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An Optimization Model for Integrated Urban Planning: Development and Application to Algeria's Reghaïa and Heraoua Municipalities

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Abstract In this paper, I develop an optimization model for integrated urban planning for land use at the municipality level, in which decisions arise from an area-based weighted-GDP maximisation algorithm whose weights represent the sustainability and implementability of the land uses. The model favours the involvement of stakeholders in urban governance, but does not use complicated assessment procedures for non-economic indicators or relative weights to combine economic, social and environmental indicators; instead, the integration between economic activities and environmental status is represented objectively and non-linearly by referring to initial and sustainability conditions. The model accounts for both human and environmental dynamics by adopting a spatial structure that permits compromises between economic information (available at a macro level) and ecological information (available at a micro level). A single value is attached to each urban governance, with an elicitation of future decisions (including acceptance of the status quo) and the ability to provide an evaluation of past decisions: some environmental policies are considered. The model's predictions are based on reasonably reliable knowledge that can be easily collected, with reliability determined by calculating the confidence level. The resulting urban governance can then be presented and further analysed within a geographical information system. A case study of the model's application to Algeria's Reghaïa and Heraoua municipalities provides insights into optimal urban governance, with and without water quantity or quality policies, in terms of resource sustainability, sectoral development, and pollution sustainability. I also assess the previous master plan in terms of the land uses suggested by the model.

Keywords Optimization model · Integrated urban planning · Municipality planning · Algeria

Introduction

There is a growing consensus (e.g., UN-Habitat 2009a) that, despite the importance of personal factors, urban land use is a dominant factor that exacerbates or mitigates human health and well-being. Consider, for example, the effects of land use on economic health (e.g., income and jobs), social inequalities (e.g., the population structure within a neighbourhood or a town), and the health of the environment (e.g., air pollution). To control land development, Barton (2009) advocated the development of strategic policies for housing, commerce, and transportation so that vested interests would not prevail over the common good. Rather than discussing the institutional process of training and building capacity (e.g., partnerships and networking) or the institutional management of knowledge (e.g., public information and communication skills), I will focus on the *outcomes* of urban public decision-making in this paper. This is an important consideration because unplanned urban development guided solely by market forces can have serious negative social and environmental impacts.

Three main land-use policy tools are available to urban decision-makers: they can control (i) specific development and uses of urban sites, (ii) general or specific urban development through the application of fiscal tools, or (iii) land markets through the dissemination of information and

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by implementing guidelines for public participation in decisions (Rebelo 2009). On this basis I will focus on *urban planning*, and specifically on the use of zoning ordinances, land-use coefficients, and public investment to support municipal decisions, while disregarding the underlying regulatory and financial system.

There is growing consensus (e.g., UN-Habitat 2009a) that urban planning should be viewed as a self-conscious, flexible, and strategic collective (societal) effort to imagine or re-imagine a town, city, urban region, or wider territory, and to translate the results into priorities for investment, conservation measures, settlement of new and upgraded areas, and strategic infrastructure investments, and into principles that will guide land-use regulations. The goal is to account for the potential impacts of development in terms of how the development will shape future environmental, social, economic, and spatial relationships (King and others 2003). In particular, a shift from *urban planning* to *urban management* has been advocated. For example, Pauleit and Duhme (2000) stressed that, in practice, the environmental, social, and economic implications of the spatial pattern of a city's human activities must be understood to integrate sustainability principles into urban development. Indeed, environmental planning that does not account for human actions will tend to fail, and urban planning that does not accommodate or include environmental needs and processes will jeopardize human beings and their societies (Silva and others 2008). Next, a shift from *urban management* to *urban governance* has been advocated. For example, UN-Habitat (2009b) highlighted the need to foster a closer and more effective engagement of civil society in the public policy-development process; the goals are to integrate planning, management and governance; to tighten linkages among the sectors and parts of a city; to ensure coordinated flows of functions, helping to make the city function as a holistic entity at multiple scales; and to reaffirm human agency by bringing together many stakeholders, including those who have created problems, those who are affected by the problems, and those with the institutional responsibilities, tools, instruments, and resources to manage the problems.

Indeed, modern institutional planning, which is typically a top-down, technical, and expert-driven approach, may not give sufficient weight to community priorities and as a result, can impede the implementation of policy. However, UN-Habitat (2009b) notes that stakeholder participation requires a suitable political system (one that encourages active citizenship and that is committed to equity and the redress of wrongs) and well-organised civic institutions that specify the processes and outcomes of participation as well as relying on financial and human resources. In this context, I will focus on *integrated urban planning* (IUP), whose key words are participatory, interdependent, and holistic (Begum 2007). In this paper, I use IUP as a synonym for a combination of the following processes: *urban governance*, whose keywords are equity, sustainability, subsidiarity (decentralisation), efficiency, transparency, accountability, civic engagement, and security (UN-Habitat 2009b); *landscape planning*, which Silva and others (2008) defined as "activities that integrate both natural ecological needs and human socio-economic needs"; and *smart growth*, which Gabriel and others (2006) defined as a "growth management or development plan that enhances the economy, protects the environment and preserves or improves a community's way of life or that leads to Pareto optimal value of precisely defined measures identified by stakeholders".

Several scales of models for urban planning have been reported in the literature. For example, Awad and Aboul-Ela (2003) solved a non-linear programming model, in which they divided a Syrian city into many residential neighbourhoods and divided each of them into repeatable units called "modules", to obtain the optimum physical design of one module by satisfying geometric, density, and other constraints. Baban and others (2008) applied a geo-informatics approach to define suitability rankings for development on hillsides on the island of Tobago. In the present paper, I focus on *municipal IUP*.

The purpose of my study was to build upon models from the planning literature, using them as a reference on which to develop a land-use optimization model for IUP at the municipality level. In the land-use IUP literature, several studies used ecological models and cellular automata, but none has yet performed a holistic analysis of the interactions between urban development and the environment in which it occurs (Silva and others 2008). Although papers exist on landscape ecology and planning, they typically neglect human socio-economic needs (for example, Kattwinkel and others 2009; Kong and others 2010). Similarly, there has been work on urban and environmental dynamics, but these papers typically disregard aspects of planning (for example, Alig and others 2004; De Almeida and others 2003). One can also find papers on cellular automata and ecological models, but the approach is typically not holistic (Berling-Wolff and Wu 2004; Stevens and others 2007). Finally, there has been work on integrated planning, but typically at a watershed scale (Lin and others 2009; Meyer and others 2009). The studies I have cited here are all spatial in nature, but are not models based on stakeholder participation; instead, they are either optimization or dynamics models.

Moreover, UN-Habitat (2009b) provides guidelines about the characteristics of IUP, which include strategic spatial planning, the use of spatial planning to integrate public-sector functions, new approaches to land regulation and management, participatory processes and partnerships at the neighbourhood level, bottom-up master planning that is oriented towards achieving social justice, and planning aimed at producing new spatial forms. However, it does not suggest an optimization procedure and it does not provide a list of indicators that can be used in an overall assessment of IUP.

Another useful approach comes from a recent *non-deterministic* package, in which Silva and others (2008) combined an (urban) cellular automata simulation model (SLEUTH) with an countervailing environmental cellular automaton to include both urban and environmental considerations in a dynamics-based modelling approach. In this approach, the ability to include planning policy in the simulation of future scenarios (i.e., offensive, defensive, opportunistic, and protective strategies) made it possible to support decision-makers in establishing strategies that would enhance the sustainability of the urban landscape. However, Silva and others did not implement an optimization algorithm, and did not determine the statistical significance of their results.

In the present paper, my goal was to develop a land-use optimization model for IUP at the municipality level that combines the *main* potentials highlighted above (i.e., the use of economic, social, and environmental indicators within an outcome-oriented framework, of alternative scenarios and policies, and of an integrated approach). In addition, I attempted to compensate for the *main* inadequacies described above (the lack of optimization procedures, the application of problematic evaluation procedures, the lack of confidence levels for the outcomes, the use of problematic indicators, the lack of an overall value for the management strategies, and the use of a limited number of economic and ecological criteria). My goal was to provide a fuller exploration of the coupled human–environment system.

Prato (2007) did not include social indicators in his model, he applied relative weights within a multi-criterion analysis; unfortunately, the resulting model did not formalise the integration between economic activities and the environment, refer to private resources, or consider human and natural dynamics. Despite these limitations, Prato's contribution to the literature on multi-objective land use represents a good starting point for the present model because he provided decisions on which project to choose based on a multi-objective maximisation and minimisation approach, using the characteristics of patches and the objectives of decision-makers; that is, he provides an optimization model to represent *non-linear* processes. Wang and others (2004), Gabriel and others (2006), and Lin and others (2009) discuss alternative optimization approaches for land use.

Economic activities both affect and are affected by the environment. For example, environmental changes such as coastal erosion, land subsidence, sea level rise, flooding, and salt water intrusion may affect coastal economic activities, with a range of consequences for the depletion of surface water and groundwater, as well as solid, liquid, and air pollution and land degradation. Next, coastal economic activities can affect the environment through solid, liquid, and air pollution as well as through exploitation of water and land resources that can, in turn, affect the causal activity or other local economic activities. Because the range of effects is large, I will focus on depletion and pollution of surface water and groundwater as a result of economic activities. This approach can easily be extended to additional economic and environmental parameters.

To examine these relationships, I will develop an optimization model for integrated urban land-use planning at the municipality level, in which decisions arise from an area-based weighted-GDP maximisation algorithm whose weights represent the sustainability and implementability of the land uses. The analysis will elicit future decisions (including acceptance of the status quo) and it will provide an evaluation of past decisions.

To demonstrate how the model works, I will perform a case study of two municipalities in Algeria. The analysis focuses on crucial economic activities and land uses that rely on essential environmental functions under certain environmental constraints, including existing environmental policies.

The structure of the paper is as follows. In the second section, I develop the model. In the third, I present the case study. In the fourth section, I estimate the main model parameters for that case study, and in section five, I present the main results of the numerical optimizations. Section six summarises the main insights provided by the model, and discusses its advantages and limitations. Section seven provides an overall assessment of the model.

Development of the Model

In this section, I develop an optimization model that meets the requirements identified above. For consistency, I have used lower-case letters for parameters, and capital letters for decision and state variables.

Let us assume a situation with i areas ($i = 1, 2, \ldots, I$) and j alternative activities ($j = 1, 2, \ldots J$) that can be undertaken in these areas. To account for land-use conflicts, I have assumed that only specified activities can be carried out in each area, with each activity represented by a local stakeholder; for example, in area 1, planners must choose between agriculture and industry. I have assigned a GDP per km^2 to each area, as in the study by Gao and others (2007), according to the potential economic return from the activity assigned to that area.

Note that this structure can be expanded to include any number of activities, and could therefore be used to compare (for example) different types of housing development. Moreover, the model is an area-based approach, and can therefore be easily implemented using a GIS-based planning tool. Finally, the structure can be expanded to account for any number of areas, thereby allowing analysis at spatial scales ranging from micro to macro.

In addition, let us assume that there are s sites ($s = 1, 2, \ldots S$) where the j potential alternative activities can be undertaken, depending on the site's environmental status k ($k = 1, 2, \ldots K$). In particular, I represent the site's environmental status in terms of values of some pollutants k, on the assumption that certain pollution levels will make a site unfit for certain activities. For example, either tourism or agriculture can be planned around a lake, depending on the lake's water quality. In the model, I have used a single parameter to represent a clean environment of 1-km^2 area and avoid the requirement for complicated and problematic assessment procedures for non-economic indicators. Consider, for example, the criticisms against using cost-benefit analysis to estimate social or environmental impacts (e.g., Campbell and Brown 2005). In other words, I assume that a political process exists such that all stakeholders discuss and agree upon a single economic value for a clean environment of 1-km^2 area. This eliminates the need for problematic approaches such as shadow pricing and estimates of willingness to pay.

Note that this structure can be expanded to include any number of environmental indicators for each site. Next, a consideration of the potential alternative activities for each area depends on the assumed time horizon, with a longer horizon allowing a larger set of potential activities to be implemented (e.g., because efforts to mitigate pollution may allow a formerly unsuitable area to be used for a new activity).

The decision to be taken at time $t+1$ about which activity j to undertake in area i is represented by $D_{i,j}(t+1)$, such that $D_{i,j}(t+1) = 1$ if activity j is chosen for area i at time $t+1$, whereas $D_{i,j}(t+1) = 0$ if it is not chosen. An activity chosen at time $t+1$ might be different from an activity chosen at time t. For example, $D_{i,j}(t+1) = 1$ and $D_{i,j}(t) = 0$. The activity change at time $t+1$ in area i produces a change in the economic value of area i, $\Delta V_i(t)$, that depends on the difference in GDP per km^2 between the new and old activities (vj' and $v_{j'}$ respectively), and on the area extent (A_i), so that $\Delta V_i(t) = A_i[v_{j'}D_{i,j'}(t+1) - v_j D_{i,j}(t)]$ is the change in economic value of area i if activity j at time t is replaced by activity j' at time $t+1$. The activity change at time $t+1$ in area i produces a change in total pollution k at site s, $\Delta P_{k,s}$, such that $\Delta P_{k,s}(t) = A_i[p_{k,j'}D_{i,j'}(t+1) - p_{k,j}D_{i,j}(t)]$ is the change in the level of pollutant k if the activity j at time t is replaced by activity j' at time $t+1$, where $p_{k,j}$ is the quantity of pollutant k per km^2 produced by activity j. This represents spatial integration of economics with the environment, where the decision to undertake activity j in area i changes the amount of pollutant k at site s.

Note that this procedure will directly assess the economic values of each area and the pollution levels produced by each activity, and that an input–output approach could be used to permit indirect assessments if sufficiently reliable data is available. For example, consider a matrix that evaluates the indirect GDP and a matrix that measures the indirect pollution when an industrial activity is replaced by an agricultural activity. Moreover, the linkages between activities undertaken in area i and the pollution discharged at site s are based on hydrological or biological analysis, thereby making the model intrinsically multidisciplinary. Finally, environmental indicators are chosen so that their impacts on various activities are considered.

The total change in pollution at site s affects the activities at that site, so that v_j changes. The present model accomplishes this by multiplying v_j by the factor $E_s = \prod_k E_{k,s} = \prod_k \{[\text{Max } P_{k,s} - P_{k,s}(t) - \Delta P_{k,s}(t)]/[\text{Max } P_{k,s} - P_{k,s}(t)]\}$, where $P_{k,s}(t)$ and Max $P_{k,s}$ are the current level of pollutant k and the maximum sustainable level of pollutant k at site s, respectively. $E_{k,s} = 1$ if $\Delta P_{k,s}(t) = 0$, whereas $E_{k,s} = 0$ if $\Delta P_{k,s}(t) = \text{Max } P_{k,s} - P_{k,s}(t)$. This also represents spatial integration of economics with the environment, since a change in pollutant k in site s will change the economic value of activity j in area i.

Note that E_s internalizes the impacts of environmental deterioration on economic activities. For example, the value of GDP per km^2 for seashore tourism will decrease to account for the public health issues that result from increased pollution of the sea. Moreover, E_s depends nonlinearly on initial conditions: a given level of deterioration of the environment will produce a small impact when the initial pollution level is low, but will produce a large impact when the initial pollution level is close to its sustainable maximum. Finally, Max $P_{k,s}$ depicts the sustainability of economic activities by making an intrinsically dynamic concept static. For example, international, national, or regional institutions might legislate that the pollution load in lake water cannot exceed a specified level.

The following simplifying assumptions are made:

- The impact of increased or decreased pollution on economic activities is instantaneous, whereas it takes $T_{j'}$ periods for a change to activity j' from activity j to produce a difference in the economic value of area i: $\Delta V_i(t) = (1/[(1+r)^{T_{j'}}])A_i[v_{j'}D_{i,j'}(t+1) - v_j D_{i,j}(t)]$, where r is the discount rate.

- The value of an economic activity in area i is evaluated using an annual time step, hence the value of the clean environment in area i is also evaluated annually.
- The cost to eliminate each unit of pollutant k (i.e., to fully remove 1 unit) is c_k, and $\sum_k c_k\,[P_{k,s}(t) + \Delta P_{k,s}(t)]\, D_{i,\text{environment}}(t+1)$ is the cost to be borne if area i near site s is chosen for environmental conservation ($D_{i,\text{environment}}$).

Several economic constraints could be considered. For example, if the demographic pressure must be met by increasing urban construction to provide homes:

$$\sum_i A_i\left[D_{i,\text{urban}}(t+1) - D_{i,\text{urban}}(t)\right] \geq \text{Min}\,\Delta A_{\text{urban}}$$

where $D_{i,\text{urban}}$ represents the decision to undertake urban development in area i and ΔA_{urban} is the estimated minimum additional area to be allocated to housing development. Similarly, expected industrial growth could be represented as $\Delta A_{\text{industry}}$.

Several social constraints could also be considered. For example, if the employment level must increase:

$$\sum_i A_i \sum_j e_j\left[D_{i,j}(t+1) - D_{i,j}(t)\right] > 0$$

where e_j is the employment per km^2 provided by economic activity j. Analogously, an even distribution among the stakeholders of the benefits arising from alternative management strategies could be included.

Several environmental constraints could also be considered. For example, if the use of water must be sustainable:

$$\sum_i A_i \sum_j w_j\left[D_{i,j}(t+1) - D_{i,j}(t)\right] \leq \Delta W$$

where w_j is the water use (m^3/km^2) by activity j, whereas ΔW is the maximum sustainable change in water use, which is potentially affected by the dynamics of the natural environment (e.g., salt water intrusion). In addition, changes in water availability caused by changes such as a rise in sea level or subsidence of land could be depicted by introducing constraints that arise from the expected changes in water availability.

Note that considering economic, social, and environmental indicators as constraints avoids the need to use complicated and problematic assessment procedures for non-economic indicators. For example, consider the criticisms of using shadow prices for houses, labour, or water when these factors are introduced in an objective function (e.g., Campbell and Brown 2005). Next, because the values of activities are often known on a larger spatial scale than the scale chosen for analysis, typically at a regional rather than municipal level, rescaling of the data is required. However, a statistical test was used to relate the variance of each activity's economic value around the mean to determine whether the overall model outcomes were statistically significant. In particular, under the assumptions of a normal distribution for each activity's economic value, equality of variances (σ^2), and correlations (ρ) among the economic values of the activities, the maximum value of σ^2 to achieve a significant result ($P < 0.10$) was calculated by solving the following inequality, under the assumption that each comparison between means was not correlated with other differences: $2\,N\,(1-\rho)\,\sigma^2 \leq 1$. Here, the 1 on the right-hand side of the equation represents the value that the term on the left-hand side would take in the formula for the confidence interval for differences of means if the distribution under consideration were a standard normal distribution, and N represents the number of changes in land uses.

An example will show how the model works by focusing on the model's temporal, spatial, integration and non-linear aspects.

For the sake of simplicity, let us refer to only three activities (j = agriculture, urban (housing) development, and tourism) and only two areas ($i = 1$ and 2). In addition, let us assume that $v_{\text{agriculture}} = 400$ €/km^2, $v_{\text{urban}} = 5000$ €/km^2, and $v_{\text{tourism}} = 2000$ €/km^2 are the GDP per km^2 from these three land uses, whereas $A_1 = 1$ km^2 and $A_2 = 0.5$ km^2 are the sizes of the two areas. This situation can be depicted by vector $A = [A_1, A_2]$, of dimension 1 times $I = 2$, and by vector $V = [v_{\text{agriculture}}, v_{\text{urban}}, v_{\text{tourism}}, v_{\text{environment}}]$, of dimension $J = 4$ times 1, with $v_{\text{environment}}$ taken as a parameter representing the value of land used for environmental purposes (e.g., conservation). Moreover, let us assume that agriculture and environmental conservation are the prevailing activities in areas 1 and 2, respectively: $D_{1,\text{agriculture}}(t) = 1$ and $D_{2,\text{environment}}(t) = 1$. This can be depicted by matrix D(t) of dimension $I = 2$ times $J = 4$:

	Agriculture	Urban	Tourism	Environment
A_1	1	0	0	0
A_2	0	0	0	1

Finally, let us specify that urban (housing) development and tourism can be potentially implemented in areas 1 and 2, respectively. This can be depicted by matrix D(t+1) of dimension $I = 2$ times $J = 4$:

	Agriculture	Urban	Tourism	Environment
A_1	$D_{1,\text{agriculture}}(t+1)$	$D_{1,\text{urban}}(t+1)\,F_{\text{urban}}$	0	0
A_2	0	0	$D_{2,\text{tourism}}(t+1)\,F_{\text{tourism}}$	$D_{2,\text{environment}}(t+1)$

where $F_{urban} = 1/[(1+r)^{T_{urban} \times D_{1,urban}(t+1)}]$ and $F_{tourism} = 1/[(1+r)^{T_{tourism} \times D_{2,tourism}(t+1)}]$ are the discount factors linked to periods required for housing development and tourism to produce an economic value difference, with r being the discount rate.

In terms of *time*, the economic value change in area 1 is $\Delta V_1(t) = A_1\ [v_{agriculture}\ D_{1,agriculture}(t+1) - v_{agriculture}\ D_{1,agriculture}(t)] = 0$ if agriculture is chosen at time $t+1$ (i.e., $D_{1,agriculture}(t+1) = 1$), whereas it is $\Delta V_1(t) = A_1\ F_{urban}\ [v_{urban}\ D_{1,urban}(t+1) - v_{agriculture}\ D_{1,agriculture}(t)] = 1 \times 1 \times [5000-400] = 4600$ if agriculture is replaced by housing development at time $t+1$ (i.e., $D_{1,urban}(t+1) = 1$), with $F_{urban} = 1$ at $r = 0$ for simplicity. Similarly, the value change in area 2 is $\Delta V_2(t) = A_2\ [v_{environment}\ D_{2,environment}(t+1) - v_{environment}\ D_{2,environment}(t)] = 0$ if environment is chosen at time $t+1$ (i.e., $D_{2,environment}(t+1) = 1$), whereas it is $\Delta V_2(t) = A_2\ F_{tourism}\ [v_{tourism}\ D_{2,tourism}(t+1) - v_{environment}\ D_{2,environment}(t)] = 0.5 \times 1 \times [2000 - v_{environment}] = 1000 - 0.5\ v_{environment}$ if environment is replaced by tourism at time $t+1$ (i.e., $D_{2,tourism}(t+1) = 1$), with $F_{tourism} = 1$ at $r = 0$ for simplicity. In matrix form: A × [D(t+1)−D(t)] × V.

For the sake of simplicity, let us refer to three potentially polluted sites (s = water in the ground (aquifer), lake, and sea) and to two pollutants (k = biological oxygen demand, BOD, and chemical oxygen demand, COD). For these sites, let us assume: $p_{BOD,agriculture} = 2$ t/km^2, $p_{COD,agriculture} = 10$ t/km^2, $p_{BOD,urban} = p_{BOD,tourism} = 73$ t/km^2, and $p_{COD,urban} = p_{COD,tourism} = 90$ t/km^2. Moreover, let us assume that the total pollution changes due to changes in activity will affect 20% of the groundwater and 80% of the surface water, with the latter result affecting 20% of the sea water and 80% of the lake water. Thus: $b_{BOD,sea} = b_{COD,sea} = 0.16$, $b_{BOD,lake} = b_{COD,lake} = 0.64$, and $b_{BOD,aquifer} = b_{COD,aquifer} = 0.20$. Finally, let us assume that lake pollution affects the value of agriculture in area 1, whereas sea pollution affects the value of tourism in area 2, with E_s being a function of current pollution levels and future pollution changes at site s to represent these impacts. In matrix form, this can be depicted by matrix X(t) of dimensions $S = 3$ times $I = 2$ for current activities:

	A_1	A_2
Aquifer	0	0
Lake	E_{lake}	0
Sea	0	1

and by the matrix X(t+1) of dimensions $S = 3$ times $I = 2$ for potential activities:

	A_1	A_2
Aquifer	0	0
Lake	1	0
Sea	0	E_{sea}

In matrix form: A × Z × [X(t+1) × D(t+1)−X(t) × D(t)] × V, with matrix Z of dimensions $I = 2$ times $S = 3$ depicting the dependence of activity j in area i on pollution levels at site s:

	Aquifer	Lake	Sea
Area 1	0	1	0
Area 2	0	0	1

where X(t+1) × D(t+1) is given by:

	Agriculture	Urban	Tourism	Environment
Aquifer	0	0	0	0
Lake	0	1	0	0
Sea	0	0	E_{sea}	0

And X(t) × D(t) is given by:

	Agriculture	Urban	Tourism	Environment
Aquifer	0	0	0	0
Lake	E_{lake}	1	0	0
Sea	0	0	0	1

For spatial integration of economics with the environment, the impact of economic activities on environmental deterioration implies changes in total pollution levels. In particular, if agriculture is replaced by housing (urban) development in area 1 at time t+1 and environment is replaced by tourism in area 2 at time t+1, then in the lakes:

$\Delta P_{BOD,lake}(t) = 0.64 \times A_1\ [p_{BOD,urban}\ D_{1,urban}(t+1) - p_{BOD,agriculture}\ D_{1,agriculture}(t)] + 0.64 \times A_2\ [p_{BOD,tourism}\ D_{2,tourism}(t+1) - p_{BOD,environment}\ D_{2,environment}(t)] = 0.64 \times 1\ [73 - 2] + 0.64 \times 0.5\ [73 - 0] = 68.80$ t and $\Delta P_{COD,lake}(t) = 0.64 \times A_1\ [p_{COD,urban}\ D_{1,urban}(t+1) - p_{COD,agriculture}\ D_{1,agriculture}(t)] + 0.64 \times A_2\ [p_{COD,tourism}\ D_{2,tourism}(t+1) - p_{COD,environment}\ D_{2,environment}(t)] = 0.64 \times 1\ [90 - 10] + 0.64 \times 0.5\ [90 - 0] = 80.00$ t.

In the sea:

$\Delta P_{BOD,sea}(t) = 0.16 \times A_1\ [p_{BOD,urban}\ D_{1,urban}(t+1) - p_{BOD,agriculture}\ D_{1,agriculture}(t)] + 0.16 \times A_2\ [p_{BOD,tourism}\ D_{2,tourism}(t+1) - p_{BOD,environment}\ D_{2,environment}(t)] = 0.16 \times 1\ [73 - 2] + 0.16 \times 0.5\ [73 - 0] = 17.20$ t and $\Delta P_{COD,sea}(t) = 0.16 \times A_1\ [p_{COD,urban}\ D_{1,urban}(t+1) - p_{COD,agriculture}\ D_{1,agriculture}(t)]$

$+ 0.16 \times A_2$ $[p_{\text{COD,tourism}}$ $D_{2,\text{tourism}}(t+1) - p_{\text{COD,environment}}$ $D_{2,\text{environment}}(t)] = 0.16 \times 1\,[90 - 10] + 0.16 \times 0.5\,[90 - 0] =$ 20.00 t.

Next, the impact of environmental deterioration on economic activities implies a reduction of economic values. In particular, let us assume the following differences between the maximum sustainable level and the current level (i.e., the maximum sustainable change): 100 t for BOD pollution in the lake, 400 t for COD pollution in the lake, 20 t for BOD pollution in the sea, and 100 t for COD pollution in the sea. Thus, the value of agriculture in area 1 is reduced by the factor $E_{\text{lake}} = E_{\text{BOD,lake}} \times E_{\text{COD,lake}} =$ [(100−68.80)/100] × [(400−80.00)/400]; that is, it is reduced to 0.31 times 0.80 = 24.96%. Similarly, the value of tourism in area 2 is reduced by the factor $E_{\text{sea}} = E_{\text{BOD,sea}} \times E_{\text{COD,sea}} =$ [(20−17.20)/20] × [(100−20.00)/100]; that is, it is reduced to 0.14 times 0.80 = 11.20%.

In terms of *space*, housing development in area 1 could only be replaced by agriculture, whereas the environment in area 2 could only be replaced by tourism (i.e., spatial dependence of activities). In this example, this is represented by the vector D(t+1). Next, the value of agriculture in area 1 and the value of tourism in area 2 depend on the environmental status of the lake and the sea, respectively, and the status of these environments depends on the activities undertaken in other areas (i.e., spatial interdependence of activities). In this example, this is depicted by the matrixes X(t+1), X(t), and Z.

In terms of *non-linearity*, the value of agriculture in area 1 and the value of tourism in area 2 are reduced by factor E_s ($E_{\text{lake}} = 0.2496$, $E_{\text{sea}} = 0.1120$), which are obtained by multiplying the pollution factors ($E_{\text{lake}} = E_{\text{BOD,lake}} \times E_{\text{COD,lake}}$ and $E_{\text{sea}} = E_{\text{BOD,sea}} \times E_{\text{COD,sea}}$) and by referring to the differences between the maximum sustainable level and current level of pollution (i.e., the maximum sustainable change) for each pollutant k at each site s.

For the sake of simplicity, let us assume that whenever the environment is chosen in area i (here, area 2) all pollutants at relevant sites s (here, the sea) are eliminated: c_{BOD} and c_{COD} are the costs to eliminate each unit of BOD and COD pollution. Moreover, let us assume that demographic pressure requires that at least Min ΔA_{urban} must be allocated to housing development. Finally, let us assume that whenever housing development is chosen in area i (here, area 1), solid waste is collected: c_{SOL} is the cost to collect a unit of solid waste, and $p_{\text{SOL,urban}}$ is the quantity of solid waste per km^2 produced by housing development.

In this example, the optimization model for IUP is given by:

$$\text{Maximize}\left(D_{1,\text{agriculture}}(t+1), D_{1,\text{urban}}(t+1), D_{2,\text{tourism}}(t+1), D_{2,\text{environment}}(t+1)\right)$$
$$A_1\left[v_{\text{agriculture}}D_{1,\text{agriculture}}(t+1)E_{\text{lake}} + v_{\text{urban}}D_{1,\text{urban}}(t+1) - v_{\text{agriculture}}D_{1,\text{agriculture}}(t)E_{\text{lake}}\right]\left\{1/\left[\left[(1+r)^{\text{T}_{\text{urban}}D_{1,\text{urban}(t+1)}}\right]\right\}+\right.$$
$$A_2\left[v_{\text{environment}}D_{2,\text{environment}}(t+1) + v_{\text{tourism}}D_{2,\text{tourism}}(t+1)E_{\text{sea}} - v_{\text{environment}}D_{2,\text{environment}}(t)\right]\left\{1/\left[(1+r)^{\text{T}_{\text{tourism}}D_{2,\text{tourism}(t+1)}}\right]\right\} -$$
$$D_{2,\text{environment}}(t+1)\left\{c_{\text{BOD}}\left[P_{\text{BOD,sea}}(t) + \Delta P_{\text{BOD,sea}}(t)\right] + c_{\text{COD}}\left[P_{\text{COD,sea}}(t) + \Delta P_{\text{COD,sea}}(t)\right]\right\} - A_1 D_{1,\text{urban}}(t+1)c_{\text{SOL}}p_{\text{SOL,urban}}$$

Subject to:

$$A_1\left[D_{1,\text{urban}}(t+1) - D_{1,\text{urban}}(t)\right] \geq \text{Min}\ \Delta A_{\text{urban}}$$

With:

$$E_{\text{lake}} = E_{\text{BOD,lake}} \times E_{\text{COD,lake}}$$
$$E_{\text{BOD,lake}} = \left[\text{Max}P_{\text{BOD,lake}} - P_{\text{BOD,lake}}(t) - \Delta P_{\text{BOD,lake}}(t)\right]/\left[\text{Max}P_{\text{BOD,lake}} - P_{\text{BOD,lake}}(t)\right]$$
$$E_{\text{COD,lake}} = \left[\text{Max}P_{\text{COD,lake}} - P_{\text{COD,lake}}(t) - \Delta P_{\text{COD,lake}}(t)\right]/\left[\text{Max}P_{\text{COD,lake}} - P_{\text{COD,lake}}(t)\right]$$
$$\Delta P_{\text{BOD,lake}}(t) = b_{\text{BOD,lake}}\left\{A_1\left[p_{\text{BOD,urban}}D_{1,\text{urban}}(t+1) + p_{\text{BOD,agriculture}}D_{1,\text{agriculture}}(t+1) - p_{\text{BOD,agriculture}}\right.\right.$$
$$\left.\left.D_{1,\text{agriculture}}(t)\right] + A_2\left[p_{\text{BOD,tourism}}D_{2,\text{tourism}}(t+1) + p_{\text{BOD,environment}}D_{2,\text{environment}}(t+1) - p_{\text{BOD,environment}}D_{2,\text{environment}}(t)\right]\right\}$$

$$\Delta P_{\text{COD,lake}}(t) = b_{\text{COD,lake}}\{A_1[p_{\text{COD,urban}}D_{1,\text{urban}}(t+1) + p_{\text{COD,agriculture}}D_{1,\text{agriculture}}(t+1) - p_{\text{COD,agriculture}} D_{1,\text{agriculture}}(t)] + A_2[p_{\text{COD,tourism}}D_{2,\text{tourism}}(t+1) + p_{\text{COD,environment}}D_{2,\text{environment}}(t+1) - p_{\text{COD,environment}} D_{2,\text{environment}}(t)]\}$$

$$E_{\text{sea}} = E_{\text{BOD,sea}} \times E_{\text{COD,sea}}$$

$$E_{\text{BOD,sea}} = [\text{Max } P_{\text{BOD,sea}} - P_{\text{BOD,sea}}(t) - \Delta P_{\text{BOD,sea}}(t)] / [\text{Max } P_{\text{BOD,sea}} - P_{\text{BOD,sea}}(t)]$$

$$E_{\text{COD,sea}} = [\text{Max } P_{\text{COD,sea}} - P_{\text{COD,sea}}(t) - \Delta P_{\text{COD,sea}}(t)] / [\text{Max } P_{\text{COD,sea}} - P_{\text{COD,sea}}(t)]$$

With $F_j = 1/\left[(1+r)^{Tj\,Di,j\,(t+1)}\right]$

$$E_s = \prod_k E_{k,s}$$

$$E_{k,s} = [\text{Max}P_{k,s} - P_{k,s}(t) - \Delta P_{k,s}(t)] / [\text{Max}P_{k,s} - P_{k,s}(t)]$$

$$\Delta P_{\text{BOD,sea}}(t) = b_{\text{BOD,sea}}\{A_1[p_{\text{BOD,urban}}D_{1,\text{urban}}(t+1) + p_{\text{BOD,agriculture}}D_{1,\text{agriculture}}(t+1) - p_{\text{BOD,agriculture}} D_{1,\text{agriculture}}(t)] + A_2[p_{\text{BOD,tourism}}D_{2,\text{tourism}}(t+1) + p_{\text{BOD,environment}}D_{2,\text{environment}}(t+1) - p_{\text{BOD,environment}} D_{2,\text{environment}}(t)]\}$$

$$\Delta P_{\text{COD,sea}}(t) = b_{\text{COD,sea}}\{A_1[p_{\text{COD,urban}}D_{1,\text{urban}}(t+1) + p_{\text{COD,agriculture}}D_{1,\text{agriculture}}(t+1) - p_{\text{COD,agriculture}} D_{1,\text{agriculture}}(t)] + A_2[p_{\text{COD,tourism}}D_{2,\text{tourism}}(t+1) + p_{\text{COD,environment}}D_{2,\text{environment}}(t+1) - p_{\text{COD,environment}} D_{2,\text{environment}}(t)]\}$$

where $p_{\text{BOD,environment}} = p_{\text{COD,environment}} = D_{1,\text{urban}}(t) = 0.$

Note that, in this example, in order to achieve a significant result ($P < 0.10$), the following inequality must be met: $2 \times 2\ (1-\rho)\ \sigma^2 \leq 1$, since I have assumed 2 changes in land uses (i.e., in area 1, from agriculture to housing (urban) development, and in area 2, from environmental conservation to tourism).

In general, the optimization model for IUP is given by:

Maximize ($D_{i,j}$ (t+1))

$$\sum_i A_i \sum_j F_j Z_{i,s}[X_{s,i}(t+1)D_{i,j}(t+1)V_j - X_{s,i}(t)D_{i,j}(t)V_j] - \sum_i A_i \sum_s Z_{i,s} \sum_k c_k[P_{k,s}(t) + \Delta P_{k,s}(t)]D_{i,\text{environment}}(t+1) - \sum_i A_i D_{i,\text{urban}}(t+1) c_{\text{SOL}} p_{\text{SOL,urban}}$$

Subject to:

$$\sum_i A_i[D_{i,\text{urban}}(t+1) - D_{i,\text{urban}}(t)] \geq \text{Min } \Delta A_{\text{urban}}$$

$$\sum_i A_i[D_{i,\text{industry}}(t+1) - D_{i,\text{industry}}(t)] \geq \text{Min } \Delta A_{\text{industry}}$$

$$\sum_i A_i \sum_j e_j[D_{i,j}(t+1) - D_{i,j}(t)] > 0$$

$$\sum_i A_i \sum_j w_j[D_{i,j}(t+1) - D_{i,j}(t)] \leq \Delta W$$

$$\Delta P_{k,s}(t) = B_{k,s} \sum_i A_i \sum_j \{p_{k,j}D_{i,j}(t+1) - p_{k,j}D_{i,j}(t)]\}$$

Where $B_{k,s}$ depicts the proportion of pollutant k discharged at site s.

Note that, by choosing different land uses, a single objective is pursued: the increase in overall weighted GDP per year for the study areas, where weights represent the sustainability (E_s) and implementability (F_j) of the land uses. Next, in order to achieve a significant result ($P < 0.10$), the following general inequality must be met: 2 $(1-\rho)\ \sigma^2\ [I - \sum_i D_{i,j^\circ}(t+1)] \leq 1$, where I is the number of areas under consideration, and j° is set at the activity chosen at time t in area i.

The set of parameters and state variables used in this example are summarised in Table 1.

Five observations are noteworthy in this example. First, several numerical optimizations with alternative values attached to a clean environment avoid the need to use relative weights to combine the economic, social, and environmental indicators. Second, the application of the model to times t and $t-1$ would make it possible to assess the overall values of decisions taken in the past. Third, the suggested framework and the applied procedure are straightforward, and the only parameter that is not objectively specified is the value of a clean environment; however, expressing the environment's value in terms of the values of the alternative economic activities could promote

Table 1 The set of parameters and state variables used in the example of the model

A_i	Size of area *i*
v_j	GDP per km^2 produced by activity *j*
$p_{k,j}$	The amount of pollutant *k* per km^2 produced by activity *j*
Max $P_{k,s}$	The maximum sustainable level of pollutant *k* at site *s*
c_k	The treatment cost per unit for pollutant *k*
e_j	The employment (no./km^2) provided by activity *j*
w_j	The water use (m^3/km^2) by activity *j*
T_j	Time required to implement activity *j*
Max ΔW	The maximum sustainable change in water use
Min ΔA_j	The minimum land allocation to activity *j*
$P_{k,s}(t)$	The current level of pollutant *k* at site *s*
$D_{i,j}(t)$ in [0,1]	The current activity *j* undertaken in area *i*

discussion and negotiation among the stakeholders. Fourth, numerical optimizations performed with and without alternative environmental policies (e.g., an increase in the wastewater treatment rate, an increase in water conservation) would allow an assessment of the impact of various alternatives on optimal decisions as well as their overall benefits or costs. Fifth, the results of numerical optimizations can be easily displayed using GIS software, with different decisions for each area represented in different colours, and histograms can be overlaid on the display to communicate changes in economic, social, or environmental indicators in each area.

The Case Study

To meaningfully apply the optimization model for IUP that I described in Sect. 2, I chose Algeria's Reghaïa and Heraoua municipalities, in the Province of Alger (Fig. 1). These municipalities include Reghaïa Lake and Boumerd beach: the lake is a Ramsar Convention site, with an internationally acknowledged environmental value, and it is currently used to supply irrigation water, mainly to Reghaïa municipality. However, it could potentially become a stimulus for tourism development, mainly for Heraoua municipality. In addition, the Kadous beach is near the Ile Aguéli marine protected area; thus, it has environmental value, but could be further exploited by both municipalities to change from short-trip tourism to residential tourism. Heraoua is a good example of an agriculture-driven economy, whereas Reghaïa is a good example of an industry-driven economy.

Both municipalities have been included in several previous research projects (e.g., the Algerian Coast Management Through Integration and Sustainability study, within

Fig. 1 The province (Willaya) of Alger and the municipalities (Communes) of Reghaïa (*grey*) and Heraoua (*black*). Scale: 1:1 000 000

the Short and Medium Term Action Plan supported by the European Union; the Programme d'Amenagement Cotier (PAC), within the Plan Bleu supported by the United Nations). Thus, considerable information is available, often at the municipality level but sometimes at a provincial or regional level.

Although I chose to carry out my analysis in this case study at the municipality level, the use of a continuous control variable (i.e., the percentages of various land uses) allows the consideration of a larger scale by specifying the relative importance of economic activities or environmental functions in each area. Moreover, the chosen area does not make it possible to focus on fishery activities, because there is currently no aquaculture near the coast and there is no significant river that must be included in the analysis. Finally, I chose to apply the model to a developing country, where future land uses are still being decided. However, by obtaining data on past decisions and present conditions, a developed country could also have been analysed to identify areas where a restructuring process should take place.

Estimation of the Model's Parameters

In this section, I estimate the parameters of the model developed in the second section using data for Reghaïa and Heraoua at the municipal ("Commune" in Algeria) level, where possible, and at the provincial (Willaja) or regional (PAC) level where insufficient detailed data was available. The differences between the two economies (industry-oriented for Reghaïa and agriculture-oriented for Heraoua) suggested that it would be most useful to perform separate sectoral calculations for the two municipalities, followed by calculating an average for each sectoral indicator and standardizing all indicators to provide a value per km^2.

PAC (2004a) specifies the amount of water used and paid for by the industrial, service, and urban sectors in both municipalities: 28 044, 127 688, and 899 972 m^3, respectively, for Reghaïa, and 454, 38 213, and 183 284 m^3, respectively, for Heraoua. It also provides estimates of the leakage rate (50%) and the proportion of the homes supplied by the public water network in Reghaïa (54.7%) and Heraoua (62%). This made it possible to calculate the amount of surface water used in sectors other than agriculture. I then assumed that the remaining amount of water required by the urban and service sectors was obtained from groundwater with no leakage, whereas industrial groundwater use for both Reghaïa and Heraoua was 6×10^6 m^3, as suggested by PAC (2006). In addition, PAC (2005a) provided data on the agricultural patterns in Reghaïa and Heraoua, as well as the average agricultural water use (4000 m^3/ha). Combined with information about land-use patterns, this let me calculate the amount of surface water used by agriculture based on a regional ratio of 1:3 for surface to groundwater use, as suggested by PAC (2006), for Reghaïa, and based on a 3:1 ratio for Heraoua, as suggested by a local hydrological analysis (Table 2).

PAC (2005b) validates this approach and the assumptions, because its assessment of water uses for Reghaïa and Heraoua municipalities in sectors other than agriculture are consistent with the water use values obtained by the abovementioned approach: the total water use was reported as around 14×10^6, which is similar to the value of 13 427 284 (Table 2). For the sake of simplicity, I assumed that water use by the tourism sector equalled that by the urban sector.

PAC (2004a) specifies the total annual discharge of BOD and COD for the industrial sector of Reghaïa: 11 687 and 9740 t, respectively. This made it possible to calculate the wastewater discharge for the industrial sector, by applying the water uses calculated above. Moreover, PAC (2004b) identifies the discharge per inhabitant per day of BOD and COD (50 and 60 g, respectively), the total amount of solid waste per inhabitant per year (474 and 442 kg, respectively, for Reghaïa and Heraoua), and the percentage of solid waste not collected (10 and 46%, respectively, for Reghaïa and Heraoua). Combined with data on the average population density (4000 inhabitants per km^2) at a regional level reported in PAC (2006), this made it possible to calculate the wastewater and solid discharge for the urban sector. Finally, I based the water pollution coefficients for the agricultural sector on information about livestock farms in Reghaïa and Heraoua (with 1% of the total discharge assumed to be wastewater from dairy farms), and assumed that the solid pollution coefficients for agriculture and industry were 1/10th and 10 times those of the urban sector, respectively (Table 3).

Note that industrial pollution depends heavily on the industrial pattern, and the main industrial activity in Reghaïa is a smelter (3.117 km^2). Because no information was available for the tiny amount of industrial activity in Heraoua (0.077 km^2), I used the same pollution coefficient for both municipalities. For simplicity, I assumed that water pollution by the tourism sector equalled that produced by the urban sector.

Next, I calculated the maximum annual sustainable pollution discharges into the aquifer, lake, and sea water using data on the total BOD and COD discharged at a regional level (88.377 and 106.050 t, respectively) based on PAC (2004a), and rescaled them for the Reghaïa and Heraoua municipalities using the proportion of the regional population living in the two municipalities. This led to an estimated 1.747 and 2.096 t of BOD and COD, respectively, for both municipalities combined. I then combined

Table 2 Surface and groundwater use by the agricultural, industrial, service, and urbanization sectors of Reghaïa and Heraoua municipalities

	Annual water consumption					
	Total (m^3)			Value per unit area (m^3/km^2)		
	Reghaïa	Heraoua	Total	Reghaïa	Heraoua	Average
Surface water						
Agriculture	4 104 621	838 662	4 943 284	300 000	100 000	200 000
Industrial	102 537	1 465	104 002	32 903	18 939	25 921
Service	466 793	123 268	590 061			
Urban	3 290 574	591 239	3 881 813	541 851	230 687	386 269
Total surface water	7 964 526	1 554 633	9 519 159			
Groundwater						
Agriculture	1 368 207	2 515 987	3 884 194	100 000	300 000	200 000
Industrial	61 907	1 195	6 000 000	19 865	15 450	1 878 686
Service	281 828	100 561	382 388			
Urban	1 986 693	482 326	2 469 019	327 144	188 192	257 668
Total groundwater	3 698 635	3 100 068	12 735 602			

Table 3 Pollution coefficients for the agricultural, industrial, service, and urbanization sectors of Reghaïa and Heraoua municipalities

	Annual coefficient (t/km^2)		
	BOD	COD	Solids
Agricultural	2.065	9.995	50.1
Industrial	3.050	3.659	5010
Service	73.000	87.600	501
Urban	73.000	87.600	501

these figures with data on total water use (both surface water and groundwater) and water discharge (into aquifer, lake, and sea water) at a municipal level, and compared them with the *average* water quality indicators specified in PAC (2004a): 10 and 40 mg/l for BOD and COD, respectively, with 5 and 20 mg/l as *threshold* values for good water quality (Table 4).

Note that 100% of agricultural, 20% of urban, and 0% of industrial pollution is likely to be discharged into the aquifer water, whereas 0% of agricultural, 80% of urban, and 100% of industrial pollution is likely to be discharged into the lake water. Only activities based near the coast are likely to discharge wastes directly into the sea. For simplicity, I assumed that 20% of the pollution discharge affected aquifers, whereas 80 and 20% of the remaining 80% were discharged into the lake and the sea water, respectively. I assumed that the costs for treatment of water pollution and management of solid pollution were 0.634 €/m^3 respectively, as suggested by PAC (2004c).

I used the sectoral GDP percentages (12, 47, and 41%, respectively, for agriculture, industry, and services) and the per-capita income (99 098 Algerian Dinar = 1040 €) in 1998 at a national level (DGE 2001) to calculate the contribution of agriculture, industry, and services to the average income of each Algerian citizen. I then multiplied these figures by the populations of Reghaïa and Heraoua (66 215 and 18 167) in 1998 to calculate the sectoral GDP levels in these two municipalities based on the assumption that their economic structures were similar to the Algerian average. However, this assumption is not correct, since Reghaïa is a highly industrial municipality, whereas Heraoua is a highly agricultural municipality: agriculture and industry cover 58 and 13% of Reghaïa's total area, respectively, versus 75 and 1% in Heraoua. Thus, I used the *average* sectoral GDP per km^2 in both municipalities, in order to estimate the economic value of *old* and *new* activities: 437, 62 613, and 24 481 €/km^2 for agriculture, industry, and services, respectively, with the service activities assumed to account for 20% of the urban area. Because I was interested in tourism rather than services as a whole, and because no information was available for Reghaïa and the single hotel in Heraoua collapsed during the 2003 earthquake, I therefore assumed that the GDP per km^2 for tourism equalled the GDP for services.

Table 4 Maximum sustainable change in pollution loads in aquifers, lakes, and sea water

	Maximum annual sustainable change in pollutant load (t)	
	BOD	COD
Aquifer	30.043	121.153
Lake	96.139	387.689
Sea	24.034	96.922

Moreover, I applied the economically active population rate (80%), the sectoral employment percentages (17, 18, 18, and 14% for agriculture, industry, services, and urban (residential) construction, respectively), and the employment rate (80%) in 1998 at the national level (DGE 2001) to the populations of Reghaïa and Heraoua to obtain the employment structure if the economic structure in both municipalities was the same as the Algerian average. Since this is not the case, I calculated the sectoral employment per km^2 in both Reghaïa and Heraoua, and then calculated the mean, in order to estimate the employment level arising from *old* and *new* activities: 97, 3 648, 338, and 40 employees per km^2 in the agriculture, industry, service, and urban (residential) construction sectors, respectively, with all buildings assumed to be constructed by local firms and assumed to require renovation every 5 years.

Finally, I used the average number of people per house (6) and the average number of houses per km^2 (4000) from PAC (2004b), and assumed that 20% of per-capita income was related to house expenditures, to obtain the average value of the urbanised area: 4 992 000 €/km^2 (Table 5).

To determine current land uses, I used Google Earth data from 2004 to determine the areas devoted to agriculture and industry, as well as the areas covered by housing development, beaches, and natural vegetation (Fig. 2).

To define the potential land uses, I used PAC (2005a). This report specifies the dune area (1 km^2, approximately evenly divided between Reghaïa and Heraoua municipalities), the location and size of the areas suitable for tourism development (1.04 km^2 on the western side of the lake), and the size of the protected marine area (8.630 km^2, which corresponds to the "environment" activity type). I also submitted a questionnaire to the technical offices of both municipalities to learn their land management perspectives, including those that were not specified in the existing master plans. Finally, I incorporated more realistic predictions for the growth of industry and (illegal) housing development that were not set out in the master plan. This led to the identification of seven key areas to include in the model (Fig. 3): in areas 1 and 3, urban use could replace

Table 5 The economic indicators for Reghaïa and Heraoua municipalities

	GDP (€/km^2)	No. of employees/km^2	Required increase in area (km^2)
Agricultural	437	97	–
Industrial	62,613	3,648	0.551
Service	24,481	460	–
Urban	4,992	40	0.413–1.208

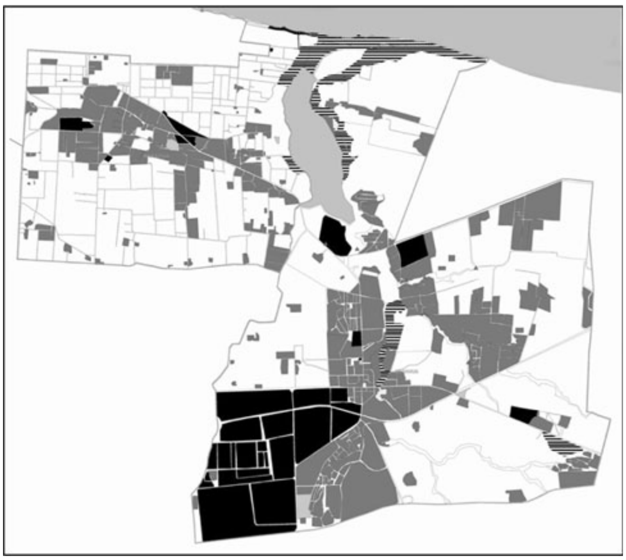

Fig. 2 Land uses in the Reghaïa and Heraoua municipalities in 2004. Legend. Industry (*black*), agriculture (*white*), environment (*horizontal stripes*), urban (housing) development (*grey*). *Source*: Google Earth 2004, and PAC 2005a. Scale: 1:100 000

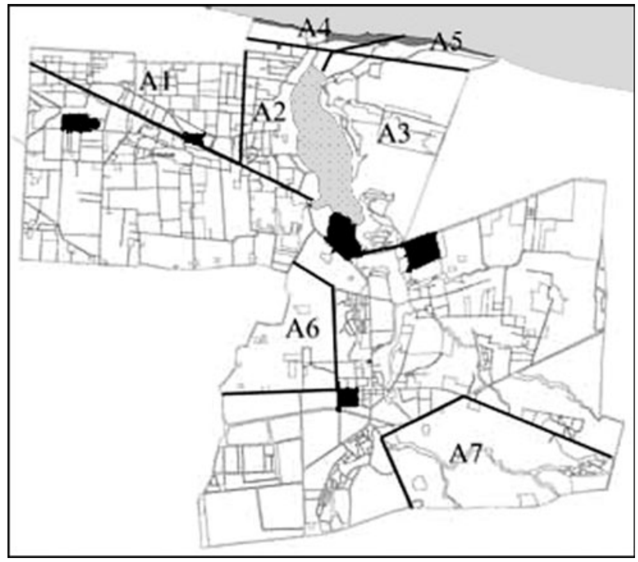

Fig. 3 The seven study areas under consideration in Reghaïa and Heraoua municipalities. Public infrastructure equipment is highlighted in black. Scale: 1:100 000

agricultural use; in area 2, tourism or housing development or environment uses could be developed in the agricultural area; in areas 4 and 5, either tourism or environment could be developed; and in areas 6 and 7, industry or housing development could be developed in the agricultural area. The following sizes of the seven study areas were used: $A_1 = 1.04$ km^2, $A_2 = 1.04$ km^2, $A_3 = 2.08$ km^2, $A_4 = 0.52$ km^2, $A_5 = 0.52$ km^2, $A_6 = 2.08$ km^2, $A_7 = 2.08$ km^2.

To describe the economic dynamics of the municipalities, I applied the 1% yearly industrial growth rate suggested by PAC (2005c) to the industrial area in 2005 in order to estimate the additional industrial area required in 2020 (0.551 km^2, equivalent to 17% of the current area). To describe the social dynamics, I used the populations of Reghaïa and Heraoua in 2005 estimated by PAC (2005c) to make the land use observed in 2005 consistent with the population level recorded in 1998. I then applied the maximum and minimum estimated population increases in 2020 in PAC (2004b) to these figures, together with the average number of people per house (6) and the average number of houses per km^2 (4000), to obtain the required maximum and minimum additional urban area required in 2020: 1.208 and 0.413 km^2, respectively (i.e., 14 and 5% of the current area; Table 5).

Table 6 summarizes the values of the parameters and state variables. Five observations are worth making here. First, PAC (2005c) estimated the coastal loss rate as ranging from 0.45 m/year (presumably without sand extraction) to 1.9 m/year (presumably with sand extraction), leading to an estimated beach loss of 6.75–28.5 m by 2020, and, consequently, to an estimated beach extent of 11.50 up to 43.25 m by 2020. For the sake of simplicity, I assumed that tourism would not be affected by this coastal loss, and subsequent analysis revealed that this assumption was not relevant. Second, I assumed that it would take 5 years to establish industry and tourism activities, 2 years to construct new urban areas, and 1 year to develop an environmental protection area, with a 5% interest rate applied to discount the economic value difference. Third, the master plan that will promote housing development away from coastal areas, PAC (2005c), has not been taken into account here in order to avoid a requirement for other areas to bear the population pressure of the two expanding municipalities. Fourth, I did not distinguish between the rural and urban populations, and did not apply different expected growth rates to these two populations. Similarly, I did not differentiate the relationship between water use by the different sectors (from alternative sources) and pollution discharge by the different sectors (to alternative sites) for each part of the study area. Fifth, the procedures and assumptions I applied suggest that it is possible to calibrate

Table 6 The set of values for parameters and state variables used in the analysis of Reghaïa and Heraoua municipalities

	Value per year		Sector					Water		
			Agricultural	Industrial	Service	Urban	Environment	Aquifer	Lake	Sea
v_j	$\times 10^3$ €/km^2		0.437	62.613	24.481	4.992				
$p_{k,j}$	t/km^2	BOD	2.065	3.050	73.000	73.000				
	t/km^2	COD	9.995	3.659	87.600	87.600				
	t/km^2	Solid	50.1	5010	501	501				
Max $P_{k,s}$–$P_{k,s}(t)$	t	BOD						30.043	96.139	24.034
	t	COD						121.153	387.689	96.922
e_j	no./km^2		97	3648	460	40	10			
w_j	$\times 10^6$ m^3/km^2	Surface water	0.2	0.025	0.386	0.386				
	$\times 10^6$ m^3/km^2	Ground water	0.2	1.878	0.257	0.257				
T_j	years		2	5	5	2	1			
Min ΔA_j	km^2	Low		0.551		0.413				
	km^2	High				1.208				

Total Max $\Delta W = 3.184 \times 10^6$ m^3 for ground water; Total Max $\Delta W = 2.379 \times 10^6$ m^3 for surface water; Average $c_k = 0.634$ €/t for BOD, COD, and solid urban waste

the IUP model using regional data even when local data are not available, although more detailed local information would improve its reliability. However, the most tentative parameters were the GDP values attached to the economic activities (i.e., these parameters could be considered stochastic variables with known (regional) means but estimated (unknown) variances), and the model carries out differences between variables with a positive covariance (i.e., an increase in variability of GDP compared with the regional mean in one sector is likely to be associated with an increase in other sectors).

Consider the following example of how the model can be implemented if data at the municipality level are not available. Here, I have assumed that the total value of agricultural GDP is available at the provincial level, but must be applied at the municipal level along with the other municipal land uses.

The solution I adopted was to use the average value (i.e., the province-level agricultural GDP divided by the province-level agricultural land use to provide agricultural GDP per km^2), to assume a normal distribution for the province-level agricultural GDP, and to estimate the relationship between the significance of the optimization results and the variance (σ^2) of the agricultural GDP at the province level, because the model compares average GDP values (μ) and because the normal distribution is defined by two parameters (μ and σ).

An alternative solution (currently being applied in my subsequent research) could have been to specify alternative statistical distributions for a known total province-level agricultural GDP (for example, an exponential or chi square distribution, defined by the parameters λ and ρ, respectively). In this approach, I will perform a series of numerical simulations under the constraint of the total by applying algorithmic inference (Apolloni and others 2006) to obtain an empirical cumulative distribution function and will identify the specific distribution by choosing λ and ρ of the distribution with the highest probability to be observed. I will then estimate the variance of the distribution ($1/\lambda^2$ and 2 ρ, respectively) to perform statistical tests of significance for the results. Additional information could be introduced, such as the minimum and maximum values for the statistical distribution (e.g., agricultural GDP per km^2 is never below 200 € and never above 600 €) or specific correction factors for agricultural GDP per km^2 (e.g., a 20% higher value in the study municipality than elsewhere in the province). Note that this data down-scaling process would make the model stochastic.

Results

The goal of the model was to maximise the weighted economic value obtained by changing the current land uses, constrained by the potential land uses. This analysis accounted for the economic dynamics (industry growth until 2020) and social dynamics (population growth until 2020), as well as social constraints (employment maintenance) and environmental constraints (surface and groundwater sustainability; pollution sustainability in the lake and sea water). Thus, it can suggest land uses based on the value attached to the environment, with these values potentially equalling the GDP values for the agricultural, urban, tourism, and industrial sectors.

To highlight the potential of the model for the case study in the third section, I performed four main groups of numerical optimizations: Later, I test the sensitivity of the results to alternative values for the clean environment; I assess the impact of policies that affect water quantity; I estimate the impact of policies that affect water quality; I estimate the impact of combining policies that affect water quantity and quality.

PAC (2004a) notes that it is difficult to evaluate the potential groundwater in Reghaïa and Heraoua, although it could be reasonably assumed that the aquifer is currently being exploited at almost its maximum level. On this basis, I assumed that an additional 25% of groundwater is available for future uses. For simplicity, I evaluated the potential surface water similarly, although this assumption will turn out to not affect the simulation results. Finally, I used a continuous control variable: the proportions of the land uses for the seven areas totalled 1 so that the land uses could be interpreted as percentages.

Optimal Land Uses in Alternative Scenarios Without Water Policies

Table 7 presents the optimal land uses in an average year without any water policies implemented, and Fig. 4 displays the optimal land use in each of the seven study areas if the value attached to the environment equals the industrial GDP. Seven main points are worth highlighting:

- The available groundwater is always exploited to its maximum level, whereas the surface water is redundant: this is because of the larger groundwater use coefficient for the industrial sector than for the agricultural sector, together with the conversion of several areas originally devoted to agriculture into industrial areas.
- The additional pollution caused by this change never reaches its maximum annual sustainable level, although BOD discharged into the aquifer and the sea should be controlled.
- The housing development reaches its maximum level (1.208 km^2), whereas the industrial area ranges between 2 and 4 times the minimum required (0.551 km^2).
- Tourism activity is never suggested; environmental preservation is suggested instead.
- Agriculture and industry show opposite (although non-linear) changes due to the larger economic value coefficient for the industrial sector, together with the absence of assumptions about the minimum required area of agricultural activities.
- Employment preservation does not represent a constraint, since employment increases in all scenarios.
- The additional economic value is significant, and it increases non-linearly with increasing value attached to the environment.

The second section emphasised the long-run perspective of an IUP optimization model: planning land use is a long-term decision-making process. Thus, I performed a sensitivity analysis of alternative scenarios. In particular, DGE (2001) provided data on precipitation in dry and very dry years, which amount to 74 and 63%, respectively, of the level in average years. The resulting decrease in total surface water and groundwater suggest that, based on the numerical optimizations presented above, a groundwater shortage in dry years will hamper industrial development. Moreover, DGE (2001) predicted the reduction of surface water that would result from climate change (ranging from 15 to 30%), but this impact seems to be insignificant because of the high reliance on aquifer water. Finally, PAC (2005c) predicted potential coastal losses (i.e., beach area extent from 43.25 to 11.50 m). The numerical optimizations suggested that the development of tourism would not be prevented by coastal loss.

Optimal Land Uses in an Average Year With Water Quantity Policies

Three main policies that affect the quantity of water have been suggested by PAC (2004a): a 20% water saving in agriculture due to the introduction of innovative irrigation techniques; a 20% increase in domestic water consumption permitted by the use of desalination facilities; and a 20% water saving in industry arising from the re-use of treated wastewater. Table 8 presents the results of the numerical optimizations for all of these policies combined, and Fig. 5 displays the optimal land use in each of the seven study areas if the environment is evaluated as the tourism sector.

Three main differences compared with the results with no water policies are revealed by this analysis. The suggested industry area is almost four times the original value as a result of the water quantity policies, although it decreases with increasing value attached to the environment. Pollution indicators were also slightly lower everywhere than in the situation with no water policies. Tourism appears as a marginal activity (i.e., only around the lake), and is only optimal if the value attached to the environment is sufficiently low (i.e., as the agricultural sector).

Optimal Land Uses in an Average Year With Water Quality Policies

I assumed a single main water quality policy for Reghaïa and Heraoua: an 80% treatment rate for water discharged into the lake (versus the current level of 15%). Table 9

Table 7 Optimal land uses in an average year for Reghaïa and Heraoua municipalities without water policies

Environment values[a]	Agricultural (agr)	Urban (urb)	Tourism (tou)	Industrial (ind)
A_1				
agr	0.957	0.823	0.545	0.948
urb	0.042	0.175	0.454	0.050
A_2				
agr	0.002	0	0	0
urb	0	0	0	0
tou	0.009	0	0	0
env	0.988	1	1	1
A_3				
agr	1	1	1	1
urb	0	0	0	0
A_4				
tou	0	0	0	0
env	1	1	1	1
A_5				
tou	0	0	0	0
env	1	1	1	1
A_6				
agr	0.134	0.362	0.823	0.271
ind	0.414	0.357	0.145	0.381
urb	0.451	0.279	0.030	0.346
A_7				
agr	0.834	0.352	0.027	0.690
ind	0.057	0.434	0.650	0.101
urb	0.108	0.213	0.322	0.208
ΔGDP ($\times 10^3$ €)	36	82	102	99
Δemployment (no.)	3462	5843	5869	3538
Δurban land use (km^2)	1.208	1.208	1.208	1.208
Δindustrial land use (km^2)	0.982	1.647	1.655	1.005
Δgroundwater use ($\times 10^6$ m^3)	1.314	2.561	2.574	1.353
Δsurface water use ($\times 10^6$ m^3)	−0.350	−0.337	−0.336	−0.353
Δsolid pollution (t)	5319	8613	8649	5425
ΔBOD aquifer (t)	17	17	17	17
ΔCOD aquifer (t)	14	13	13	13
ΔBOD lake (t)	46	46	46	46
ΔCOD lake (t)	37	34	34	36
ΔBOD sea (t)	14	14	14	14
ΔCOD sea (t)	11	10	10	11
Maximum variance of sectoral values[b]				
$\rho = 0.30$	0.345	0.290	0.274	0.342
$\rho = 0.60$	0.603	0.508	0.480	0.598
$\rho = 0.90$	2.412	2.030	1.919	2.391

env environment

[a] Agricultural, housing development, tourism, and industrial economic values were set to 0.437, 4.992, 24.481, and 62.613 thousand €, respectively. Numerical optimizations presented in the column labelled "Agricultural" were obtained by using 0.437 (the agriculture economic value) as the value of the clean environment; a similar approach was used for the other columns

[b] Maximum variance of normally distributed sectoral values (GDP per km^2 for relevant activities) to have a 90% significance of optimization outcomes based on the covariance (ρ) between them: a maximum variance smaller than 1 means a more condensed distribution than the standardised normal distribution

Table 8 Optimal land uses in Reghaïa and Heraoua municipalities in an average year with water quantity policies implemented

Environment values[a]	Agricultural (agr)	Urban (urb)	Tourism (tou)	Industrial (ind)
A_1				
agr	0.788	0.804	0.994	0.997
urb	0.211	0.195	0.005	0.002
A_2				
agr	0	0	0	0
urb	0	0	0	0
tou	0.052	0	0	0
env	0.947	1	1	1
A_3				
agr	0.677	0.672	0.672	0.672
urb	0.322	0.327	0.327	0.327
A_4				
tou	0.036	0.004	0	0
env	0.963	0.995	1	1
A_5				
tou	0.005	0.002	0	0
env	0.994	0.997	1	1
A_6				
agr	0	0	0	0
ind	0.847	0.844	0.749	0.999
urb	0.152	0.155	0.250	0
A_7				
agr	0	0	0	0
ind	1	1	1	0.748
urb	0	0	0	0.251
ΔGDP ($\times 10^3$ €)	179	183	190	228
Δemployment (no.)	13752	13700	12992	12981
Δurban land use (km^2)	1.208	1.208	1.208	1.208
Δindustrial land use (km^2)	3.842	3.837	3.640	3.638
Δgroundwater use ($\times 10^6$ m^3)	6.169	6.137	5.766	5.760
Δsurface water use ($\times 10^6$ m^3)	−0.786	−0.817	−0.824	-0.824
Δsolid pollution (t)	19540	19476	18498	18482
ΔBOD aquifer (t)	19	18	17	17
ΔCOD aquifer (t)	11	10	10	10
ΔBOD lake (t)	51	48	47	47
ΔCOD lake (t)	30	27	27	27
ΔBOD sea (t)	15	14	14	14
ΔCOD sea (t)	9	8	8	8
Maximum variance of sectoral values[b]				
$\rho = 0.30$	0.200	0.202	0.214	0.214
$\rho = 0.60$	0.349	0.354	0.375	0.375
$\rho = 0.90$	1.397	1.416	1.500	1.501

env environment

[a] Agricultural, housing development, tourism, and industrial economic values were set to 0.437, 4.992, 24.481, and 62.613 thousand €, respectively. Numerical optimizations presented in the column labelled “Agricultural” were obtained by using 0.437 (the agriculture economic value) as the value of the clean environment; a similar approach was used for the other columns

[b] Maximum variance of normally distributed sectoral values (GDP per km^2 for relevant activities) to have a 90% significance of optimization outcomes based on the covariance (ρ) between them: a maximum variance smaller than 1 means a more condensed distribution than the standardised normal distribution

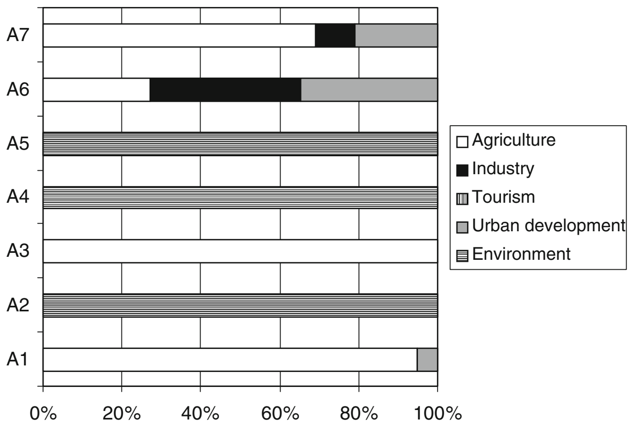

Fig. 4 Optimal land uses in an average year for Reghaïa and Heraoua municipalities without water policies if the value of a clean environment is evaluated based on the industrial sector data (i.e., using the numerical optimizations presented in the column labelled "Industrial" in Table 7). Environment is always suggested in A_5, whereas at least 25% of A_6 devoted to housing development seems to be optimal, provided no water policies are implemented

presents the numerical optimizations depicting this policy, and Fig. 6 displays the optimal land use in each of the seven study areas if the environment is evaluated as the housing development sector.

The simulations revealed two main differences compared with the situation with no water policies. The suggested industry area almost doubled as a result of the water quality policies if the value attached to the environment is very small (i.e., as the agricultural sector). The pollution indicators were also slightly lower in the aquifer and sea water, for which the treatment rate has not changed.

Optimal Land Uses in an Average Year with Both Water Quantity and Water Quality Policies

Table 10 presents the results of numerical optimizations that combine the water quantity and quality policies discussed in the two previous sub-sections. Figure 7 displays the optimal land use in each of the seven study areas if the value attached to the environment equals the agricultural GDP.

The simulations revealed three main differences compared with the results of the simulation with no water policies. The suggested industry area is almost seven times larger, although it decreases with increasing value attached to the environment. The pollution indicators were also slightly lower in all water sources. Tourism appears as a relevant activity both around the lake and along the coast if the value attached to the environment is sufficiently low (i.e., as the agricultural sector).

Discussion

The results of the case study of two Algerian municipalities provided the following insights that can guide future IUP decisions in this area:

- Determining the optimal land use makes it possible to increase total GDP, even after accounting for economic and social dynamics and the social and environmental constraints.
- Based on the estimated increase in total GDP in the various scenarios, policies based on water quantity appear to be more urgent than policies based on water quality.
- The combination of the water quality and water quantity policies makes it possible to achieve sustainability of the optimal land use even in dry and very dry years, when groundwater shortages would arise. Because of the heavy reliance of industry on aquifer water, changes in surface water appear to be irrelevant for industrial development.
- The industrial sector is held back by its reliance on groundwater rather than by its environmental impacts. In addition, the urban (housing) development sector should be developed to meet the demands of the social dynamics, the agriculture sector appears to be residual, and the tourism sector should be developed, provided that both water quantity and water quality policies are carefully implemented.
- Greater attention should be paid to the amount of BOD discharged into aquifer and sea water, whereas COD discharge is a less pressing issue.

The results of the analysis of various scenarios revealed the following observations about past land-use decisions:

- The master plan's suggestion that no housing development should occur in A_1 seems to be optimal if the value attached to the environment is sufficiently large (i.e. as the industrial sector).
- Housing development is never suggested in A_2, which is consistent with the master plan.
- The master plan's suggestion that 20% of A_3 should be devoted to housing development seems to be optimal if the water quantity policies are implemented.
- The tourism development in A_4 prescribed by the master plan can be supported if both the water quantity and water quality policies are implemented.
- Environment is always the suggested use in A_5, which is consistent with the master plan.
- The master plan's suggestion that at least 25% of A_6 should be devoted to housing development seems to be optimal if no water policies are implemented.

Table 9 Optimal land uses in Reghaïa and Heraoua municipalities in an average year with water quality policies

Environment values[a]	Agricultural (agr)	Urban (urb)	Tourism (tou)	Industrial (ind)
A_1				
agr	0.791	0.875	0.588	0.844
urb	0.207	0.123	0.410	0.154
A_2				
agr	0	0.2160	0	0
urb	0	0	0	0
tou	0	0	0	0
env	1	0.783	1	1
A_3				
agr	1	1	1	1
urb	0	0	0	0
A_4				
tou	0	0	0	0
env	1	1	1	1
A_5				
tou	0	0	0	0
env	1	1	1	1
A_6				
agr	0.359	0.169	0.634	0.241
ind	0.519	0.611	0.286	0.499
urb	0.120	0.219	0.078	0.259
A_7				
agr	0.294	0.428	0.123	0.503
ind	0.348	0.271	0.579	0.251
urb	0.356	0.299	0.297	0.244
ΔGDP ($\times 10^3$ €)	87	92	111	134
Δemployment (no.)	6417	6524	6403	5541
Δurban land use (km^2)	1.208	1.208	1.208	1.208
Δindustrial land use (km^2)	1.807	1.837	1.802	1.563
Δgroundwater use ($\times 10^6$ m^3)	2.862	2.918	2.854	2.403
Δsurface water use ($\times 10^6$ m^3)	−0.332	−0.332	−0.333	−0.339
Δsolid pollution (t)	9407	9556	9386	8195
ΔBOD aquifer (t)	17	17	17	17
ΔCOD aquifer (t)	12	12	12	13
ΔBOD lake (t)	11	11	11	11
ΔCOD lake (t)	9	8	9	10
ΔBOD sea (t)	14	14	14	14
ΔCOD sea (t)	10	10	10	10
Maximum variance of sectoral values[b]				
$\rho = 0.30$	0.279	0.309	0.269	0.296
$\rho = 0.60$	0.489	0.541	0.471	0.518
$\rho = 0.90$	1.956	2.163	1.883	2.073

env environment

[a] Agricultural, housing development, tourism, and industrial economic values were set to 0.437, 4.992, 24.481, and 62.613 thousand €, respectively. Numerical optimizations presented in the column labelled "Agricultural" were obtained by using 0.437 (the agriculture economic value) as the value of the clean environment; a similar approach was used for the other columns

[b] Maximum variance of normally distributed sectoral values (GDP per km^2 for relevant activities) to have a 90% significance of optimization outcomes based on the covariance (ρ) between them: a maximum variance smaller than 1 means a more condensed distribution than the standardised normal distribution

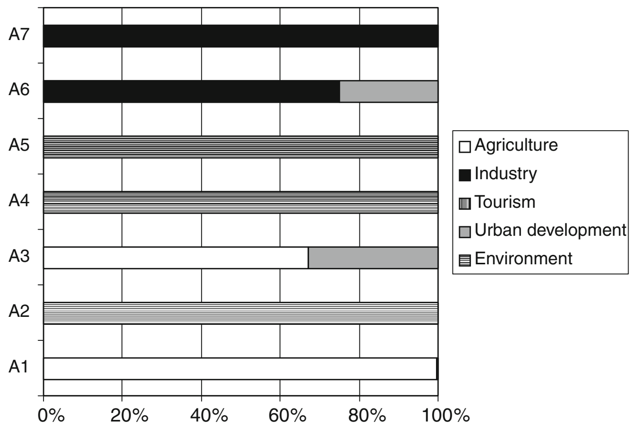

Fig. 5 Optimal land uses in an average year for Reghaïa and Heraoua municipalities with water quantity policies if the value of a clean environment is evaluated based on the tourism sector data (i.e., using the numerical optimizations presented in the column labelled "Tourism" in Table 8). No housing development in A_1 and 20% of A_3 devoted to housing development seem to be optimal, provided water quantity policies are implemented

- The master plan's suggestion that at least 20% of A_7 should be devoted to housing development can be optimal if no water quantity policies are implemented.

The main *strengths* of the approach implemented in this paper can be summarised as follows. It does not assume that concern for the environment is attached to specific stakeholders such as environmentalists (as in the study by Gabriel and others 2006), and it does not rely on revealed- or stated-preference methods to attach a value to the environment (as in the study by Berling-Wolff and Wu 2004). Instead, it chooses a compromise solution that embodies views that are often diametrically opposing by assuming that stakeholders can agree upon a value attached to the environment.

It includes planning policies in the simulation of future scenarios, as in the studies by Silva and others (2008) and Stevens and others (2007), and it provides rankings of alternative management strategies, as in the studies by Berling-Wolff and Wu (2004), Lin and others (2009), and Prato (2007), by accounting for the consequences of different activity distributions within the available area.

Since potential solutions may be missed when using a weighting method, a single-objective optimization perspective, such as those of Kong and others (2010) and Lin and others (2009), has been preferred to a multi-objective optimization approach, such as those of Gabriel and others (2006), Prato (2007), and Wang and others (2004). This eases the process of determining values by different stakeholders because only a single value must be agreed upon (i.e., a value attached to the environment) rather than a set of relative weights attached to alternative objectives.

Positive and negative feedback loops are identified, unlike in the study by Berling-Wolff and Wu (2004), and non-linear casual links are used, as in the study by Silva and others (2008), by integrating economic and ecological issues, unlike in the study by Stevens and others (2007).

The model developed in the present study is unlike empirical-statistical models (e.g., multiple linear regression or logit regression), in which the probability of future land-use change patterns depends on changes in the driving factors specified in various scenarios (Lin and others 2009), and is unlike simulation models (e.g., stochastic or dynamic process-based models), in which large-scale patterns emerge from local-scale interactions as a result of demand, the suitability of locations for particular uses, and conversion rules (Berling-Wolff and Wu 2004). Instead, the present model predicts land-use dynamics as a function of the objectives and values defined by policy-makers and stakeholders in different scenarios. Policy-makers need a normative tool that determines the optimal land-use configuration in terms of costs and effects (given a set of prior conditions, criteria, and decision variables), but to predict urban dynamics, they also require a positive approach that accounts for high-level constraints imposed by stakeholders, planners, developers, and government agencies, which significantly shape the development landscape. Of course, this assumes that cities are governed by both bottom-up and top-down processes.

It is sensitive to local characteristics and variability in these characteristics because it includes robust theoretical considerations such as those of Kong and others (2010) and Silva and others (2008).

It achieves a compromise between over-stylised (overly general) models and over-detailed models because estimation of the parameters and state variables is based on a relatively short list of data, unlike in the study by Berling-Wolff and Wu (2004). Enough details are used to capture the tradeoffs of stakeholders, yet the model is sufficiently general to be computationally feasible.

The applied sustainable GDP metric includes a spatial component that reflects long-run steady-state conditions, unlike in the studies by Prato (2007) and Kong and others (2010), but uses short planning periods to account for the volatility of urban development.

It includes an environmental component for regional planning in a computable optimization application, unlike in the studies by Prato (2007) and Kattwinkel and others (2009), but like the studies of Wang and others (2004), Gabriel and others (2006), Meyer and others (2009), and Lin and others (2009). It adopts a simultaneous optimization strategy, as in the study by Lin and others (2009), rather than a sequential optimising strategy. The latter is constrained by earlier developmental steps that are unlikely to be optimal for subsequent steps.

Table 10 Optimal land uses in Reghaïa and Heraoua municipalities in an average year with water quantity and quality policies

Environment values[a]	Agricultural (agr)	Urban (urb)	Tourism (tou)	Industrial (ind)
A_1				
agr	0.999	0.899	0.784	0.975
urb	0	0.100	0.215	0.024
A_2				
agr	0	0	0	0
urb	0	0	0	0
tou	0.096	0	0	0
env	0.903	1	1	1
A_3				
agr	1	0.672	0.672	0.672
urb	0	0.327	0.327	0.327
A_4				
tou	0.487	0	0	0
env	0.512	1	1	1
A_5				
tou	0.018	0	0	0
env	0.981	1	1	1
A_6				
agr	0.065	0	0	0
ind	0.735	1	0.854	0.759
urb	0.198	0	0.145	0.240
A_7				
agr	0	0	0	0
ind	1	0.797	1	1
urb	0	0.202	0	0
ΔGDP ($\times 10^3$ €)	165	176	203	229
Δemployment (no.)	13089	13346	13775	13063
Δurban land use (km^2)	0.413	1.208	1.208	1.208
Δindustrial land use (km^2)	3.610	3.738	3.858	3.660
Δgroundwater use ($\times 10^6$ m^3)	5.760	5.952	6.176	5.803
Δsurface water use ($\times 10^6$ m^3)	−0.830	−0.821	−0.818	−0.823
Δsolid pollution (t)	18167	18988	19581	18596
ΔBOD aquifer (t)	11	17	17	17
ΔCOD aquifer (t)	4	10	10	10
ΔBOD lake (t)	8	12	12	12
ΔCOD lake (t)	7	10	10	11
ΔBOD sea (t)	9	14	14	14
ΔCOD sea (t)	3	8	8	8
Maximum variance of sectoral values[b]				
$\rho = 0.30$	0.207	0.208	0.202	0.213
$\rho = 0.60$	0.363	0.365	0.353	0.373
$\rho = 0.90$	1.452	1.458	1.411	1.491

env environment

[a] Agricultural, housing development, tourism, and industrial economic values were set to 0.437, 4.992, 24.481, and 62.613 thousand €, respectively. Numerical optimizations presented in the column labelled "Agricultural" were obtained by using 0.437 (the agriculture economic value) as the value of the clean environment; a similar approach was used for the other columns

[b] Maximum variance of normally distributed sectoral values (GDP per km^2 for relevant activities) to have a 90% significance of optimization outcomes based on the covariance (ρ) between them: a maximum variance smaller than 1 means a more condensed distribution than the standardised normal distribution

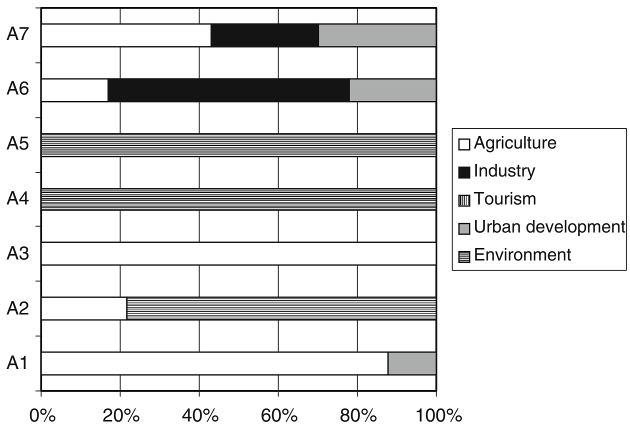

Fig. 6 Optimal land uses in an average year for Reghaïa and Heraoua municipalities with water quality policies if the clean environment is evaluated based on the housing development sector data (i.e., using the numerical optimizations presented in the column labelled "Urban" in Table 9). Environment is always suggested in A_5, whereas at least 20% of A_7 devoted to housing development seems to be optimal, provided no water quantity policies are implemented

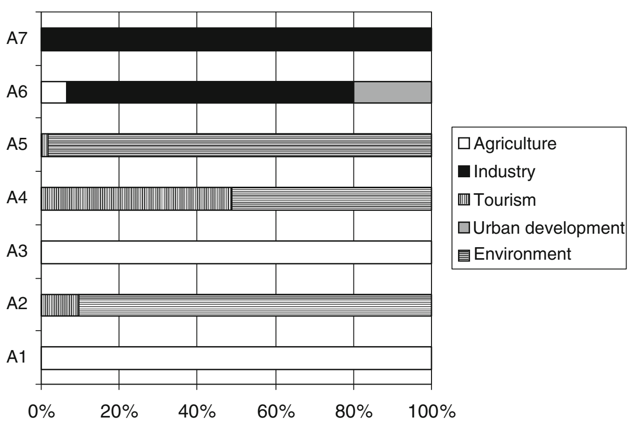

Fig. 7 Optimal land uses in an average year for Reghaïa and Heraoua municipalities with water quantity and quality policies if the clean environment is evaluated based on the agricultural sector data (i.e., using the numerical optimizations presented in the column labelled "Agricultural" in Table 10). Housing development is never suggested in A_2, and the tourism development in A_4 can be supported, provided both quantity and quality water policies are implemented

It applies a holistic and multidisciplinary approach, unlike in the studies by Kattwinkel and others (2009), Lin and others (2009), and Berling-Wolff and Wu (2004), by considering several sectors or segments, as in the studies by Gabriel and others (2006) and Meyer and others (2009). This follows from the belief that understanding the links between socio-economic driving forces, the functioning of the urban system, and its environmental performance, is crucial for the development of sustainable cities.

It is not purely experimental, since it permits a real application, as in the studies by Wang and others (2004), Silva and others (2008), and Lin and others (2009). It can be easily transferred to other case studies.

Its purpose is to generate spatially explicit results that account for specific goals, as in the study by Meyer and others (2009), instead of reproducing a particular landscape, as in the study by Lin and others (2009).

The spatial land-use patterns affect not only ecological and physical processes, as in the study by Lin and others (2009), but also account for potential future socio-economic conditions.

Unlike studies that take advantage of the built-in visualisation, spatial data handling, user interface, database querying, and geo-processing operations provided by GIS software (e.g., Stevens and others 2007), the present study suggests that after optimization is completed, an urban planner could generate visual output that describes the effects of various environmental and urban policies, and could quantify the economic, social, and environmental impacts that occur in each area.

The main *weaknesses* of the approach implemented in this paper can be summarised as follows. Energy demands are disregarded, unlike in the study by Pauleit and Duhme (2000), but could be easily introduced into the model. The model has a rigid structure, although some degree of rigidity is unavoidable for any model that must be tailored to local conditions. It disregards indirect environmental and economic impacts, but the availability of better data might make it possible to incorporate an input–output model. It lacks an easy computer interface that would let it form the basis of an urban planning spatial decision-support system, which was suggested but not implemented by Stevens and others (2007). However, I plan to develop this application in my future research. It is deterministic, even though a confidence analysis is performed. Few land-use types are included, although the economic values of additional types could be properly estimated with more available data. Alternative rational targets could be chosen for sustainable urban development, such as reducing urban traffic or improving air quality, as in the study by Borrego and others (2006), or such as optimising house heating or water supply or sewage disposal. Nonetheless, the sustainable GDP metric seems to meet all the *theoretical* (reliable, holistic, objective, transparent, scientific, consistent) and *practical* (salient, aggregated, self-referent) criteria that have been suggested in the literature.

Conclusions

Although it is difficult to fit location models (i.e., mathematical models for representing and solving spatial planning problems) into a particular category (Murray 2010), one could summarise the main features of the spatial model presented in the present paper by noting that it is a discrete allocation model (i.e., it says which activity should be undertaken in each area). In addition, it is deterministic in structure, but accounts for uncertainty in the parameter data using mean parameter values and estimates the statistical significance of the results based on the distribution of parameter values. Although the model refers to only two periods, it is dynamic because it reflects a change between two periods, and it could be implemented recursively to cover more periods. In addition, the model can account for multiple public and private sectors (e.g., the environment, agriculture, industry, tourism, housing development), and can provide an exact optimization solution in terms of a single objective. Here, that objective was to increase the overall weighted GDP for the study areas, with weights representing the sustainability and the implementability of various land uses.

In other words, the results of the case study emphasized that the optimization model for IUP that I developed in this paper has the *main* required theoretical and practical features described in the literature. However, UN-Habitat (2009b) provided normative principles against which all planning systems should be assessed, in recognition of the fact that no single model or approach to planning can be applied everywhere:

- to recognise and to respond to current and impending needs for protection of environmental and natural resources, and to account for the ecological consequences of any urban project;
- to recognise and promote social justice;
- to be participatory (i.e., driven by stakeholders or the community rather than solely by experts), and to facilitate and encourage open and ongoing public dialogue between various partners or groupings on planning processes and outcomes;
- to recognise and respond to cultural, socio-economic, and spatial diversity;
- to be flexible rather than end-state-oriented and fixed, with the outcomes being highly diverse and dependent upon stakeholder preferences or local policy directions;
- to be linked to budgetary and decision-making systems; and
- to be strategic (i.e., focused on those aspects or areas that are important to overall plan objectives).

Therefore, the present optimization model for an IUP seems to be a significant step forward in meeting the characteristics recommended by UN-Habitat (2009b).

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