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Decision support based on bio-economic simulations for irrigated agriculture

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Abstract
Irrigation allows to increase crop yields and to expand the agricultural frontier. Hence it guarantees food and fiber production for a growing world population. In areas of arid and semi-arid climate, however, it is essential to link irrigation and drainage in order to control for salts in the root zone. In areas of humid or sub-humid climate, drainage is also necessary to prevent waterlogging. Simulation models can be used as a tool for decision support for management and design of irrigation and/or drainage projects. This paper introduces a simulation model for decision support for irrigated agriculture, whose flexibility in terms of input data requirement makes it also appropriate for developing countries. The model is composed of two independent modules. Module 1 is a bio-physical model that is based on a root zone water and salt balance, applicable to the production units. Module 2 captures the socio-economic component which is applicable to irrigation perimeters or rural properties. It involves optimization procedures (linear programming) and risk analysis. Optimization procedures consider constrains on water, labor, area and markets. Risk analysis uses Monte Carlo simulations to generate suitable parameters. The model, which is currently in its testing phase, has been applied to projects in different regions in Brazil. Its potential as a decision support tool for irrigated agriculture and technology diffusion in other situations is now verified. Two applications examples are presented.

1 Introduction
Irrigation has been fundamental to guarantee the supply of agricultural products. Its importance increases with world demographic growth. The benefits of irrigation are: larger economic returns to agricultural activities due to higher productivity, expansion of the agricultural frontier, improvement of economic conditions for rural communities, and others. The establishment of drainage systems in wet areas leads to similar benefits as irrigation. In dry areas, where irrigation is practiced, drainage is an effective measure to control salinity, a problem faced by the majority of irrigated areas.

The need for the integration of irrigation and drainage in the design and management of projects is evident. An appropriate soil-water-plant-salinity management is important to guarantee sustainable agricultural production at high levels. Unfortunately, appropriate management is often lacking. Computer simulation models can be effective decision support tools for the design and management of irrigation-drainage projects, apart from contributing to agrotechnology transfer, particularly when provided with a user-friendly interface. However, few models of this kind are applicable in developing countries. One of the causes is the lack of a sufficient database.

This paper introduces a computational model for decision support for irrigated agriculture. Its flexible input data base makes it appropriate also for developing countries. The ultimate purpose of the developing the model is to provide a tool (endowed with a friendly graphic interface) for decision makers in irrigated agriculture.

2 Objectives of the model

The simulation model is a decision support tool, that allows:

(a) To simulate the performance of different management and designs of irrigation and/or drainage projects, considering agronomic and economic aspects.

(b) To estimate daily values of water and salts balance in the root zone, as well as the variation of the water table depth.

(c) To design agricultural drainage systems for dry or humid areas.

(d) To determine the optimum cropping pattern and to conduct post-optimality analysis for production units or irrigation perimeters.

(e) To apply risk analysis associated to the optimum cropping pattern.

(f) To model rainfed agriculture (estimates of yields, study of the optimum cropping pattern and risk analysis).

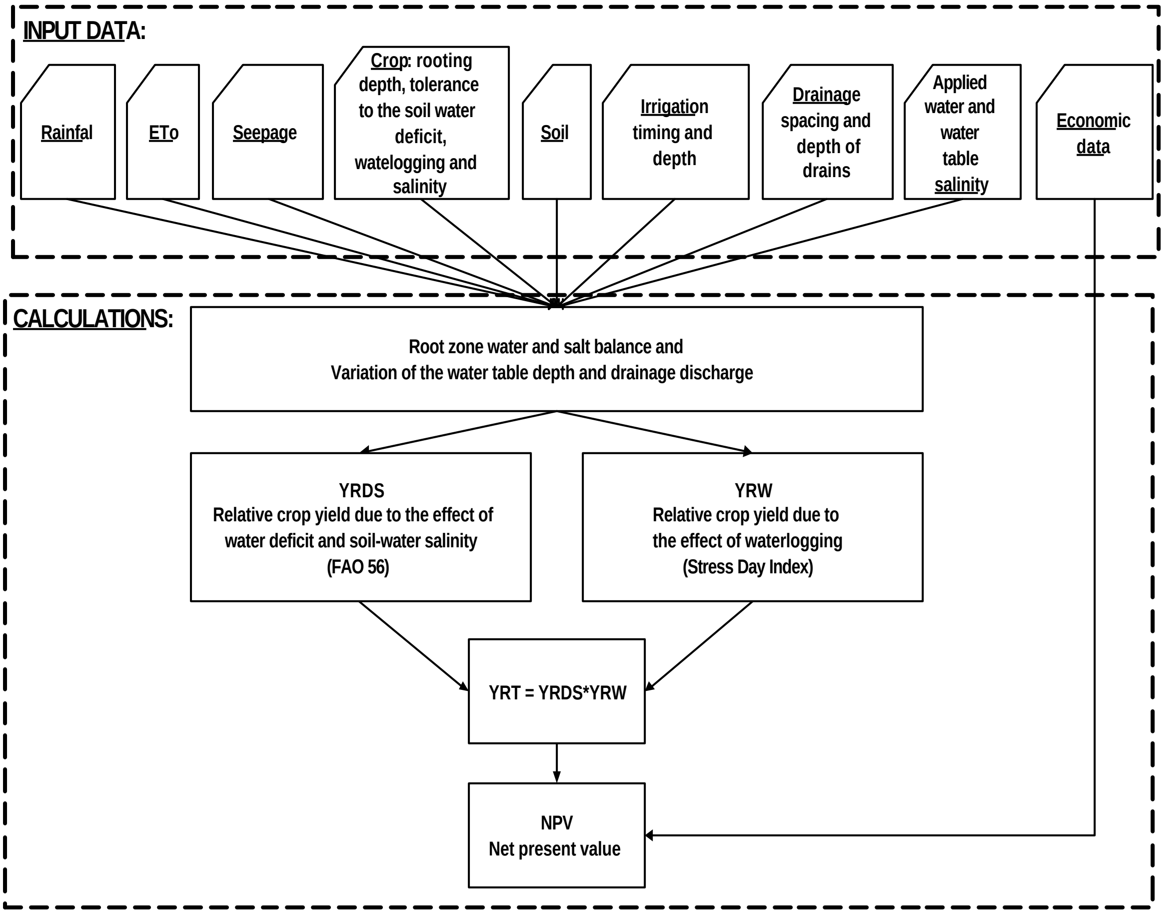
3 Model structure

Two independent modules will be implemented. The results obtained with Module 1 can be part of the input database for Module 2.

3.1 Module 1: bio-physical component

Module 1 was written in Delphi[i], a software that is endowed with a user-friendly graphic interface, that also interacts with the user. It is applicable to the study of production units[ii] (tasks a, b, c and f, listed under objectives (the section 2)). The input data and calculations in Figure 1 are schematized.

Figure 1: Scheme of input data and calculations



ETo: reference evapotranspit arion

Data inputs can be made directly into the forms or reading text files. Crop data files and the climatic data base CLIMWAT of FAO can also be accessed. Daily or monthly climatic data (rainfall and ETo) are required. In case monthly data are supplied, these will be turned into daily data. In every year one to three croppings can be considered.

The principal components of the water and salt balance in the crop root zone will be counted daily, thereby simulating the water table position. The water balance is expressed by the equation

1. $\Delta arm = irr + pre + fa - etr - \Delta arms - esc - per$

Where:

Δarm	=	change in the water depth stored in the root zone, mm
irr	=	irrigation depth, mm
pre	=	precipitation, mm
fa	=	upward flux from water table, mm
etr	=	actual crop evapotranspiration, mm
Δarms	=	change in the water depth stored on the surface, mm
esc	=	runoff, mm
per	=	deep percolation, mm

Due to interdependence among water balance components, Equation 1 is subject to an iteration process.

The calculation procedure for upward flux from the water table uses the equation of Darcy-Buckingham written in the finite differences form. The unsaturated soil hydraulic properties, given by the functions soil water retention, è(ø), and hydraulic conductivity, K(ø), are processed according to the van Genuchten model (VAN GENUCHTEN, 1980), where è is the volumetric water content [L^3L^{-3}], ø is the water pressure head [L] and K is the hydraulic conductivity [LT^{-1}].

To estimate runoff the user can opt between the Curve Number methodology (Soil Conservation Service, 1972) and use of a maximum superficial storage.

Using a simplified approach, the salt movement is considered to be proportional to the water movement. In the root zone, the incoming and outgoing amount of salt is proportional to the incoming and outgoing water flux, respectively. The Kraijenhoff Van of Leur - Maasland drainage equation (PIZARRO, 1985) is used to predict the water table position and the discharge in the lateral drains.

The root zone water, the salt balance and the water table position indicate how the root zone is subject to conditions of water deficit, salinity and waterlogging. Three crop yields: (1) relative crop yield derived by considering the effect of soil-water deficit and soil-water salinity (YRDS) (2) relative crop yield derived by considering the effect of waterlogging (YRW), and (3) the total relative yield (YRT) are calculated for each crop. YRDS is calculated using the methodology described by ALLEN et al. (1998). YRW is calculated using the *stress day index* (SKAGGS, 1990). The calculations of both, YRDS and YRW, consider the environmental conditions in the root zone and the crop's tolerance to water deficit, salinity, and waterlogging. YRT is the product of YRDS and YRW. Subsequently YRT will be the basis to calculate net present value (NPV)[iii].

Considering a series of input climatic data with *n* years, *n* values of YRT and *n* values of NPV will be calculated for each combination of spacing between lateral drains and depth of drains. Mean and standard deviation for YRT and NPV are calculated and provide inputs for defined probability density functions (PDFs), with normal distribution. The best configuration of the drainage system is the one that provides the largest NPV for a level of probability specified by the user.

Alternative irrigation management practices can be tested to verify which management provides best results according to NPV and the use of water. Mean and standard deviation are also calculated for yearly irrigation requirement, being defined as PDFs with normal distribution.

If the simulation is accomplished for a current year, the user can verify the irrigation timing and requirement. In this case, the model will serve as a management support tool.

3.2 Module 2: socio-economic component

Module 2 will also be developed in Delphi. The intention is to develop a software endowed with a graphic interface, that facilitates to optimize the NPV for irrigation projects or farms using an linear programming (LP) approach. The currently developed model also considers a number of risks farmers or project managers are facing. The methodology and the structure of this module are now built in Excel and @Risk[iv]. It is applicable to the study of different production scenarios that can be adopted by rural properties or irrigation perimeters (tasks d, e and f, in the section 2).

3.2.1 Linear programming - LP

A LP model is used to maximize profit. The user can establish a framework for a period of one or more years. The objective function is:

2. $$\max U = \sum_{i=1}^{N} (P_i Y_i - C_i) X_i$$

Where:

U	=	net present value (profit), $
i	=	integer number for the activity
N	=	number of activities
P	=	present value of the price received for a specific crop, $ kg^{-1}
X	=	activity^{v} or cultivated area, ha
Y	=	yield, kg ha^{-1}
C	=	present value of the production cost per unit area, $ ha^{-1}

Constraints on water, labor, land and market, are imposed on a monthly basis. Furthermore, the yearly constraint for water is imposed too. Constraints on water are given by the equations:

3. $$\sum_{i=1}^{N} W_{im} X_i \leq V_m \qquad (m = 1, 2, ..., 12)$$

4. $$\sum_{i=1}^{N} \sum_{m=1}^{12} W_{im} X_i \leq Vt$$

Where:

W	=	monthly irrigation requirement, m^3 ha^{-1}
m	=	month
V	=	monthly constraint on water, m^3
Vt	=	yearly constraint on water, m^3

The costs C_{ijk} are composed for:

- Irrigations costs (cost of irrigation water, costs of the energy spend for irrigation, costs of labor needed for irrigation, and costs of the irrigations system);
- Drainage costs (costs of implantation and maintenance of the drainage system);
- Labor costs;
- Other costs (seed, pesticides, fertilizers, machinery, other inputs, and services).

Other cultivation patterns can be determined via optimizing the use of water. The objective function for that is:

5. $$\min Wt = \sum_{i=1}^{N} \sum_{m=1}^{12} W_{im} X_i$$

where Wt is the total water requirement in m^3.

The following income equation is added:

6. $$\sum_{i=1}^{N} (P_i Y_i - C_i) X_i = ë$$

where ë should be varied over its feasible range. The largest value of ë will be that obtained for U by the equation 2.

3.2.2 Risk analysis

The technical coefficients or irrigation requirements, W_{im}, in the equations 3 and 4 are subject to an expressive variability, whose main source usually is the variability in the amount of rainfall. The irrigation requirement also depends on the evapotranspiration demand and upward flux from the water table which itself depends on the water table level and soil type. Therefore, variations of evapotranspiration demand and water table level are also sources of variation in the irrigation requirement.

The irrigation requirement can be accessed from the water balance in the root zone, as given in equation 1. When a shallow water table is verified (what causes an expressive upward water flux) the determination of the water balance components has a certain complexity due to their interdependence. In this case, iteration procedures are necessary to calculate the water balance components. If the water balance is applied for a series of years, parameters that define a probability density function (PDF) for the irrigation requirement can be obtained. This task can be carried out by the Module 1.

Another characteristic of the coefficients W_{im} is that it is probable that the correlation coefficients are close or equal to 1 each month. On one hand, this means that in a certain month the total irrigation requirement can reach values considerably above the average. On the other hand, the volume of available water in this month should be below the average, since irrigation requirement and water availability for irrigation are generally correlated negatively. It is therefore evident, to consider the importance in the variability of irrigation requirement. The probability that the amount of available water be enough to supply the irrigation requirement of a production scenario obtained with the linear programming should be verified. That is done with a risk analysis.

Risk analysis should be applied on each production scenario obtained with the linear programming. Risks analysis built into the model does not only consider the variability in irrigation requirement but also in yield, product prices, and discount rate. Monte Carlo simulations are carried out using probability distributions of those parameters. The risk analysis supplies information about the probability distribution for the outputs' NPV and if the total irrigation requirement can exceed some constraint (monthly or yearly).

The simulations made with Module 1 supply the mean and the standard deviation for the irrigation requirement and yield, which define the PDF for a normal distribution. It is advisable that the user also supplies the values maximum and minimum for irrigation requirement and yield. That can be achieved, for instance, by considering the values obtained at the levels of 95% and 5% of probability, respectively. That information can also be received through simulations with the Module 1. The PDF would then be normal truncated. Elicitation of PDF for irrigation requirement and yield can also be received from other sources, such as research or knowledge of farmers or technicians. Some applicable procedures for elicitation of probability distributions are described in HARDAKER, HUIRNE AND ANDERSON (1997).

PDFs for interest rate and price should be defined by the user that can opt for normal or triangular distributions, among others.

4. Application examples

The model, which is currently in its testing phase, has been applied to projects in different regions in Brazil. Two applications examples from the following localities are presented here:

- Piracicaba - São Paulo - Brazil
- Irrigation perimeter of Jaíba - Minas Gerais – Brazil

4.1 Piracicaba – Module 1 application

The main input data are as follows:

- Climate: humid, 21 years of daily data of rainfall and potential evapotranspiration
- Soil: clay-loam
- Crop: corn; planting: 8/10; harvesting: 14/02
- Irrigation: application interval: 14 days, if depletion of moisture >0; application depth: 20 mm
- Drainage system: subsurface lateral drains; spacing between lateral drains from 5 to 100 m, with increments of 5 m, depth of drains: 1.2 m; effective diameter: 0.1 m

The economic input data are showed in the Table 1.

Table 1: Economic input data

Drainage costs	
Cost of the meter of installed lateral drain	R$ 5.00 m^{-1}
Cost of cleaning and implantation of collector drains	R$ 350.00 ha^{-1}
Cost of maintenance of collector drains	R$ 10.50 $ha^{-1}year^{-1}$
Cost of maintenance of the drainage net	0.5% of the installation
Lifetime of the drainage system	25 years
Irrigation costs	
Cost of irrigation water	R$ 17.82 / 1000 m^3
Cost of energy	R$ 0.17 KWh^{-1}
Specific energy consumption	173 KWh / 1000m^3
Other variable costs	R$ 0.01750 $(m^3/ha)^{-1}$
Cost of the irrigation system	-
Production	
Sale price	R$ 108.33 ton^{-1}
Production costs	R$ 600.00 ha^{-1}
Yearly discount rate	12%

An input data base as illustrated in Figure 1 was used.

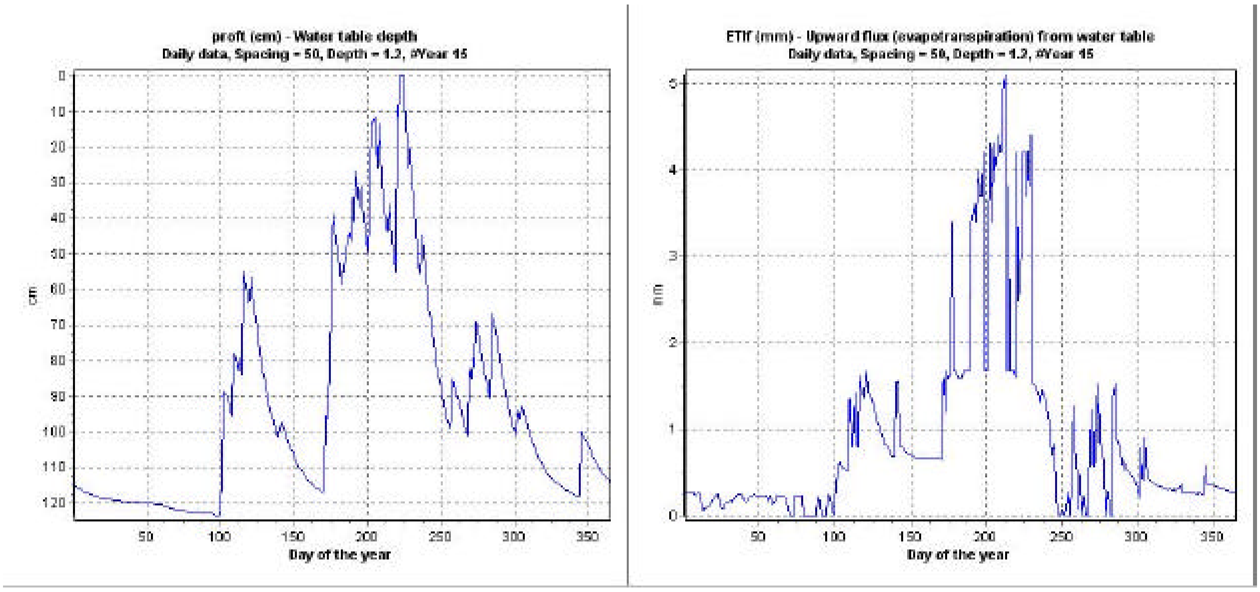
The output of the simulations can be divided into two groups:

- water and salt balance
- performance and profitability of the project

The outputs for daily components of the water and salt balance in the root zone are presented in tables and charts. Figure 2 shows two charts for water table level and upward flux from water table, which is a component of the actual evapotranspiration (yet another source is the water stored in the root zone), for the spacing between lateral drains of 50 m and the year number 15. Results of water and salt balance are also presented on yearly base.

Figure 3 shows a form with results obtained for relative yield, YRT, and net present value, NPV, among other parameters. The chart in this form presents the averages of YRT and NPV for 21 years for each spacing between lateral drains. The highest average NPV is R$ 3812.69 for a spacing of 45 m. In case NPV is considered at the level of 20% of probability (0.2 fractile), the highest NPV is R$ 3415.71 for a spacing equal to 40 m. In this case, the design security level of the drainage system increases. Table 2 shows some outputs for NPV, YRT and irrigation requirement.

Figure 2: Model charts for water table depth and upward flux from water table



(water table depth) (upward flux)

Figure 3: Output form showing the average values obtained for relative yield, YRT, and net present value, NPV, for different spacing between lateral drains

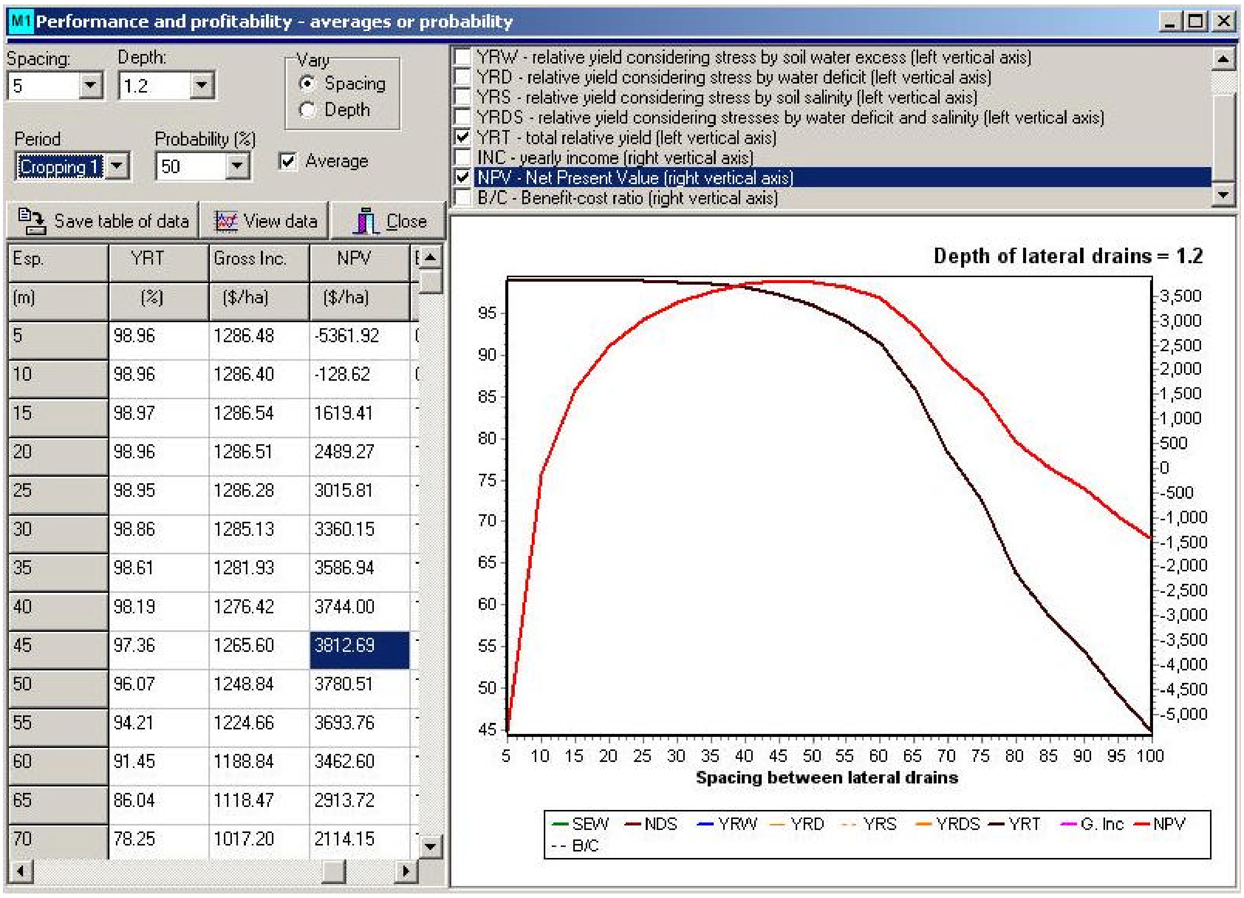


Table 2: Some outputs for NPV, YRT and irrigation requirement

Probability level (%)	Spacing between lateral drains (m)	NPV (R$/ha)			YRT (%)		Irrigation requirement (mm)	
		On the probability level	Average	Std. Dev.	Average	Std. Dev.	Average	Std. Dev.
50*	45	3812.69	3812.69	515.91	97.36	3.70	69.52	30.08
20	40	3415.71	3744.00	390.07	98.19	2.38	72.38	29.98

* on the average

4.2 Irrigation perimeter of Jaíba – Module 2 application

The following general situation holds for this perimeter:

- Climate: Semi-arid - last border between Northeast and South Center areas (Brazil).
- Water source: São Francisco River
- Soils: well drained without salinisation risk and without drainage cost
- Average annual rainfall: 900 mm / year
- Irrigable area: 26790 ha (first stage of implementation completed)
- Land division[vi]:
  - Occupied lots of 5.0 ha: family agriculture; 1376
  - Occupied lots of 20 ha: managerial agriculture 167
  - Occupied lots of 50 ha: managerial agriculture 18

For model application the following information was used:

- The application was made for a lot of 5 ha.
- Crops most planted in 2002: banana, papaya, corn, bean and onion (2 varieties).
- Period of study: 4 years.
- The irrigation requirement was obtained considering averages of monthly precipitation and reference evapotranspiration (Penman), crop coefficients and soil water capacity.
- Data of costs for irrigation and other costs were obtained from the irrigation district.
- Irrigation rates:
  - K2 - R$ 19.87 / 1000 m^3
  - K1 - R$ 62.22 / ha
- Cost of energy: 0.17 R$/KWh.
- Consumption of energy: 173 KWh/1000 m^3.

The considered constraints are shown in the Table 3.

Table 3: Constraints

Market or production (ton)			Resource constraints		
Banana	<=	50	Irrigation (m^3/month)	<=	6000
Papaya	<=	25	Irrigation (m^3/year)	<=	28000
Maize	>=	0.4	Labor (day-man/month)	<=	180
Bean	>=	0.05	Land (ha)	<=	4.5

Figure 4 shows a partial layout of the Jaiba project, area C2, with lots from 5 to 20 ha.

Figure 4: Partial layout of the Jaiba Project

The results of the linear programming model (equation 2) are shown in the Table 4. The NPV obtained for this scenario was R$ 13924.00. Table 6 presents solutions when equation 5 is used for different values of ë in equation 6.

Table 4: Results of the linear programming model – equation 2

	Banana	Papaya	Maize		Bean			Onion summer		Onion winter
Year	B1	P1	M1	M2	F1	F2	F3	O1	O2	0W1
1	0.714	0.877	0.067	0.067	0.026	0.026	0.026	1.929	2.230	1.595
2	0.714	0.877	0.067	0.067	0.026	0.026	0.026	2.183	2.239	0.656
3	0.714	0.877	0.067	0.067	0.026	0.026	0.026	2.053	2.239	1.484
4	0.714		0.067	0.067	0.026	0.026	0.026	2.183	2.239	1.484

* NPV = R$ 13924.00

In a second step, risk analysis was applied to the results of the LP obtained with equations 2 and 5. Probability density functions and their parameters (feasible values), which were used as inputs in the risk analysis, are presented in Table 5.

Table 5: Parameters used in the probability density functions

Truncated normal distribution				
	Mean	Standard	Minimum	Maximum
Yield	Mean	0.07mean	0.7mean	1.3mean
Irrigation requirement	Mean	0.09 - 0.15 mean*	$f_{0.05}$**	$f_{0.95}$
Triangular distribution				
	Minimum	Most likely	Maximum	
interest rate	0.075	0.1	0.12	
Price	0.5mean	Mean	1.4mean	

* Varying for each culture

** $f_{0.05}$ or 0.05 fractile is that value of irrigation requirement IR which probability of IR < $f_{0.05}$ = 5%

Table 6 shows results for the linear programming and risk analysis, considering solutions obtained by equation 2 and equation 5, for different values of ë (equation 6).

Table 6: Results of linear programming (LP) and risk analysis

Solution (LP)		1	2	3	4	5	6
Equation (LP)		2	5	5	5	5	5
NPV Optimum	R$	13924					
NPV = ë =	R$		13000	12000	11000	9000	5000
Water requirement (4 years)	m^3	62311.0	44776.2	34082.9	28853.8	21308.7	11036.8
NPV							
Mean	R$	7886.98	7922.26	7567.81	7025.62	5953.92	3708.22
Std. deviation	R$	9084.51	8314.75	8014.79	7531.60	6487.21	3805.02
Prob*. For NPV = 0	%	19.73%	16.81%	17.10%	17.93%	18.49%	16.52%
Prob. for NPV = target**	%	73.88%	73.14%	71.14%	69.86%	67.75%	63.17%
$f_{0,1}$***	R$	-3636.77	-2691.85	-2729.80	-2757.96	-2359.70	-1271.61
$f_{0,9}$	R$	19443.15	18534.19	17857.21	16704.97	14396.76	8620.46
Yearly irrigation requirement for the first year							
Mean	m^3	27157.49	25414.63	14688.15	12177.00	12177.00	8472.80
Std. deviation	m^3	794.26	754.76	500.52	443.74	441.58	269.49
$f_{0,1}$	m^3	26141.00	24442.37	14037.25	11594.88	11594.04	8116.73
$f_{0,9}$	m^3	28187.22	26386.75	15342.90	12758.22	12754.85	8817.02
Prob. For 28000 m^3	%	85%	100%	100%	100%	100%	100%

* Prob. = probability

** Target is the optimum value of NPV or ë

*** $f_{0.1}$ or 0.1 fractile is that value of NPV which probability of NPV < $f_{0.1}$ = 10%

Some characteristics of the output PDFs for NPV and yearly irrigation requirement for the first year are verified in Table 6. It has been observed that the means of NPV had decreased in subsequent solutions, except between the solutions 1 and 2. The standard deviations in NPV had decreased from the solution 1 to 5. However, no expressive differences for the probability of obtaining NPV = 0 occurred. Means and deviations for irrigation requirement decreased from solution 1 to 5. For solution 1, an important information is the probability equal to 15% of the yearly irrigation requirement for the year 1 to exceed the constraint value (28000 m^3). This is not verified for the other solutions.

The difference among the crop pattern obtained by the solutions 1 and 2 is the area for winter onion, whose planting was completed in the fifth month. Considering that the decision of growing or not growing winter onion should not necessarily be taken in the beginning of the year, the decision maker (farmer) could wait until the fourth month and apply the analysis again on the basis on actual values of irrigation requirement for the first 4 months. Subsequently he/she could take the decision to grow or not to grow this crop. This shows that the analysis carried out with Module 2 should be periodically applied to consider the changes in the conditions that would affect the decision.

5. Outlook

Tests represent an important stage in the development of computer models. The potential of the model as a decision support tool for irrigated agriculture and technology diffusion should be verified in different situations.

It is important to confront obtained results of simulations carried out with the Module 1, such as components of the root zone water and salt balance, variation of water table depth, and estimate of crop yields, with observed data. Local calibrations should be done as an adjustment mechanism for improving the quality of the results. Module 1 is structured in sub-routines, which facilitates future modifications to improve implemented procedures or include other procedures, in order to seek more flexibility in relationship to the use options. For instance, alternative procedures to estimate runoff and relative yield in response to the waterlogging can and should be implemented. Alternatives are already in process.

Module 2 can be supplemented with other features such as recursive analysis. Module 2 can also be modified to additionally consider capital constraints, farmers risk behavior and other aspects.

It is hoped that the combination of several technologies for decision support, in one computer package and with a friendly interface, can contribute to the distribution of these technologies, reaching rural assistants, technicians, and managers.

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[i] Versions 3, 5; Borland Software Corporation – http://www.borland.com/delphi.

[ii] Unit of production refers to an area subject to a same system and management of irrigation and, or drainage, growing the same crop or sequence of crops in one year, with a same soil type in what refers to physical characteristics that affect the water movement.

[iii] It is not necessary that lifetime of the project has the same number of years that the series of climatic input data.

[iv] Excel: Microsoft Corporation; @Risk: Palisade Corporation, http://www.palisade.com.

[v] Each activity is defined by the crop growing in a certain period, soil type, and irrigation-drainage scheme.

[vi] Managerial agriculture can compose area of up to 800 ha.