JOURNAL OF THE AMERICAN WATER RESOURCES ASSOCIATION
AUGUST AMERICAN WATER RESOURCES ASSOCIATION 2003

A FRAMEWORK FOR QUANTITATIVE SMART GROWTH IN LAND DEVELOPMENT[1]

Glenn E. Moglen, Steven A. Gabriel, and Jose A. Faria[2]

ABSTRACT: Increasing awareness about the problems brought on by urban sprawl has led to proactive measures to guide future development. Such efforts have largely been grouped under the term "Smart Growth." Although not widely recognized as such, the "smart" in Smart Growth implies an optimization of some quantity or objective while undertaking new forms of urban development. In this study, we define Smart Growth as that development plan that leads to the optimal value of a precisely defined measure identified by a stakeholder or stakeholders. To illustrate a formal, quantitative framework for Smart Growth, this study develops definitions of optimal development from the perspectives of four different types of stakeholders: a government planner, a land developer, a hydrologist, and a conservationist subject to certain development constraints. Four different objective functions are posed that are consistent with each of these stakeholders' perspectives. We illustrate the differences in consequences on future development given these different objective functions in a stylized representation for Montgomery County, Maryland. Solutions to Smart Growth from the individual perspectives vary considerably. Tradeoff tables are presented that illustrate the consequences experienced by each stakeholder depending on the viewpoint that has been optimized. Although couched in the context of an illustrative example, this study emphasizes the need to apply rigorous, quantitative tools in a meaningful framework to address Smart Growth. The result is a tool that a range of parties can use to plan future development in ways that are environmentally and fiscally responsible and economically viable.
(KEY TERMS: economics; geographic information systems; land use planning; optimization; Smart Growth; watershed management.)

Moglen, Glenn E., Steven A. Gabriel, and Jose A. Faria, 2003. A Framework for Quantitative Smart Growth in Land Development. J. of the American Water Resources Association (JAWRA) 39(4):947-959.

INTRODUCTION

Concerns about the many deleterious effects of urban sprawl such as air and water pollution, loss of open space, and increased traffic congestion have resulted in a widespread movement towards more intelligent, planned forms of future development. Such development has, in recent years, become referred to as "Smart Growth." The goals of Smart Growth as presented to the public by politicians and planners vary by location but several themes consistently emerge: preservation of open space, protection of environmentally sensitive areas, and support for further development of existing urban areas (including urban renewal).

Smart Growth, as presented above and in general, is based on a set of principles or ideals. It is, however, ambiguously defined from a quantitative perspective. As an example, a small town bordered by a large tract of forest or farmland might be approached with development plans that would urbanize this tract of land. Is this Smart Growth? Lacking quantitative measures, this is a difficult question to address.

Truly intelligent Smart Growth should be quantifiably superior to any other proposed land development plan. As another example, imagine that same small town is presented with two alternative development plans. Some townspeople might favor Plan A while others prefer Plan B. Interviews with those preferring Plan A might reveal that they dislike Plan B's location. Meanwhile, a survey of those preferring Plan B indicates they would side with the greater economic benefits that Plan B would bring. These interviews have identified quantities (location and economic benefits) that are valued by the townspeople. Their preferences depend on which plan optimizes the quantity they value.

A quantitative definition of Smart Growth does not exist. For instance, Smart Growth is often defined in

[1]Paper No. 02097 of the *Journal of the American Water Resources Association*. **Discussions are open until February 1, 2004.**
[2]Respectively, Associate Professor, Assistant Professor, and Research Assistant, Department of Civil and Environmental Engineering, University of Maryland, College Park, Maryland 20742 (E-Mail/Moglen: moglen@eng.umd.edu).

very general terms, such as: "…growth that is economically sound, environmentally friendly, and supportive of community livability – growth that enhances our quality of life" (O'Neill, 1999). However appealing this definition might be, this type of terminology does not lend itself well to being measured quantitatively. Further, definitions of Smart Growth may vary considerably depending on the individual or group expressing its goals (Downs, 2001).

A problem faced by Smart Growth advocates is demonstrating or defending the assertion that a given development plan actually represents Smart Growth. In this paper, we propose to define Smart Growth in rigorous, quantitatively explicit terms. We assert that measures can be created that quantify some key characteristic of all possible development alternatives. We define Smart Growth as that development plan that leads to the optimal value of a precisely defined measure identified by a stakeholder or stakeholders. In the example above, measures that quantify location or economic benefits need to be identified to satisfy our definition of Smart Growth. Development alternatives may then be quantified in terms of these measures. A plan that either maximizes the economic benefits measure or minimizes the negative consequences of development location can be declared "Smart Growth" given these measures and the definition of Smart Growth we employ in this work. An advantage of using this definition for Smart Growth is that is does not single out the objectives of any one individual as the sole arbiter of what constitutes Smart Growth. Any objective that influences land development decisions and is quantitatively measurable represents Smart Growth from the perspective of those who hold that viewpoint.

The objective of the work presented here is to distill some of the principles of Smart Growth into explicit, quantitative expressions that can be objectively optimized using standard mathematical tools. In this work, the townspeople from the hypothetical example will be replaced by "stakeholders" that have been chosen to represent a range of potential quantities that might legitimately be valued. This work will then develop a framework to optimize the various stakeholders' viewpoints. In the form of a case study, hypothetical Smart Growth development in a stylized representation of Montgomery County, Maryland, will be determined.

BACKGROUND

In this work, a single or multiple objective optimization will be interpreted as Smart Growth. For brevity, we will discuss the multiple objective case with the understanding that it includes the single objective optimization as a special case. Land development in the context of balancing the interests of multiple stakeholders has been considered in a variety of settings in previous works. Often such an exercise can be characterized in the framework of multiobjective optimization. As compared to single objective optimization having just one objective function being minimized (or maximized) subject to a set of feasibility constraints, the multiobjective version has a finite number of objectives, each to be optimized subject to constraints. In our setting, each objective function relates to a goal of a land development stakeholder to be described below. The constraint set includes general restrictions for all the land under consideration (such as growth rates). This multiobjective formulation is a more difficult problem that the traditional single objective or system optimization in that these individual objectives are often competing. Consequently, what is best for one of the objectives may not be advantageous for the others. A different notion, that of "Pareto optimality," is needed for this setting. Loosely speaking, a Pareto optimal solution to a multiobjective optimization problem is such that an improvement in one of the objectives must come at the expense of at least one of the other ones (Cohon, 1978; Steuer, 1986). In other words, if at least one of the objectives can be improved and the others do "no worse," then the current point is not Pareto optimal.

Multiobjective optimization and land development have been considered in a variety of works; for brevity we review only a few of the works below. Two of the early works in this area were by Bammi and Bammi (1975, 1979), in which they presented a multiobjective optimization model for a land use plan in DuPage County, Illinois. In this work, they considered weighted combinations of objectives that minimized conflict between adjacent land uses, travel time, tax costs, adverse environmental impact, and costs of community facilities. For each of their 147 planning regions, their linear programming model generated acreage totals by land use type, which were then allocated by planners on a parcel by parcel basis. Wright *et al.* (1983) considered a multiobjective integer programming model for land acquisition which addressed three objectives: area of a cell, acquisition cost, and compactness of the developed cells. The authors developed a specialized algorithm due to the possible presence of "gap points" (Cohon, 1978). The largest problem they considered involved 30 cells that had 146 binary variables and 69 constraints and at that time, was at the limit of general purpose multiobjective integer programming algorithms. Aspects of this work were extended in Benabdallah and Wright (1992). The work by Gilbert *et al.* (1985) also considered a multiobjective integer programming model in land development, in this case with four objectives to be optimized: the acquisition and development cost, the "amenity" distance, the "detractor" distance, and the shape objective. An interactive, partial enumeration scheme was presented to solve land development problems for Norris, Tennessee, represented by 900 cells of approximately 2.5 acres each. Lastly, the recent book edited by Beinat and Nijkamp (1998) describes a good collection of multiobjective land use papers with Geographic Information System (GIS) components.

METHODS AND APPROACH

Montgomery County, Maryland, is located immediately north of Washington, D.C. Because of its proximity to Washington and Baltimore, Montgomery County is urbanized to a greater degree than most other counties in the state. At the same time, the county has proactively sought to approach new development more moderately and has taken steps to preserve its environmental resources (Moglen, 2000). As of 1997, the land use distribution was 44.3 percent urban area, 24.5 percent agricultural area, and 28.5 percent forestland, with the remainder (2.7 percent) in water and wetlands. Figure 1 shows the spatial distribution of land use in Montgomery County.

Land development takes place across a continuum of densities. Zoning codes controlling development density in Maryland are categorized in terms of dwelling units per acre (du/ac). In keeping with SI units, density will be presented in terms of dwelling units per hectare (du/ha) with the equivalent density in du/ac presented in parentheses. High density row houses often support 19.8 or more du/ha (8 du/ac). Very low density development is becoming an increasing concern in the State of Maryland with densities on the order of 0.12 du/ha (0.05 du/ac). Although the framework that will be presented in this paper could support a much broader range of development densities, we chose to focus on three residential densities, termed: high density (19.8 du/ha, 8 du/ac), medium density (9.9 du/ha, 4 du/ac), and low density (2.4 du/ha, 1 du/ac). It was desired to model commercial and industrial development in our framework as well. Because these two classes of development can vary tremendously in terms of their land area needs, our model allows these classes to vary continuously in their potential land area needs. Ultimately, this produces five different development types that our framework will consider: low density residential, medium density residential, high density residential, commercial, and industrial.

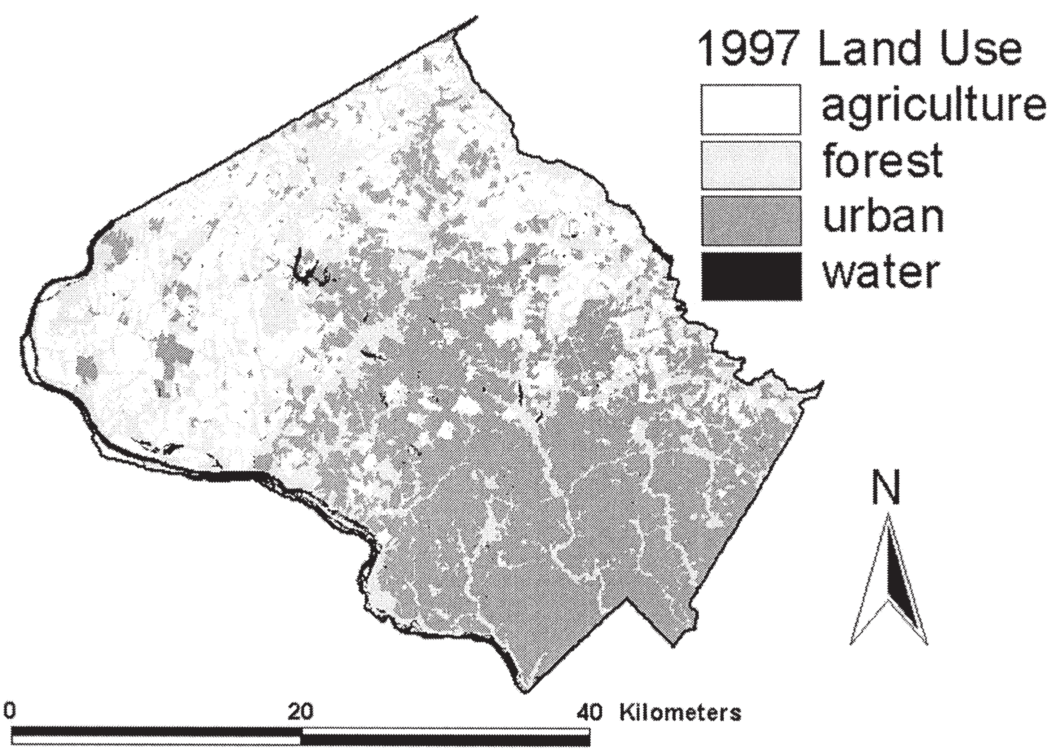

Figure 1. Land Use Distribution in Montgomery County, Maryland, in 1997.

This paper uses the context of Montgomery County's actual, existing land parcel boundaries to develop and illustrate our framework for Smart Growth development. GIS technology was used extensively in this work to track current land use, zoned land use, parcel size and location, and the many quantities that were of concern to our idealized stakeholders. Many of the parcels selected in this study were zoned as "Rural Density Transfer," a zoning category associated with rural legacy programs in the county. This category in itself has some interesting implications on future growth. However, since the focus of this paper was on illustrating development to one of five different potential urban conditions, we developed a heuristic to assign new zoning categories to such parcels. This heuristic reassigned parcels zoned as "rural density transfer" to one of the five development types discussed above based on adjacent zoning types and proximity to major roads. The reassignment results in a "stylized" representation of zoning in the county. While this new zoning scheme strays from the actual zoning in the county, it allows the illustration of our methods without clouding the results with complexities beyond the scope of the paper.

For this study, 810 parcels were selected as potential candidates for future development. To be selected, each parcel was required to be at least 0.0405 hectares (0.1 acres) in area, to be privately owned, and to have a current land use of either agriculture or forest. As illustrated in Figure 1, historical development patterns have led to a concentration of urban area in the southern part of the county closest to Washington, D.C., although considerable development in recent decades has urbanized the central part of the county, especially along the I-270 corridor from the D.C. beltway to the northwest through this area. Table 1 provides the distribution of the potential development parcels among the five zoning categories considered and summarizes the characteristics of these parcels. Owing to the location of existing development, our search criteria tended to locate parcels in the northern and western regions of the county as illustrated in Figure 2. Also shown in Figure 2 is the zoning category assigned to each selected parcel either in actuality or following the heuristic described above.

Contrasting Stakeholder Perspectives

Let us take the perspective of four different classes of stakeholders and examine the consequences of optimal development from their unique vantage points. We acknowledge that the generalized characteristics of viewpoints we outline here cannot possibly be as nuanced or complex as actual stakeholders. Nevertheless, this paper intends to capture some of the primary motivations of these varied stakeholders and contrast how their viewpoints result in different realizations of optimal development. We have endeavored to strike a compromise between realism and computability of the stakeholder objectives. The reader needs to understand that the optimization of more detailed objectives would require computational resources and specialized methods beyond the scope of this work. Consistent with Downs' (2001) observation that different groups and individuals may have different interpretations of the meaning of "Smart Growth," the optimal development realizations for each of our stakeholders will be interpreted in this paper as Smart Growth for the particular stakeholder or stakeholders whose objectives are being optimized.

The Hydrologist. This stakeholder is interested in preserving the environmental well being of the landscape especially with regard to runoff processes and systems affected by runoff processes. Some objectives this stakeholder might embrace include a desire to minimize changes to such processes as flooding, erosion, deposition, or nonpoint source loadings of a range of nutrients and pollutants. Our hydrologist

TABLE 1. Characteristics of Potentially Developable Parcels.

Zoning Category	Number of Parcels	Total Area (hectares)	Total Dwelling Units	Number of Parcels in Conservationist 1 Area	Number of Parcels in PFAs
Low Density Residential	311	8,257	20,254	154	3
Medium Density Residential	177	4,025	39,698	32	8
High Density Residential	20	273	5,384	0	5
Commercial	16	217	–	7	9
Industrial	286	5,205	–	60	6

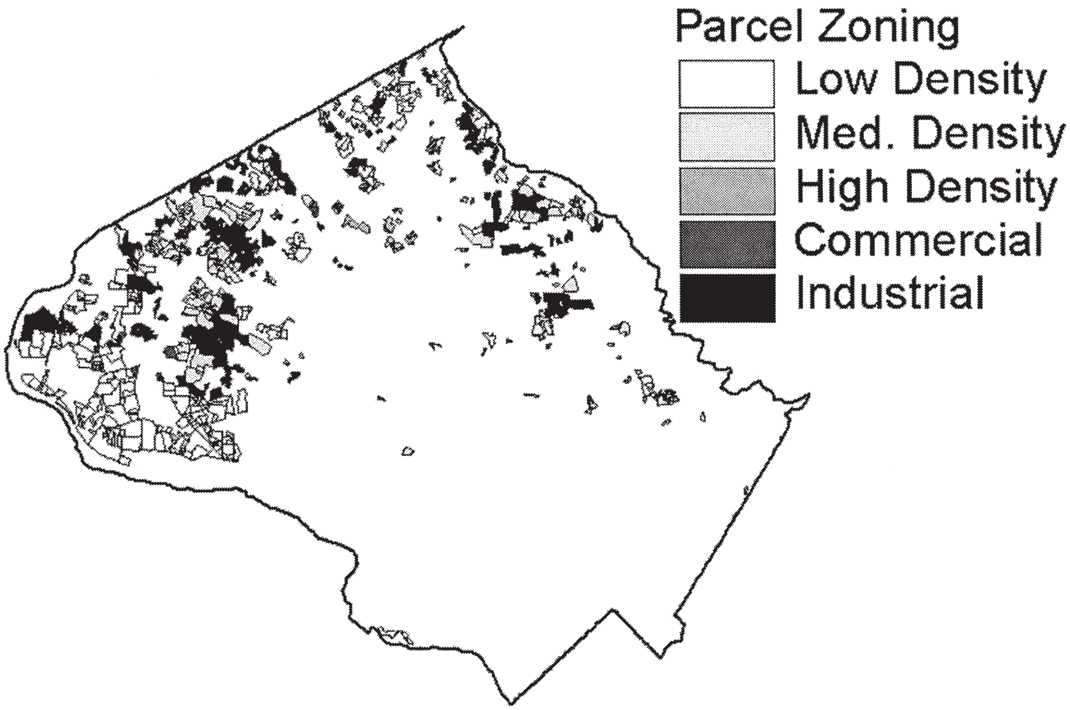

Figure 2. Location and Zoning Category of Selected Parcels in Montgomery County, Maryland.

observes that the deleterious effects of urbanization are strongly correlated with imperviousness (Schueler, 1994; Arnold and Gibbons, 1996). Using increased imperviousness as a surrogate for the negative consequences of urbanization, we propose the following objective function for the hydrologist.

$$\min \sum_{i=1}^{n} \left(d_i \Delta I_i A_i \right) \tag{1}$$

where n is the number of total parcels under consideration; d_i is a land development variable for parcel i equal to 1 if parcel i is developed, 0 otherwise; ΔI_i is the change in imperviousness associated with developing parcel i; and A_i is the area of parcel i. Note that ΔI_i and A_i are GIS determined attributes of each parcel. The symbol "min(·)" indicates the desire of the stakeholder in question to minimize the quantity in question. Thus, we see that the hydrologist's objective function is to select those parcels that minimize the total area weighted change in imperviousness.

The Conservationist. This stakeholder seeks to protect a species or area that is in danger of outright destruction should development take place in a given location. The conservationist may take a stance of disallowing any further development in an area if development in this area would threaten the continued well being of a particular species or harm a unique natural area. The spirit of environmental protection is common to both the conservationist and the hydrologist. However, the conservationist is portrayed here to draw firm outlines of areas in which no additional development is to take place while the hydrologist is seeking a global minimization of change in imperviousness that does not recognize any specific location as having greater or lesser value. In this work, we portray the conservationist as being informed of the watershed based organization of the landscape. Preserving a given stream that is home to some rare fauna depends on controlling activities going on in the watershed draining to that stream. Because of the specific nature of the organization of a drainage network, potentially harmful activities in close proximity to a protected stream but in an adjacent watershed, may not be relevant to that stream because the stream and activity are hydrologically separated. By the same token, other activities potentially quite distant from the stream are relevant because they are upstream of the location being protected. Areas sharing a common watershed are defined by shared hydrologic unit codes (HUCs) as described in Seaber *et al.* (1987). We propose the following objective function for the conservationist.

$$\min \sum_{i \in S_C} d_i A_i \tag{2}$$

where d_i, A_i are defined as in Equation (1) and the set S_C is the subset of (restricted) parcels that the conservationist wants to stop from being developed. This characterization of the conservationist is similar to that of the hydrologist, except the conservationist is only concerned with steering development out of some subset of the region subject to urbanization compared to the hydrologist's desire to minimize imperviousness globally over the region. Further, the hydrologist discriminates between different types of development that lead to different levels of imperviousness, whereas the conservationist here considers all development to be equally undesirable.

The Government Planner. We propose here an objective function for the government planner that is consistent with the spirit of those being used currently within the State of Maryland. Planners have identified areas throughout the state that are designated to be "Priority Funding Areas" or PFAs. These PFAs are generally areas that already have been urbanized to a considerable degree. Maryland wishes to promote further urbanization and redevelopment in these areas through a range of tax, loan, or other incentives. The reasoning given for steering development to these already urbanized areas is that the infill and redevelopment of urbanized areas make for more complete utilization of existing resources (water and sewer service, roads, and schools) while preserving the open space that might otherwise be lost to a more sprawl type development (Pelley, 1999). We propose the following objective function for the government planner.

$$\max \sum_{i \in S_{PFA}} d_i A_i \tag{3}$$

where d_i, A_i are defined as in Equation (1) and the set S_{PFA} is the subset of PFA parcels that the government planner wants to be developed. This objective function, in form, is essentially the opposite of the objective function proposed in Equation (2) by the conservationist. Where the conservationist was looking to steer development away from certain regions identified for conservation, the government planner is attempting to steer development into regions identified for further urbanization.

The Land Developer. The developer's view of optimal development may deviate considerably from the views of the other stakeholders. We propose that the developer is seeking to maximize profit obtained through the purchase of undeveloped land, subdivision of that land into individual parcels, and finally construction and ultimate sale of the improved parcels to other individuals. We recognize that the developer's true profit function is dependent on a complex process involving individual decisions on tracts of land that vary in potential value. This value might be based on distance to both desirable (parks, shopping areas, places of employment) and undesirable (heavy industry, landfills, prisons) locations. Further, the developer might face the option of subdividing the landscape into numerous, modest quarter-acre homes or fewer but more upscale, larger lot houses. In this study, we have simplified the developer's decisions by dictating the type of construction that would be undertaken on a given piece of land and the profit to be gained from the development of that land into any one of five different types of construction: low density residential, medium density residential, high density residential, commercial, and industrial. The developer's objective function thus becomes

$$\max \sum_{i=1}^{n} d_i p_i \tag{4}$$

where p_i is a measure of the economic profit of the parcel if developed and d_i is the binary development variable discussed in Equation (1). As an aside, we should note that this stakeholder is discussed as if he is a single individual. Because of the magnitude of development that is discussed here, the reader should consider the developer to actually represent a group of individuals and/or companies whose collective goal is to maximize the profit from Equation (4).

The value of the parcel was determined by applying the following logic. First, the values for low density (LD), medium density (MD) and high density (HD) residential parcels were taken to be the average tax assessment per parcel in each group (ϕ_{LD}, ϕ_{MD}, ϕ_{HD}) multiplied by an estimate of the maximum number of units that would result if the parcel were developed (area of the parcel divided by the density of the parcel). Based on data from Montgomery County, Maryland (MDP, 2000), these values were determined to be \$449,500, \$291,400, and \$256,700 per unit for low, medium, and high density residential units, respectively. The densities of the residential areas were taken as: 2.47 du/ha (1 du/ac) lots for low density, 9.88 du/ha (4 du/ac) lots for medium density, and 19.8 du/ha (8 du/acre) lots for high density consistent with definitions used by both the Maryland Department of Planning (MDP, 1999) and the U.S. Department of Agriculture-Soil Conservation Service (USDA-SCS, 1985).

For the commercial and industrial parcels, a slightly different approach was used to determine the value of the parcel. Specifically, the average tax assessment per m^2 of the structure for commercial and industrial parcels was established, resulting in ϕ_{COM} and ϕ_{IND} equal to \$3,397/m^2 and \$2,075/m^2 of structure, respectively. Next, a statistical regression analysis was used to calibrate a simple linear model relating the area of the parcel to the structure size (measured in m^2) for commercial and industrial parcels, respectively, useful for predicting the typical structure size on yet undeveloped parcels. These equations took the form,

$$a_i = b + mA_i \tag{5}$$

where a_i is the area of structure i in m^2. The values of (b_{COM}, b_{IND}) were determined to be (1,445 m^2, and 858.6 m^2) while (m_{COM}, m_{IND}) were (2,235 m^2/ha, and 2,664 m^2/ha), respectively. The resulting equations for predicting total value, v_i, of a developed parcel as a function of development type are presented below in Equations (6a) through (6e).

$$v_i = \phi_{LD} \cdot \frac{A_i}{\rho_{LD}} \tag{6a}$$

$$v_i = \phi_{MD} \cdot \frac{A_i}{\rho_{MD}} \tag{6b}$$

$$v_i = \phi_{HD} \cdot \frac{A_i}{\rho_{HD}} \tag{6c}$$

$$v_i = \phi_{COM}\left(b_{COM} + m_{COM} \cdot A_i\right) \tag{6d}$$

$$v_i = \phi_{IND}\left(b_{IND} + m_{IND} \cdot A_i\right) \tag{6e}$$

where Equations (6a) through (6e) estimate the value of low density residential, medium density residential, high density residential, commercial, and industrial parcels, respectively. In these equations, ρ_{XX} are the three residential housing densities. The profit, p_i, realized for the development of parcel i was taken to be a direct fraction (20 percent) of the value of that parcel

$$p_i = 0.2v_i \tag{7}$$

Constraints

The second element of any optimization is the definition of constraints that represent the conditions that must be obeyed in the process of optimizing the objective function. The primary set of constraints in the optimizations considered in this study is determined by the pressures for construction of new residential or business space. From 1990 to 1996, Montgomery County averaged 3,500 new residential units per year. The 1997 land use distribution (MDP, 1999) in the county was such that 33.9 percent (by area) of the urban development was low density residential, 44.7 percent medium density, 11.6 percent high density, 5.9 percent commercial, and 3.9 percent industrial. We assumed that the current land use distribution would persist, implying an annual development pressure of: 1,064 high density units, 2,047.5 medium density units, and 388.5 low density units. Again, assuming current land use distributions, annual development of commercial and industrial land would be 27.4 ha (67.7 ac) and 18.1 ha (44.7 ac), respectively. Our optimizations used these figures and a five-year time horizon for the solution, allowing a 20 percent margin above and below the mean value to set the maximum and minimum number of units to be developed. The precise bounds applied in this optimization are summarized in Table 2.

Although not constraints in the formal optimization sense, some further rules that were imposed merit discussion here. Each parcel had an identified zoning category (e.g., low density residential, commercial, etc.) that was dictated up front by our database of available parcels. Construction of this type was the only permissible form on that parcel. We recognize that, in reality, zoning variances and other tools might be employed to change the nature of development on any one tract of land, however, we do not allow for this possibility within our optimizations. Further, we do not allow for only the partial development of any one parcel, thus any parcel identified for development would be developed in its entirety.

Illustration

Two contrasting optimizations based on the conservationist's objectives are provided here as an example of our model. Figure 3a shows the outlines of the U.S. Geological Survey's 14-digit HUCs as they span Montgomery County, Maryland. The HUCs identified for protection by Conservationists 1 and 2 are indicated. The parcels located in these HUCs would make up the subsets $S_{c,1}$ and $S_{c,2}$ of protected parcels as identified by Conservationists 1 and 2, respectively. Also shown in Figure 3a are the 54 parcels selected by our algorithms to optimize the objective function of Conservationist 1. Notice that essentially all development is steered away from Conservationist 1's protected area towards parcels located elsewhere in the county. The three small commercial parcels that are developed in the protected area are the consequence of the

TABLE 2. Five-Year Bounds on Development in Montgomery County, Maryland.

Zoning Category	Number of Dwellings to Develop		Area of Land to Develop in hectares (in acres)	
	Lower Bound	Upper Bound	Lower Bound	Upper Bound
Low Density Residential	1,554	2,331	–	–
Medium Density Residential	8,190	12,285	–	–
High Density Residential	4,256	6,384	–	–
Commercial	–	–	109.3 (270.0)	164.3 (406.0)
Industrial	–	–	72.4 (179.0)	108.5 (268.0)

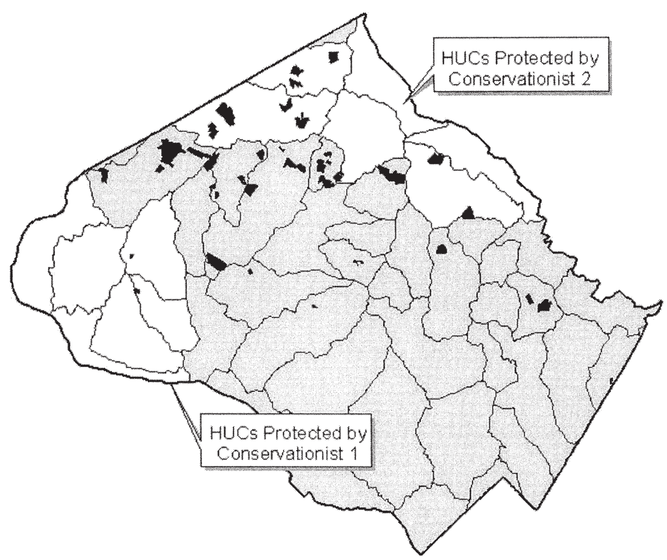

Figure 3a. Optimized Development for Conservationist 1. Highlighted background area shows HUCs protected by Conservationist 1.

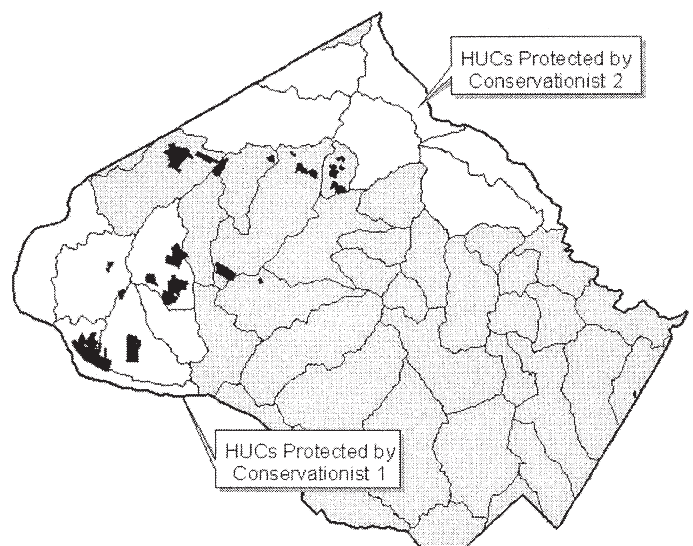

Figure 3b. Optimized Development for Conservationist 2. Highlighted background area shows HUCs protected by Conservationist 2.

constraint requiring at least 109.3 ha (270.0 ac) of commercial development. There existed only 94.4 ha (233.3 ac) of commercially developable land outside of Conservationist 1's protected area. The three additional parcels provide an additional 17.0 ha (42.0 ac) of development inside of the protected area for a total of 111.4 ha (275.3 ac) of commercial development. This is the smallest amount of commercial development that is possible within the protected area that will still satisfy the lower bound constraint for commercial development. In contrast, Figure 3b shows the analogous optimization protecting Conservationist 2's HUCs located in the northern part of the county. Since the conservationists have identified competing areas to protect, optimization of the goal of one comes at the expense of the other. These two figures visually convey that our algorithms behave as intended.

RESULTS

Table 3 summarizes the development decisions across all cases that were examined. Table 4 provides the objective functions realized for each case from the perspective of each stakeholder. A description of the cases considered and discussion of the findings is provided below.

Three different types of optimizations were performed. First, the objective function for each individual stakeholder was optimized individually, ignoring the goals of the competing stakeholders. The effect was to produce a land development plan that was best from the perspective of each particular stakeholder. These optimizations were denoted by Cases "1H,","1C," "1P," and "1D" for the hydrologist, conservationist (Conservationist 1's objectives were used throughout the remainder of this study), government planner, and developer, respectively. Because the

TABLE 3. Summary of Optimization Results.

Case	Number of Parcels Developed	Total Area Developed (ha)	Number of Residential Units Developed: Low Density	Medium Density	High Density	Area Developed (ha): Commercial	Industrial
1H	28	1,863	1,560	8,190	4,256	109.3	77.0
1C	54	1,993	1,585	8,564	5,384	111.4	98.3
1P	57	2,031	1,620	8,790	5,384	124.9	85.7
1D	52	2,734	2,331	12,285	5,384	164.3	108.4
2	36	1,927	1,554	8,564	4,355	110.6	98.3
3H	30	1,866	1,554	8,194	4,259	110.6	76.9
3C	36	1,927	1,554	8,564	4,355	110.6	98.3
3P	37	1,949	1,554	8,824	4,259	110.6	98.3
3D	46	2,369	1,578	12,205	4,437	158.9	108.2

objective functions of the other stakeholders are not considered at all, we should note that land development plans obtained in this way are not necessarily Pareto optimal (Cohon, 1978).

TABLE 4. Summary of Objective Function Outcomes (values in bold indicate optimized quantity).

Case	Impervious Area (ha)	Conservationist Area (ha)	PFA Area (ha)	Profit ($\$10^6$)
1H	**658**	1,064	173	1,091
1C	727	**17**	153	1,208
1P	761	1,008	**344**	1,230
1D	997	1,446	206	**1,584**
2	689	77	177	1,143
3H	662	492	182	1,096
3C	689	77	177	1,143
3P	694	77	209	1,154
3D	847	100	182	1,449

Second, having performed these four separate optimizations, Case "2" involved the application of equal normalized weights to each of the individual objective functions summed collectively. Weights were normalized such that the contribution of each parcel to each stakeholder's objective function was normalized to range between 0 and 100 to maintain numerical optimization fairly among the different stakeholders. This is an example of the "weighting method" (Cohon, 1978), which when positive weights are used (which was the case with this analysis) will be guaranteed to produce a Pareto optimal solution. Such a solution will represent a compromise of sorts between the competing stakeholder interests. It will generally represent a solution that is inferior to the one(s) that come from the separate optimizations but will be "best for all" in the Pareto optimal sense. Of course, there is in general more than one Pareto optimal solution, but our intention in this work was merely to demonstrate the importance of such a perspective. Enumerating all the Pareto optimal points was not really the purpose here and is further complicated computationally by a "duality gap" resulting from the binary development variables (Cohon, 1978).

Finally, a third set of optimizations was performed. These were similar to Case "2," but illustrate the effect of adding increased weight to a specific stakeholder's contribution to the overall objective function. In Case "2," the weight for each stakeholder's contribution is unity. In Cases "3H," "3C," "3P," and "3D" we double the weight corresponding to the hydrologist, conservationist, government planner, and developer, respectively.

The results of these optimizations can be examined from a variety of perspectives. The first thing to notice is that, from the perspective of the individual stakeholders, the "1X" cases, as summarized in Table 4, produce the best value of the objective function (shown in bold) for each stakeholder relative to the all other cases studied. For example, Case "1H" produces the lowest additional impervious area (658 ha) of any run. Likewise, Case "1C" has the lowest development area (17 ha) within the HUCs that Conservationist 1 wishes to protect. In Case "1P," the government planner is able to steer the maximum value of 344 ha of new development into PFAs. Finally, the developer's profit of $\$1,584 \times 10^6$ is maximized in Case "1D."

Comparing Tables 3 and 4 reveals some other trends. Run "1H," which minimizes the increase in impervious area, is characterized by developing all five categories of potential development to essentially the lower bounds of the development constraints indicated in Table 2. Similarly, profit in run "1D" is maximized by selecting enough parcels to develop to the upper bounds of the development constraints. Notice in Table 2 that for high density residential development, the upper bound constraint (6,384 units) is not realized because there is an insufficient amount of high density residential parcel area to produce this many units. Instead (see Table 1), the potential parcels support the development of only 5,384 units, which is the amount chosen by the developer to help maximize his profits.

The tradeoffs between the various optimizations are perhaps viewed most readily by normalizing the values presented in Table 4 by the optimized quantity achieved in the "1X" cases. Table 5 presents the same information given in Table 4, but in this normalized fashion. For instance, the column marked "Hydrologist" contains the column of data shown in Table 4 with the heading "Impervious Area," but normalized by the minimum impervious value of 658 ha realized in Case "1H." This column now provides a quick assessment of the hydrologist's perspective on each of the other cases examined. The larger the value in this column, the further from the hydrologist's optimum that particular case was. For instance, Case "1D," which optimizes the developer's objective function, produced 997 impervious hectares. In Table 5, this normalized value is 997/658 = 1.51. In other words, when the developer's objective function is optimized, the result is 1.51 times the imperviousness than when the hydrologist's objective function is optimized.

Table 5 quickly reveals some other trends. Note that both the hydrologist and the conservationist are trying to minimize their respective objectives, whereas the government planner and developer are trying to maximize theirs. This means that doing worse for the hydrologist and conservationist translates to a value in Table 5 greater than one but a value less than one for the government planner and developer. So for example, we see that by optimizing the conservationist's perspective (Case "1C"), the developer's objective is only 76 percent of what it could be if optimized for the developer. Case "2" reflects the Pareto optimal solution we obtained for equal normalized weights across all stakeholder objective functions. We see that when taking all the stakeholder objectives into account simultaneously, all the stakeholders do somewhat worse than if they were the only player. The hydrologist does the least worse (given our choice of weights) since his objective (total change in imperviousness) only rises 5 percent (from 1.00 to 1.05). The objective of the conservationist does the least well in going from a factor of 1.00 to 4.53, a 353 percent increase in development of his protected areas. Lastly, the developer and the government planner's objectives also suffer, respectively, 28 percent and 48 percent under this scheme. The "3X" cases illustrate the effect of placing increased weight on a particular stakeholder's objective function. The bold entries in these rows indicate the normalized objective function values for the stakeholder receiving the increased weighting. Except in the case of the conservationist, notice that these values are closer to one than the corresponding entry under Case "2." As described earlier, a normalized value closer to one indicates results closer to the absolute optimum, thus the weighting has the effect of moving the stakeholder whose objective receives increased weight closer to his individual optimum result. That the conservationist's normalized value is the same in Cases "2" and "3C" indicates that double weighting his objective function is not sufficient to improve this stakeholder's outcome in the compromise cases.

TABLE 5. Normalized Objective Function Values From the Perspective of Each Individual Stakeholder Dependent on Stakeholder. The value in parenthesis in the column headings indicates the normalizing quantity (optimized value of the objective function for that stakeholder).

Case	Hydrologist (658 ha)	Conservationist (17 ha)	Government Planner (344 ha)	Developer ($1,584 x 10^6^)
1H	**1.00**	62.6	0.50	0.69
1C	1.10	**1.00**	0.45	0.76
1P	1.16	59.3	**1.00**	0.78
1D	1.51	85.1	0.60	**1.00**
2	1.05	4.53	0.52	0.72
3H	**1.01**	28.9	0.53	0.69
3C	1.05	**4.53**	0.52	0.72
3P	1.05	4.53	**0.61**	0.73
3D	1.29	5.86	0.53	**0.91**

DISCUSSION

Because it bears so heavily on issues of land management, land development, the environment, and economic vitality, Smart Growth is inherently tied to processes that extend beyond the realm of the objective optimizations presented in this work. Nevertheless, the case study and framework we have presented here is valuable because it provides a language in which parties with disparate viewpoints can communicate effectively. Further, just the act of assembling a Smart Growth optimization such as those illustrated in this work would engage all in a useful exercise to have each stakeholder explicitly state and quantify the characteristics of future growth that are important to that individual.

Although the cases presented here were based on both stylized representations of zoning in the county and somewhat simplified representations of stakeholder objectives, some general observations about the optimizations presented in this work can be made that are germane to Smart Growth. First, when bringing together groups with disparate viewpoints, it is probably best to focus initially on areas of common ground. In this spirit, it is worth noting that there were 17 parcels that were included in all the single objective function ("1X") cases. Considering that all optimizations chose to develop between 28 and 57 parcels (see Table 3), this would indicate that there was outright agreement on 30 to 61 percent of the development choices. Such commonly agreed upon parcels represent a special subset of development decisions – growth that would be considered "smart" by all parties. Second, even without performing an actual optimization, the government planner could visually examine the dataset and see that his choices are quite limited. Figure 4 shows the location of PFAs within Montgomery County and the 810 potential development parcel outlines considered in this work. The planner should be able to rapidly determine that the intersection of these two sets of areas (the parcels that reside within PFAs) is very small. In the planner's optimization, all 31 PFA parcels in the potential development set were selected for development. This means that PFA parcels were rather scarce and indicates that the original rules for identifying the

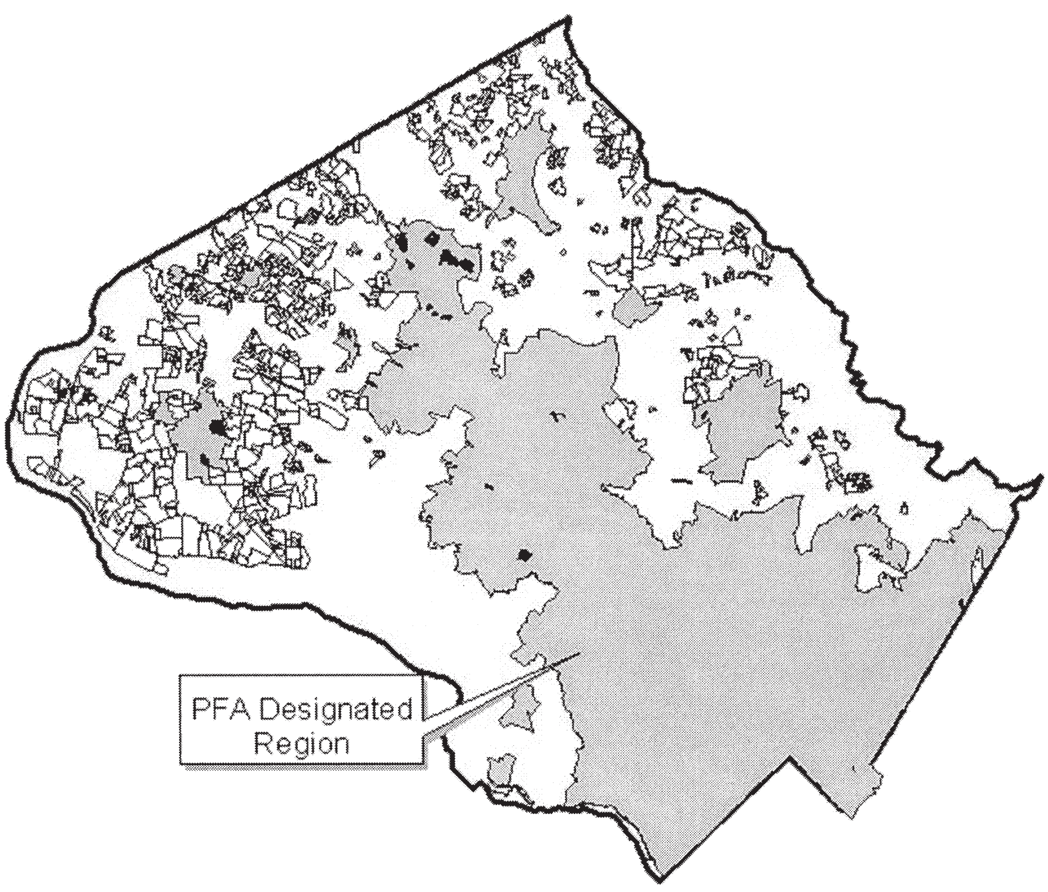

Figure 4. Potential Development parcels (shown in white) and Location of Priority Funding Areas (PFAs, shown in dark gray) in Montgomery County, Maryland. Parcels shown in solid black are within PFA boundaries.

potential development set were, with few exceptions, spatially disjointed from PFA locations. The conclusion is that the remaining new development area within PFA boundaries is small and that the government planner may need to redefine PFA boundaries if this mechanism for steering growth to certain locations is to be effective beyond the next few years.

This paper also effectively illustrates some of the potential ambiguities in the proposed framework. Cases "2" and "3X" deal with the concept of simultaneous optimization of the viewpoints held by all stakeholders. A weighting system was proposed and the "3X" cases contrasted with Case "2" show how doubling the weight of one stakeholder's objective relative to the others influences the outcome. The previous section discussed and Tables 4 and 5 summarized how the weighting scheme indeed was generally successful in skewing the results of an optimization towards a particular stakeholder. But the question this naturally raises is, "How should the weights be determined?" More generally, one could consider preference based methods as described by others (e.g., Cohon, 1978; Steuer, 1986), but these methods are not within the scope of this paper.

Even larger questions lurk behind the framework as presented: "How should the objective functions for various stakeholders be solicited? What stakeholders' views should be considered?" These questions are beyond the scope of this paper and return much of the future growth debate back to its societal origins. But, we now contend, that the framework presented here gives the parties involved in the decision making process the capacity to examine the process objectively and quantitatively. The question asked in the introduction: "Is this Smart Growth?" can now be answered within the context of the framework we have established.

SUMMARY

This paper presented a framework for bringing quantitative decision making to the land development process. This framework was based upon characterizations of four different stakeholder viewpoints and methods from optimization theory. An objective function consistent with each stakeholder's values was proposed. These objective functions were then optimized individually and collectively within the context of future development in Montgomery County, Maryland. By our definition of Smart Growth presented in the Introduction, all of these optimal outcomes are considered Smart Growth within the framework we have established. Further, this framework could readily be applied to other counties or an entire state, provided that appropriate geographic data are available for such areas.

The results of the optimizations were consistent with expectations based on the various stakeholders valued quantities: the hydrologist was able to realize minimal imperviousness, the conservationist was able to steer development away from protected areas, the planner was able to encourage development within PFAs, and the developer was able to maximize profits. Compromise optimizations were able to simultaneously achieve each of the above outcomes, but to a lesser degree than when the optimizations were performed from just a single stakeholder's viewpoint. A weighting method was presented that was successful in emphasizing a particular stakeholder's objective function relative to the others.

Issues of both common ground and differences between the stakeholders were identified. Using the framework developed in this paper, it is possible to identify land parcels that are universally agreed upon to be good development decisions. Spatial or structural conflicts such as a lack of developable land within the government planner's PFAs or a generalized scarcity of parcels for high density residential development were identified using our framework. For instance, one potential problem identified in this work was that just five years of incremental growth steered into PFAs consumes essentially all the developable land within these boundaries. For PFAs to remain an effective tool for guiding future growth, the planner will need to continually evaluate growth within PFAs and possibly modify or expand such boundaries as the supply of developable land within such areas is consumed.

Because of the complex societal nature of this problem, our method ultimately returns to questions that are beyond the scope of this paper. Which stakeholders to engage, how to quantify their viewpoints, and how to weigh conflicting viewpoints were identified as complex questions that our method cannot address. However, if other means can be used to answer such questions the framework established here can be used to objectively and quantitatively make Smart Growth decisions.

ACKNOWLEDGMENTS

The authors gratefully acknowledge support received to perform this study from the National Center for Smart Growth Research and Education at the University of Maryland, College Park, Maryland. The authors also thank the Maryland Department of Planning for the use of their MdProperty View and Land Use Land Cover data. This work has benefited substantially from the thoughtful critique of three anonymous reviewers.

LITERATURE CITED

Arnold, Jr., C. L. and C. J. Gibbons, 1996. Impervious Surface Coverage: The Emergence of a Key Environmental Indicator. Journal of the American Planning Association 62(2):243-258.

Bammi, D. and D. Bammi, 1975. Land Use Planning: An Optimizing Model, OMEGA. The International Journal of Management Science 3(5):583-593.

Bammi, D. and D. Bammi, 1979. Development of Comprehensive Land Use Plan by Means of a Multiple Objective Mathematical Programming Model. Interfaces 9(2):50-63.

Beinat, E. and P. Nijkamp, 1998. Multicriteria Analysis for Land-Use Management. Kluwer Academic Publishers.

Benabdallah, S. and J. R. Wright, 1992. Multiple Subregion Allocation Models. Journal of Urban Planning and Development 118(1):24-40.

Cohon, J. L., 1978. Multiobjective Programming and Planning. Academic Press, New York, New York.

Downs, A., 2001. What does "Smart Growth" Really Mean? Planning 67(4):20-25.

Gilbert, K. C., D. D. Holmes, and R. E. Rosenthal, 1985. A Multiobjective Discrete Optimization Model for Land Allocation. Management Science 31(12):1509-1522.

MDP (Maryland Department of Planning), 2000. MDProperty View (2000 Edition). Planning Data Services, Baltimore, Maryland.

MDP (Maryland Department of Planning), 1999. Land Use Land Cover in Maryland (1997 Edition). Planning Data Services, Baltimore, Maryland.

Moglen, G. E., 2000. Urbanization, Stream Buffers, and Stewardship in Maryland. Watershed Protection Techniques 3(2):676-680.

O'Neill, D., 1999. Smart Growth: Myth and Fact. ULI:The Urban Land Institute, Washington, D.C.

Pelley, J., 1999. Building Smart-Growth Communities. Environmental Science and Technology 33(1):28A-32A.

Seaber, P. R., F. P. Kapinos, and G. L. Knapp, 1987. Hydrologic Unit Maps. U.S. Geological Survey Water-Supply Paper 2294, 63 pp.

Schueler, T., 1994. The Importance of Imperviousness. Watershed Protection Techniques 1(3):100-111.

USDA-SCS (U.S. Department of Agriculture-Soil Conservation Service), 1985. National Engineering Handbook, Supplement A, Section 4, Hydrology, Chapter 10. U.S. Department of Agriculture, Washington, D.C.

Steuer, R. E., 1986. Multiple Criteria Optimization: Theory, Computation, and Application. John Wiley and Sons, Inc., New York, New York.

Wright, J., C. ReVelle, and J. Cohon, 1983. A Multiobjective Integer Programming Model for the Land Acquisition Problem. Regional Science and Urban Economics 13:31-53.