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Sustainability and Environmental Externalities of Mediterranean Irrigated Lands: a dynamic system model

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1. Introduction

Traditional irrigated lands have constituted one of the most characteristic agro-landscapes in the Mediterranean. In addition to their socio-economic importance, irrigation systems have played a major ecological and environmental role. However these valuable agro-landscapes are progressively decaying and disappearing due to recent socio-economic changes, which, at the same time, are promoting the development of new irrigated lands outside the river valleys and with very different environmental, social and economic characteristics. These new irrigated lands constitute complex systems of rapid evolution and have a major effect on land, water resources, landscape, biodiversity and the ecological value of extensive tracts of the Mediterranean area, especially in arid and semi-arid environments like those of south-eastern Spain.

The irrigated lands of Mazarrón and Aguilas, in the coastal area of Murcia province, SE Spain, constitute a good example of new intensive Mediterranean agriculture, based on groundwater exploitation. The intensive use of groundwater resources has led to the over-exploitation of local aquifers and to seawater intrusion, water salinization and the falling off water tables. Moreover, the continued expansion of irrigated lands has meant taking over areas of high ecological value, threatening part of the habitat of endangered protected species. Some of these effects constitute full environmental *externalities* while others also negatively influence the profitability of irrigated lands because of decreasing available space, scarce water resources and, especially, low water quality due to salinization. All these factors establish complex relationships which condition the general behaviour of the system.

Although major efforts have been done to try to overcome the problem of water scarcity through the increase of the available water resources, the water deficit and associated environmental problems have become worse. Which are the reasons of this unexpected failure?. Behind the considerable number of exogenous and endogenous factors which affect the different elements of the system, some persistent trends and major driving factors of the system behaviour can be identified through a systemic approach like system dynamics. We have developed the *New Irrigated Lands* dynamic model to try to answer this question through a better general understanding of the major factors and relationships implied in the generation of water demands in this agricultural system. This might be of help to share a common view between the stakeholders about the origin of the problem and the type of solutions that might be adopted.

Although the system dynamics methodology has been frequently applied to socio-environmental systems, the number of research works regarding agricultural systems, especially in the case of irrigated lands, is quite scarce. However, in recent years there is an increasing interest (Muñoz 1991; Saysel, 1999; Martínez-Fernández *et al.*, 2000; Martínez-Vicente *et al.*, 2000; Saysel, 2001) to explore through system dynamic models the socio-economic and environmental interactions of the Mediterranean irrigated lands and their role on the management of natural resources.

The dynamic model will also be used to assess the current and long term sustainability of the intensive irrigated lands of Mazarrón and Aguilas using several pressure and state indicators, which form part of the model variables. The pressure indicators considered include the area occupied by irrigated land, water consumption, nitrate and phosphate leaching and the production of plastic wastes. The state indicators of sustainability include the water level of aquifers, water conductivity, soil conductivity and several indicators concerning the environmental quality of the areas occupied by new irrigated lands. In this work we present the main results regarding the overall behaviour of the system and the environmental effects linked to water. Additional information about the whole model and results can be found in Martínez (2000) and Martínez & Esteve (2002).

2. Overview of the *New Irrigated Lands* dynamic model

The *New Irrigated Lands* dynamic model includes five sectors: Irrigated Land, Profitability, Available Area, Water Resources and Pollution. Figure 1 presents a simplified diagram showing the main factors and relationships.

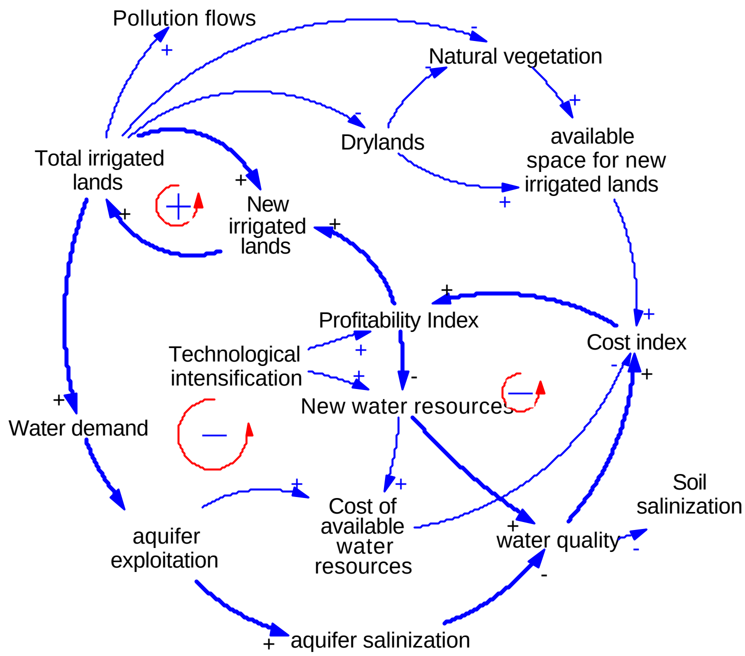

Figure 1. Simplified diagram of the New Irrigated Lands model

The increase in irrigated land generates several environmental effects, some of which also constitute greater economic costs and lower profitability, which eventually may slow down the expansion of irrigated lands. All these effects are included in several positive and negative feedback loops, some of which are emphasized in Figure1, and integrated into an aggregated profitability index. As an example, we describe one of the negative feedback loops: the greater the area of irrigated lands, the higher the water demand, so aquifer exploitation increases and piezometric levels go down. This increases water extraction costs, which affects profitability and slows down the irrigated land expansion. The exploitation of aquifers also induces salinization of the aquifers. Irrigation with this low quality water immediately affects the quantity and quality of production and hence the relative profitability of the affected irrigated lands, which promotes a search for external water resources from alternative sources like water transfers from other surface and subterranean water systems and marine desalination. Other environmental effects such us the remaining available area for new irrigated lands are also included in the aggregated costs index through other feedback loops.

The figure 2 shows a simplified diagram of the irrigated land sector with the area of irrigated tree crops, open air horticultural crops, greenhouses, dryland, natural vegetation (scrublands) and dams for irrigation. The whole set of variables and parameters was determined using data obtained from the fieldwork and environmental and spatial modelling. The area occupied by each one of the three types of irrigated land varies with time through a total of 12 rate variables representing land use changes. The rate of change of each land use depends on a profitability index, calculated as the differences of profitability between each land use and the aggregated costs index.

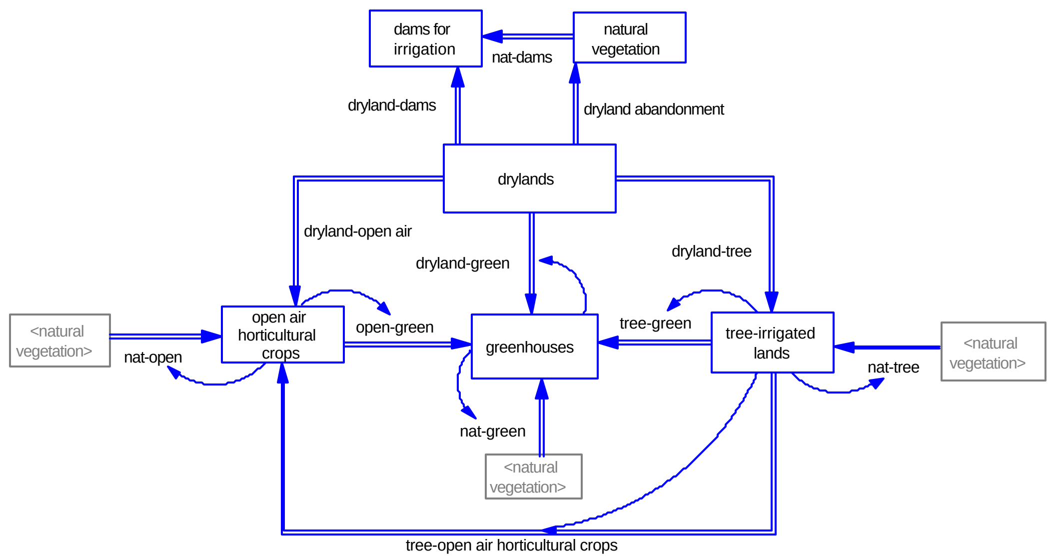

Figure 2. Simplified diagram of the irrigated land sector showing the level (boxes) and rate (flow arrows) variables representing the main uses and land use changes. nat-dams: natural vegetation to dams; nat-open: natural vegetation to open air irrigated horticultural crops; open-green: open air irrigated horticultural crops to greenhouses; tree-green: irrigated tree crops to greenhouses; nat-tree; natural vegetation to irrigated tree crops; nat-green: natural vegetation to greenhouses.

The water resources sector includes two variables of level: the water level in the Mazarrón and Aguilas aquifers and available external resources from alternative water sources (figure 3) The level in the aquifers varies as a function of two inflows: natural recharge from rainfall and drainage and percolation from irrigation, and two outflows: springs and pumping. The rate of pumping depends on water demand, the quality of irrigation water and the availability of water resources from other sources. On the other hand, the aquifer water level determines the piezometric level and the irrigation water quality, one of the factors which has a major effect on the relative profitability of irrigated land and its rate of growth.

The profitability sector includes the specific index of technological intensification of each type of irrigated land and its relative profitability ratio, which have a major effect on land uses changes, and the aggregated costs index, which summarises the combined effects on costs induced by the quality of the irrigation water, the cost of water pumping, the water deficit and the remaining available area for new irrigated lands. Because of the past and current behaviour of these irrigated land systems, which show no market-related problems, exogenous restrictions to the expansion of irrigated lands are not considered.

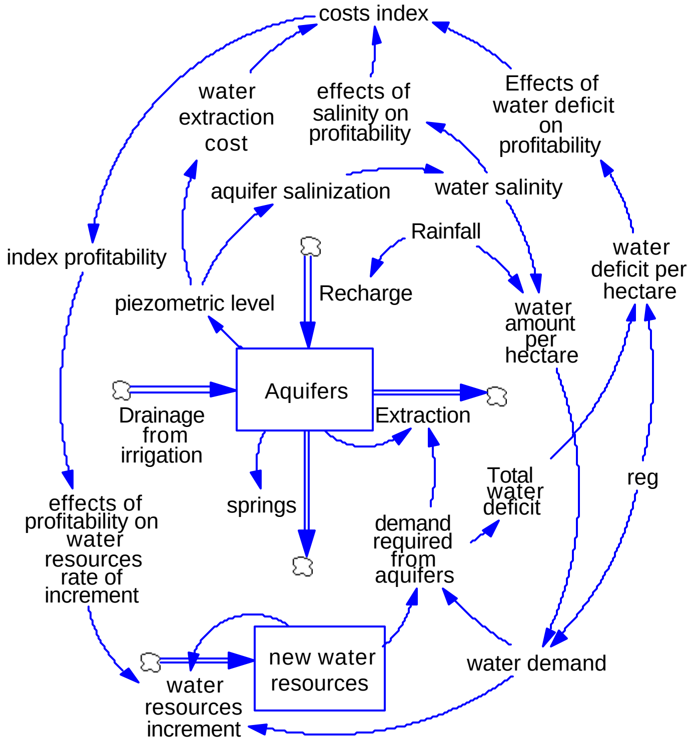

Figure 3. Simplified diagram of the water resources sector

As regards the available space sector, the main variables included are dryland, high quality natural vegetation (scrublands), low quality natural vegetation (generated through succession processes after dryland abandonment) and the fraction of drylands and natural vegetation environmentally susceptible to being transformed into new irrigated lands. The environmental model of irrigated lands, or potential distribution model (Martínez & Esteve, *in press*), allowed the determination of several important variables and parameters of this sector including the maximum area of irrigated lands. This is based on the presence probability of irrigated lands in each cell unit of the study area. This maximum area reaches around 28,000 ha in the whole study area, of which 17,000 ha are already irrigated lands.

Finally, the pollution sector includes several processes, in particular soil salinization and non-point agricultural pollution (nitrate and phosphate leaching) due to leakage from irrigation and the production of plastic wastes from greenhouses. Most of crops of open-air horticultural crops and greenhouses are not cultivated directly in the soil but in artificial substrata which are substituted each two years, so soil salinization does not affect the crops. These environmental effects, hence, do not constitute direct costs to the irrigated land sector, so they can be mainly considered as pure environmental externalities generated by the system.

3. Simulation results

The dynamic model simulation from 1960 to the present time gives results similar to the corresponding real data series, showing the increment of irrigated lands from 1,200 ha in 1960 to 17,000 ha in 1999 (Figure 4) and the exponential growth of greenhouses. The relative profitability index exhibits a notable fall between 1980 and 1990, principally because of the deterioration in irrigation water quality generated by the over-exploitation of aquifers, and consequent salinization (Figure 5).

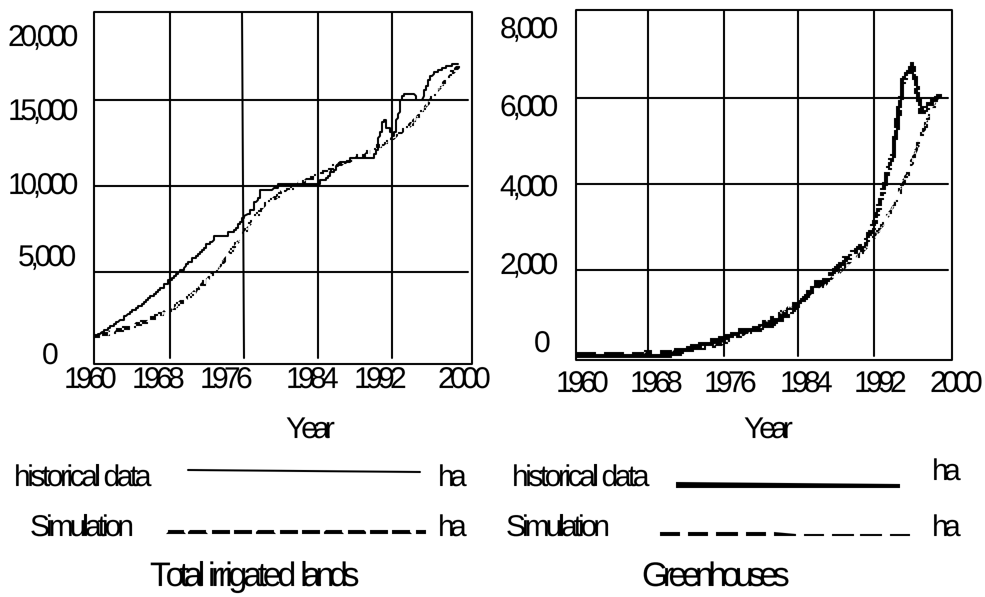

Figure 4. Temporal evolution of total irrigated lands and greenhouses from 1960 to 1999. Historic data and simulation results

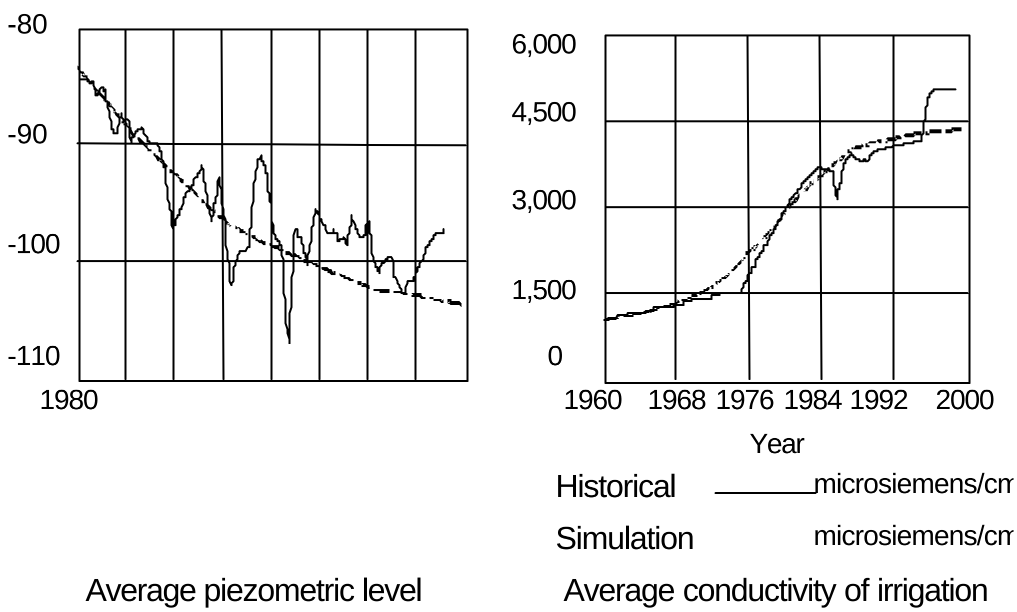

Figure 5. Temporal evolution of the average piezometric level of aquifers and the average conductivity of irrigation water. Historical data and simulation results

As regards pollution flows, during the last years, the level of nitrate and phosphate leaching has doubled due to the greater extension and intensification of irrigated land. Finally, the production of plastic wastes from greenhouses shows a pronounced increase, reaching around 6,600 tons per year.

In synthesis, the model shows a shift from the initial prevalence of positive feedback loops promoting exponential growth to the dominance of negative feedback loops, when the system begins to perceive its own local restrictions in key factors like the quantity and quality of water resources. However, although this has slowed down the growth rate of the irrigated land, it remain far from a dynamic equilibrium with the existing resources. Several current initiatives and public policies are attempting to overcome the main perceived local restriction to current irrigated land, water scarcity, through a significant increase of external water resources. The idea is to transfer large quantities of water from the Ebro basin to the irrigated lands bordering de Mediterranean in Spain, as described in the Spanish National Water Plan.

4. Application of Validation Procedures to the *New Irrigated Lands* Model

Validation has constituted a basic issue during the whole model development processes. A period of 25 years was considered, since this was considered suitable for the main dynamic assumptions of the dynamic model to be relevant. Structural validation tests, the basic approach in the validation of dynamic system models (Barlas 1996) were applied to validate the *New Irrigated Lands* model, including the analysis of dimensional consistency, extreme condition tests, sensitivity analysis and a comparison with historical data series. The following presents some of the validation results.

The aim of the *extreme condition tests* is to verify the realistic behaviour of the model far beyond the conditions under which the model was been developed. The *New Irrigated Lands* model showed a satisfactory response to several extreme condition tests such as the absence of profitability or the extreme salinization of irrigation water, cases in which, as it might be expected, the irrigated land area is drastically reduced (Figure 6).

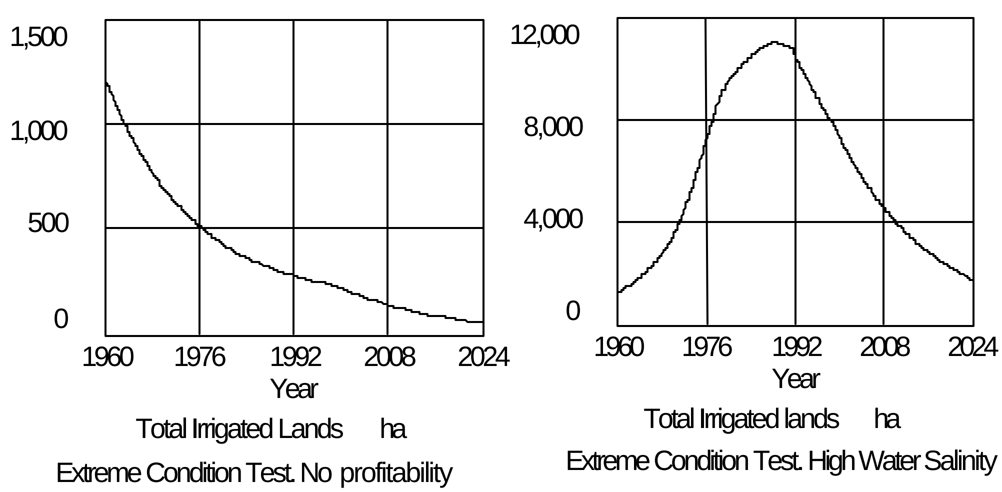

Figure 6. Extreme condition tests. If profitability is very low (left) or water salinity is very high (right) the area of irrigated lands quickly decreases

The sensitivity analysis evaluates the model's robustness to changes in the values of the different parameters. Robust models should show smooth, generally quantitative but not qualitative changes in the general patterns of dynamic behaviour.

The sensitivity analysis of a broad set of model parameters, like the initial value of aquifer water level and the Montecarlo simulation, in which all tested parameters were simultaneously varied, confirmed the robustness of the *New Irrigated Lands* model (Figure 7).

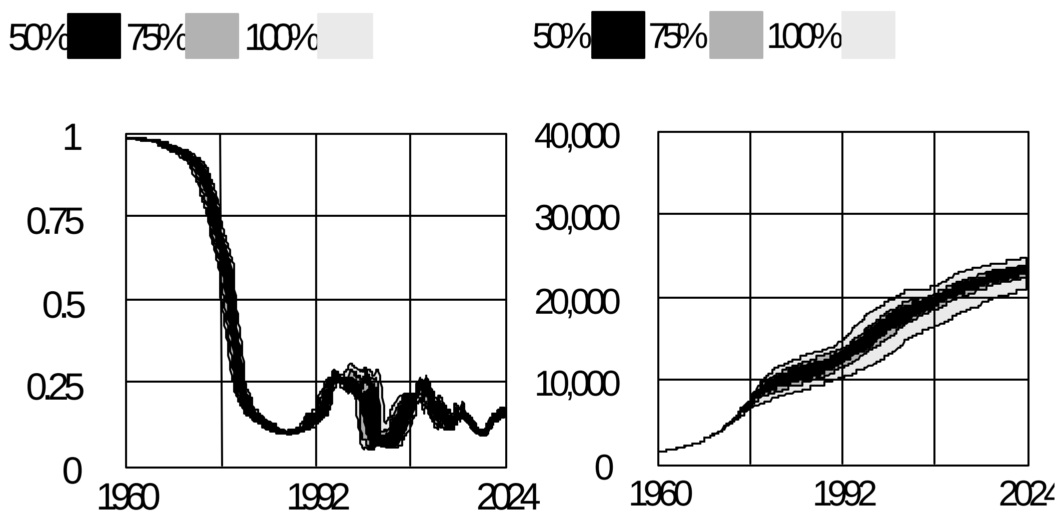

Figure 7. Sensitivity Analysis. Variation range of the aggregated cost index in response to changes in the value of the initial aquifer water level (left) and variation range of total irrigated land under the Montecarlo simulation (right). Grey tones indicate the confidence intervals of 50, 75, and 100 per cent.

5. Environmental externalities of the new irrigated lands

The main environmental externalities associated with the system under study are linked to the two main natural resources consumed by the new irrigated lands of Mazarrón and Aguilas: space and water. The evolution of such externalities was analysed by reference to several state indicators of sustainability related with space (Protected Open Space, Special Conservation Areas and habitats of *Testudo graeca* and *Periploca angustifolia*) (Martínez & Esteve, *in press*) and water (level of aquifers, aquifer water salinity and natural discharge through springs). Some of the main results, mainly referred to water quantity and quality, are briefly described.

The dynamic model simulated the negative temporal evolution of aquifers during recent decades by reference to aquifer levels, natural outflows through springs, piezometric levels and aquifer water salinity (figure 5). The fall in piezometric levels, the exhaustion of aquifer water reserves and progressive salinization have direct and indirect effects on the irrigated land system in the form of growing costs, as explained with the *New Irrigated Lands* model. However, the fall in the piezometric levels generates another effect, which may be considered as a pure environmental externality: the loss of springs and other natural outflows from aquifers along with associated wetlands and biodiversity. This constitutes a very important state indicator of the sustainability both for agricultural systems and the management of aquifers in Mediterranean environments. The model shows a considerable reduction of natural outflows through springs since the 1960s (figure 8).

Simulation results and historical data indicate that aquifer over-exploitation has led to the loss of 86 per cent of initial natural outflows. This drastic reduction of water flows is probably responsible for the elimination of a great number of wetlands and a reduction in biodiversity, an important ecological loss in the context of Mediterranean arid systems like those existing in south-eastern Spain and a clear sign of the unsustainability of these intensive irrigated lands.

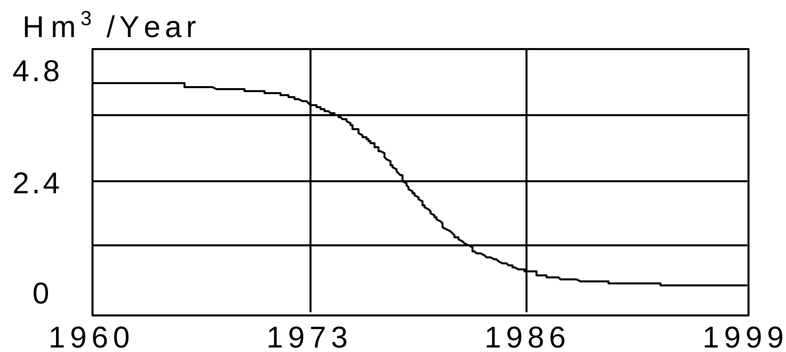

Figure 8. Evolution of annual discharge of Mazarrón and Aguilas aquifers through springs. Simulation results

In addition, the consumption of aquifer water reserves implies the loss of non-renewable natural resources of considerable strategic, social, environmental and economic importance. In fact, aquifer over-exploitation and the exhaustion of water reserves constitute the clearest example of desertification in the European context and a real paradigm of environmental and economic unsustainability (Martínez & Esteve, 2000).

Finally the non-point pollution due to the nitrate and phosphate leaching have increased due to the geater extension and intensification of irrigation. There is a clear gradient in the intensity of pollution flows from irrigated tree crops to open air horticultural crops to greenhouses, the last being responsible for the highest fertiliser inputs and generating the most plastic wastes. Results show a negative temporal evolution of the pressure indicators of unsustainability considered in the model in relation to pollution. Estimated nitrate and phosphate leaching reaches around 7,500 and 50 tons per year respectively (Figure 9), while heavy storms may generate exceptionally high leaching episodes. The effect of this agricultural non-point pollution is beginning to manifest itself both in the increase of nitrate content of the aquifers and in the first symptoms of eutrophication processes in the ephemeral channels of the study area and in the closest coastal marine environments.

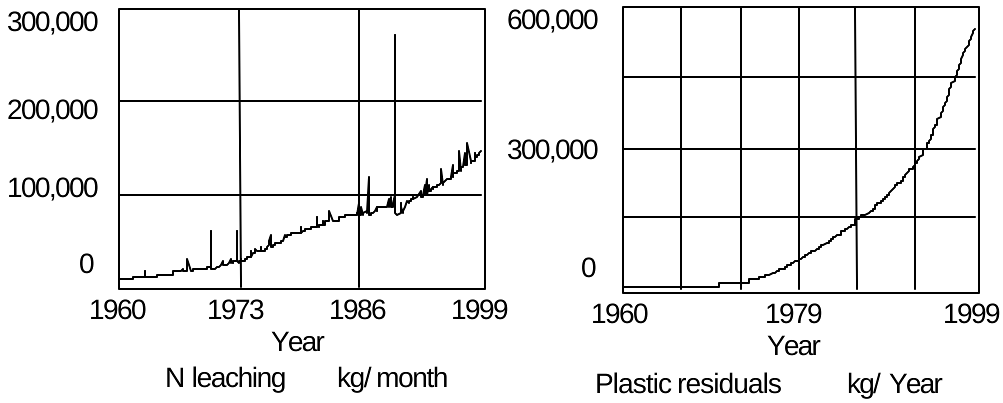

Figure 9. Temporal evolution of N leaching (left) and plastic wastes (right) generated by the irrigated lands

6. Exploration of scenarios

Several scenarios concerning the availability of space and water resources have been proposed in order to explore the possible dynamic evolution of the whole system. All these scenarios were projected over the time horizon for which the model was validated, covering the period 1999-2024. The main scenarios considered are the following:

1.- *Base Trend*. All model parameters remain unchanged, assuming the continuation of current trends over the next 25 years. This means maintaining the current increasing rate of increment of water usage, as may be expected from recently approved current initiatives, in particular the Spanish National Water Plan and the transfer of water from the Ebro basin to the irrigated lands in south-eastern Spain. This scenario, according to current expectations, attempts to overcome water scarcity, the main local limiting factor for current irrigated lands. On the other hand, no special environmental policies are adopted.

2.- *No External Water Resources*. This represents a pessimistic scenario in which the availability of water resources does not increase.

3.- Technological Intensification and Partial Increment of Water Resources. This assumes a reduced rate of increase in the external water supply. On the other hand it considers an increase in the technological innovation for use in irrigated lands, which partially counterbalances the increased costs due to scarce water resources.

4.- *Weak Nature Conservation Policy*. To the characteristics of the latter scenario, it is added a weak nature conservation policy, which excludes the transformation into irrigated lands of protected areas except in zones with quaternary materials, indicating a more natural aptitude for agricultural uses.

5.- *Strong Nature Conservation Policy*. To the characteristics of scenario three, a broad nature conservation policy is added, which excludes new irrigated lands in entire protected areas and in the high quality habitat of *Testudo graeca* (areas with a probability of presence greater than 70 per cent) and *Periploca angustifolia* (areas with a probability of presence greater than 25 per cent).

Here we briefly present some of the results regarding the environmental effects linked to water consumption of the Base Trend scenario.

Under the base scenario the current trend to increases in irrigated land continues during the next 25 years to reach 23,500 ha by the end of the simulation period., due to the increase of greenhouses, while open-air horticultural crops and irrigated-tree crops shows a slight reduction (figure 10).

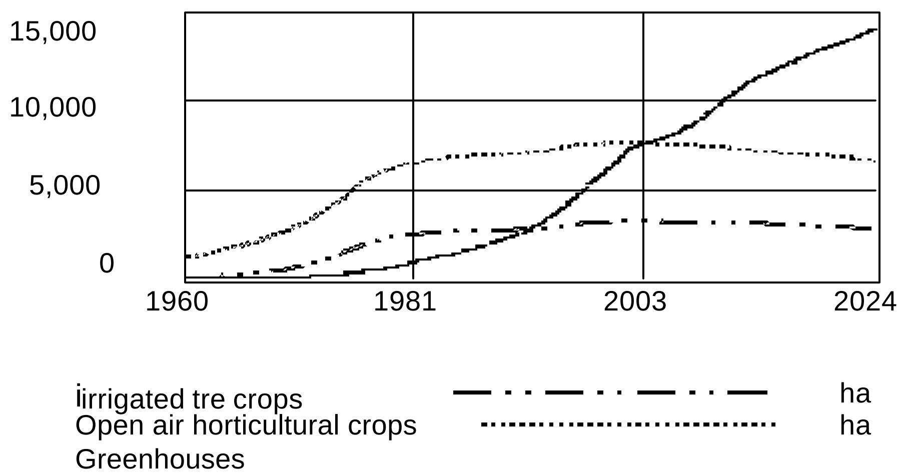

Figure 10. Base Trend scenario. Temporal evolution of the different types of irrigated lands

On the other hand aquifer-overexploitation leads to the rapid exhaustion of available water reserves and pumping is reduced to a minimum. Although the high rate of increase of external water resources is maintained, such resources are not enough to counterbalance the aquifer exhaustion, so an important water deficit appears, which affects the profitability index and slows down but does not stop the increase of irrigated lands. The Base Trend scenario of increased water resources, which is actually being implemented through the National Water Plan and the water transfer from the Ebro river to SE Spain, cannot eliminate the water deficit because it depends not only on the available water but also on other endogenous and feedback loops of the system, so, any increase in the supply of induces a further expansion or irrigated lands and a greater demand for water and, hence, a greater problem of water deficit, which shows a highly counter-intuitive behaviour. This is also another example of the classic archetype of system resistance to apparently obvious solutions, frequently described in many other systems (Meadows *et al.*, 1992, Puigdefabregas, 1995, Wolstenholme, 2003)

7. Some conclusions

Most models dealing with the environmental effects of agriculture usually concentrate on the generation of several types of pollution and normally do not consider the spatial dimension. However the intensive agriculture of new irrigated lands in the Mediterranean area generates negative effects not only in terms of the production of pollution but also in terms of natural resources consumption, in particular water resources and available area. Both, water and land consumption have a major impact on the conservation of the valuable biodiversity of many Mediterranean areas, especially in arid and semi-arid ecosystems like those of south-eastern of Spain.

In Mazarrón, Aguilas and other arid Mediterranean areas, the dynamics between the increase in irrigated land, the growing inertia of the system, its incapacity to adapt to available resources and widespread aquifer over-exploitation clearly fits the general process of desertification. The unrealistic perceptions about the relationships between irrigated land and water resources also contribute to this. The increase in water resources does not lead to the elimination of the problem because several system feedback loops between different factors lead to a further increase in irrigated land and continuation of the water deficit. In fact irrigated land is the factor that induces the water resources problem, both as regards the intensive agricultural system itself (water deficit) and as regards the natural systems (loss of springs and wetlands and associated biodiversity). Finally, it is also required to adopt an adaptive management in order to cope with this complex socio-environmental system.

8. References

Barlas, Y. 1996. Formal aspects of model validity and validation in system dynamics. *System Dynamics Review*, **12:** 183-210.

Martínez Fernández, J. 2000. *Modelos de simulación dinámica en el estudio de las externalidades ambientales de los regadíos en sistemas áridos y semiáridos del Sudeste Ibérico*. PhD. Universidad de Murcia.

Martínez Fernández, J. ; Esteve Selma, M.A.; Calvo-Sendín, J.F. 2000. Environmental and socio-economical interactions in traditional irrigated lands: a dynamic system model. *Human Ecology*, **vol 28, nº 2**, 279-299.

Martínez Fernández, J. y Esteve Selma, M.A. 2002. Un modelo dinámico del regadío de Mazarrón y Aguilas y sus efectos ambientales. In Martínez Fernández, J. y Esteve Selma (Coords.): *Agua, regadío y sostenibilidad en el Sudeste Ibérico*. Bilbao. Bakeaz-Fundación Nueva Cultura del Agua. pp. 73-105.

Martínez Fernández, J. & Esteve Selma, M.A. Assessing the Sustainability of Mediterranean Intensive Agricultural Systems through the Combined Use of Dynamic System Models, Environmental Modelling and Geographical Information Systems. In

M. Quaddus and A. Siddique (Eds): *A Handbook of Sustainable Development Planning: Studies in Modelling and Decision Support.* Edward Elgar Publishers. Cheltenham, UK. *(in press*).

Martínez Fernández, J. Esteve Selma, M.A.. 2000. Sequía estructural y algunas externalidades ambientales en los regadíos de la cuenca del Segura. *Ingeniería del Agua*, **7:** 165-172.

Martínez Fernández, J; Esteve Selma, M.A.; Calvo Sendín, J.F. 2000. Environmental and socioeconomical interactions in the evolution of traditional irrigated lands: a dynamic system model. *Human Ecology*, **28 (2)**: 279-299.

Martínez Vicente, S.; Martinez Valderrama, J.; Ibañez Puerta, J. 2000. Trend and Scenary. A Simulation model of Desertification by Salinization in the Coastal Irrigated Agriculture: The Hispamed-Dessal model. In: *A Surveillance System for Assesing and Monitoring of Desertification*. Projet No. 902 at Expo Hannover. CD-Rom Copyright CSIC.

Meadows, Donella H., Dennis Meadows, Jorgen Randers, 1992. *Beyond the Limits: Confronting Global Collapse*, *Envisioning a Sustainable Future*. Post Mills, VT: Chelsea Green Publishing Co.

Muñoz, A. 1991. *Recursos naturales y crecimiento económico en el Campo de Dalías*. Agencia de Medio Ambiente. Sevilla.

Saysel, A.K. 1999. *Dynamic simulation model for long term comprehensive environmental analysis of GAP*. PhD. Bogazici University. Istambul.

Saysel, A.K.; Barlas, Y. 2001. A dynamic model of salinization on irrigated lands. *Ecological Modelling*, **139 (2-3)**: 177-199.

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