19 - IRRIGATION DEMAND AND DELIVERY SIMULATION: THE SEDAM DSS MODEL

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Abstract: The SEDAM model (sector demand and distribution model) is a decision support tool developed for searching and evaluating the best scenarios when planning the combined improvement of farm and distribution systems in surface irrigation districts. SEDAM simulates the water demand and delivery at the sector level and aggregates the results to the district level. It operates with a GIS database in combination with the irrigation scheduling simulation model ISAREG for and the surface irrigation DSS model SADREG (described in a companion paper). SEDAM includes a multicriteria analysis module that helps the users, mainly irrigation managers, to formulate and evaluate alternatives in respect to user-selected performance, economic and environmental criteria. These include land and water productivity, farmers' incomes, water saving, and irrigation environmental impacts. The model generates scenarios based on system management actions relative to the delivery and the farm irrigation system. Each scenario expresses a set of measures corresponding to a strategy of improvement planned at the sector level, which refer to improved practices at farm level - relative to irrigation scheduling, land levelling, farm water distribution, or inflow rate control, and at delivery level, relative to upstream inflow rates, delivery rules and daytime delivery. The canal network delivery model uses a simplified volume balance approach and computations include the estimation of canal seepage and runoff, as well as the lag time before the steady state flow regime is established. Fields are clustered according the user and a rotational delivery scheme is considered in relation to crop scheduling. A 10-day time step is adopted for the simulation. Results concern both farm and off-farm improvements and are made available through the GIS database in spatially distributed formats. This paper describes the model and shows results of its application to an irrigation district in Fergana, Central Asia.

Keywords: Surface irrigation, Irrigation modernization and improvement, Decision support systems, Demand and delivery hydrographs.

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Introduction

The collective irrigation systems are complex to plan and manage. The distribution system constraints, such as the water scarcity and conveyance capacity and the control devices, condition both the field delivery and the on-farm performance. This requires more elaborated technical solutions and a more advanced decision-making process, where the multiple decision makers (associative authorities and farmers) share their responsibilities. The decision-making process could be effectively improved with the decision support system (DSS) methodology.

DSS is an integrated approach to solve complex problems, combining the computer calculation and data store capabilities, with human knowledge and perception and the support of mathematical models, providing decision-maker aid to identify the problems, to generate the alternatives, to evaluate and select them. It is recognized that DSS improves the decision process quality, with a faster and better data access, integrated with models, and the evaluation of a large number of alternatives. It allows a dynamic tool to facilitate the communication and negotiation between the several decision makers

The multicriteria methodology is very useful to assist the decision-maker on the evaluation and selection tasks, namely in environmental decision problems, where trade-offs between cost and environmental impact criteria plays a crucial role on decision (Manoliadis, 2001). This methodology consider the several points of view inherent to the decision problem, some of them adversative or conflicting, and requires that the decision-maker explicit his preferences and priorities. Optimization through multicriteria aims the better compromise between different interests or point of views (Roy and Bouyssou, 1993). The multicriteria analysis can be integrated in a DSS framework, ameliorating the learning process and facilitating the interaction with the user. The improvement of farm irrigation systems in large surface irrigation projects is well supported by DSS tools, which application can be performed both at field and district levels if linked with a GIS (Malazewski, 1999). A case study of an integrated irrigation modelling using multicriteria analysis, on a DSS framework with spatially distributed data, is reported in this paper.

Models and Data

SEDAM is a DSS aimed at modelling and evaluating water demand and delivery at scale of an *irrigation sector* for planning purposes and ranking alternative scenarios relative to both the farm and delivery surface irrigation systems (a sector is the area served by a branch canal and respective distributor canals). It is conceived to aid irrigation managers to formulate and evaluate development issues that aim at achieving objectives of sustainable agricultural development, soil and water use and environmental friendliness. Among others, these include water saving, soil conservation, and higher yields and farmers incomes. The model establishes scenarios based on system management actions, related with the delivery network system and the-farm irrigation systems (Gonçalves *et al.*, 2003; 2004). Each scenario expresses a set of measures and practices required to implement a management strategy to plan water use at Sector level, i.e. corresponding to an area managed by a Water Users Association (WUA). It allows the evaluation of impacts due to the implementation of each scenario; so different Sector scenarios can be compared and ranked through a multicriteria analysis. Results refer to the network operation, the demand and supply hydrographs with a 10 days time step, and the field and sector performance indicators.

SEDAM integrates several models and databases (Fig. 1). To formulate crop irrigation scheduling plans and to model on-farm demand it applies GISAREG (Fortes *et al.*, 2005a, b); and to generate on-farm surface irrigation alternatives the DSS SADREG (Gonçalves *et al.*, 2005) is used in an interactively procedure to explore an optimization search based on multicriteria methodology. The canal network water delivery is modelled using a volume balance approach, where the geometric and hydraulic network characteristics are integrated with device controls, delivery rules and hydraulic constraints. It includes the computation of an initial lag time before the establishment of the steady state flow regime, of canal seepage when canals are unlined, and runoff of the non-delivered water. For delivery purposes, the fields are clustered according the farmers uses and the characteristics of the distribution canals and ditches. A rotational delivery scheme is considered in relation to crop scheduling made on.

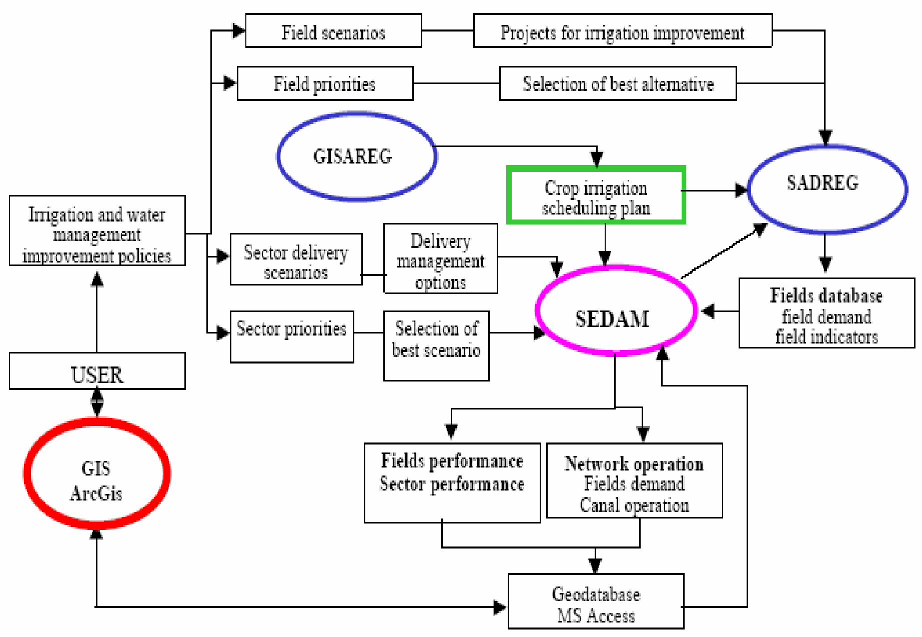


Fig. 1. SEDAM's models and database integration.

SEDAM databases store all input, output and internal data in a structure of tables following the relational concept. The GEODB database is built in MS Access and validated in ArcGIS software; thus, it stores spatial and non-spatial data. The SADREG (Gonçalves *et al.*, 2005) workspace database stores information about the fields, in particular the design alternatives for irrigation improvement, according the field scenarios (a workspace is an organized data set characterizing each field). The GISAREG database (Fortes *et al.*, 2005a, b) stores the information about the irrigation scheduling for each field and group of fields delivery.

Scenarios to improve irrigation water management

The improvement of irrigation water management at the WUA scale implies decisions at both the delivery and farm levels. SEDAM handle this decision-making problem through building up, ranking and evaluating scenarios covering a wide range of measures and practices. Each scenario represents a step further in irrigation systems' improvement, which may be implemented sequentially during a selected period. The global system performance depends upon decisions relative to the farm and the distribution/delivery systems. However, despite the DSS is able to better support the decision-making process, attaining the desired performance results depends on the ability of managers to facilitate farmers participation in the decisions and on the support given to farmers to implement the targeted improvements. The procedure for assessing impacts relative to different scenarios is outlined in Fig. 2.

The *farm irrigation scenarios* concern the implementation of improved practices at farm level such as the adoption of adequate irrigation scheduling, including deficit irrigation, land levelling or land smoothing practices aimed at improving advance and infiltration uniformity, control of inflow rates, including the use of appropriate equipments or devices, control of operational water losses and runoff reuse techniques. Each *farm irrigation scenario* corresponds to a *project* in SADREG application (Gonçalves *et al.*, 2005), which results from a multiple combination of decision variables. Each *project* represents a step further in field irrigation improvement, so more demanding in terms of management, irrigator skills, and capital investment.

The *delivery scenarios* refer to alternative management decisions relative to water delivery to farms supplied by a collective irrigation system managed by a WUA or by the irrigation district authority. Generally, they refer to the upstream discharge into the distributor canals, the outlet discharges, daytime supply period, the delivery duration, and the establishment of alternative delivery rules, including a rotational scheme of deliveries and the definition of a priority sequence of fields inside the sector. The inflow discharge and the daytime supply period are assumed constant during the whole irrigation season. Each combination of two of these values generates a delivery scenario. The management user may apply SEDAM to assess impacts at the *sector* level when changing these supply parameters. In particular, when a decrease on supply is required for water saving purposes, this simulation is useful to assess the feasibility of more severe supply restrictions.

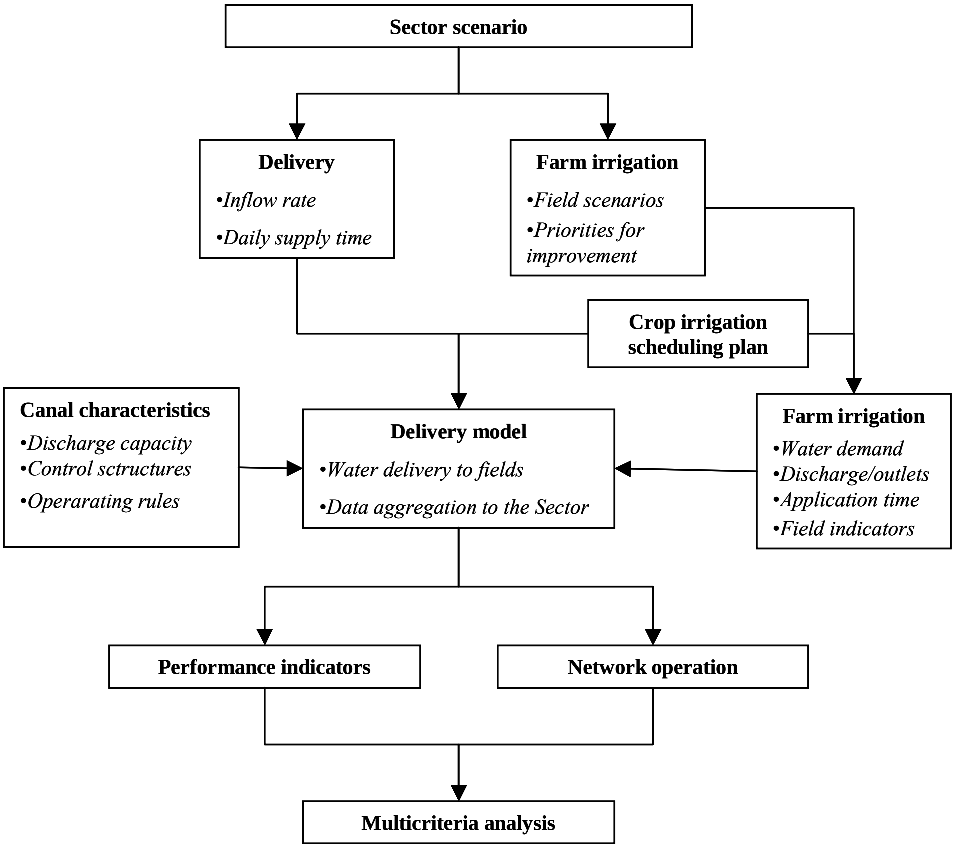


Fig. 2. Flow chart of SEDAM from scenario initiation to multicriteria analysis.

Improved scenarios for water savings and improved crop conditions are developed in agreement with the decision making process summarized in Table 1, where objectives, decision variables and constraints are described in relation to both the farm and the delivery irrigation systems.

The scenarios are built by combining different “improvement variables” that express decision maker priorities or operative conditions. There are four improvement variables: (A) relative to farm priorities to select a field irrigation design; (B) field scenarios relative to improving farm irrigation; (C) alternative upstream inflow rates to the sector; and (D) alternative daily supply times.

The variables C and D are operative and play a major role in WUA planning and operation. Thus, sector scenarios are essentially developed on base of A and B variables in combination with C and D.

Table 1. Decision making process for improved irrigation and water savings.

	Farm system	**Delivery system**
Decision maker	Farmers (grouped to a distributor)	WUA authority and farmers representatives
Objectives	▪ minimizing costs ▪ maximizing yields ▪ maximizing benefits ▪ minimizing soil salinity ▪ maximizing water savings	▪ minimizing costs ▪ maximizing yield & benefits ▪ minimizing impact on the drainage system ▪ maximizing social benefits (e.g. employment, farmers income)
Decision variables	▪ field inflow rates ▪ irrigation method ▪ irrigation scheduling ▪ land conditions (land levelling, slope, length) ▪ tail-water reuse	▪ inflow rate at the sector head end ▪ daily supply time ▪ delivery schedule
Constraints	▪ water costs ▪ land area cropped ▪ land taxes ▪ agronomic field practices	▪ canal system network ▪ maximum inflow rate

The improvement variables refer to the following levels:

- Variable A – A1, when priority is given to economic issues; A2, if priority is assigned to environmental impacts and water savings, and A3 if priorities are balanced;
- Variable B – there are 9 levels as summarized in Table 2 with reference to SADREG field projects (see Gonçalves *et al.*, 2005);
- Variable C – levels corresponding to different sizes of the upstream inflow rates, varying from 0.8 to 1.6 ls^{-1} ha^{-1};
- Variable D – levels refer to different daily supply time, from 16 to 24 h d^{-1}.

Table 2. Scenarios to improve farm irrigation in relation to the SADREG projects.

	Field scenario and respective level of application to the sector (proportion in the total area)										
	P0	P1	P2	P3	P4	P5	P6	P7	P8	P9	Description
B0	1	0	0	0	0	0	0	0	0	0	Present
B1	0	1	0	0	0	0	0	0	0	0	Actual farm systems with an improved scheduling (*)
B2	0	4/8	1/8	1/8	1/8	1/8	0	0	0	0	Partial improvements in furrow irrigation
B3	0	0	1/4	1/4	1/4	1/4	0	0	0	0	All area under improved furrow irrigation
B4	0	0	1/4	0	1/4	0	1/4	0	1/4	0	Continuous and surge flow with every-furrow option
B5	0	0	0	1/4	0	1/4	0	1/4	0	1/4	Continuous and surge flow with alternate-furrow option
B6	0	0	0	0	1/4	1/4	0	0	1/4	1/4	Continuous and surge flow adopting deficit irrigation
B7	0	0	1/8	1/8	1/8	1/8	1/8	1/8	1/8	1/8	Continuous and surge flow with alternate furrows and deficit irrigation
B8	0	0	0	0	0	0	1/4	1/4	1/4	1/4	Surge flow with alternate furrows and deficit irrigation

(*) Improved irrigation scheduling with controlled cut-off times also for levels B2 through B7.

Demand and distribution simulation

For delivery purposes, the fields are clustered along the secondary distributor canal according the users/farmers through an appropriate tool in the GIS interface. Then field groups are created, which are sets of fields supplied by the same distributor canal and having homogenous irrigation scheduling since they have the same crops and soil type, so they also have the same delivery schedule.

The SEDAM application is performed following several steps (Fig. 3):

1. Initialising GIS:
   a) Selection of SADREG workspaces that characterize the typified fields;
   b) Defining the fields groups (clustering) with the GIS tool.
2. Creation of scenarios for the sector; which requires that the user inputs the following:
   a) The farm priorities, i. e., the weights assigned to the different criteria in SADREG, that are used to select an optimized farm irrigation relative to the scenario being built;
   b) The degree of farm irrigation improvement, expressed by the proportion of fields within the sector that adopt an improved farm irrigation project (defined in SADREG);

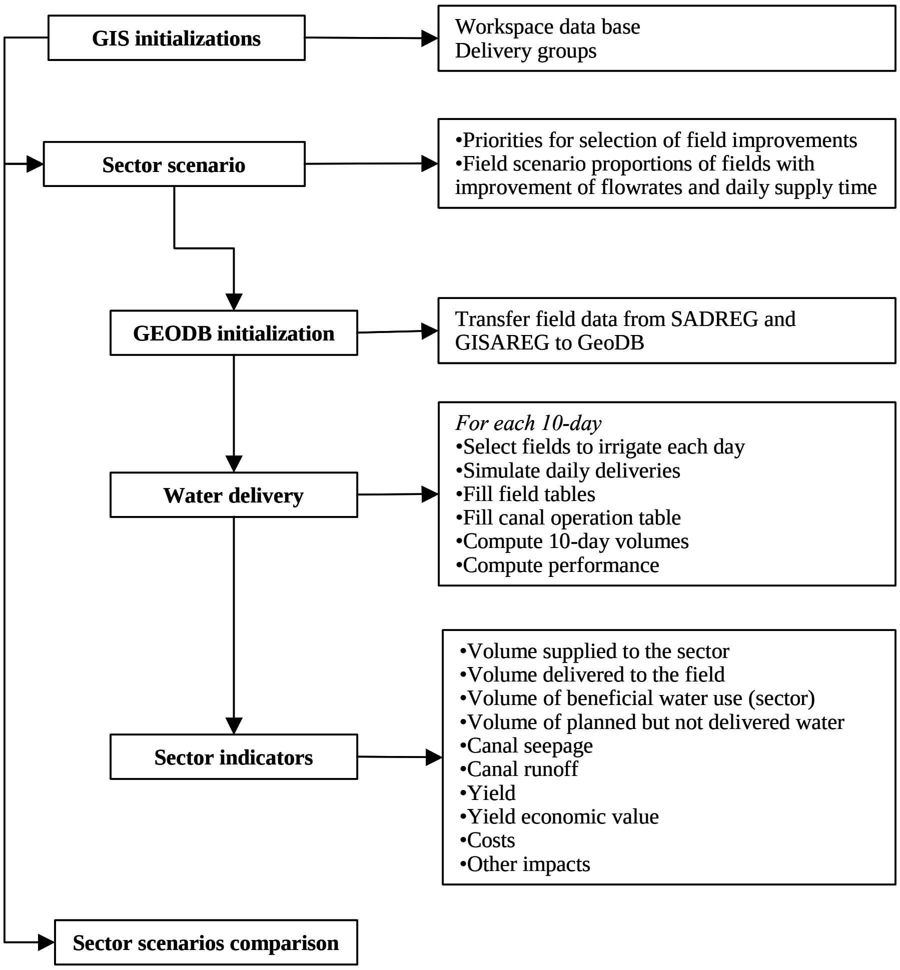


Fig. 3. Sequence of operations from initialization to scenarios comparison.

c) The upstream inflow rate (l s^{-1});
d) The daily supply time (h d^{-1}).

3. Initialization of the GEODB database for the new sector scenario, which includes:
    a) Loading field data relative to
        i. The selected farm irrigation alternative;
        ii. The degree of irrigation improvement (item 2b), above);
        iii. The irrigation schedule corresponding to the farm irrigation improvement defined in SADREG.
    b) Loading the *fields' tables* with data stored in the respective SADREG workspaces relative to:
        i. Delivery system number of outlets and respective discharges;

   ii. Demand application time and inflow rate;
   iii. Irrigation performances (application efficiency, distribution uniformity, runoff and percolation losses, yield, costs, land levelling and erosion impacts on soil);
   iv. Irrigation attributes (referred in Table 1 relative to the farm).

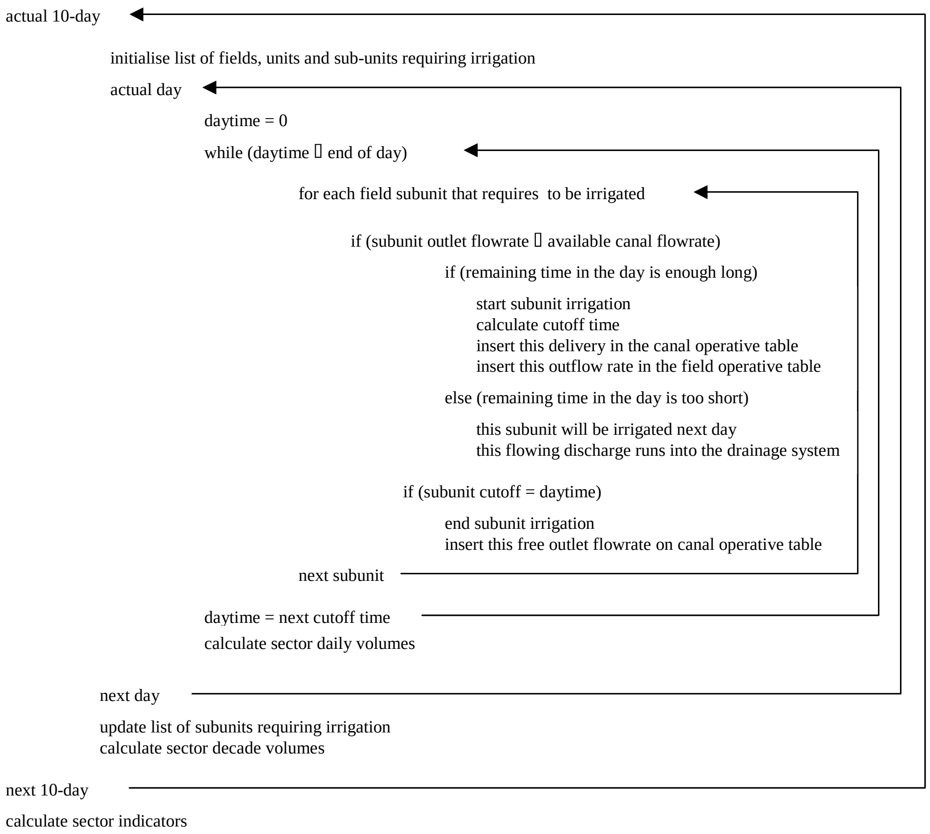
4. Execute the simulation of the delivery for the new sector scenario (Fig. 4). The canal delivery model applies the following delivery rules and procedures:
   a) A rotational delivery scheme is considered in relation to crop irrigation scheduling, based on a sequential group of fields previously prepared by the user;
   b) For each field, the delivery is assumed to be performed by all the respective outlets under restriction of the available discharge flowing in the distributor canal;
   c) After ending irrigation of any field, the delivery to the next field starts after a time lag estimated from the reach length between both fields, the discharge flowing in that canal reach and the average flow velocity;
   d) A field starts to be irrigated when the day time available is not larger than the application time; otherwise it will be irrigated the next day;
   e) If a field is not supplied for irrigation during the current 10-day period, it will be irrigated by the beginning of the next 10-day;
   f) When a field ends the irrigation, the water that stays available will be distributed to the next field in the sequential delivery table; the next field will only start the irrigation after a lag time, calculated from the reaches length; the lag time is calculated based on the average flow velocity and the length of canal reach:

   $$t_{lag} = L_{reach} / V_{av} \qquad [1]$$

   where t_{lag} (s) is lag time between any change in delivery and the time when the steady state flow regime is re-established, L (m) is the reaches distance between the former and the new delivery control points, and V_{av} (m/s) is average canal flow velocity (default=0.5 m/s) ;
   g) The canal seepage is estimated as a fraction of the flowing water volume proportional to the discharge and the reach length:

   $$Q_{seepage} = Q_{in} \times f_{seepage} \times L_{reach} \qquad [2]$$

   where $Q_{seepage}$ (m^3/s) is seepage flow, L_{reach} (m) is length of the canal reach, Q_{in} (m^3/s) is the average discharge flowing in the reach, and $f_{seepage}$ (%/100 m) is a seepage factor characteristic for each type of canal.



```
actual 10-day
    initialise list of fields, units and sub-units requiring irrigation
    actual day
        daytime = 0
        while (daytime  end of day)
            for each field subunit that requires  to be irrigated
                if (subunit outlet flowrate  available canal flowrate)
                    if (remaining time in the day is enough long)
                        start subunit irrigation
                        calculate cutoff time
                        insert this delivery in the canal operative table
                        insert this outflow rate in the field operative table
                    else (remaining time in the day is too short)
                        this subunit will be irrigated next day
                        this flowing discharge runs into the drainage system
                if (subunit cutoff = daytime)
                    end subunit irrigation
                    insert this free outlet flowrate on canal operative table
            next subunit
        daytime = next cutoff time
        calculate sector daily volumes
    next day
    update list of subunits requiring irrigation
    calculate sector decade volumes
next 10-day
calculate sector indicators
```

Fig. 4. Flow chart of delivery computations during each 10-day period.

5. View results of new sector scenario. The layout is saved on GEODB and results are viewed through tables or GIS graphics including:
    a) Field distribution data, including start and end of irrigation;
    b) Network operation data, relative to the discharge at control structures during irrigation period;
    c) Water volumes, including effective supply, seepage and runoff;
    d) Performance indicators related with economic and environmental impacts.
6. Compare sector scenarios through multicriteria analysis as referred in the next section.

GIS Integration

The GIS application is a SEDAM extension designed for data input and analysis of results. Since the database contains entities with geographic representation (fields, reaches or nodes), it seems logical to explore these capabilities. Some tasks that the user must perform, like to create and sort delivery groups, attribute SADREG workspaces (characterizing the typified fields) to the actual fields or to define boundaries of each sector, become easier through GIS. In addition, the user can launch both SEDAM and SADREG models directly over the sector or a single field which he wants to simulate or view data. The GIS application allows calling SADREG from the user-selected field (Fig. 5) or the SEDAM execution from a user-selected sector.

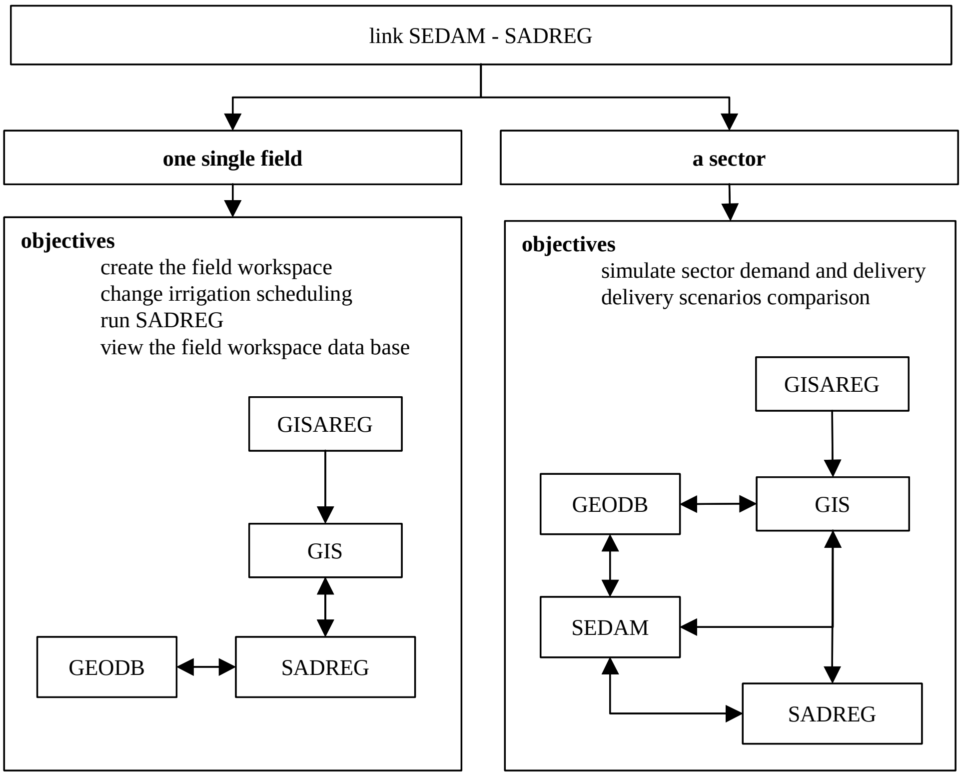
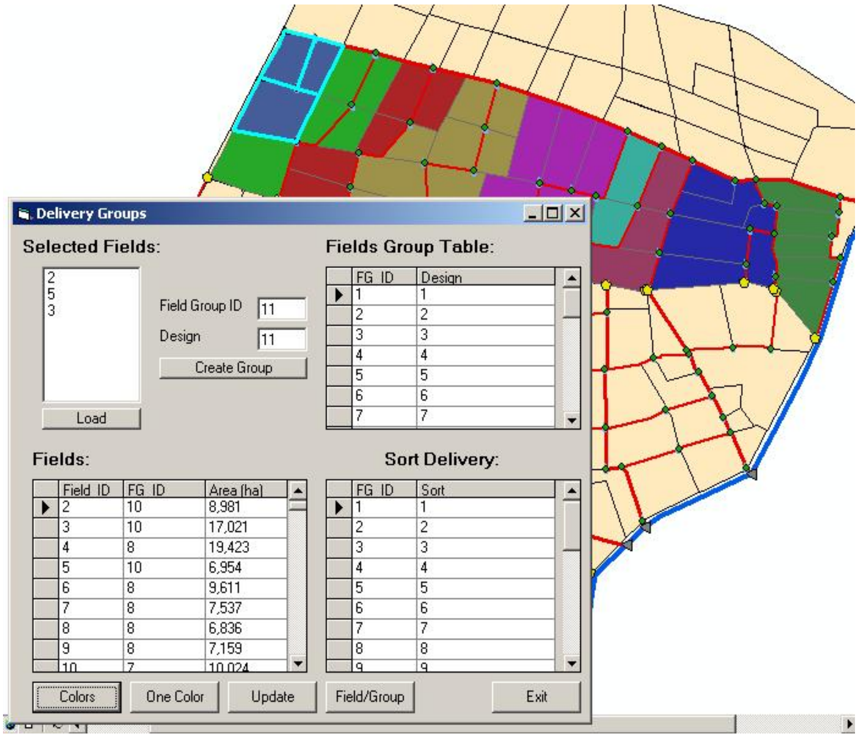


Fig. 5. SADREG application modes in interaction with the GIS database GEODB.

The GIS toolbars interface concerns several functionalities:

- GIS-SEDAM – these functions perform interactions with the SEDAM database.
    - Run SEDAM model selecting a sector scenario. The selection is made on the map (sector) and from a list of existing scenarios for the selected sector;
    - Create and sort delivery groups by selecting fields from the map (Fig. 6);
    - View operational results in the Table Results selecting a field or a reach on the map;
    - View operational graphic results selecting a field or a reach on the map.



Delivery Groups

Selected Fields:

2
5
3

Field Group ID: 11

Design: 11

Fields Group Table:

FG ID	Design
1	1
2	2
3	3
4	4
5	5
6	6
7	7

Fields:

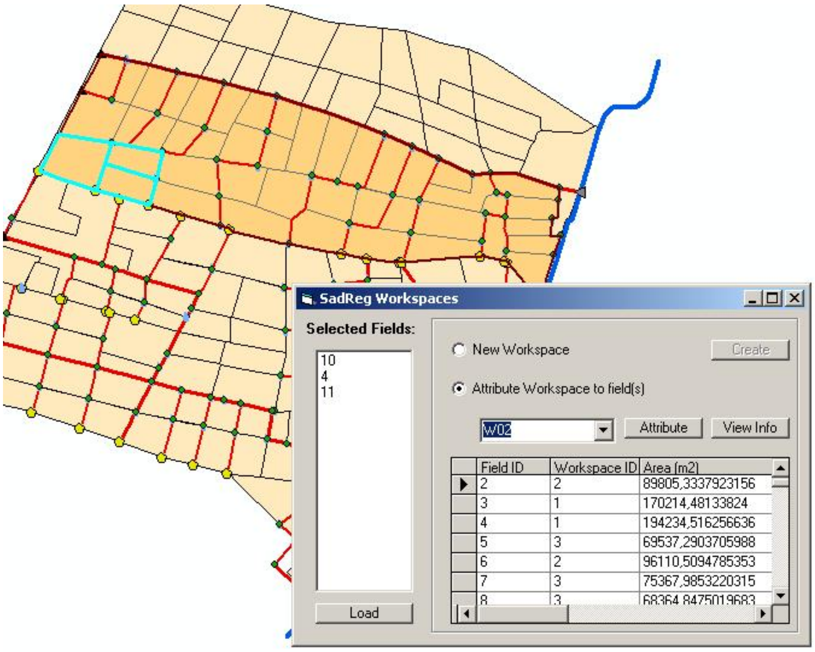
Field ID	FG ID	Area (ha)
2	10	8,981
3	10	17,021
4	8	19,423
5	10	6,954
6	8	9,611
7	8	7,537
8	8	6,836
9	8	7,159
10	7	10,024

Sort Delivery:

FG ID	Sort
1	1
2	2
3	3
4	4
5	5
6	6
7	7
8	8
9	9

Fig. 6. Tool to define the delivery groups along a canal where the user selects the fields in the map and the table is automatically built up and the map results coloured.

- GIS-SADREG – these functions perform interactions with the SEDAM database and the SADREG model and database:
    - o Run SADREG model selecting a field on the map;
    - o Create new workspaces and attribute workspaces to fields (Fig. 7);
    - o Create new irrigation projects.
- Data-Type Conversions – functionalities to import and export data between SEDAM, SADREG and GISAREG databases.



Selected Fields:
10
4
11

○ New Workspace

● Attribute Workspace to field(s)

W02

Field ID	Workspace ID	Area (m2)
2	2	89805,3337923156
3	1	170214,48133824
4	1	194234,516256636
5	3	69537,2903705988
6	2	96110,5094785353
7	3	75367,9853220315
8	3	68364,8475019683

Fig. 7. Workspace link from field map.

Multicriteria analysis

The multicriteria analysis is performed by considering the criteria and attributes described in Table 3 and referring to the following:

- Expected benefits to the farmers;
- Foreseen costs for the farmers and the WUA; and
- Environmental benefits including water savings.

The utility functions U relative to the criteria in Table 3 are as follows:

- Benefits: $U_i = \alpha_{Mi} \cdot (X_i - X_{i.\min})$ [3]
- Costs: $U_j = 1 - \alpha_{Mj} \cdot (X_j - X_{j.\min})$ [4]
- Environmental issues: $U_k = 1 - \alpha_{Mk} \cdot (X_k - X_{k.\min})$ [5]

where the values adopted for α and the range for X are given in Table 3. Adopting user-defined weights (λ_j) for every criteria j, the global utility value is

$$U = \sum_{j=1}^{7} \lambda_j \cdot U_j \qquad [6]$$

Table 3. Criteria and attributes utilized for multicriteria analysis.

Criteria	**Attributes**	$\mathbf{X_{min}}$ (a)	$\mathbf{X_{max}}$ (a)	α_M (a)
Benefits	Land productivity (kg/ha)	2683	3030	0.00288
	Land economic productivity (€/ha)	805	909	0.00960
	Water productivity (kg/ m$^{3)}$	0.0863	0.9763	1.1235
	Water economic productivity (€/ m$^{3)}$	0.0259	0.2928	3.74513
	Beneficial water use fraction (-)	0.1528	0.7260	1.744
	Yield value to total cost ratio (-)	0.2504	2.107	0.5386
Costs	Total cost per unit water use (€/m$^{3)}$	0.1033	0.1535	19.899
	Fixed cost per unit water use (€/m$^{3)}$	0.0012	0.0314	33.012
	Variable cost per unit water use (€/m$^{3)}$	0.1019	0.1474	21.997
	Delivery operating cost (€/m$^{3)}$	0.8040	2.1440	0.7463
Environmental issues	Total water use (sector and fields) (m^3/ha)	9111	20522	8.763E-05
	Runoff to water use ratio (field) (-)	0	0.568	1.759
	Percolation/salinization risk (m^3/ha)	330	7400	0.141E-03
	Land levelling impacts on the soil (cm)	0	3.92	0.255
	Soil erosion risk index (index)	1	9	0.125
	Canal seepage (ratio)	0.082	0.113	32.42
	Canal runoff (ratio)	0.207	0.365	6.313

(a) These values are calculated automatically and are dependent of the application

The multicriteria analysis used to rank the simulated scenarios is performed as follows:

- The performance indicators (Table 4) relative to the sector for the simulated scenarios are read from the corresponding GEODB table and the respective averages are computed;

Table 4. Performance indicators relative to the irrigation sector.

Indicators	**Description**
Number of delivery days (N_{days})	Number of days per year required for irrigation
Field supply (m^3)	Volume of water supplied to the fields
Beneficial water use, field (m^3)	Volume of water supplied and beneficially used in the fields
Field percolation (m^3)	Volume of leaving the fields by deep percolation
Field runoff (m^3)	Volume of runoff water from the fields
Field delivery deficit (m^3)	Volume of water not supplied during the planned 10-day delivery period
Supply (m^3)	Volume of water supplied to the sector
Canal seepage (m^3)	Volume of seepage water in the canal system
Canal runoff (m^3)	Volume of water flowing from the canal system to the drainage system
Operational cost of delivery (€)	Total costs of operating the canal system
Yield (kg)	Yield of the cotton crop assumed as reference
Yield value (€)	Value of the crop yield
Field fixed costs (€)	Farm fixed costs
Field variable cost (€)	Farm variable costs
Field total cost (€)	Farm total costs
Land levelling impact (cm)	Soil depth affected by soil cutting
Soil erosion impacts	Index on erosion risk depending on soil characteristics

- The utility values are computed from the average indicators (Eq. 3 to 5);
- The user defined weights for the criteria are read from the respective file, and the global utility value is computed (Eq. 6);
- The scenarios are ranked according the global utility values.

Application and Results

A SEDAM application to a Sector of Fergana irrigation District, Uzbekistan, was performed (Fig. 8). The SADREG workspace was developed and was linked (Fig. 7) to this sector (Gonçalves *et al.*, 2005).

The field delivery groups were prepared from the GIS interface (Fig. 6), which shows to be an useful tool to plan water delivery, combining field and network knowledge to plan a better delivery schedule.

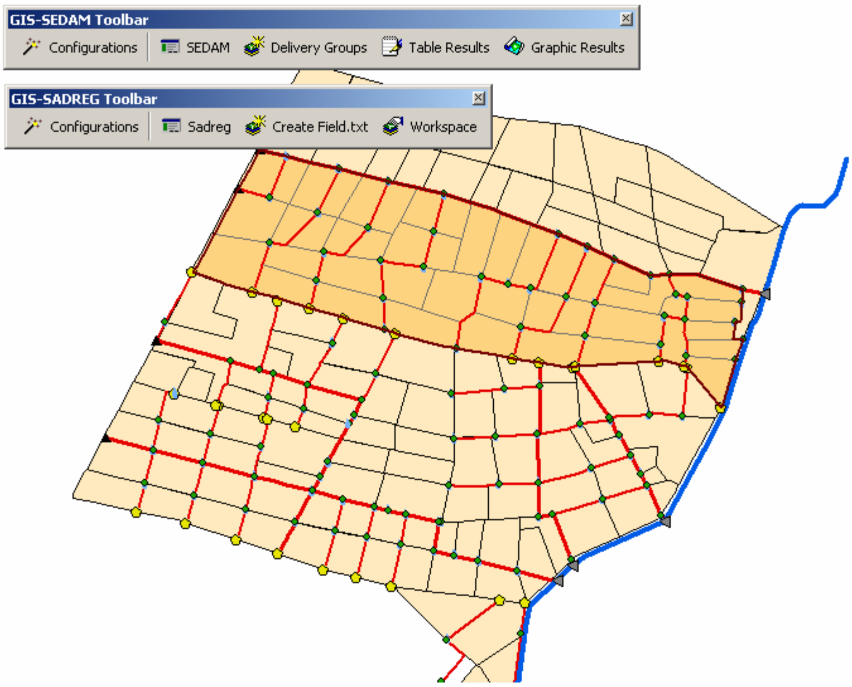


Fig. 8. Map of a sector of Fergana irrigation District and the toolbars with GIS functionalities relative to both models SADREG and SEDAM.

The Sector scenarios considered in this study were generated from the combination of decision variables represented in Table 5, applying in all cases a sector supply discharge of 1.5 m^3s^{-1} (corresponding to a unitary discharge of 3.2 $l\ s^{-1}ha^{-1}$).

Table 5. Sector scenarios profile.

Scenarios		Daily delivery time = 20 h d^{-}	
		A1 Priority to economics	A2 Priority to environment
B0	Present	✔	
B1	Present with improved scheduling		✔
B2	Partial improvements in furrow irrigation		✔
B3	All area under improved furrow irrigation		✔
B4	Continuous and surge flow; every-furrow option		✔
B5	Continuous and surge flow; alternate-furrow option		✔
B6	Continuous and surge flow; deficit irrigation		✔
B7	Continuous and surge flow; alternate furrows and deficit irrigation		✔
B8	Surge flow; alternate furrows and deficit irrigation		✔

The output results for field supply are presented in a table through SEDAM and in a graphic through a GIS extension (Fig. 9.), which presents the daily inflow hydrograph and the 10-day estimated supply and delivery deficit.

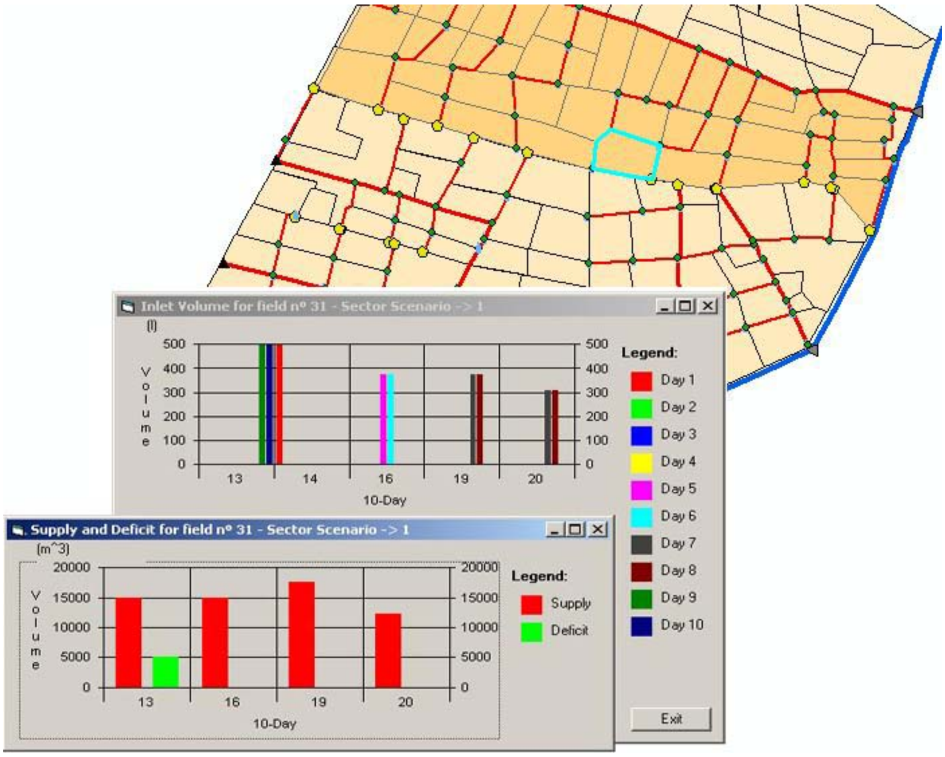


Fig. 9. Graphical results of the daily supply hydrograph and estimated supply and delivery deficit for the field 31 and scenario B1.

The results relative to all scenarios comprise all indicators (Table 4) and attributes (Table 3) characterizing each scenario, as well as the respective utilities (Eq. 3 to 6), which are exported to Excel files for further analysis. Examples are those in Fig. 10 to 15.

The 10-day volumes supplied to the sector, delivered to fields, infiltrated as canal seepage and fields percolation, and flowing out as fields and canal runoff are shown in Fig. 10, 11 and 12 for the scenarios B0, B1 and B6, respectively and the total volumes supplied to the sector are presented in Fig. 13 for all scenarios. The results evidence the water saving impacts due to field improvements: irrigation scheduling (from B1 to B8), land levelling and furrow irrigation systems (B2 to B8).

The present scenario B0 (Fig. 10) shows that the sum of the volumes of canal and field runoff and field percolation are larger than the beneficial water use. While percolation may be non-reusable if percolating to a saline water table, canal runoff and field runoff return to the river or are reusable downstream, so are not lost but imply operational costs and management problems.

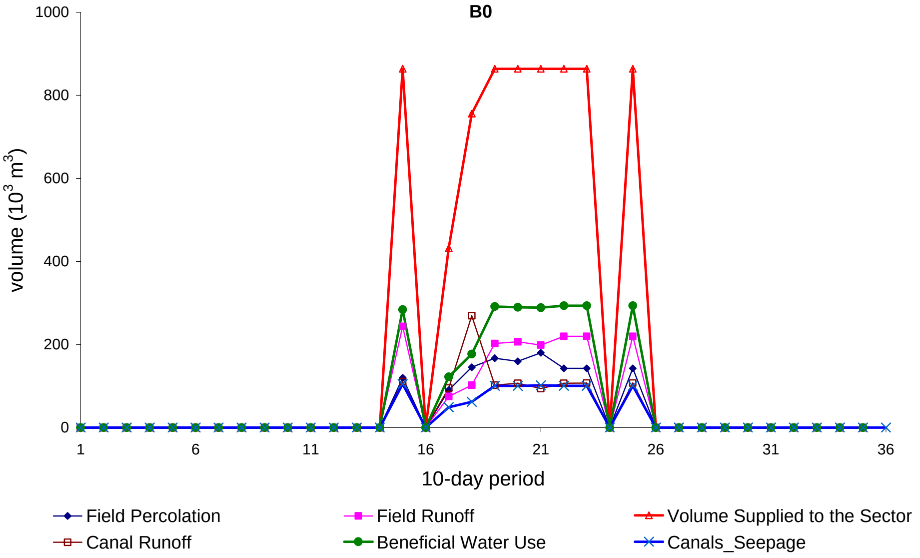


Fig. 10. Scenario B0, present: 10-day supply volumes and water use components.

The scenario B1 (Fig. 11) refers to the application of an improved irrigation scheduling with very precise cut-off times for application of only 60 mm per irrigation event but maintaining the actual farm irrigation systems. This situation is very difficult to be adopted because irrigation depths represent about half of present; however, it is possible when a very good inflow control would be applied at field level, so also highly reducing field runoff and percolation. Results at distribution level are excellent because the delivery times for 20 l s^{-1}

outlets produce optimal daily rotation among fields, so enormously reducing canal runoff. Though, the sum of canal runoff, field runoff and field percolation are still higher then the beneficial water use.

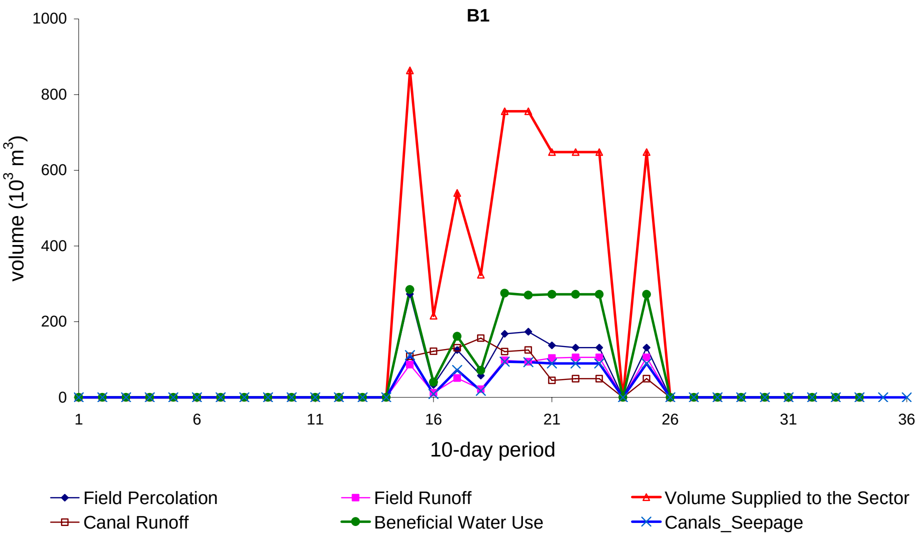


Fig. 11. Scenario B1, precise cut-off times: 10-day supply volumes and water use components.

The improved farm irrigation scenarios concern an irrigation scheduling where a more realistic 80 mm depth is considered. Then the time duration of delivery for 20 l s^{-1} outlets asks a time duration of delivery per field of about 12 h; so, adopting a 20 h delivery duration per day makes it not possible to supply 2 fields during the same day unless that either the outlets have a larger discharge or the delivery duration become 20 h per day (these strategies are not yet simulated but the model has the capabilities for running for several alternatives on the delivery conditions without requiring changes). Due to these limitations, the scenarios B2 to B8 lead to results that are only slightly better than the unrealistic scenario B1, which evidences the importance of accurately considering the delivery conditions in agreement with the field water application. The scenario B6 leads to an improved beneficial water use, which is explained by: (a) irrigation timings and depths in agreement with crop demand; (b) land levelling used that favours the control of field percolation and runoff; however, the runoff is not so well controlled as for scenario B1 because by the end of the irrigation season the soil infiltration is lower, less water infiltrates and more water runs out of the field; (c) deficit irrigation, which allows that the beneficial water use be higher than the non-beneficial fraction by the beginning of the season despite reversing this situation by the end (Fig. 12).

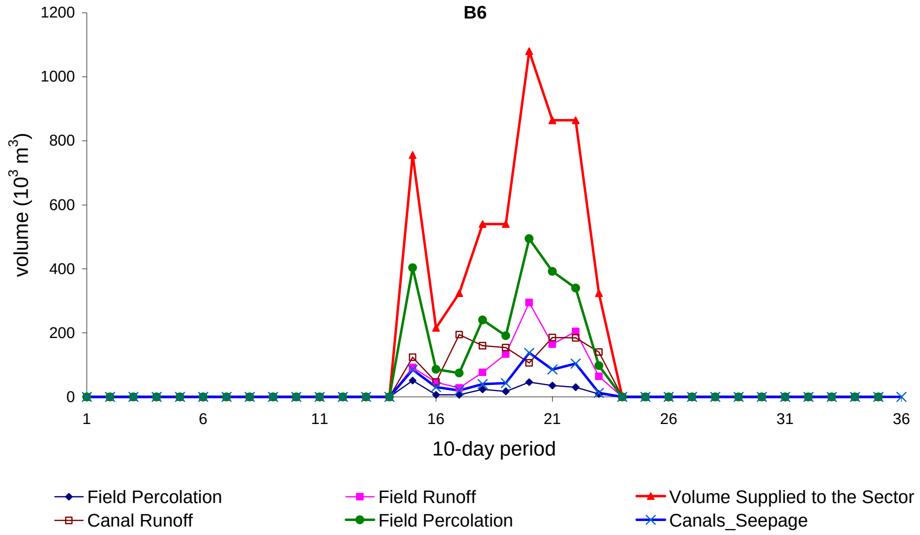


Fig. 12. Sector 10-day supply volumes and water use for scenario B6.

The Fig. 13 shows the seasonal water use volumes per each scenario and the respective components. It identifies both the beneficial and non-beneficial water uses and the respective changes for every scenario. The scenarios that assume a full development of field irrigation (from B3 to B8) show the best water saving performance at farm level. As commented above, a significant result is the reduction of field percolation for the improved scenarios, with a very positive impact on salinization control. However, the decrease of percolation is followed by the increase of field runoff, which may be reused.

The Fig. 14 refers to economic data - water economic productivity (for cotton), and fixed and variable costs per unit of water use. The variation of field fixed and variable costs are small due to low investments and low costs of labour. On the contrary, the water economic productivity is a main factor that relates to water saving.

The scenario B6 has the higher water economic productivity since it is the scenario that presents the lower water volume supplied to the sector and the highest beneficial water use fraction, but also it concerns deficit irrigation.

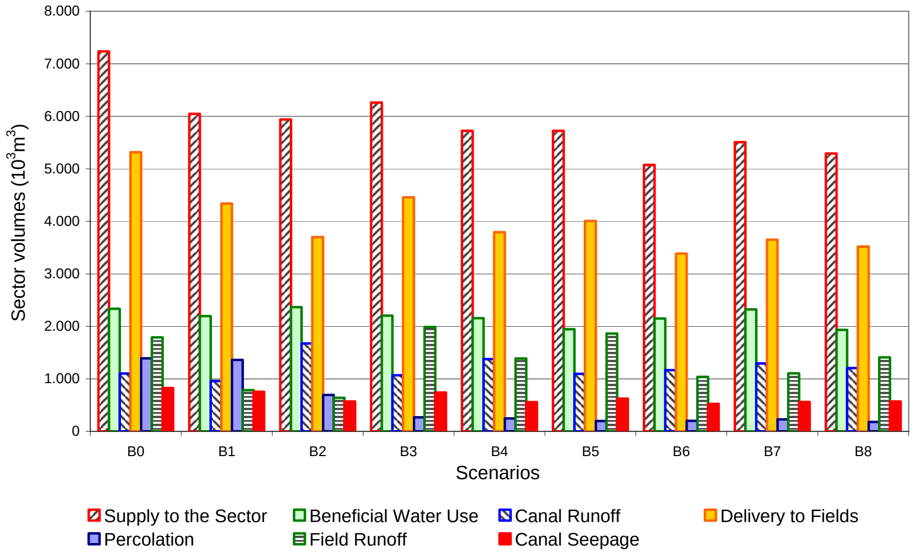


Fig. 13. Seasonal water use – total, delivered, beneficial and non-beneficial –for scenarios B0 to B8.

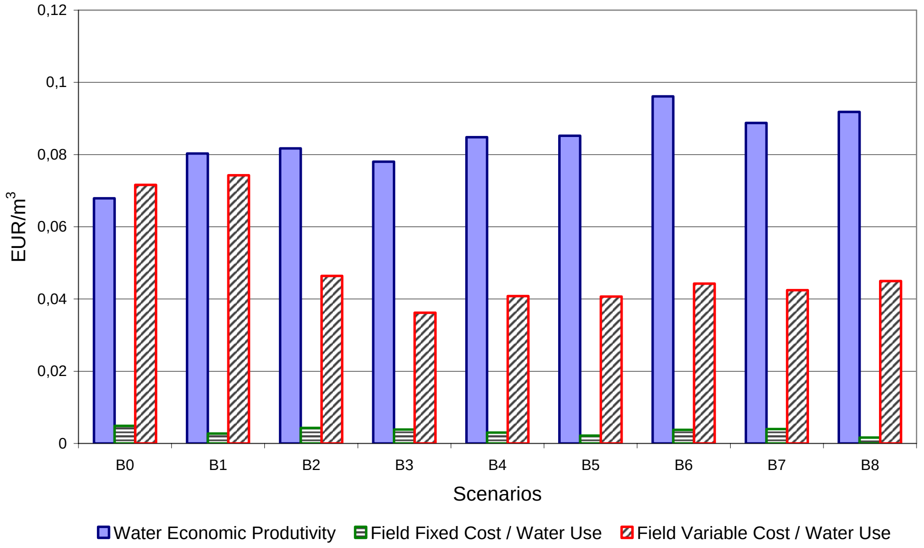


Fig. 14. Economic attributes by sector scenario.

Fig. 15 presents the global utility relative to all scenarios. It shows small differences among all improved scenarios B1 to B8, all much above present conditions. Differences are small because scenarios do not show significant differences in land productivity and relative to costs due to low investments and low labour costs.

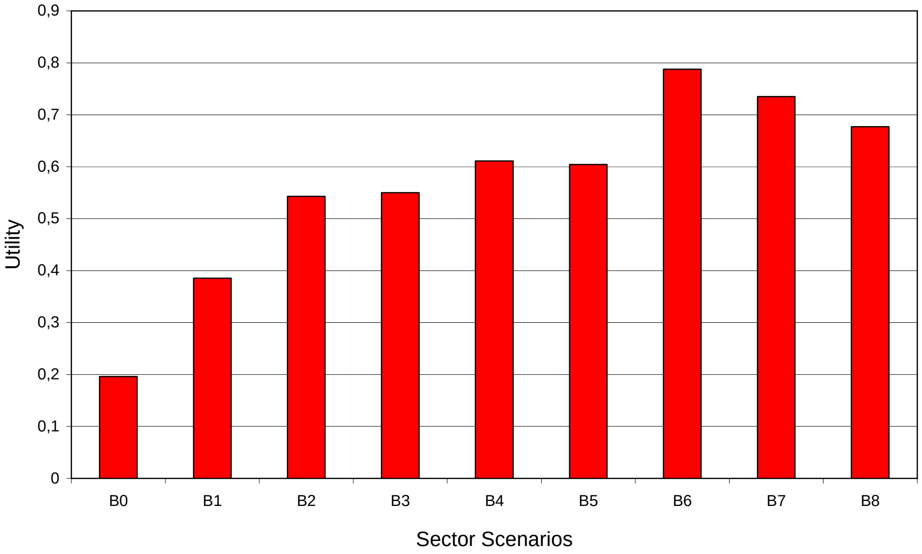


Fig. 15. Global utilities relative to the Sector scenarios.

Conclusions

It can be concluded that the SEDAM model has the potential to become a valuable tool to support decision-making relative to the improvements both of the farm irrigation system and the distribution system. However, it requires the production of a quite large database, the characterization of appropriate improvements, and information on the delivery system more accurate than that available for this simulation. The GIS integration increases the model capability to access input spatial data and favours a user-friendly interface both to run the model and to view the results. Nevertheless, since results for every scenario concern a large number of indicators and attributes, the auxiliary use of Excel for analysis of results is also required.

Results for Fergana Valley indicate that there is a large potential for solving the existing water use and salinity problems when the management of the distribution system is coordinated with farm irrigation improvements, mainly aiming that deliveries match the farm irrigation scheduling. Improvements require modernization of the farm systems, which are well identified through the SADREG results (Gonçalves *et al.*, 2005) such as surge-flow, land levelling, furrow length adjustment and, mainly, the appropriate control of inflow discharges and application timings and duration. Improvements in delivery, relative to duration and timing are also required.

Canal runoff is significant for all scenarios and its improvement would require a better assessment of delivery. This may be done in a later phase by considering together the advances proposed by Dukhovny and Tuchin (2005) relative to performance improvement of irrigation canals. However, combining this mathematical modelling and the approach in this paper requires a long term modelling study that was not possible in the time span of this project. In fact, the approach in SEDAM focus on relating the modernization of farm irrigation and the respective consequences on water demand and related delivery while that by Dukhovny and Tuchin (2005) mainly deals with hydraulics modelling. Joining both approaches may also lead to develop a real time demand and delivery model.

The high canal runoff proves that the establishment of adequate delivery rules is essential to guarantee an effective distribution, both aiming at water saving and increasing farmers incomes. Results herein were obtained for a distribution option where the supply duration is 20 hours per day and delivery is performed with a fixed discharge at the outlets and the delivery duration equals the field application time. Further improvements need to be tested where outlets discharges would be variable to improve the delivery duration to fields.

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