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Policy Relevant Modelling: Relationships Between Water, Land Use, and Farmer Decision Processes

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ABSTRACT

This paper presents a policy-relevant model based approach to assessing land-use change that is based upon a number of transdisciplinary mechanisms. We report the development of a modelling platform which supports analysis of the interactions between slope, aquifer, and catchment dynamics, together with the actions of farmers as they change their crop profiles and consequently their water needs. The master-equation based farmer decision making model, driven by rule based decision trees derived within the context of a conceptual framework which accommodates both the human and natural processes and their interdependencies, is central to the method presented in this paper. Our conclusions relate to both the function and process of integrative assessment and we present characteristic model outputs to highlight the interactions between the farmers and their natural environment.

Keywords: modelling, water, policy relevance, human decision making.

1. INTRODUCTION

Tensions inevitably occur between science, policy and the world as it is interpreted and negotiated by different actors – including scientists and policy makers. Knowledge generated by scientific research can be difficult to assimilate and exploit. It also tends to be determined by the agenda and interests of the scientist and the body funding the work. By focusing upon the range of responses and interpretations at the local level, policy relevant research moves from the disaggregate to the aggregate. By contrast, policy and policy research, in common with much science, invariably adopts a top-down approach that is grounded in the aggregate and applied to the disaggregate.

The paper presents field work undertaken in the Argolid region of southern Greece that combines qualitative data about social interaction and decision making with information about the natural landscape within which they take place. These interactions, which occur across disparate spatial and temporal scales, are represented through an Integrative Modelling Framework that facilitates the exploration of local land-use scenaria in response to different local and regional policy options. The framework includes models of the weather, hydrological flows across catchments, aquifer flows, pumping and irrigation, and farmer decision making. The dynamics of crop growth, vegetation cover, soil porosity and composition, and erosion are also represented. This framework has been developed into a 'state-of-the-art' decision support tool with the ability to simulate complex policy scenaria and to be used, under supervision, by decision makers in the study area.

Policy-relevant frameworks that seek to incorporate a complex systems decision support model for sustainable land-use inevitably require the integration of human and environmental processes which are operating across disparate spatial and temporal scales.

The computer simulation models constituting the Integrative Modelling Framework reported here were developed from existing models of hydrological flows across catchments [1], of aquifer flows, pumping and irrigation [2, 3] and of farmer decision making relating to the selection of crops based upon perceived profits and market forces [4]. The framework also includes dynamics of crop growth, vegetation cover, soil porosity and composition, and erosion [5]. The theoretical basis for this modelling framework is driven both by a 'model' of integrative research and by a conceptual framework able to address the socio-cultural aspects of change.

The 'model' of *Integrative Research* encompasses the spectrum of phenomena and processes relevant to the

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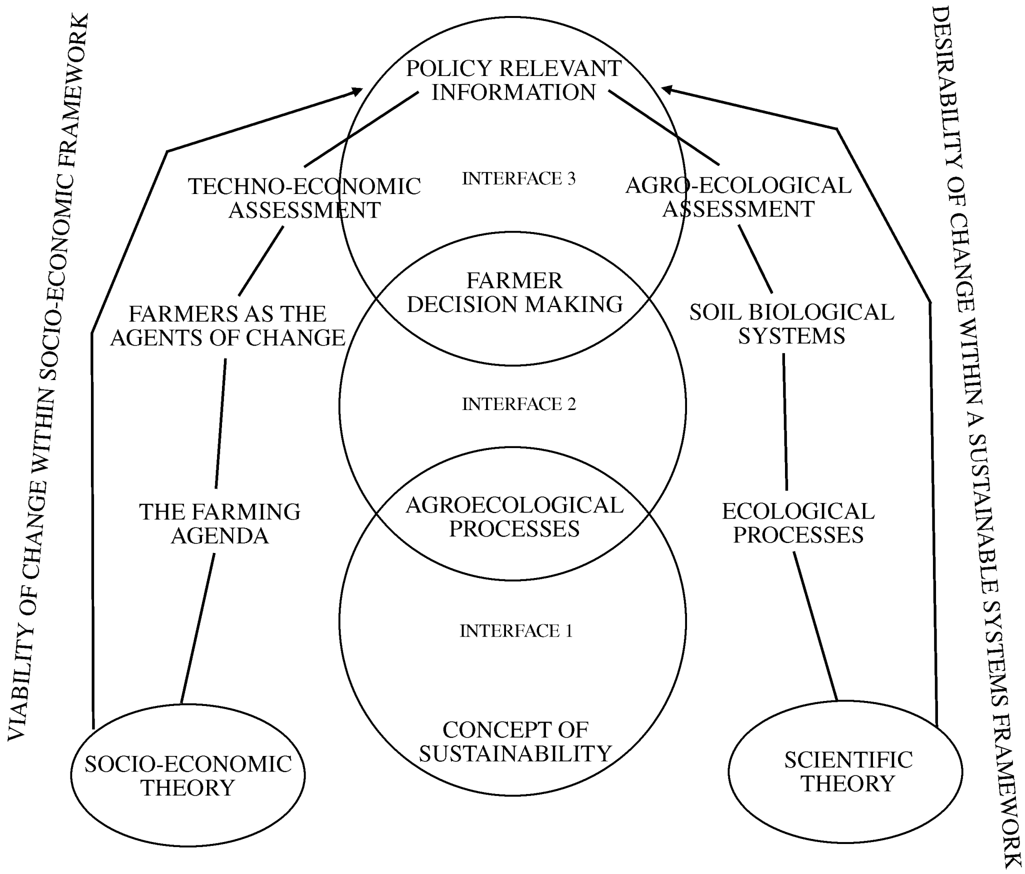


Fig. 1. A representation of the human and the natural processes involved in integrative research on sustainable land use.

examination of sustainable agricultural practices (see Fig. 1). Both the socio-economic and the natural dimensions are addressed, together with the qualitative reality which encompasses the socio-natural spectrum from the pure ecological to the high level implementation of policy. As discussed by Park and Seaton [6], there are three clearly identifiable interfaces within this spectrum:

- *Interface 1*, the interpretation of the concept of sustainability at an ecological level.
- *Interface 2*, the linking of ecological processes to the attitudes and behaviours of the agents of change (in this instance, the local farmers).
- *Interface 3*, linking the actions and perceptions of the agents of change to policy issues.

The *Conceptual Framework* addresses the socio-cultural aspects of change, identifying what may be termed as opportunity spaces, decision spaces and policy spaces [7] (see Fig. 2). The opportunity space represents the set of all possible choices by local actors, whether perceived or not, the decision spaces describe the perceived set of choices, and the policy space reflects the extent of intended influence of related policy mechanisms. Thus, this conceptual framework incorporates:

- Social Enquiry techniques for eliciting information from local actors such as farmers, farming co-operatives, politicians and decision makers. Thus it is possible to define decision spaces for different actors; this definition will, of course, only be a characterisation of reality, as shown in Figure 2.
- The identification of information networks, information flows, and the responses of local actors to new information and knowledge. This elucidates the relationships between the policy and decision spaces and assists in the definition of appropriate scenaria for assessment through simulation.
- The dynamics of scale and hierarchical structures which affect both the environmental constraints of response and the cultural predispositions to change.

The conceptual framework described above provides the mechanism by which the socio-natural environment and the individual actors in the system may be characterised. It addresses the broad concept of multi-dimensional opportunity spaces which reflect the various issues of spatial and temporal scales, hierarchies and information networks which must be understood before it is possible to simulate the effects of humans in the environment along with their interdependencies and non-linear dynamics and emergent

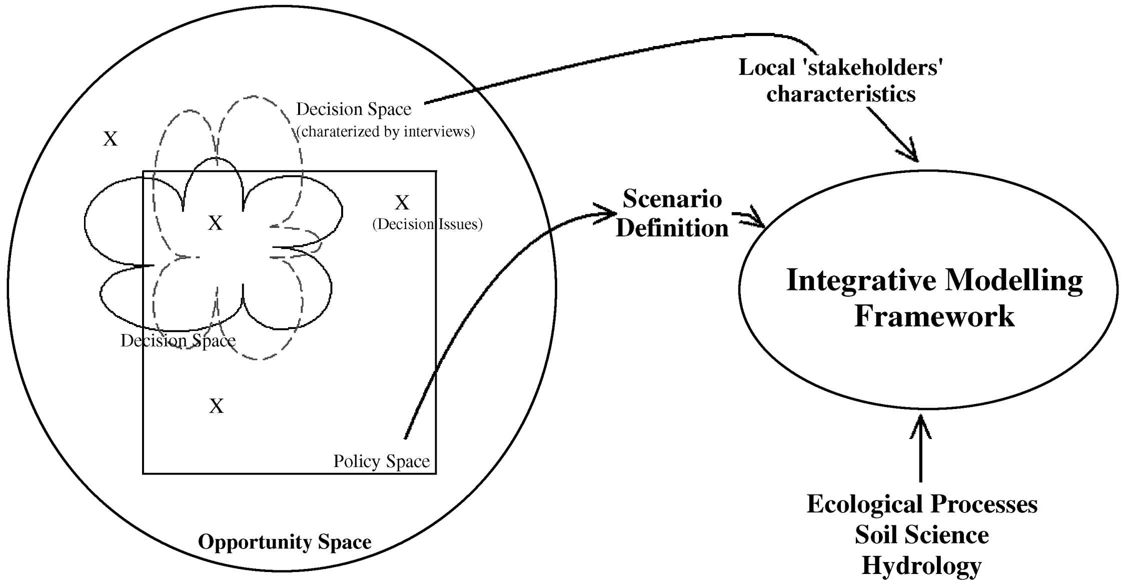


Fig. 2. Diagrammatic representation of the Conceptual Framework which encompasses the socio-cultural aspects of change and drives the application and use of the models.

responses. Thus, the opportunity spaces are seen to encompass multiple decision spaces, policy spaces and decision issues, which have been mapped onto a conceptual model to provide an abstract representation of actors (farmers) within their natural environment. A combination of these abstract spaces (opportunity, decision and policy) serves to define scenaria for the simulation of the effects and responses to various policy instruments which may be used to influence the dynamics of these socio-natural interactions.

2. AN INTEGRATIVE MODELLING FRAMEWORK

2.1. Methodological Approach

The Integrative Modelling Framework, comprising a number of dynamic spatial models of the key human and environmental processes, is driven by the dynamics of the conceptual framework and the policy issues which have emerged from the study areas [8].

A central requirement in the development of models of spatially and temporally diverse and interdependent phenomena is a recognition of complexity and persistent evolutionary change as suitable concepts for understanding 'reality,' in preference to mechanistic perceptions of change implying tendencies towards homeostasis. It has been noted elsewhere that it is precisely this ability to evolve which has been removed in order to arrive at mechanistic models of 'reality' [9]. In this paper we represent qualitative change through conceptualisations of dynamic landscapes whereby spatial characteristics of phenomena are represented by the landscape, and temporal characteristics by the qualitative changes in the landscape over time.

This framework acknowledges ideas of complexity and evolution that have emerged from contemporary research, such as diversity and non-average behaviour, adaptability, sensitivity and resilience, non-linearities, feedbacks, interdependencies, uncertainty and surprise (see Allen et al. [10] for further discussion). The latter issues, when related to anthropogenic development, emerge from the coupling of human spatial and temporal scales with smaller and larger ones in nature [11]; we can note, for example, how the macro-scale (subsidies) can influence the micro-scale behaviours (farmers) resulting in rapid localised hydrological changes (aquifer salinisation).

The representations of the human and natural environments used in the work reported here have necessarily been simplified, specifically to facilitate the linking of these disparate phenomena. This process of model development reflects the inevitable trade-offs between reality, generality and precision which will always occur [12].

The need to include local actors, or 'stakeholders,' in the description, specification and interpretation of the models has been emphasised elsewhere [7]. Such involvement has included the identification of issues and the behavioural characteristics of farmers (description through social enquiry activities) [13], the specification of sub-models and data by local scientists [14, 15] and the contextualised interpretation of simulation outputs by local experts [16].

Finally, the requirement for an iterative approach to the development of a model and the definition of policy spaces driving the model is clear. If, instead of static descriptions (GIS), we conceptualise a suite of interacting dynamic models (Fig. 3) as simulating the *opportunity space*, and embedded models of local actors as simulating the *decision spaces*, the purpose is to identify appropriate *policy spaces*.

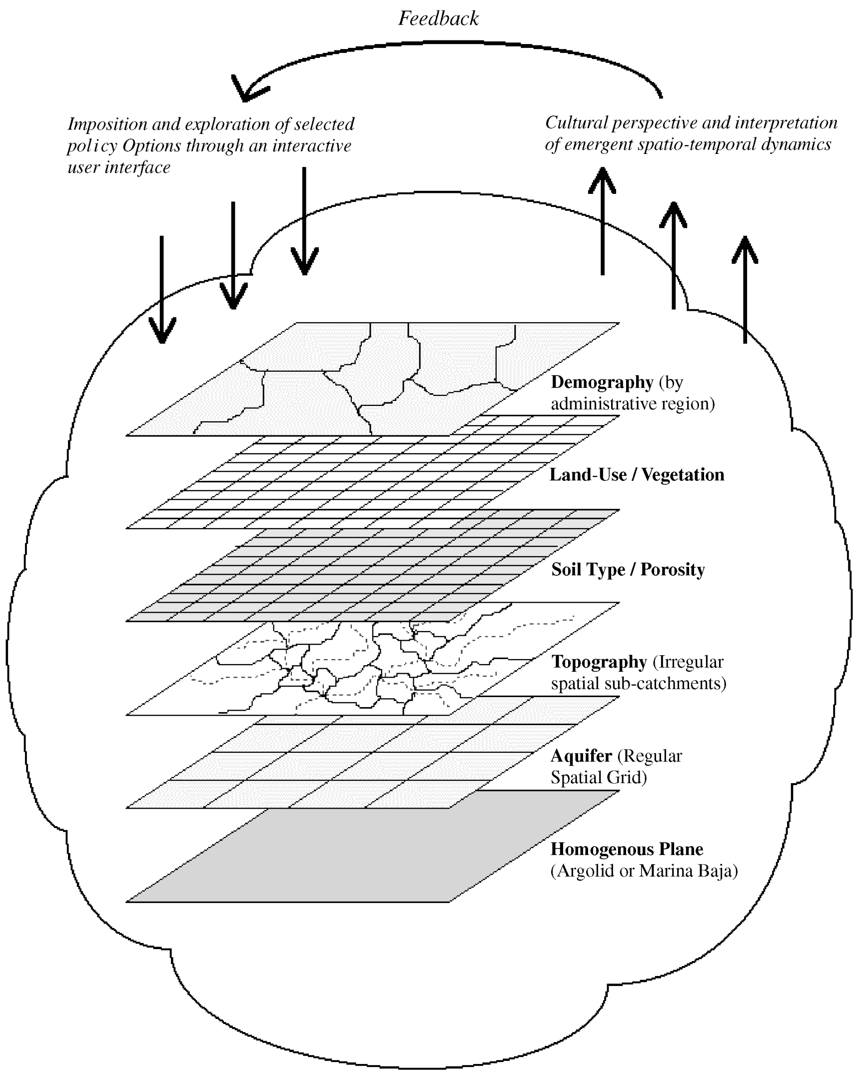


Fig. 3. A conceptual representation of the multiple interacting models and the feedback involved in evaluating policy options and interpreting the emergent spatio-temporal dynamics.

Thus, through the feedback between the model output (interpretation) and its inputs (scenario definition), it is possible to represent the cultural context for exploring different policy options.

2.2. Model Structure

The Integrative Modelling Framework we describe retains most of the characteristics of each individual model, and, by using a common central database and a high level driver – which co-ordinates the disparate temporal and spatial scales – is able to present these characteristics within a more holistic framework whereby the interactions between the sub-models highlight many of the critical dynamics of change which previously could only be dealt with through user definition of extraneous influences.

Starting with a physical definition of the boundaries of the study area, additional models are overlaid and interactions and interdependencies defined, to build the integrated model. These models relate to:

- The aquifer hydrological and salinity dynamics on a regular spatial grid;
- The surface river hydrology with its topographically defined irregular spatial boundaries;
- The soil and slope hydrology defined using a regular grid within the catchments, and finally
- The human dynamics (in this instance, the local farmers) and demographic influences using both regular spatial representations and predefined administrative regions.

Driving this suite of models are definitions of selected policy scenaria from which the emergent spatio-temporal dynamics of the system can be interpreted to facilitate redefinition of scenaria as required by the conceptual framework, accounting for the socio-cultural perspectives evident in the region.

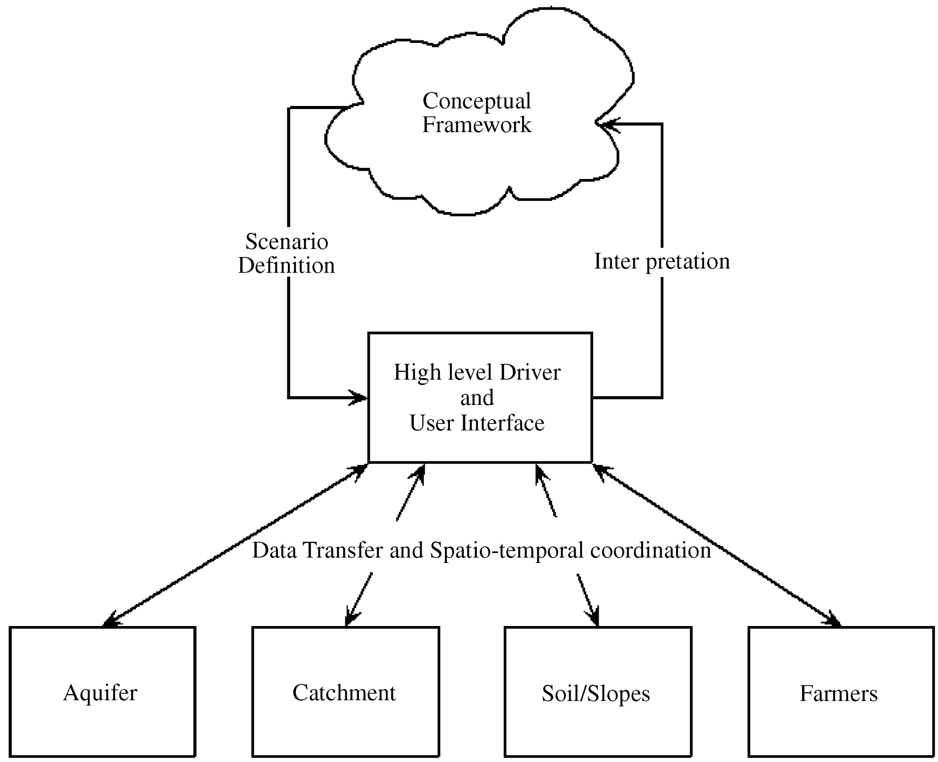


Fig. 4. Schematic representation of the user interface and interactions between the models and their relationship to the Conceptual Framework.

Figure 4 highlights the manner in which each individual sub-model has been allowed to retain an appropriate degree of autonomy within the modelling framework. Such an approach ensures that each model maintains its specific internal spatial definitions and timesteps, at the same time providing access to a shared database through the meta-level driver and user interface. Thus, the co-ordination of space and time (annual, daily and hourly changes) and the flow of data between the sub-models is facilitated by the driver, and the user interface provides an environment for the definition of selected policy scenaria.

2.3. Issues of Scale

The quantitative dimension of the socio-natural contexts being considered is represented predominately by the environmental processes affecting and affected by the local farmers. In the present context these processes are associated with the surface and sub-surface hydrology. The individual models, which have emerged from various EU projects [5, 17–19] each operate within and across disparate spatial and temporal scales, varying temporally from the hourly (for slope hydrology, surface runoff, etc.) to the annual (crop choice decision making), and spatially from 100 m through 1 km (aquifer model) to the spatial dimensions of entire sub-catchments in the region.

More complex (and more significant for increased understanding of the system) than the spatial disparities between the individual models are the temporalities involved. As shown in Figure 5, the temporality of *events* of the individual models varies from the hourly to the annual, mirroring the short-term, localised effects and the long-term, regional effects of change. However, we also find that the temporalities of the *effects* varies from the daily (runoff) to decades when observing the effects of annual crop choice dynamics emerging from the simulated farmers in the system. We present outputs which highlight these temporalities for changes in aquifer levels and salinity over 5 years, and crop distributions over 5 decades.

3. TECHNICAL DESCRIPTION OF THE MODELS

Each of the four sub-models have been developed as stand-alone modules which have been calibrated and/or validated in various contexts in the Argolid Valley (Greece) [3, 4], the Marina Baixa (Spain) [5] or the Rhône Valley (France) [1]. The four models can be categorised into two groups:

i. The quantifiable (natural) phenomena: the slopes, aquifer and catchment sub-models; and
ii. The qualifiable (human) phenomena: the farmer decision making model.

Some of the key flows between the four sub-models are shown in Figure 6.

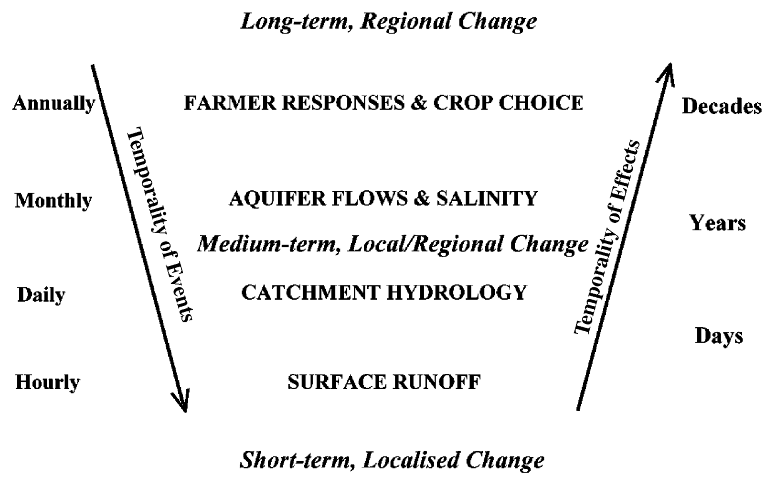


Fig. 5. Identification of the temporalities involved within the Integrative Modelling Framework, highlighting the temporalities of events, the temporalities of the effects of change and the relationship with localised or regional change.

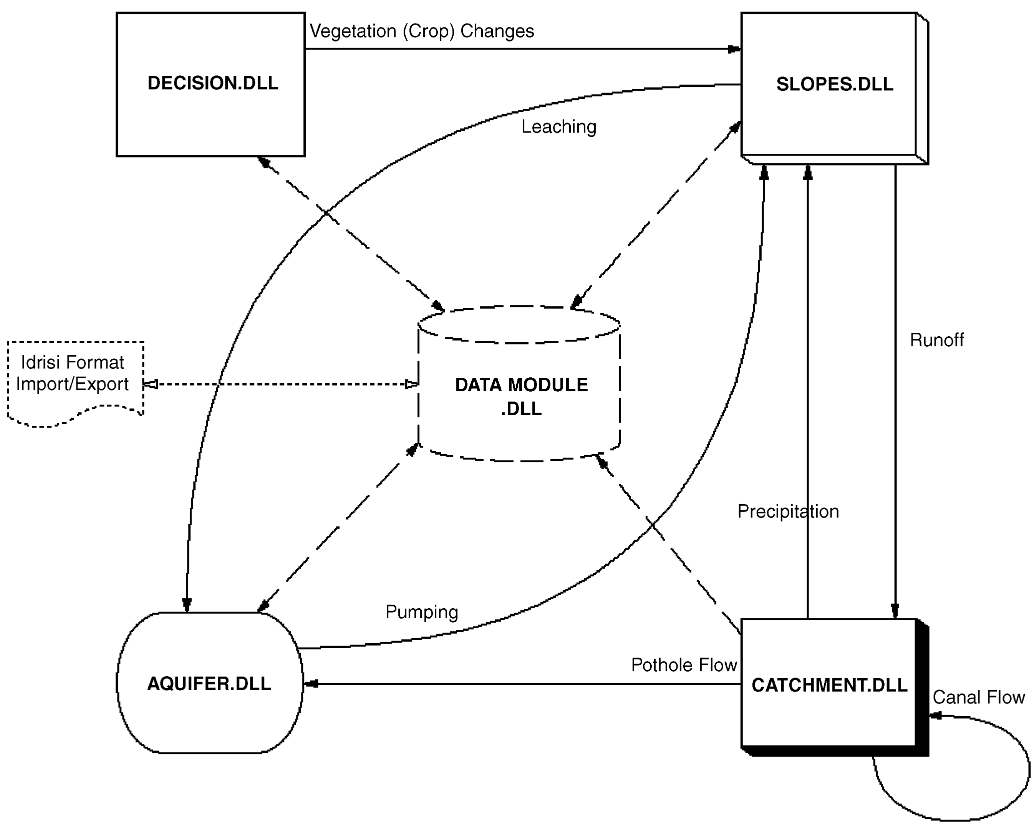


Fig. 6. A schematic representation of the flows of data between each of the sub-models in the Integrative Framework.

4. SLOPE MODEL

The Slope sub-model is developed from simplifications of the mechanisms that operate between vegetation cover and soil type, water availability and storage capacity, water infiltration, evaporation and run-off; although potentially significant, the effect of variations in temperature has not been incorporated at this stage. The model demonstrates complex, non-linear responses to different average amounts of rainfall, slope and aspect, and provides a base for the dynamic linkage of multi-scalar phenomena. The slope sub-model thus underlies the natural environment dimension within the integrative framework, acting as a link between the surface waters (rivers, etc.) and the aquifer and providing much of the environmental information required by the Farmer Decision Making sub-model.

This model is based on the influence of natural vegetation cover upon the dynamics of surface runoff and erosion, and the combined effects of these upon soil water storage. This required the simple definition of dynamics of vegetation growth to account for the growth of new plants – influenced also by the density and type of existing vegetation, the decay rate of existing plants, and the spatial diffusion of vegetation to adjacent cells in the model. With the decay rate linked to the water storage capacity of the soil (through the generation of organic matter) two positive feedbacks are incorporated into the model involving vegetation growth, soil water and erosion. The generic form of the equation describing vegetation density and the spread of vegetation across a slope may be given by:

$$\Delta x = bx_i\left(\frac{S_i}{(1+S_i)}\left(1-\frac{\sum N_j x_j}{xMax}\right)\right) - mx_i + K(x_{neighbours} - x_i) \quad (1)$$

where: x_i is the vegetation density at location i., S_i = water stored in the soil at i., N_j = the niche overlap between vegetation types, xMax = maximum vegetation possible in zone, b = growth rate of x, m = decay rate of x, and K = rate of sideways diffusion.

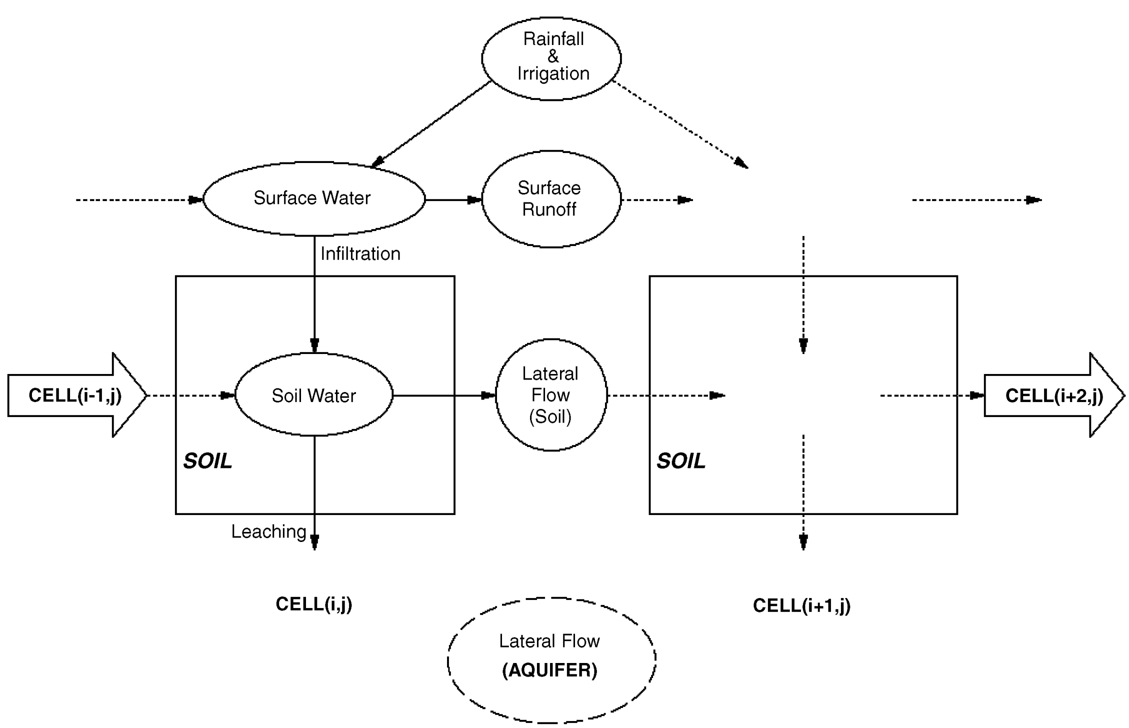
The model addresses hydrological dynamics relating to surface runoff, infiltration, leaching rates and sub-surface lateral flows based upon equations which have been adapted from work elsewhere addressing hydro-chemical interactions within the soil domain [20]. A schematic representation of the flows implemented in the model is shown in Figure 7. These hydrological dynamics provide the spatial contextualisation for the effects of vegetation density and changing soil water storage capacities. The surface runoff and sub-surface lateral flows are both dependent upon the amount of surface water present:

$$\text{Runoff} = (1-\mu) * SPR * \text{Surface Water} \quad (2)$$

$$\text{Lateral Flow} = \mu * SPR * (\text{Surface Water} + \alpha * \beta * \text{Soil Water}) \quad (3)$$

where: SPR = the Standard Percentage Runoff, μ = the proportion of surface water which infiltrates (Vegetation dependent), and, α and β are parameters, are required to control sub-surface flows when there is no surface water present.

The Standard Percentage Runoff (SPR) used here is a proxy for, and is based upon, the HOST (Hydrology Of Soil Types) classification system which categorises soil hydrological processes by defining the predominant flow paths through the soil [21]. It can provide an indication of the aggregate runoff characteristics for a given soil type, but is also affected by both vegetation cover and slope.



NB. Spatial relationship between CELL(i,j) and CELL(I+m,j+n)
is determined by topographical data

Fig. 7. A schematic representation of the spatial hydrological flows implemented within the Slope Model.

The vertical flows, involving infiltration from the surface and leaching from the soil water, can be defined by:

$$\text{Infiltration} = \mu * \text{Surface Water} \tag{4}$$

and:

$$\text{Leaching} = \lambda * \mu * \text{Surface Water} \tag{5}$$

where: λ inhibits leaching until the soil water is close to saturation.

Finally, the dynamics of erosion are dependent upon runoff, and thus implicitly surface vegetation cover, and may be described by:

$$\text{Erosion} = K_{\text{erode}} * \text{Runoff} * \text{Soil Depth} \tag{6}$$

where: K_{erode} is a constant relating to soil type.

Building on this basic representation of slope dynamics, a number of enhancements have been implemented such as:

- The incorporation of different soil types into the derivations of Standard Percentage Runoff (SPR) to reflect the spatial distribution of soils in both the Marina Baixa and the Argolid.
- The modification of the infiltration parameter, μ, to address additional vegetation types.
- The adaptation of K_{erode} to address additional soil types.
- The incorporation of terracing in the model, affecting the dynamics of both surface runoff and erosion.
- Definition of the spatio-temporal variations in rainfall dynamics across a number of years for each sub-catchment.
- The addition of the dynamics of crop dependent irrigation practices on surface water volumes and aquifer levels.
- The inclusion of the ability of farmers in the landscape to switch crops, again affecting runoff and erosion dynamics.

The effects of irrigation, terracing and changes to crops by farmers highlight the most significant characteristics of the slope model. These relate to the interactions of farmers with the environment, and are emphasised by the existence of feedback loops both directly and indirectly affecting the hydrological flows and erosion dynamics (Fig. 8):

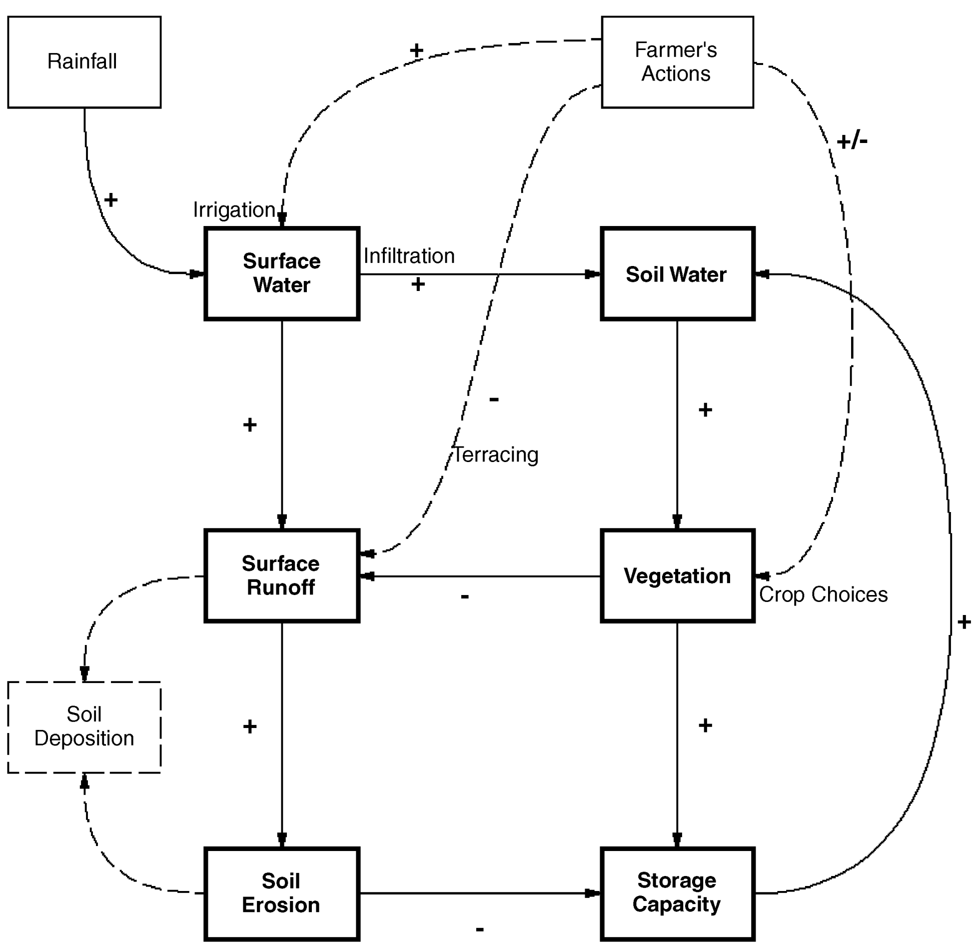


Fig. 8. The major feedback loops involving human interactions affecting the hydrological processes and erosion dynamics. A +'ve implies a positive influence, and a −'ve implies a negative influence.

- A *non-spatial* feedback whereby increased soil water increases vegetation growth, thus also increasing the soil storage capacity; and
- A *spatial* feedback whereby increased soil water increases vegetation growth, thus reducing runoff and erosion, and increasing the storage capacity due to the *net* erosion/deposition.

5. THE AQUIFER SUB-MODEL

The Aquifer sub-model addresses both the water and solute flows in a more generic fashion than existing 'off-the-shelf' models such as *Modflow* [22] or *Aquifem* [23] and requires smaller amounts of data. It operates upon a contrasting conceptual basis, whereby instead of determining the next steady state of pressure heads in the aquifer, this model calculates the actual spatial flows at each timestep and revises the resultant pressure heads accordingly. In this way the external stresses can change at each timestep, enabling it to address intermittent pumping in individual cells as opposed to relying upon predefined spatialised stresses. With identical mathematical equations being used, both the model reported here and Modflow should produce identical results, *ceteris paribus*. The model domain takes the form of a regular grid of cells, of specific size, with water heights and solute concentrations being calculated at the centres of cells, and volumetric flows being calculated at cell boundaries, as shown schematically in Figure 9. The aquifer can consist of a number of different layers, although currently only uses a single, vertically unconfined aquifer.

The model domain consists of a series a specified datasets that define the characteristics of the aquifer for each cell (grid node), using the topographic height, the depth of the aquifer base, the hydraulic conductivity, storativity, initial water height, and initial salt concentration. Each cell is classified to identify at each timestep the type of calculations that will be performed to account for springs (flow between model layers), water head, and north-south and east-west water flows.

This classification allows the aquifer to be defined very precisely and the boundary conditions set appropriately so that the underlying flow directions can be specified to correlate with the geological structure of the aquifer. This does not preclude 'reverse' flows which may, for example, be provoked by over-abstraction of water for irrigation thus lowering the water level of the aquifer relative to 'downhill' cells.

The model calculates the three-dimensional flows of water within the aquifer and generates new water heads based upon these flows. The numerical equations used are derived from Darcy's Law (Equation 7) of flow through porous media in combination with the equation of continuity.

$$Q = -KA\frac{\Delta h}{\Delta x} \tag{7}$$

where: $Q =$ *volumetric flow of water per unit time,* $A =$ *cross-sectional area through which the water flows,* $h =$ *difference in height,* $x =$ *distance travelled, and* $K =$ *hydraulic conductivity.*

The equation of continuity ensures that the outflow from a cell, less the inflow is equal to the change in storage:

$$\left(\frac{\Delta q_x}{\Delta x} + \frac{\Delta q_y}{\Delta_y} + \frac{\Delta q_z}{\Delta_z}\right) = -S_s\frac{\Delta h}{\Delta t} + R \tag{8}$$

where: $qx, qy, qz =$ *volumetric flows parallel to the x, y, and z axes respectively;* $x, y, z =$ *the co-ordinate axes;* $t =$ *time;* $h =$ *head, height of the water surface within the aquifer;* $S_s =$ *specific storage, the volume of water released from storage per unit change in head (h) per unit volume of aquifer; and* $R =$ *recharge, volume of inflow to the system per unit volume of aquifer per unit time.*

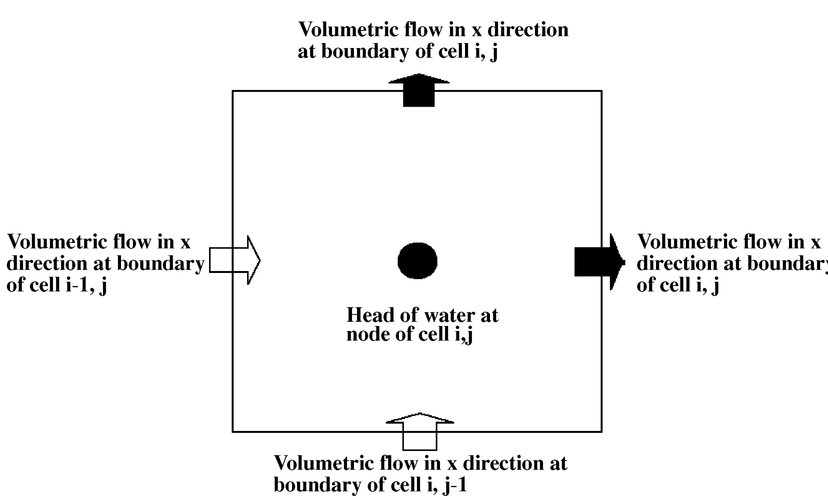


Fig. 9. A schematic representation of the flows calculated for each cell in the aquifer.

Combining Darcy's Law (in three dimensions) and the water balance equation we have the non-linear Boussinesq equation:

$$\frac{\Delta}{\Delta x}\left(K_x\frac{\Delta h^2}{\Delta x}\right)+\frac{\Delta}{\Delta y}\left(K_y\frac{\Delta h^2}{\Delta y}\right)+\frac{\Delta}{\Delta z}\left(K_z\frac{\Delta h^2}{\Delta z}\right) = 2S_s\frac{\Delta h}{\Delta t}-2R \tag{9}$$

At each timestep the head of water is calculated based upon the existing head plus the flows into (and out of) the cell. Since a single layer is being used to describe the aquifer and the basement beneath the aquifer is assumed to be impermeable, there are no flows across the lowest boundary of the aquifer (in the Argolid the base of the aquifer consists of impermeable clay and iron). Vertical flows down into the aquifer are exogenous and result from the farmers' decisions to abstract from or recharge the aquifer, and from percolation (leaching) from the slope model. The model can handle multiple aquifer layers, although the lack of vertically defined geological data for the Argolid means that the model is applied here using a single layer.

Solute transport is based upon a simple particle tracking routine, which traces the advection of solutes associated with the volumetric flows of water. The resulting mass transports are used to calculate the new salt concentrations. For simplicity, it has been assumed that advection is the only process by which solutes can be redistributed through the aquifer. Processes such as dispersion and (chemical) reactive processes are not considered, in keeping with normal practice in hydrological modelling [24]. Multiple solutes can be traced simultaneously, each having distinct sources which are defined externally. The sea is a special case forming one boundary to the model. The model is applied here with one solute, concentrating upon salinity since this is of high significance in the Argolid.

The timestep used within the model, and its spatial resolution, are determined by the conditions for numerical stability. The stability criterion used is that for transient flows in an unconfined aquifer with Dupuit assumptions [25]:

$$K\sqrt{Q\frac{\Delta t}{S\Delta x\Delta y}}\gg 1 \tag{10}$$

where: Δt = timestep, Δx = grid size in the x direction, Δy = grid size in the y direction, and other variables as described above.

6. THE CATCHMENT SUB-MODEL

The Catchment model, which has been adapted from an earlier model of the Scheldt Estuary [26] has been applied to the Argolid Valley with additional dynamics implemented to address the transportation of water between catchments (using canals or pipelines). The model is based upon the concept of stream orders within a catchment and allows the simulation of linked sub-catchments within an overall watershed. Stream orders are defined so that flows naturally accumulate from the lower to the higher stream orders and are an accepted mechanism for river system modelling [27].

With runoff flows driving the flows in the lower stream orders, the effect of lower level streams upon the main rivers is accumulated as follows:

$$Qaf_j = \left(NOStreams_j - 2\cdot NOStreams_{j+1}\right)\cdot\frac{StreamLength_n}{AccStreamLenth_{j+1}}\cdot DelayContrib_j\left(\frac{\Delta t_n}{2}\right) \tag{11}$$

where: $DelayContrib_n(t_n)$ is a function that makes a lineair interpolation between $Q_{j,t}$ and $Q_{j,t-1}$ depending on a point in time (t_n) between both.

These accumulated lower stream order flows are then incorporated into the main river flow for the given sub-catchment, thus:

$$Q_{n,t} = Incoming_n\cdot CatchArea_n\cdot C_2+\sum_{j=1}^{n-1}Qaf_j + 2\cdot DelayContrib_n(\Delta t_n) \tag{12}$$

where:

t	Time of this calculation (tens of days)
t_n	time a discharge entered stream n (tens of days)
n	Streamorder
$NOStreams_n$	Number of Streams of order n
$CatchArea_n$	Average catchment area of a stream of order n (km^2)
$AccStreamLenth_n$	Accumulated length of all streams of order n or higher in a catchment (km)
$StreamLength_n$	Average length of a stream of order n (km)
$Incoming_n$	Average incoming runoff of a stream of order n (mm)
$Q_{n,t}$	Discharge at time t at streams of order n (m^3/s)
Qaf_n	Flows accumulated from other tributaries (m^3/s)
Δt_n	Time needed to flow from begin to end of a stream of order n (tens of days)

The model addresses both the river water flows and quality across the simulated catchments. These flows and quality are determined by stream orders but are driven by the rainfall/evapotranspiration balances, spatial aggregations of agricultural nutrient inputs (nitrates and phosphates) and by the demography of the region which will influence the water quality depending upon the existence and effectiveness of water treatment plants. The water quality variables which are modelled include phytoplankton, zooplankton, matter in suspension, dissolved organic matter (rapidly, averagely and slowly hydrolysable), particulate organic matter (rapidly, averagely and slowly hydrolysable), bacteria, oxygen, nitrogen, phosphates, and ammonia.

Through integration with the slope model, the hydrological inputs to the catchment model reflect the hydrological dynamics emerging from the soil systems within the catchment, superseding earlier aggregated definitions. Thus, the hydrological dynamics defined by the slope model applied spatially *within* the sub-catchments facilitates the routing of surface runoff flows into the appropriate stream orders, and the farmer decision making model – again applied spatially within the catchment – can potentially define agricultural nutrient inputs which likewise would enter the streams via the slope model.

Finally, spatialised meteorological data can be defined for individual sub-catchments, and with these data varying through time, the slope model is driven by dynamic rainfall patterns which can be modified to specify potential future climate scenaria. Other developments to the catchment model include:

- The definition of reservoirs in sub-catchments by inhibiting downstream flows to simulate the existence of a dam, retaining the accumulated flows within the reservoir.
- Enabling water transfers between reservoirs, and from springs into the reservoirs.
- Allowing the abstraction of reservoir water for irrigation and human consumption, and canal water for irrigation or aquifer recharge.
- Incorporating sinkholes to allow the rivers to flow directly into the aquifer in the form of recharge; note the rivers in the Argolid which end abruptly before they reach a larger river or the sea.

7. THE FARMER DECISION MAKING (CROP CHOICE) MODEL

In the context of the work presented here, the farmer crop choice model represents the human dimension, and we show how it provides a representation of the conceptual framework which can be incorporated into a simulation model. Figure 10 highlights how the overlap between the conceptual framework (see Fig. 2) and the model revolves around the *decision issues*, themselves determined by the multiple decision spaces and policy spaces, and located within the opportunity space.

The decision spaces characterise the farmers in the system through descriptions of information networks (themes and agencies), spatio-temporal characteristics, and other information emerging from social enquiry activities. The policy spaces ideally encompass a set of decision spaces, and it is increased understanding of the policy space which emerges from the exploration of policy options through simulation. The interaction of these two conceptual spaces determines the decision issues which drive the models; issues such as crop choices, technology choices and investment choices.

In order to represent the interactions between these human characteristics and dynamics and their natural environmental context, three categories of criteria which influence the farmers' actions can be identified: natural, dynamic and 'soft' criteria.

- The *Soft Criteria* are essentially defined by the decision spaces, but are also influenced by policy spaces. These criteria may describe the degree of pluriactivity, cultural preferences, wealth, average parcel size, labour availability or type, perceptions of crop diseases and new technologies, etc.;
- The *Natural Criteria* which provide the spatial and temporal characterisations of the environmental constraints within which the farmers are required to make agronomic and economic decisions. These may include altitude, slope and aspect, land use, rainfall, temperature and wind, soil type and geology, degree of terracing, distance to markets; and
- The *Dynamic Criteria* can be changed by the farmer as a result of addressing specific decision issues. These represent the key linkage between the opportunity and decision spaces and the resultant simulation model and change in response to the current state of the system (the environmental contraints) and the characteristics of the farmers involved (socio-cultural predispositions). These criteria may include crop, irrigation type (flood or drip) or other technologies, potential sources of water (rain, borehole, canal or recycled), use of agrochemicals, or investment in tourist and service sectors.

7.1. Decision Issues

The decision issues represent the linkage between the conceptual framework and the model, and can be addressed using these three categories of influencing criteria: the soft criteria which reflect the cultural predispositions of the farmers, the natural criteria which define the environmental constraints within which they operate, and the dynamic criteria which represent all the potential changes the farmer can make. The decision issues may involve changing a crop, the use of a new technology, or the sector in which financial investments may be made; each potential decision will require a different subset of the criteria available (Fig. 11).

Within the crop choice category would be all potential changes between all possible crop types, including 'no crop.' Within the technology choice category could be included decisions relating to the use of agrochemicals or organic farming, changing between flood and drip irrigation, the erection of netting over medlar groves, the installation of air-

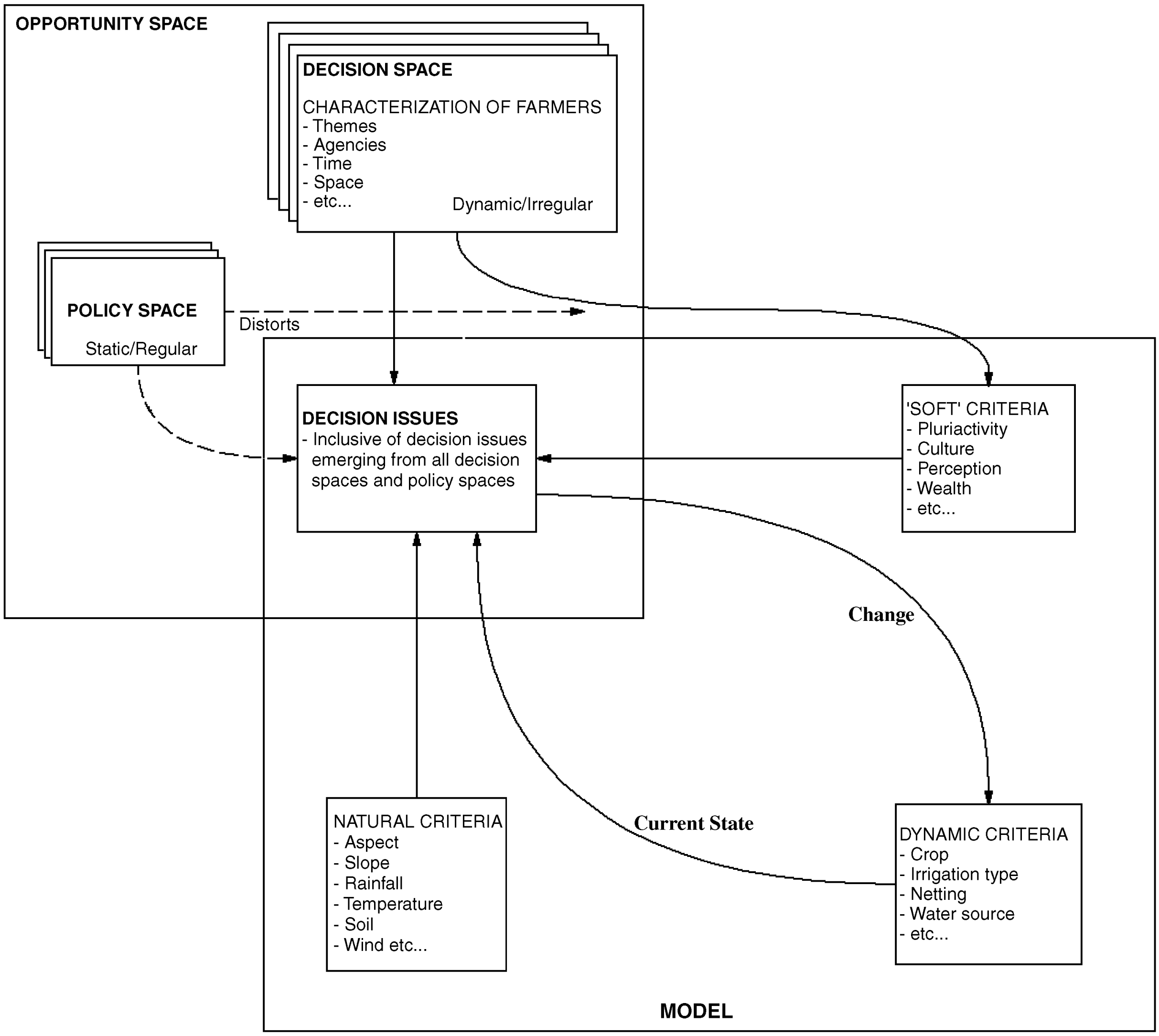


Fig. 10. A schematic representation of the relationship between the opportunity, decision and policy spaces and the formal definition of a model to address the socio-natural interactions.

mixers for frost protection, the drilling of boreholes, and the building of new terraces. Finally, within the investment category could be decisions relating to the degree of pluriactivity, full or part-time farming, the use of family or migrant labour, or investment in tourism or service sectors.

The basis of the model presented here is a Nested Master-Equation model of farmers' crop choices reported by Winder et al. [4]. This model concentrates on the crop choices only, using cost/benefit relationships alongside two factors which are difficult to measure or observe without extensive social enquiry. These culturally influenced factors are the 'likelihood' of change (stochasticity) and the perceptual 'time-frame' of the farmers' decisions. *Great care should be taken when attempting to apply this model to a real situation*. The Master-Equation used in this model may be written as:

$$T_{(i,j)} = \frac{k}{n} J e^{\beta(CB(i,j,F))} \tag{13}$$

where $T_{(i,j)}$ = the likelihood of a transition from crop i to crop j, J = the degree of stochasticity apparent in the decision making, CB = A cost/benefit function, F = Apparent time-frame involved in the decision making process, n = Number of crops, β = Constant reflecting the currency value, and k = Parameter ensuring the transition matrix values remain between 0 and 1.

This Master-Equation model only requires data to be defined in order to derive the appropriate variations in cost/benefit between different crops, related technologies, and other factors such as subsidies. We describe here how we have enhanced the master-equation model to respond to more qualitative information about the socio-natural landscape which can be represented using structured *decision trees*. The enhanced master-equation model therefore addresses:

- The cost/benefit relationship of crop changes including subsidies, crop specific infrastructure, irrigation technol-

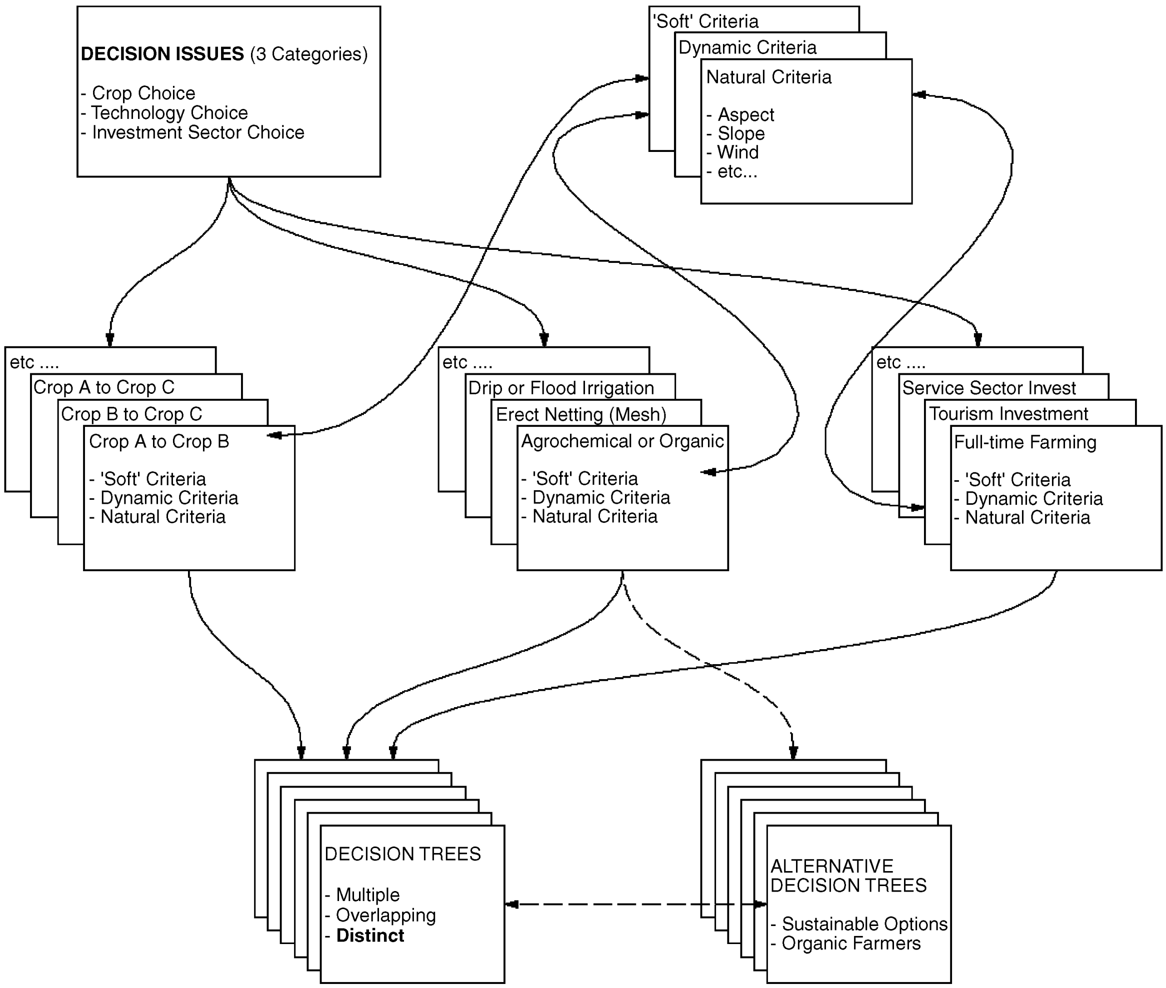


Fig. 11. A schematic representation of the transformation of the decision issues into decision trees which encompass the soft, natural and dynamic criteria.

ogies, sources and costs of water, boreholes costs, and other non-economic criteria.

- The perceptual time horizon which can respond to variations in time horizons due to specific crops (perennials and annuals automatically affecting the time horizon irrespective of cost) and variations due to cultural preferences.
- The stochasticity of farmers in the decision making processes which can be affected by cultural preferences, perceptions of environmental change and the existence of family or migrant labour, and other socio-cultural influences.

7.2. Decision Trees

The master-equation model is thus driven by sets of decision trees which have emerged directly from a combination of agronomic data, social enquiry and interpretations of the cultural implications of potential crop choice decisions. These decision trees have been converted to a logical form to allow modifications to be made to these three key parameters included in the master-equation.

Driven by the decision issues, the rules governing each decision must be described as sets of multiple, overlapping but distinct decision trees. These decision trees address the socio-cultural predispositions of the farmers, their agronomic knowledge, the environmental constraints within which the specific decision must be made, and any associated costs or actions. The decision trees have emerged from complementary work carried out in the Argolid [28].

The data required by these rule-based decision trees may relate to decisions (e.g., crop type or water source), be technological (e.g., irrigation, terracing, netting, canals & boreholes), descriptive (e.g., farmer type, water source, slope, aspect, soil type or wind), or economic (e.g., subsidy, technology costs).

A simplified example of a decision tree addressing the potential of switching crops from oranges to apricots in the Argolid is presented in Figure 12. The underlying economic aspects of the decision such as subsidies and grubout or lead-in costs have already been addressed by Winder's master equation model. Assuming this suggests a switch to apricots is profitable, the farmer will then look at the sources of

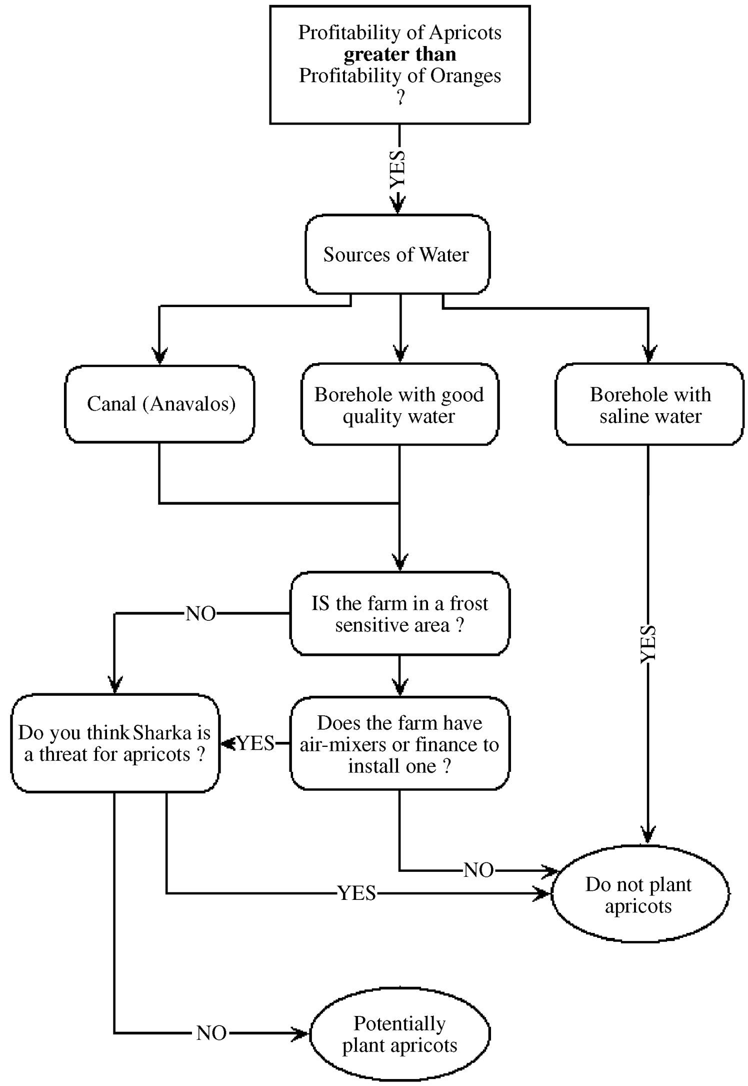


Fig. 12. An example of a simplified decision tree emerging from the social enquiry. This tree reflects the process of deciding whether to replace oranges with apricots in the Argolid.

water; there must be irrigation water available to grow apricots. Either canal or aquifer water may be used (or finance to drill a new borehole), but if the salinity of the aquifer water is too great then apricots will not be grown even if they appear more profitable. Once a source of good water has been verified the farmer will note whether the area is sensitive to frost, and if so whether he has air-mixers to compensate or the finance to install one; apricots are easily damaged by frost.

All these conditions having been met we would expect the farmer to decide to grow apricots. However, the agricultural history of the Argolid includes the Sharka virus which has in the past destroyed the apricot production. This has affected the perceptions of the threat of Sharka by some farmers in the region, and where this perception remains, it is very unlikely that existing oranges will be replaced by apricots. Similar decision trees have been defined for other crop choice decisions such as a change from oranges to vegetables, olives, lemons or tobacco and vice-versa. Details have been documented elsewhere [13] but are not presented here due to space.

There remains an inherent degree of risk with some of these potential decisions since, for example, the drilling of a new borehole will result in additional costs which affect the econometric calculations. The risk emerges since it is not known whether good quality water will be available until *after* the borehole has been drilled. On the other hand, the installation of air-mixers will incur additional costs, but are guaranteed to provide a mechanism to counteract the effects of frost.

The formalisation of the decision trees into a rule-based logical form uses generic representations which are dynamically linked to reflect the inherent structure of the decision trees. The information retained in, or immediately accessible to the records (rules) used by the model include the following:

- Type of record (Descriptive, Technology, Decision, Economic)
- Criteria Name (Crop type, Water source, Slope, Aspect, etc.)
- Options (e.g., orange, Medlar, etc.)
- Current State (e.g., Medlar)
- Switching Costs (e.g., to switch from Medlar to oranges or lemons)
- Influencing Criteria (i.e., pointers to other records)
- Additional Costs (i.e., associated with influencing criteria)
- Timescale limits (e.g., timescales across which a decision may be made)
- Stochasticity (i.e., influence upon the likelihood of change)

Within these records the necessary information relating to whether one criterion affects another can be maintained (*Influencing Criteria*). The *Switching Costs* may describe, for example, the grubout or labour costs, whereas the *Additional Costs* could describe the cost of drilling a borehole, the cost of which is independent of the crop.

The model we have described here addresses the interactions of the farmers with their environment from both the macro and the micro levels. Whereas many multi-agent models [29] and micro-simulation models [30] explicitly work from the micro-level, with actors (agents) moving through space, this model simulates the actions of farmers at given spatial locations. The farmers themselves are not moving, but they are changing the socio-natural state of individual parcels of land. The master-equation provides a probabilistic macro context within which the decision trees recreate the cultural predispositions and environmental constraints which affect decisions. The result is to accommodate the various human and natural processes which operate across these scales. The simulation outputs presented below highlight some of the emergent characteristics of these socio-natural interactions.

8. SIMULATION OUTPUTS

It is, of course, impractical to show a comprehensive set of outputs from various scenaria which have been simulated with this modelling framework. More details of these scenaria have been reported elsewhere [8, 31]. The simulation results presented below are based upon a 3-crop version of the model (oranges, apricots, and olives) in order to illustrate the format of the output rather than provide a comprehensive analysis of the project findings. The initial spatial distribution of these crops was derived from the present day definitions of land use described by the Corine data set [32] which is adequate for verifying the operation of the decision making model. Here we highlight:

1. A comparison of crop distributions after 50 years in response to the existence of subsidies on selected crops (oranges);
2. The influence of an historical knowledge of the Sharka virus upon the distribution of apricots after 50 years;
3. The effects of over-abstraction for irrigation on the aquifer levels; and
4. The salinisation of the aquifer through seawater intrusion due to reduced aquifer levels.

Both oranges and apricots are crops requiring irrigation, so in these simulations the entire main valley is covered by irrigated crops, thus emphasising the stresses on the aquifer. This is reasonable in the present day context since even olives will now be irrigated if there is available borehole water.

The simulations presented in Figure 13 show the changes in crop cover during a 50-year simulation. On the one hand we have the market prices alone influencing the crop choice decisions, whereas on the other we have applied a subsidy (price support) to the production of oranges. In the case where there are no subsidies, apricots become widespread since they are the more profitable crop. However, when subsidies are applied to oranges, we can observe that oranges remain across large areas of the valley. Although we can observe that apricots are slowly replacing the oranges in both simulations, is it only in the scenario without subsidies that relatively little orange production will remain after 50 years. These dynamics are captured by the underlying master equation model since the only difference between simulations is economic. this reflects the greater profitability of apricot production in the region. The observable effects of subsidy is to reduce the transformation from oranges to apricots to about half the rate observed with no subsidy present.

The decision tree based model incorporates information about cultural predispositions to change and the environmental constraints within which the farmers are operating. We ran a further simulation (without subsidies) but this time enabling the decision trees, in particular involving changes between oranges and apricots. After a 50-year simulation (see Fig. 14) which involved no subsidy on oranges, but now accounted for local farmers' predispositions *against* apricots as a result of earlier experiences of the Sharka Virus, the output clearly highlights the villages where there has been no experience of Sharka; in these villages apricots remain the preferred crop. However, in the villages where Sharka has been experienced, we can observe that farmers remain inclined towards orange production. Comparing this simulation with those shown in Figure 13 suggests that two completely contrasting influences (subsidies and crop specific diseases) can potentially provoke responses from local farmers which produce a similar spatial distribution of crops in villages where this learned history is significant.

These simulations only relate to the actions of farmers in the context of crop changes. The effects of such crop choices can also provoke significant changes to the dynamics of the aquifer (salinisation due to over abstraction), and to the

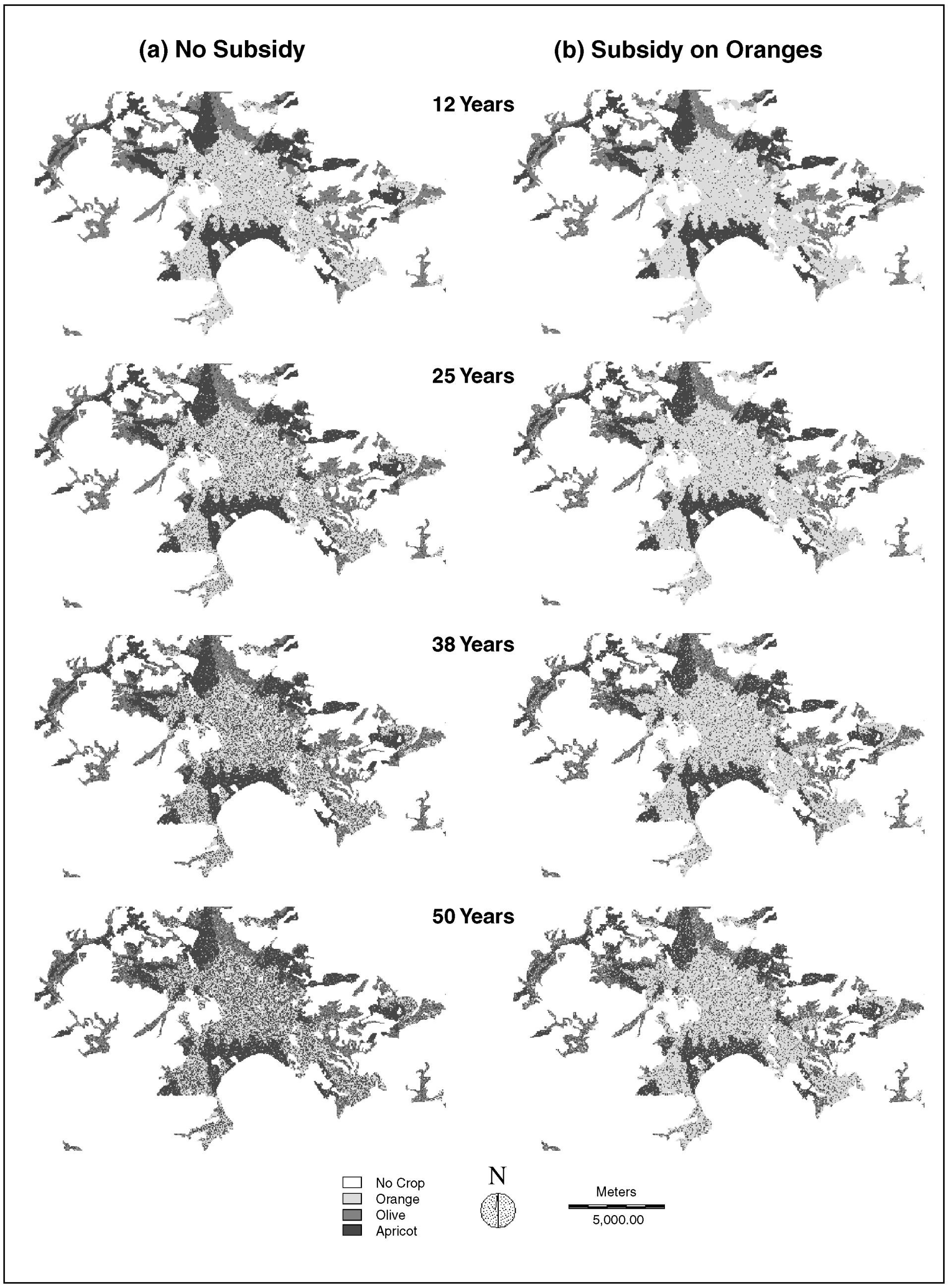


Fig. 13. The spatial distribution of oranges, apricots and olives for the 3-crop simulation after 12 years, 25 years, 38 years, and 50 years with, (a) no subsidies, and (b) a subsidy on oranges.

spatial distribution of pumping 'stresses' resulting from increased irrigation. This, of course, is emphasised when irrigated crops are widespread and rainfall is too low to adequately recharge the aquifer. Figures 15 and 16 highlight the potential effects of these stresses on the aquifer after a 5-year simulation; the former showing a dramatic lowering of the water table (darker colours) around the periphery of the main valley, and the latter showing the increasing salinity (brighter colours) around the Bay of Napflion due to sea water intrusion.

The variation in scale between the different human and natural processes incorporated into the model has been emphasised throughout. The spatial effects are clearly observable in the outputs presented, in particular here the crop distributions and the changing salinity of the aquifer. We can see in Figures 13 and 14 a qualitative change in the crop distributions across the Argolid Valley which is only observable from the perspective presented, whereas the micro-level crop decisions (1 ha parcels) drive this change. The temporal effects are more difficult to observe in a static

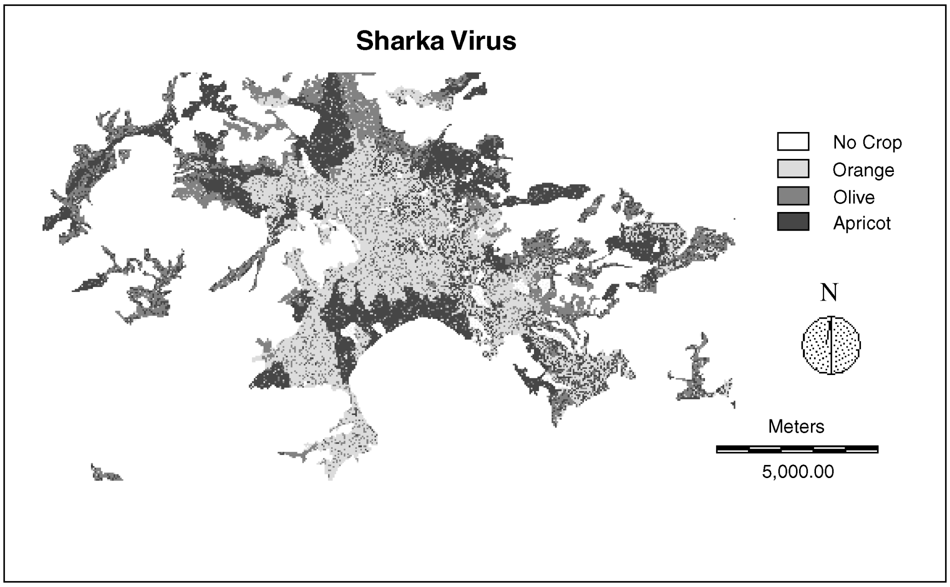


Fig. 14. Impact of the Sharka virus on crop distributions after 50 years.

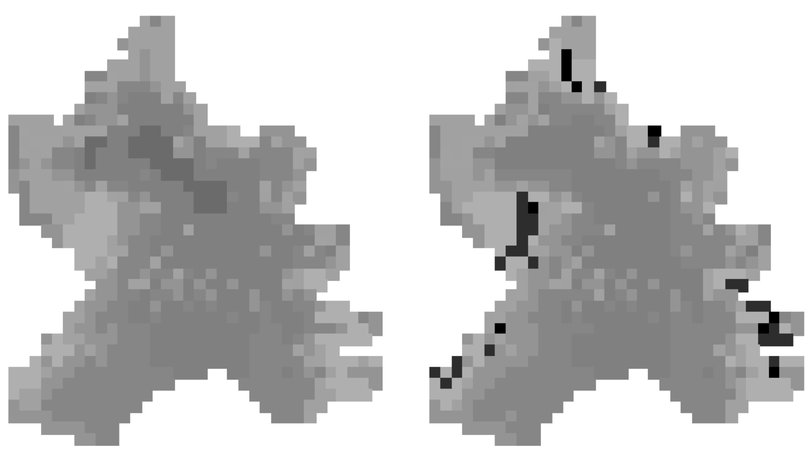


Fig. 15. Reduced aquifer levels around the periphery (dark areas) result from over-abstraction of water for irrigation.

form such as presented here; however, with selected snapshots we can still observe significant qualitative differences is the various landscapes after 5 decades, with decisions being made on an annual basis.

In the case of aquifer depletion and salinisation the relationships are less explicit since the effects of abstraction at one location will always be propagated through the aquifer, albeit delayed. However, in the outputs presented (with irrigation throughout the valley) we can observe seawater intrusion increasing steadily for 5 years. Farmers far from the coast may remain unaffected by the salinisation, and those affected may respond through crop changes or, if the salt does not kill the trees, may hope for increased rainfall or other forms of aquifer recharge before; the lead time for the first harvest may be up to 5 years.

In these simple examples an hierarchy of nested spatial and temporal scales which affects the decision making is already emerging. In the case where crops are damaged by salinity this additional factor influences subsequent crop choices, but salinisation may only be a temporary phenomenon mitigated by high rainfall or aquifer recharge in subsequent years. Exploration of these emergent dynamics and the validation of the model in such contexts is ongoing.

9. CONCLUSIONS

The static simulation outputs we have presented can only give a flavour of the potential utility of this modelling framework. The real value emerges when such outputs can be observed in dynamic real-time simulations [31], and it is at this level where scenaria can be explored by local stakeholders and decision makers. In this way the modelling framework facilitates interactive exploration of policy scenaria, thus driving the feedback identified in the conceptual framework whereby the contextualised inter-

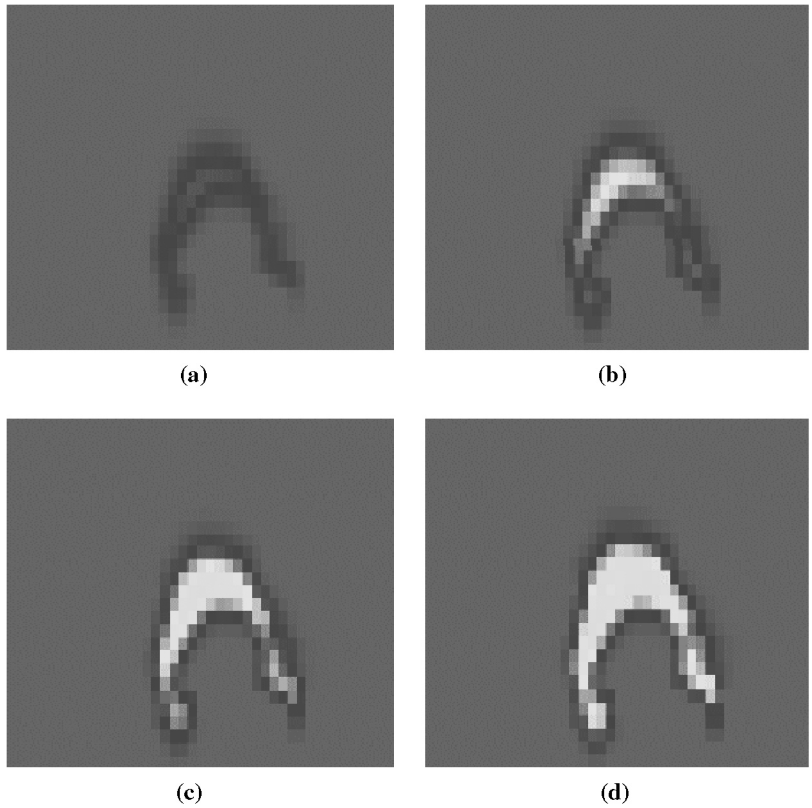


Fig. 16. Over-abstraction and reduced aquifer levels provoke sea water intrusion and aquifer salinisation after (a) 15 months, (b) 30 months, (c) 45 months, and (d) 60 months.

pretation of simulation outputs influences the definition of subsequent scenaria to be explored.

Potential further developments to the framework have emerged from this work, including both the qualitative socio-cultural aspects and the hard science of the hydrological processes implemented. The three main areas where beneficial additional developments could be made are:

- Extensions to the abstract representation of the *Conceptual Framework*;
- Alternative implementations of the decision tree based *Decision Making Model*; and
- Enhancements to the representations of water quality and re-use within the system.

Extensions to the conceptual framework could address what may be termed as *Problem Spaces*. Problem spaces may emerge as a result of conflicts within and between decision spaces and policy spaces. Conceptualising such a space may help in understanding the dynamics represented by the conceptual framework and, through implicit perturbations of the decision spaces, may be used to identify and represent non-linear characteristics through the definition of dynamic decision trees.

By allowing the decision trees to adapt in response to problem spaces, the modelling of the decision spaces themselves, along with their location specificity and adaptive characteristics could be incorporated into the Integrative Framework. Dynamic decision trees may reflect, for example, changes to farmers' cultural predispositions due to the retention of a memory of past decisions and experiences, or in response to conflicts with new policy instruments (i.e., through the problem space). Observation and interpretation of such (simulated) changes may elucidate the repercussions of the farmers' responses upon the decision and policy spaces, thus providing a mechanism whereby changes can be made to the policy scenaria as a result of previous simulations.

These possibilities for the extension of the conceptual framework present us with various alternative applications for the decision trees themselves. Alternative decision trees could be developed which relate to, for example, organic farming or managing sustainable futures. These would address key areas of socio-natural development which are becoming increasingly significant, particularly when viewed alongside current topical issues such as the levels of pesticide or herbicide residues entering the human food chain, the effects of BSE, Foot-and-Mouth, and the increasingly widespread introduction of genetically modified foodstuffs into our diets. A specific application of this integrative modelling framework to address these issues of organic farming and sustainable agriculture thus appears to be of potentially great importance.

The integrative nature of decision trees also suggests the potential adaptation of their theoretical basis to a completely novel, although related, context. The decision trees have been derived to allow us to model the *responses* of the local farmers to socio-cultural issues, to economic issues, to local, regional and national policy issues, and, of course, to their immediate natural environment. In other words, *the responses of actors within a system, both to their own perceptions and beliefs and to extraneous influences arising from a variety of spatial and temporal scales*. Why should such a useful theoretical tool be restricted to farmers? Such a tool could also be applied to, for example, local or regional politicians who also retain their individual perceptions and beliefs, and are affected by extraneous influences such as the electorate, and national and international policies, and who also are required periodically to make 'decisions.' However, the difficulty of obtaining the necessary information to understand the complex dynamics involved and to build decision trees in such a context cannot be underestimated [33–35].

The final area where further development is both appropriate and ongoing involves the harder, quantifiable science encompassed within the framework. It relates to aspects of the preceding discourse inasmuch as the issues involved in organic farming, sustainable agriculture and agrochemicals can be clearly mapped onto the hydrological characteristics of a region. There are already a number of areas where the model addresses the 're-use' of water within the system, whether through reservoir storage, aquifer abstractions or careful distribution of resources.

Water treatment and recycling is becoming increasingly important not only in more arid regions such as Greece and Spain, but also in northern European countries where there is a disparity between regions of high water availability and regions of high water usage. Adaptations to the model are already underway which incorporates a variety of water treatment technologies, facilitating the monitoring of water quality and its reuse [36]. Aside from the obvious benefits of effectively modelling water quality in rivers, this also allows us to examine the effects of using fresh, grey and/or treated water for irrigation purposes, and with adaptations to incorporate the tracking of nutrients within the system, the model can be used for more extensive assessment of the sustainability of specific agricultural practices.

Finally, it should also be remembered that the immense spatial and temporal complexity of the human-environmental interactions which have been incorporated into this Integrative Modelling Framework, reflects an achievement in itself. However, it must *always* be recognised that there will be many omissions and assumptions involved in such work, necessitating the careful interpretation of any results within both the social and natural contexts to which the model has been applied. *The use of such a modelling framework should only ever be for exploring (and learning from) potential futures, and never for precise quantifiable predictions of the future*. Development of this Integrative Modelling Framework will naturally continue, with the incorporation of additional and/or more complex representations of the various processes already included.

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