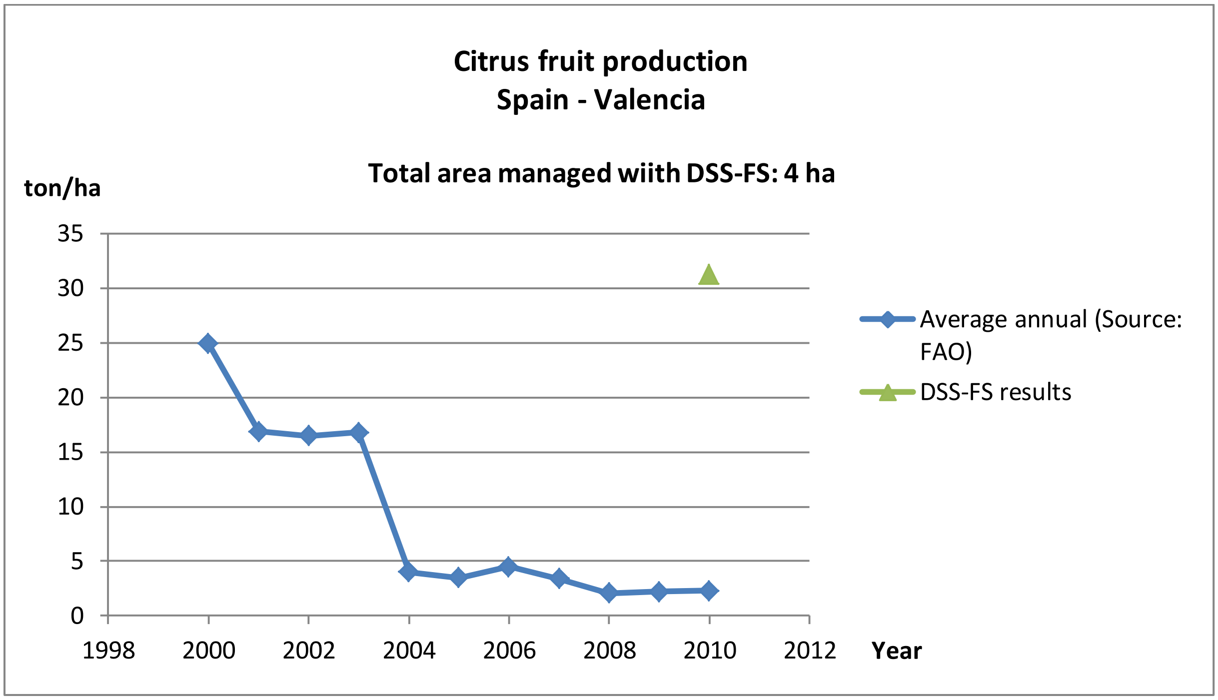


Fig. 61 - DSS-FS Results – Spain

Figure 62 showing the results with DSS-FS - tomato production in Moldova

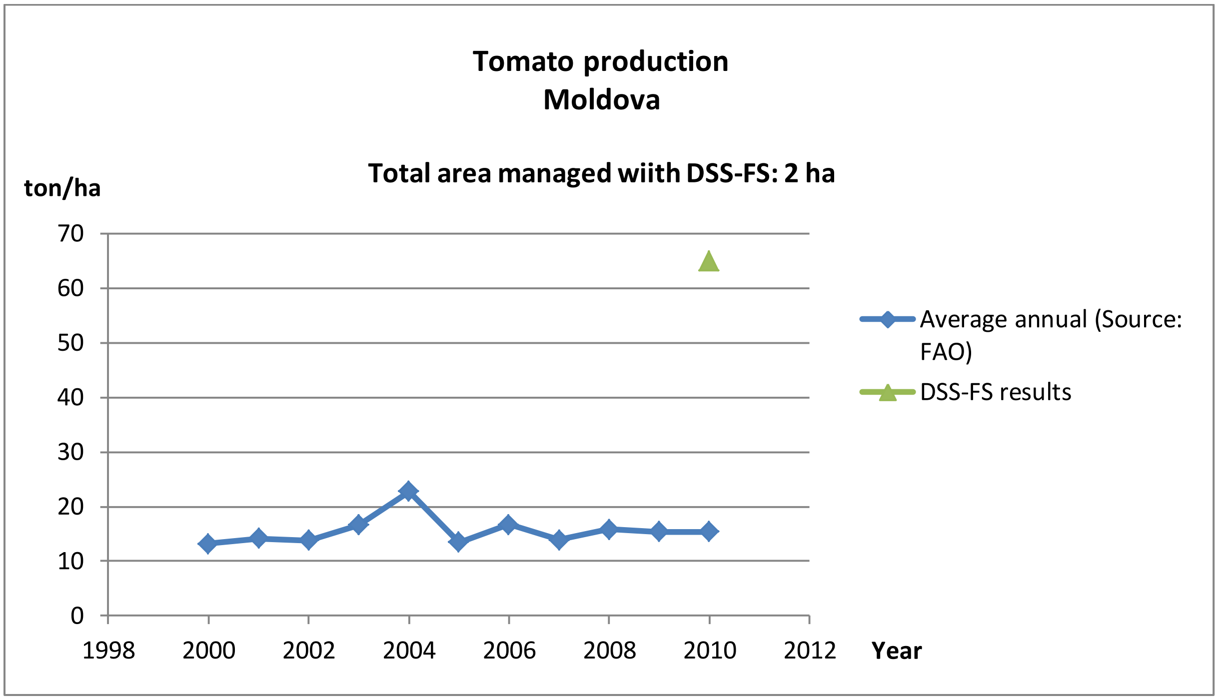


Fig. 62 - DSS-FS Results – Moldova