Environ Model Assess
DOI 10.1007/s10666-007-9130-6

# Optimal Selection of Priority Development Areas Considering Tradeoffs Between Hydrology and Development Configuration

**Jeremy J. Hargreaves · Benjamin F. Hobbs**

Received: 11 July 2007 / Accepted: 11 October 2007
© Springer Science + Business Media B.V. 2007

**Abstract** Mixed-integer linear programs are proposed for siting development and conservation areas in watersheds, addressing economic objectives (development perimeter and proximity) and ecological objectives. Links between watershed hydrology and ecology need not be well defined. Parameters for the linear programs are obtained from linearization of the SWAT hydrologic model.

**Keywords** Linear programming · Optimization · Environmental restoration · Watershed model · Land development · Hydrology · Planning · SWAT

## 1 Introduction

Stream and river environments, and the landscapes that affect them, are a major target of restoration activities [4]. Restoration efforts can significantly reduce contaminants, nutrients, and sediment from point and nonpoint sources. However, less attention has been paid to changes in flow characteristics, such as base flows or flooding that can affect the extent and quality of fish habitat by changing inundation, temperature, velocity, turbidity, and sedimentation.

Changes in flow characteristics can be caused by landscape changes, such as development, by climate change, and by changes in the operation of reservoirs. The focus of this paper is on modeling the effect of alternative land development patterns. Development alters the surface and vegetation of an area, affecting interception, transpiration, infiltration, and consequently, the rate of runoff into stream channels. These effects can be reduced through design changes, such as reducing impermeable surface and setting aside a percentage of a development area. However, some areas of a watershed are innately more suited to development than others from a hydrological perspective because of their existing land cover, soil types, and location. Thus, land development should consider locational alternatives and design changes.

Prioritizing areas of a watershed for either conservation or development to steer development in a sustainable direction has become part of modern watershed planning. In the State of Ohio (US), for example, designation of priority conservation areas and priority development areas is a primary tool for watershed development planning under the Lake Erie Balanced Growth Program [16]. Priority conservation areas (PCAs) are selected as areas too sensitive for development. This could be due to historical significance, recreational or agricultural value, or ecological importance. In this work, the ecological importance of an area is the focus, specifically the impact that developing that area would have on watershed hydrology. Priority development areas (PDAs) are areas considered favorable for development. The measure used here of favorability is the impact a development upon an area has on the hydrology of the watershed. Here, changes that increase high flows or decrease low flows during spawning months are considered less favorable for fish recruitment.

This paper proposes a method for selecting priority conservation or priority development areas within a watershed considering tradeoffs between aquatic impacts (using indices of hydrological changes) and economic costs

J. J. Hargreaves · B. F. Hobbs (✉)
Department of Geography and Environmental Engineering,
The Johns Hopkins University,
Ames Hall 313, 3800 No. Charles St.,
Baltimore, MD 21218, USA
e-mail: bhobbs@jhu.edu

J. J. Hargreaves
e-mail: jjh@jhu.edu

(using indices of the economic desirability of development). The method uses optimization (mixed-integer linear programming) to minimize the hydrological impact in a watershed, subject to a requirement that a particular number of hectares be developed. The general approach is flexible, and other hydrological, social, and economic indices can be substituted for those considered here, based upon the objectives of the watershed they are applied to. The strength of this technique is that it provides potentially useful information without knowing the exact links between watershed changes and ecosystem health due to assumed monotonicity in the relationships between each of the hydrologic indices and the aquatic health of the watershed and lake.

This analysis can be viewed as an extension of existing optimization models that are used to investigate tradeoffs among different land-use patterns [e.g., 19]. We present four models. The first selects the set of subwatersheds in the watershed that if developed, would result in the least impact on various streamflow indices (including average, low, and peak flows during critical spawning periods) for a given amount of development. In the form presented here, this model assigns PDA locations; however, by instead maximizing impact rather than minimizing, it can also be used to identify potential PCA sites. The second model limits the set of subwatersheds that can be developed to those adjacent to existing developments. This is useful in that adjacency is a proxy for ease of development, as logistical costs and infrastructure expansions, such as water and gas mains, are cheaper. The constraints and variables used to enforce adjacency are new to the literature. The third model adds a compactness objective (quantified as the perimeter of the new development) to the first model so that decision makers can tradeoff impact on watershed health with development compactness. By generating several alternatives rather than a single optimum, this model provides information on how the hydrological indices improve if less compact development is allowed. Finally, the fourth model can assess the hydrological effects of various amounts of conservation areas and allows identification of the amount and location of areas that are most important to protect.

An illustrative application shows that although the models do not quantify aquatic ecosystem impacts, they can help planning authorities to make more informed decisions, assuming that higher low flows and lower peak flows are desirable for fish habitat. The Chagrin watershed in Ohio is used as an example. The Soil and Water Assessment Tool (SWAT) hydrologic model was used to parameterize the hydrological portion of the models.

In the next section, we briefly summarize some related literature on combined land–water optimization models. The first and simplest optimization model used is presented in Section 3, and its hydrological assumptions are summarized. Section 4 then describes three variants of the basic model. Two variants add constraints to implement adjacency and perimeter objectives. The third variant is used to assess the relative benefit of different amounts of PCA assignment, assuming that development would take place in the most vulnerable unprotected areas. In section 5, the development of the Chagrin basin model is presented, including details of the hydrological model construction. We then present results from the Chagrin case study in Section 6 and suggest future research directions in Section 7.

## 2 Related Work

Many optimization models have been proposed for siting land use development or preservation considering both economic and environmental objectives. Some embed models of the response of natural systems to quantify environmental impact [8].

Various objectives have been formulated in such models. Two broad types are economic objectives, such as minimizing the cost of development or acquisition, and ecological objectives, such as minimizing the impact of development on water quality, usually nutrients or dissolved oxygen. Hydrological impacts of land development, the focus of our work, have been considered less often than water quality. As an example of a model that considers both economic and environmental objectives, Chuvieco [6] considered tradeoffs between the objectives of job creation and forest area preserved, using a linear program to select areas for agricultural development.

When the ultimate objective, such as net economic benefits or ecological health, is difficult to estimate as a function of the decision variables, proxy indices are often used instead. Useful proxies should be easily quantified, causally linked to the ultimate objective, and have a monotonic relationship with that objective so that improvement in the proxy implies that an improvement is likely in the ultimate objective. In many models, these proxies are based on the configuration of the selected sites. An example is compactness, which might be measured as the perimeter of the solution set of sites or the degree to which selected areas are adjacent to each other. Such proxies are used as a surrogate for economic value of land development in our models. As a previous example of the use of such economic proxies, Aerts et al. [1] proposed multiple objective linear programs for locating land development. Objectives included minimizing the cost of development and maximizing the compactness of natural areas. To gauge compactness, an adjacency index was used in one of their models, and buffer area in another.

One prominent area of research concerned with site configuration is nature reserve design, an area reviewed by Williams et al. [19]. There, variables such as contiguity of selected land areas are used to quantify habitat quality, which in turn is a proxy for the ultimate objectives of ecological integrity or stable populations of species of interest.

Water quantity related objectives are occasionally used in optimization-based land use models, such as those in Sections 3 and 4, below. For instance, multiobjective optimization has been used to select crop types for farming according to criteria decided upon by the stakeholders involved, including water use criteria [15]. Tang et al. [17] present a hydrologic optimization application related to the one in this paper. They used a greedy algorithm with the objective of minimizing runoff. Developments are assigned first to the best site, i.e., the one where development will cause the least change in runoff, then to the second best site and so on. Yeo and Guldmann [21] proposed an optimization model for minimizing peak flow rates in a land development problem. The model was based on regression functions that relate watershed peak discharge to the land use. Optimization was then used to site anticipated land development to minimize storm water runoff. Constraints on the optimization included rules for future development. For example, bounds were placed on the percentage watershed coverage of different land use types.

The mixed-integer linear programming models presented below differ from previous work in that they address both preservation and development (PCAs and PDAs, respectively), while considering tradeoffs between development compactness, as indicated by adjacency and perimeter, and several hydrologic indices that are closely related to aquatic ecosystem health. These techniques are particularly applicable to regions where development planning is carried out at a watershed level, such as in the Lake Erie Watershed under the Balanced Growth Program. Rather than give a prescription for future development, the models are designed to inform the assignment process for PDA and PCA areas by providing information on tradeoffs.

## 3 Basic Formulation

Before presenting the notation and formulation of the first of the four optimization models, we summarize the basic assumptions underlying the quantification of the proxies of ecosystem impact.

### 3.1 Hydrologic Model Principles

The quantitative nature of linkages between land development and the health of a water body or watershed is often poorly understood. Furthermore, the relationship is specific to each particular watershed. For some areas, due to the composition of the bed and banks, stream channels may be resistant to erosion. For others, fish species may be supported in habitat that is specific to that watershed or region. Ecosystem changes, due for instance to invasive species or climate change, make quantification of the aquatic ecosystem impact of land use changes even more difficult. Lake Erie is an example. Invasions of the zebra mussel and round goby, changed phosphorus loadings, and large shifts in fishery management policy have drastically changed the structure of the ecosystem over the last two decades, making it difficult to predict the Lake's responses to stresses [5].

Two key assumptions underlie the ecological proxies in our model. One is that the relationship between metrics characterizing the flow behavior of streams and the health of the aquatic ecosystem are monotonic. For example, if the base flow decreases during spawning periods, we assume that spawning habitat and, ultimately, ecological health decreases. This permits use of flow behavior metrics as proxies for ecological health. We can then make ordinal judgments about potential watershed developments; the impact of developing one area can be judged relative to the impact of developing other areas. However, the method tells us nothing about the magnitude of the relative ecological impacts; to do that, it is necessary to translate flow changes into changes in habitat and, ultimately, fish reproduction and survival [2].

The second key assumption is that a linear expression can be used to approximate the cumulative hydrological response of the watershed to land use changes. In particular, a first-order Taylor's series approximation of the SWAT hydrologic model [3] is used to estimate how land use changes in different locations combine to influence the long-run average values of hydrological indices of interest.

We use four metrics to gauge hydrologic-related impacts on aquatic ecosystem health: average flow rate, SD of daily flows, average high flow rate (top 10% of daily flows), and average low flow rate (bottom 10% of daily flows). In the Chagrin case study, these metrics are calculated for the months of March and April, as the spawning of walleye during this period is a major ecological concern in the watershed. Walleye are the top Lake Erie predator and a popular game fish. Greater low flows are desirable because they result in more habitat, while smaller flood flows are preferred to lower stress. Different indices may be more appropriate for other watersheds and can be substituted in the model.

## 3.2 Model Formulation

### 3.2.1 Indices and Parameters

| | |
|---|---|
| $\mathrm{AD}_i$ | The set of subwatersheds adjacent to subwatershed $i$ |
| $A_{ik}$ | Ratio: (change in whole watershed average runoff from locating development $k$ on subwatershed $i$)/(base case average runoff from whole watershed) (mm/mm) |
| $B_i$ | Boundary length of subwatershed $i$ |
| $D_{ik}$ | Ratio: (change in whole watershed flow SD from locating development k on subwatershed $i$)/(base case SD for whole watershed) (mm/mm) |
| $H_{ik}$ | Ratio: (change in whole watershed average runoff of top 10% of flows (high flows) from locating development k on subwatershed $i$)/(base case average of top 10% of flows) (mm/mm) |
| $\mathrm{HA}_i$ | Area of subwatershed $i$ ($km^2$) |
| $i$ | Subwatershed index |
| $I$ | Set of subwatersheds in the watershed |
| $I_k$ | Subset of subwatersheds that are potential sites for development $k$. These exclude locations that are already developed. |
| $k$ | Development type |
| $K$ | Set of potential development types that could take place in the watershed |
| $L_{ik}$ | Ratio: (change in whole watershed average runoff of bottom 10% of flows (high flows) from locating development $k$ on subwatershed $i$)/(base cases average of bottom 10% of flows) (mm/mm) |
| $N_k$ | The total area of hypothetical development type $k$ to be sited within the watershed ($km^2$) in the fourth (PCA impact) model |
| $N_{\mathrm{PCA}}$ | Area of watershed to be assigned as a priority conservation area ($km^2$) |
| $N_{\mathrm{PDA},k}$ | Area of watershed to be assigned as a priority development area of type $k$ ($km^2$) |
| $R_k$ | Subset of subwatersheds already developed |
| $\mathrm{SB}_{ij}$ | Length of boundary shared by edges of adjacent subwatersheds $i$ and $j$ |
| $W_A$, $W_D$, $W_H$, $W_L$ | Weights assigned to objectives of minimizing change in average flow rate, average SD, average high flow, and average low flow, respectively |

### 3.2.2 Decision Variables

| | |
|---|---|
| $f_{ijk}$ | "Development flow" variable (unitless) from subwatershed $i$ to subwatershed $j$ for type $k$, used to impose adjacency constraints |
| $u_{jk}$ | 1 if both subwatersheds $i$ and $j$ are selected, 0 otherwise |
| $x_{ik}$ | 1 if development $k$ is located in subwatershed $i$, 0 otherwise |
| $y_i$ | 1 if a priority conservation area is located in subwatershed $i$, 0 otherwise |

### 3.2.3 Basic Model

The basic model is the first and simplest of the models presented and forms the basis for the variants of Section 4 that include more complex constraints. The basic model chooses locations for development (PDAs) that minimize the weighted sum of the change in the hydrologic metrics, while siting enough development to meet constraint 2, which is a lower bound on the development area. The weights could reflect professional judgment about the relative stress that, e.g., low vs high flows place upon the populations of interest. Logical constraints 3 and 4 state that only one type of development can occur in each subwatershed. Alternative formulations could allow partial development $x_{ik} \subset [0,1]$.

$$\mathrm{Min} \sum_{i \in I_k} \sum_{k \in K} \left( W_A A_{ik} x_{ik} + W_D D_{ik} x_{ik} + W_H H_{ik} x_{ik} + W_L L_{ik} x_{ik} \right) \quad (1)$$

subject to:

$$\sum_{i \in I_k} HA_i x_{ik} \geq N_{\mathrm{PDA},k} \qquad \forall k \in K \quad (2)$$

$$\sum_{k \in K} x_{ik} \leq 1 \qquad \forall i \in I \quad (3)$$

$$x_{ik} \in \{0, 1\} \qquad \forall i \in I_k, k \in K \quad (4)$$

The disadvantage of this model is that although it is spatially explicit, it does not consider the economic value or cost of alternative developments that satisfy the area constraint 2. This could, for instance, yield fragmented development patterns. Such solutions are possibly less realistic due to the water, power, and transport infrastructure expense of scattered development occurring far from already developed areas.

The sets of sites that are available for potential development $I_k$ can be defined as those subwatersheds that have no reason to remain undeveloped other than their potential hydrological impact. If it is also important to protect locations of value such as historical sites, these can be omitted from the appropriate sets $I_k$. There may also be an objective of protecting the terrestrial habitat of particular species from development. There are two ways to achieve this. A species habitat preservation model (like those in [19]) can be combined with the models in Section 4 to explore tradeoffs among economic, hydrologic, and habitat objectives. Either the habitat to be protected can be set as a constraint and be absolutely protected, or the objective of species protection can be weighted and traded off against the economic and hydrologic proxies.

This model can also be used to identify PCAs, if instead, the objective is defined to maximize rather than minimize impacts. Then, the most sensitive subwatersheds could be identified.

The basic model and its variants are stated in general terms, allowing more than one class of development $k$ to be considered. This might be desirable if different types of development (e.g., high density commercial vs low density residential) have different hydrological impacts. However, in the application, only one class is considered.

## 4 Model Variants

Presented in this section are the three variants of the basic model just described. The first two choose priority development areas using adjacency and perimeter, respectively, as indices of economic value of development. The third is a priority conservation area assignment model that identifies the subwatersheds whose hydrology is most sensitive to development.

### 4.1 Adjacency Model: Constrain Development to Locations Adjacent to Existing Development

This model constrains new development to being contiguous to areas that are already developed. This may be a more realistic way to select PDAs, as development often occurs by expanding existing development. Costs are lower due to access to utilities, as well as easy transportation access. However, there will, in general, be a greater negative impact on watershed health than in the basic models 1–4 due to development being constrained to a smaller subset of subwatersheds. This is a result of a basic principle of optimization: adding a constraint to a model cannot improve the objective function and might worsen it.

The model elaborates upon the basic model by adding a set of variables and constraints 9–11 to force all development to occur contiguously with existing development:

$$\text{Min} \sum_{i \in I_k} \sum_{k \in K} \left( W_A A_{ik} x_{ik} + W_D D_{ik} x_{ik} + W_H H_{ik} x_{ik} + W_L L_{ik} x_{ik} \right) \tag{5}$$

subject to:

$$\sum_{i \in I_k} \text{HA}_i x_{ik} \geq N_{\text{PDA},k} \qquad \forall k \in K \tag{6}$$

$$\sum_{k \in K} x_{ik} \leq 1 \qquad \forall i \in I \tag{7}$$

$$x_{ik} \in \{0, 1\} \quad \forall i \in I_k, k \in K \tag{8}$$

$$\sum_{j \in AD_i \cap I_k} \left( f_{jik} - f_{ijk} \right) + \sum_{j \in AD_i \cap R_k} f_{jik} - x_{ik} = 0 \quad \forall k \in K, i \in I \tag{9}$$

$$\sum_{j \in AD_i \cap I_k} \left( f_{jik} + f_{ijk} \right) + \sum_{j \in AD_i \cap R_k} f_{jik} - M x_{ik} \leq 0 \quad \forall k \in K, i \in I_k \tag{10}$$

$$f_{ijk} \geq 0 \quad \forall i \in I, \forall j \in AD_i, \forall k \in K \tag{11}$$

The constraints that force development to be contiguous with already developed areas do this by constructing a tree whose root node is an already developed watershed, and other nodes are subwatersheds that the model chooses to develop. The logic is as follows. The model includes a flow variable for every adjacent combination of subwatersheds. Constraint 9 makes it impossible for a candidate subwatershed $i$ to be developed ($x_{ik} = 1$, $i \in I_k$) unless there is a unit flow from one or more adjacent subwatersheds. If that subwatershed $i$ is next to a subwatershed $j$ that is already developed ($j \in AD_i \cap R_k$), the model can set flow $f_{ji} = 1$ to allow $i$ to be developed. Alternatively, flow could come from an adjacent $j$ that was not previously developed, but is chosen to be developed by the model ($x_{jk} = 1, j \in AD_i \cap I_k$). Constraint 10 ensures that such a flow $f_{ji}$ can only be positive if that neighboring subwatershed is developed.

For example, consider two subwatersheds, 1 and 2, for which there will be two flow variables, $f_{12}$ and $f_{21}$. If a subwatershed is already developed, then no constraint 10 is imposed on flow variables out of that subwatershed, and they can be greater than zero. Say that subwatershed 1 is already developed; then $f_{12}$ can be greater than zero. Alternatively, if subwatershed 1 was not previously developed, but $x_{1k} = 1$, then Eq. 10 allows $f_{12}$ to exceed zero. But if instead $x_{1k} = 0$, then Eq. 10, instead, forces $f_{12}$ to equal 0; that is, all flows out of subwatersheds that are undeveloped must be zero. If the flow into an undeveloped subwatershed, say $i = 2$, can exceed zero, then Eq. 9 makes it possible to develop that subwatershed. On the other hand, if the inward flow is constrained to zero, then Eq. 9 forces $x_{2k} = 0$.

These constraints allow development chains; if a subwatershed is developed next to an existing development, then locations surrounding this new development can also be developed and so on. It can be readily verified that Eqs. 9–11 also ensure that clusters of undeveloped watersheds cannot be developed unless one or more are adjacent to an existing development. For instance, if neither subwatershed 1 nor 2 are adjacent to existing development or another subwatershed j with $x_{jk} = 1$, then there is no nonnegative combination of $f_{12}$ and $f_{21}$ that will allow $x_{1k} = x_{2k} = 1$ while satisfying Eqs. 9–10.

Note that if there is more than one type of development $k$, then Eqs. 9–11, as stated, will allow each type to occur only adjacent to existing development of that type. More general formulations are possible that allow more than one type of development to satisfy these contiguity constraints.

### 4.2 Perimeter Model: Constrains Development to a Specified Perimeter

This, the third model, chooses subwatersheds to be developed (PDAs) using two objectives: minimize the perimeter of the proposed development and minimize the weighted impact on the watershed. This formulation of the perimeter objective first appeared in Wright et al. [20]. The model allows planners to consider how different prioritizations between the two objectives affect the pattern and hydrological impacts of development. Like the adjacency model, this model results in less fragmented development than the basic model, making its solutions more realistic. The model is as follows:

$$\text{Min} \sum_{k} \sum_{i \in AD_j} B_i x_{ik} - 2 \sum_{k} \sum_{i \in AD_j} \sum_{j \in AD_i, j>i} \text{SB}_{ij} u_{ijk} \qquad (12)$$

$$\text{Min} \sum_{i \in I_k} \sum_{k \in K} (W_A A_{ik} x_{ik} + W_D D_{ik} x_{ik} + W_H H_{ik} x_{ik} + W_L L_{ik} x_{ik}) \qquad (13)$$

subject to:

$$\sum_{i \in I_k} \text{HA}_i x_{ik} \geq N_{\text{PDA},k} \qquad \forall k \in K \qquad (14)$$

$$2u_{ijk} \leq x_{ik} + x_{jk} \qquad \forall i \in I_k, \forall j \in AD_i, j > i \qquad (15)$$

$$\sum_{k \in K} x_{ik} \leq 1 \qquad \forall i \in I \qquad (16)$$

$$x_{ik} \in \{0,1\} \quad \forall i \in I_k, k \in K, \quad u_{ijk} \in \{0,1\} \quad \forall i \in I_k, \forall j \in AD_i, j > i, k \in K \qquad (17)$$

The new features of this model are decision variables $u_{ij}$ that indicate whether both $i$ and $j$ are developed, the perimeter objective Eq. 12, and the logical constraint 15. Because moving $u_{ij}$ from 0 to 1 will improve objective 12, $u_{ij}$ will always be chosen to be 1 if $x_i$ and $x_j$ are 1 (i.e., the highest value of $u_{ij}$ satisfying Eqs. 15 and 17 will be chosen). The perimeter objective 12 works by calculating the sum of all the borders of subwatersheds in the solution minus the borders that are shared with other subwatersheds in the solution. The resulting length is the perimeter, as all parts of subwatershed borders that are inside the developed area are subtracted [20].

Minimization of the perimeter is an economic objective as developing a compact and contiguous area is likely to be cheaper than fragmented development. Again, this is due to the reduced logistics and utility costs. However, focusing development might not only result in greater changes in overall watershed flows, but also concentrate the impacts in the developed subregion. Such concentrated impacts might be judged to cause greater damage to the watershed than fragmented solutions. Thus, in some applications, fragmentation may be desirable to limit this localized damage. To accomplish this in the model, the perimeter objective can be maximized rather than minimized; better yet, constraints could be placed on changes in flows in subareas in the watershed.

There are two approaches to solving this multiobjective problem: one is to weigh and combine the objectives, and the other is to constrain one while optimizing the other [7]. We adopt the latter approach because it is well-known that weighting may fail to uncover unsupported undominated points; the constraint method lacks this failing [7]. Such a point is a solution for which no other feasible solution is as good in all objectives, and strictly better in at least one (i.e., it is undominated), but the point is dominated by an infeasible convex combination of other feasible solutions.

To make tradeoffs between perimeter (Eq. 12) and ecological health (Eq. 13)—that is, to choose from undominated solutions—value judgments must be made. In theory, a multiattribute utility function could be elicited from managers or stakeholders, and the utility-maximizing solution chosen. However, this is usually impractical for local land use planning agencies, given the expertise and time required for valid elicitations. We suggest that the model be used in two ways: to develop undominated alternatives that represent different emphases upon the perimeter and hydrologic objectives and to investigate the sensitivity of perimeter changes on the metrics in the objective function. For example, if the basic model (Section 3.2) were to produce an optimal but fragmented development pattern, then the perimeter model might be able to find a solution with a lower perimeter but little degradation of the hydrological indices. Managers and stakeholders could also consider the tradeoffs between the two objectives, making judgments on whether a given reduction in the ecological health objective is worth the calculated improvement in perimeter.

### 4.3 PCA Assignment Model: The Relative Impact of Different Amounts of PCAs

In contrast to the above models, this, the fourth model, chooses the location of $N_{\mathrm{PCA}}$ km$^2$ of priority conservation areas explicitly assuming that development of $N_{\mathrm{PDA},j}$ km$^2$ of land will take place in the most harmful unprotected areas. By changing $N_{\mathrm{PCA}}$, a tradeoff curve can be formed showing potential avoided impact as a function of $N_{\mathrm{PCA}}$. This permits assessment of the effectiveness of different amounts of PCAs.

One theoretically appealing but impractical approach to this problem is to solve a multilevel model of the following form: choose the values of the binary decision variable $y_i$ (indicating whether or not $i$ is a PCA) that result in the least impact when a given amount of development takes place under the minimize perimeter objective, or some other proxy for development value that developers would maximize. Mathematically:

$$\mathrm{Min} \sum_{i \in I_k} \sum_{k \in K} \left( W_A A_{ik} x_{ik} + W_D D_{ik} x_{ik} + W_H H_{ik} x_{ik} + W_L L_{ik} x_{ik} \right) \tag{18}$$

subject to:

$$\sum_j \mathrm{HA}_j y_j \leq N_{\mathrm{PCA}} \tag{19}$$

$$x_{ik} \text{ solves problem } (12), (14), (15), (16'), (17) \tag{20}$$

where the revised constraint (16′) is $\sum_{k \in K} x_{ik} \leq 1 - y_i$, $\forall i \in I_k$. That is, development can take place in a sub-watershed $i$ only if it is not a priority conservation area. Constraint 20 says that the development decisions are the optimal solution for another optimization problem; hence, the "multilevel" structure of this optimization problem [7]. This is a type of Stackelberg game, in which the Stackelberg leader chooses the priority conservation areas, and the developers are Stackelberg followers who optimize their objective subject to the leader's decisions. The leader will choose PCAs to most effectively steer development in a less harmful direction, recognizing the relative economic value of different locations to developers. Similar models have been used, for instance, to analyze actions of industry and agriculture in response to government pollution and commodity policies (e.g., [9, 13])

In general, such multilevel optimization problems are extremely difficult to solve. This is particularly the case when the follower's problem (Eq. 20) is a mixed-integer problem because the trick of substituting the follower's first-order conditions for Eq. 20 is not possible because there are no first-order conditions for integer problems.

Therefore, we use a heuristic to preserve areas whose development would make the most impact. The model shown below assumes that there is only one type of development $k$; more general forms can be derived that permit differentiation among various development types. What the model does is select for hypothetical development a set of areas that maximizes hydrological impact, subject to a new set of constraints that prevents development of any areas with higher per unit (per km$^2$) impact. This can be viewed as an approximation of a "minimax" type of problem, where conservation areas are chosen to *minimize* overall impact of development under the assumption that developers will try to *maximize* its impact. The model is as follows:

$$\mathrm{Max} \sum_{i \in I_k} \left( W_A A_i x_{ik} + W_D D_i x_{ik} + W_H H_i x_{ik} + W_L L_i x_{ik} \right) \tag{21}$$

subject to:

$$\sum_{i \in I_k} \mathrm{HA}_i x_{ik} \leq N_{\mathrm{PDA},k} \tag{22}$$

$$x_{ik} \leq 1 - y_i \qquad \forall i \in I_k \tag{23}$$

$$\begin{aligned} &\left( W_A A_j y_j + W_D D_j y_j + W_H H_j y_j + W_L L_j y_j \right) / \mathrm{HA}_j \\ &\quad \geq \left( W_A A_i + W_D D_i + W_H H_i + W_L L_i \right) \\ &\quad \left( x_{ik} + y_j - 1 \right) / \mathrm{HA}_i \quad \forall i \in I_k, \forall j \in I_k \end{aligned} \tag{24}$$

$$\sum_j \mathrm{HA}_j y_j \geq N_{\mathrm{PCA}} \tag{25}$$

$$x_{ik} \in \{0, 1\} \qquad \forall i \in I_k \tag{26}$$

Constraint 22 makes sure that approximately $N_{\mathrm{PDA},k}$ units of land are developed to maximize the impact (Eq. 21), while constraint 25 ensures that at least $N_{\mathrm{PCA}}$ units of land are preserved. Constraint 24 ensures that the preserved land would have the highest impact per hectare, so that $N_{\mathrm{PCA}}$ km$^2$ maximizes the avoided impact. By parametrically increasing $N_{\mathrm{PCA}}$, the impact of the most damaging possible development is decreased.

It is also possible to enforce continuity of the hypothetical development with existing developed areas by adding constraints 9–11. Similarly, maximum perimeters could be enforced on the developed areas by adding Eqs. 12, 15, and 17, and then placing an upper bound on the perimeter. However, either addition would make an already large model even larger.

In a sense, Eqs. 21–26 is a multilevel model like Eqs. 18–20, except that the developer's objective is perversely to maximize hydrological impact rather than maximize development value. However, because of the inability to prove general results about multilevel-integer programs, we cannot claim that Eqs. 21–26 actually solves such a multilevel model to optimality; it is instead a heuristic.

This model is potentially useful if there are a relatively few sensitive locations in the watershed that if protected would have a disproportionate beneficial hydrological effect. A planning objective in this circumstance could then be to judiciously choose a few PCAs to minimize the maximum potential impact of watershed development. This model, like the others, has the shortcoming of requiring judgment on the part of the decision maker to assess what is a safe or acceptable level of impact to the watershed. However, when balancing the cost of PCAs and their effectiveness, it is certainly useful to understand what relative gains in watershed health can be achieved by increasing the area of PCAs.

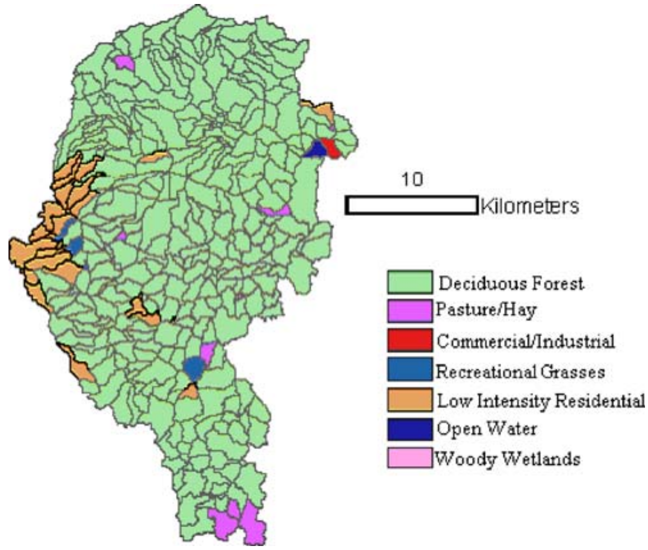


**Fig. 1** Chagrin Watershed, Ohio, subwatershed delineation and 1994 land use

## 5 Chagrin Basin Application: Model Development

### 5.1 Definition of Subwatersheds

The first stage of model construction is to define the subwatersheds themselves. In the Chagrin basin (Fig. 1), an average subwatershed size of 1km$^2$ was chosen. This size was a compromise between the desire to have very small homogenous watersheds as candidates for development with the need to keep the optimization and watershed models from becoming too large. Each subwatershed was selected, using the GIS capabilities of the watershed model we applied, to be a self-contained subwatershed of the entire watershed. All precipitation, in each of these areas, was assumed to either evaporate, enter stream channels, or percolate to ground water, with no groundwater movement across subwatershed borders. Once in the channel, flow is assumed to be conservative. More sophisticated assumptions are possible, and would be appropriate, for instance, for more arid climates.

Due to these assumptions, flows and hydrological indices derived from those flows are usually additive. For instance, an increase in mean flow in one subwatershed can be added on to the average flow rate for the entire watershed to find the average flow rate for the changed watershed.

Flow contributions from the subwatersheds were modeled using the Soil Water Assessment Tool (SWAT) [3]. We chose SWAT, as it is a distributed parameter watershed model that can be used to differentiate impacts resulting from development in different parts of a watershed. In SWAT, watersheds are conveniently disaggregated to subwatersheds, each with its own parameters.

### 5.2 Calculation of Taylor's Series Approximation of Hydrologic Impact

As there are 300 subwatersheds that can be developed, there are $2^{300}$ possible development patterns that in theory, could be considered. Of course, it is not possible to run the SWAT simulation for each combination; therefore, we used a linear approximation of the SWAT output as a function of land use changes. The contribution from a land use change $k$ in a given subwatershed $i$ to each hydrologic index is given by the following first-order Taylor's series approximation

$$H_n^{\mathrm{total}} = H_n^{\mathrm{total},0} + \sum_i \sum_k H_{ikn} x_{ik}, \tag{27}$$

where $H_n^{\text{total}}$ is the estimated value of the hydrologic index $n$ at the outlet of the watershed. $H_{ikn}$ is the change in the index $m$ resulting from a conversion of subwatershed $i$ to land use type $k$, and $x_{ik}$ has the same meaning as before: 1 if subwatershed $i$ is converted to land use type $k$; 0 if otherwise.

To determine $H_{ikn}$ for each subwatershed $i$, land use was changed for one $i$ at a time, and the SWAT model was rerun, calculating the flows and indices under that change. The resulting change in flows and indices compared to the base case was treated as the contribution from land use change in that single subwatershed. This procedure was repeated for each developable $i$.

Given those results, the impact of a given solution upon the index can be obtained as $\sum_i \sum_k H_{ikn} x_{ik}$ and inserted in the hydrologic objective function 1. To test the accuracy of the additive approximation of the SWAT model, several random land use patterns were input in to SWAT. These varied from changes in land use in one subwatershed to changes in the entire developable area. The resulting entire watershed metrics were compared to the result obtained from using the additive method. Figure 2 compares the SWAT output and approximations for two metrics: flow SD and average flow rate during the March–April spawning period.

The figure shows that for changes in land use between 0 and 100km$^2$ (about 16% of the watershed), the linear approximation is nearly identical to the SWAT model prediction. This shows that the approximation method would select the same set of optimal subwatersheds as a complex nonlinear model that explicitly incorporated the nonlinear dynamic equations of SWAT.

## 5.3 Calibration of the SWAT Model

Daily flows for the Chagrin River were used to calibrate the SWAT model following the procedure in the SWAT User Manual [14]. All data to run the model was collected and processed in ArcView 3.3 with the AVSWAT-X extension. Version 2005 of SWAT was used.

USGS land cover data from 1994 (shown in Fig. 1) and NRCS soil data [18] for Ohio was used for calibration. Because of the lack of recent land use data, this analysis is useful for illustrating the capabilities of the models, rather than actual PCA and PDA designation at this time. For each subwatershed, the dominant land cover and soil type were used. As the majority of the land cover in the watershed was deciduous forest in 1994, and therefore the major effect on flow characteristics was from rainfall on forested areas, only parameters relating to forest were adjusted for calibration.

Figure 3 compares observed and simulated data for the calibration period. This fit is comparable to that obtained in some other studies in the Lake Erie basin using SWAT (e.g., [10]), but is not entirely satisfactory for extreme low and high flows. This is important because those extreme flows affect three of the four proxies for ecosystem health (SD of daily flows, the average of the 10% lowest flows, the average of the 10% highest flows). Figure 3 reveals that the model has smoother low flow rates that are generally higher than the observed data, while peaks are higher than the observed data but are of shorter duration. Although the actual and simulated total water volumes are approximately the same, the model does not do as well at predicting the flow characteristics that matter to the health of the watershed and lake. Nevertheless, we believe that the model is still adequate for ranking subwatersheds in terms of *relative* hydrologic impact.

The relatively disappointing fit of the model might be explained in part by the lack of spatially disaggregated rainfall data. In the absence of complete rainfall records within the basin, rainfall within this watershed was interpolated from several rain gauges that lie outside the watershed. This led to peak flow rate events occurring in the simulated data that were not reflected in the observed data and vice versa. SWAT's interpolation method gave

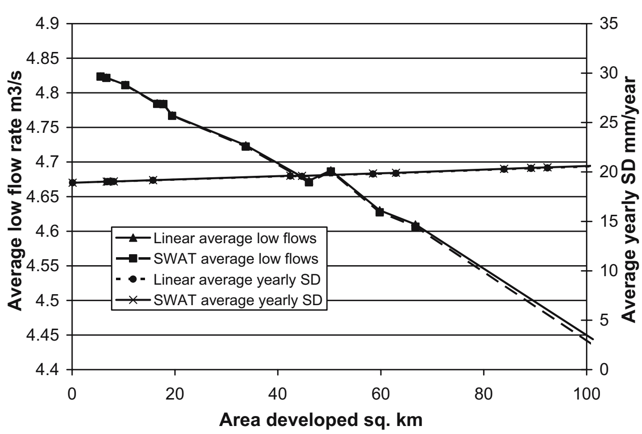


**Fig. 2** Comparison of SWAT model and Taylor's series linear approximation for random combinations of subwatersheds selected for development

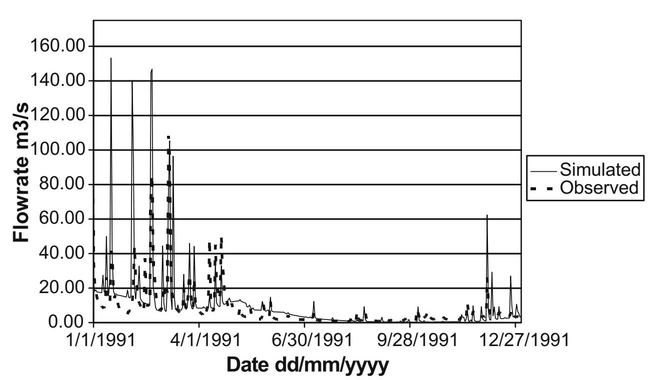


**Fig. 3** Comparison of observed and SWAT daily flows for 1991, calibration period 1989 to 1994

four different levels of rainfall intensity in four discrete bands. The average rainfall over 5years is shown in Fig. 4 for each band. Clearly, actual rainfall patterns across the watershed would be far more heterogeneous. This simplification of rainfall patterns could result in misidentification of the most sensitive areas for development.

Another simplification results from the lack of spatially disaggregated flow data. Calibration of different regions of the watershed with different parameters according to their unique conditions was not possible due to the presence of only one flow gauging station for the entire watershed. This meant, for example, that all parameters relating to forest cover were changed uniformly over the whole area during calibration. Although USGS land cover and soil data are useful for estimating parameters in the SWAT model, not all areas in the same classification will behave the same. With more gauging stations, better spatial estimation of parameters could have been achieved, and possibly, better identification of sensitive subwatersheds as well.

## 6 Chagrin Basin Application: Results

### 6.1 Basic and Adjacency Models

The basic model (Section 3) and the adjacency model (Section 4.1) are run first to designate priority conservation areas (PCAs) by maximizing the hydrological impact (1), (5), and then to designate priority development areas (PDAs) by minimizing that impact. To determine the sensitivity of each metric to land use changes, the models are run four times in each of those two modes, each time placing all the weight in the objective function on a different hydrologic metric. Table 1 summarizes the percentage change in the outflow of the watershed for each of those eight model runs. Each of the models is used to allocate 50km$^2$ of low intensity residential development, which is 8% of the entire Chagrin watershed. The PDA models represent the 50km$^2$ of development that cause the least impact to the watershed flow characteristics. The PCA models identify the 50km$^2$ having the most impact. The largest of these two models (the adjacency model) involves 1,967 continuous variables, 372 integer variables, and 1,070 constraints.

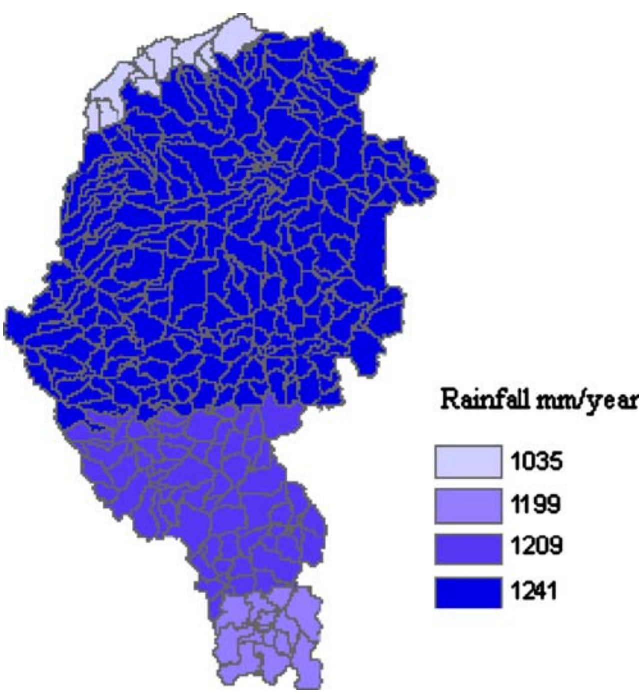


**Fig. 4** Average rainfall on the Chagrin over 5 years, derived by SWAT

The table shows that the metric that is most sensitive to land use change is low flows. The impacts under the PCA (worst) case are almost three times as large as the PDA (best) cases. The results show that the difference between developing a sensitive and insensitive area can affect low flows by over 5% for a 50-km$^2$ development.

The basic model (in PDA mode) gives the development pattern that will cause the least damage to the aquatic health of the watershed, as it has no other constraints other than minimizing impact. The impact on the watershed is higher when the adjacency constraint is imposed. This is seen in Table 1; for instance, low flows decrease by 3.16% in the PDA basic model solution, but decrease by 3.38% in the PDA adjacency model solution. However, the percentage difference between the basic and adjacency model is small across all metrics, indicating that requiring contiguity of development does not greatly increase hydrologic impacts. One reason for this is the abundance of subwatersheds available for selection when only 8% of the watershed is developed. Thus, managers and stakeholders have a lot of choice in where to locate PDAs.

The same is true for PCAs. Forcing PCAs to be adjacent to existing development protects areas that are nearly as sensitive as areas located anywhere in the watershed (basic model).

The model results presented in Table 1 are from runs with all the weight on one out of the four metrics. Figure 5 shows that the optimal development pattern under one metric is likely to differ from the pattern yielded by other metrics. Figure 5 shows graded watershed diagrams giving the percentage change across the entire watershed for each metric. The lightest locations are those that cause the least change when developed, while the darkest subwatersheds cause the most change.

The patterns of sensitivity are very different for each of the metrics. They follow several features. Boundaries between levels of sensitivity on the low flows (Fig. 5d) roughly follow those of the rain patterns. The same is true for high flows. Soil type also has a noticeable influence on

**Table 1** Percentage change in flow metrics for a 50-km$^2$ development on the Chagrin

| Weighting on | Basic model | | | Adjacency model | | |
|---|---|---|---|---|---|---|
| | PDA | PCA | Difference | PDA | PCA | Difference |
| High flows | 1.47 | 3.55 | 2.08 | 1.52 | 3.38 | 1.85 |
| Low flows | −3.16 | −8.82 | 5.66 | −3.38 | −8.68 | 5.30 |
| SD | 1.24 | 2.62 | 1.38 | 1.39 | 2.56 | 1.16 |
| Avg. runoff | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

both high and low flows impacts. The limited occurrences of land use other than deciduous forest have a strong influence on the metrics. For example, the bottom tip of the Chagrin watershed is pasture; all metrics are far less sensitive to development in this area than in the surrounding forest. SD and average flow rate are affected by the rainfall patterns and soil type as well, yet the effect is less apparent. Average flow rate shows signs of being affected by the rainfall gradient.

The results in Table 1 are for 50km$^2$ of development. In Fig. 6, we show analogous bounds for other sizes of development, ranging up to 400km$^2$, about half of the

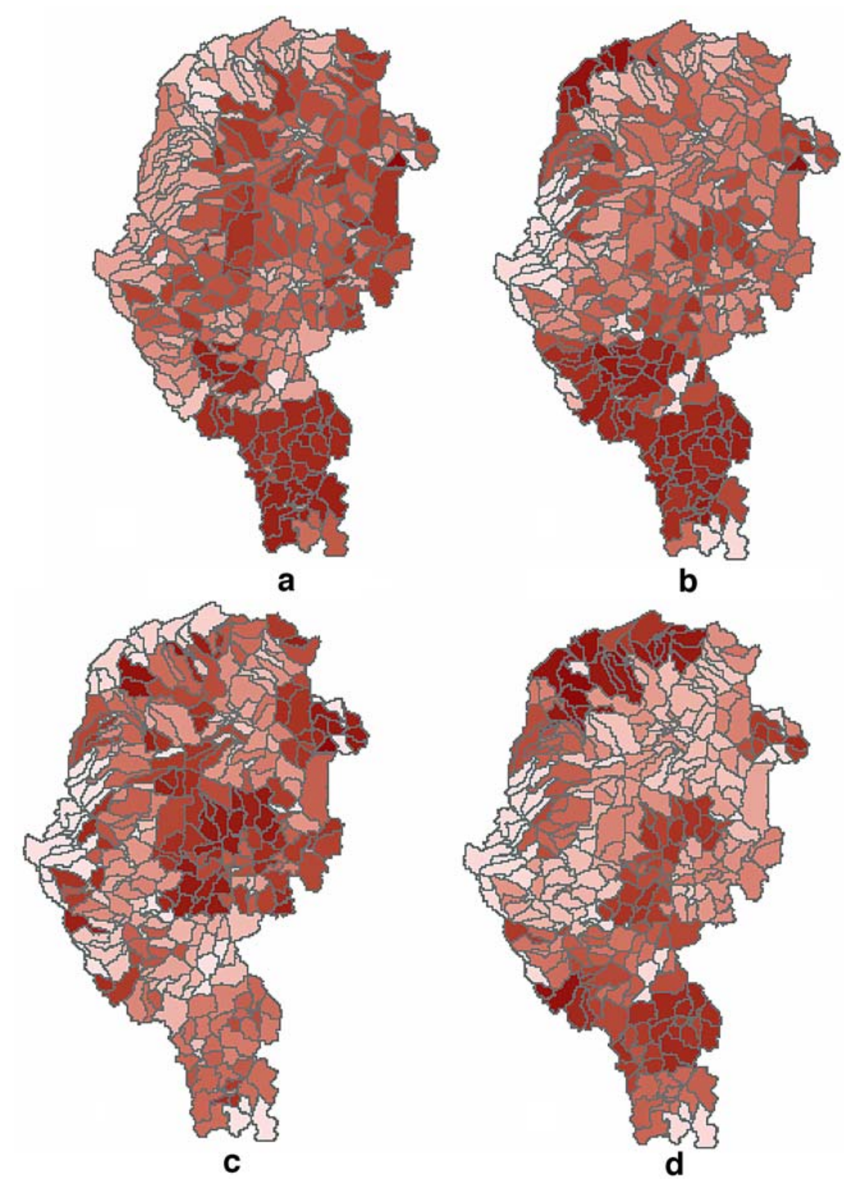


**Fig. 5** Graded percentage change in metrics from subwatershed development, darker is higher impact. **a** Average flows. **b** SD. **c** High flows. **d** Low flows

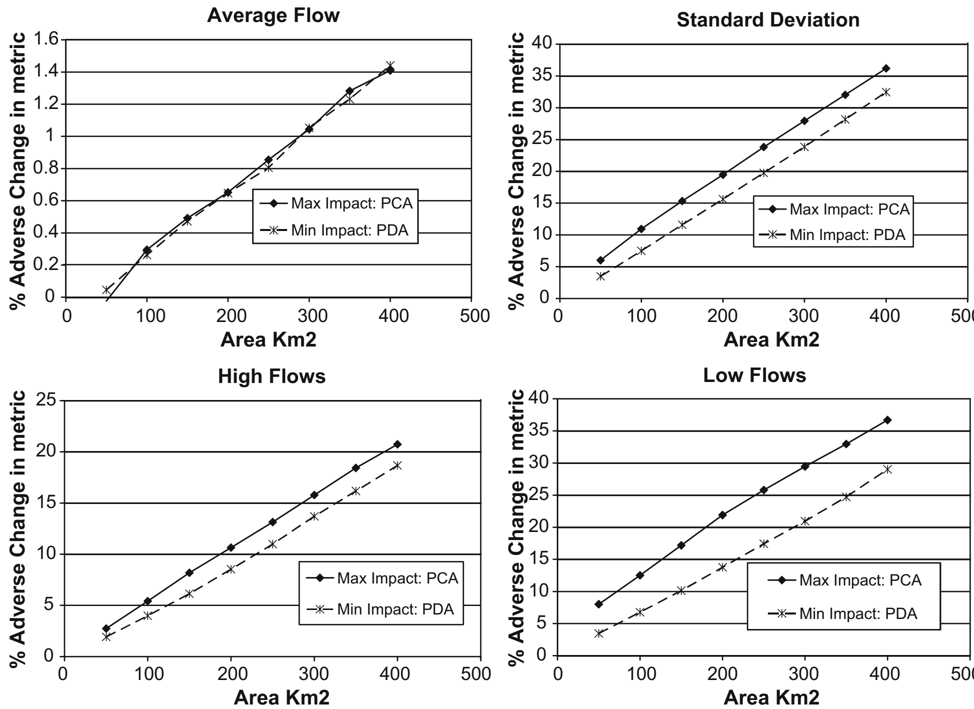


**Fig. 6** Percent change in metrics for different development areas, basic model with equal weights

watershed. These results are for the case of equal weights upon each of the metrics.

Figure 6 shows that average flow changes very little as developed area increases, largely because increases in high flows are offset by decreased low flows. There is little difference between the PDA and PCA cases; thus, the average flow metric does not discriminate between development in different areas. This suggests that average evapotranspiration is similar for different land uses.

Percentage changes in SD, high flows, and low flows all increase approximately linearly with developed area. The difference between the PCA and PDA cases for each of these metrics represents the maximum impact that can be avoided by laying aside the most sensitive areas as PCAs. The maximum difference between the PCA and PDA cases, indicating the largest possible effect of judicious PCA selection, is 3.7% for SD, 7.3% for low flows, and 1.9% for high flows.

## 6.2 Perimeter Model

Next, the perimeter model (Section 4.2) was run for a 200-km$^2$ development area, assuming equal weights on the hydrologic metrics. This model identifies PDAs that are relatively compact but have low hydrologic impact.

We find many alternative solutions with a low perimeter (i.e., high compactness) and similar objective values. For instance, the 200-km$^2$ of development found with the basic model has a perimeter of 913km. This can be reduced to 200km with the following increases in the impact indices: a factor of 1.004 for SD, a factor of 1.061 for high flows, and a factor of 0.992 for low flows. Thus, imposing the perimeter constraint increases high flow impacts the most, although not by a lot, while low flow impacts actually diminished slightly. Only after decreasing to a perimeter of 100km is there a modest increase in the hydrologic objective function. This is due to a notable rise in the percentage change in low flows alone. At 95km, the smallest feasible perimeter for 200km$^2$ of development, the change in low flows increases from 13.8%, in the unconstrained case, to 15.9%.

Figure 7 shows analogous results, but this time, for the case of a 50-km$^2$ development area. Low flows are plotted against perimeter for an objective in which 100% of the weight is placed on low flows. Again, imposing a compactness constraint upon PDAs does not significantly diminish low flows unless the constraint is very tight. The

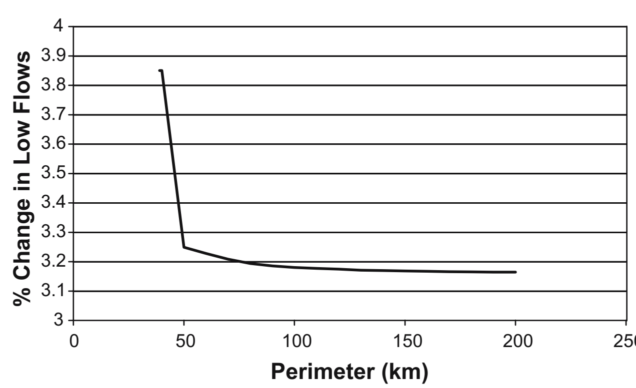


**Fig. 7** Percentage change in low flows against development perimeter for 50 km$^2$ development

relatively small increase in percentage change shows that there is flexibility in assignment of PDAs.

### 6.3 PCA Assignment Model

The information provided by the perimeter model can be useful to planners as Fig. 5 indicates that assigning PDAs is less important than assigning PCAs; there are many alternative PDAs that have similar effects. Once PCAs are assigned, development options are very flexible. The question then becomes: what area of PCAs should be assigned to adequately protect the watershed?

To find out, the PCA assignment model (Section 4.3) was run for different amounts of PCAs. Figure 8 below shows the tradeoff between area of PCAs assigned to the watershed and the impact of the most damaging 50km$^2$ development in the remaining subwatersheds. The model used placed equal weight on each of the metrics.

At 50km$^2$ of development, there is an obvious knee in the figure after which there is a long plateau. The plateau suggests that as the area of PCA sites is increased beyond 50km$^2$, there is little or no reduction in the impact of the worst possible development in the watershed. As the objective function decreases steeply as PCA area is increased from 0 to 50km$^2$, there are approximately 50km$^2$ of highly sensitive locations in the watershed. These results show that it is not worth protecting any more than 50km$^2$ of subwatersheds from an ecological perspective.

## 7 Conclusions and Future Work

Minimization of the relative impact on a watershed can be a useful tool for decision makers who are concerned with optimal siting of development within a watershed's borders. The formulations are flexible; different model objectives and constraints can be defined to suit different watersheds and the people living on them. The hydrologic indices are, of course, limited, in that they provide only a proxy for impacts on the aquatic ecology. However, using the model to analyze the impact of different development schedules can increase decision makers' awareness of the relative sensitivity of development across the watershed, and the options that are available to them to minimize its impact.

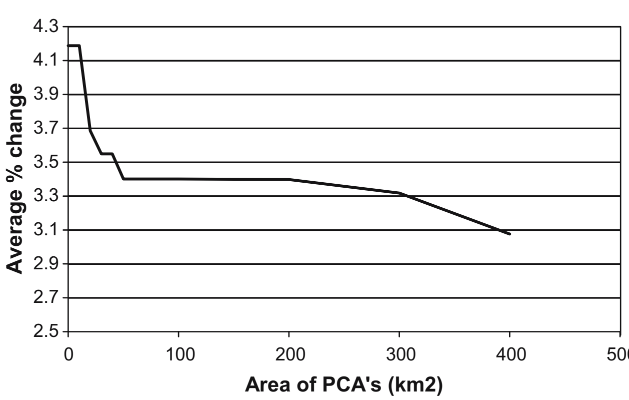


**Fig. 8** Impact of worst 50 km$^2$ development for different assigned areas of PCAs

If these models are to be actually used for planning in the Chagrin Basin or elsewhere, better data is needed. In particular, spatially disaggregated rainfall data, updated land use data, and consideration of multiple types of land development would be required.

A useful future development of these models would be the inclusion of another ecological health proxy in the objective: sediment runoff. This is a major concern for both fish habitat and lake water quality. Use of linear programming in watershed conservation has been applied before to minimize sediment loss [11]. However, developing reasonable models of watershed sediment loss as a function of land use is more difficult than calibrating flow models. The potential gains in information would have to be weighed against the cost of developing a more complex model.

A second useful addition to the models could be inclusion of a species protection model. This would combine the siting of PCAs with siting of nature reserves. If species protection is a priority, this combination might be more efficient than two separate assignments, as PCA subwatersheds could act as nature reserves. Desirable characteristics that could be represented can include reserve compactness and provisions for species migration [19].

The techniques proposed in this paper are not just applicable to the single watershed case; multiple watersheds can be considered if a means of commensurating the impacts in different watersheds can be devised. In theory, a lake and watershed-level ecological model could be used to link ecological health—in terms of ecosystem structure and function and population levels of individual species—to hydrology and habitat changes in the watershed. Efforts in this direction are reported in [2,12]. Such a capability would mean that judgments between different development scenarios would no longer be ordinal; rather than just saying one development is better than another, we could say by how much as well. It may then be possible to weigh ecological health against economic value of development, revealing how much watershed protection is worth.

Such a capability may also make it feasible to expand the scope of PCA and PDA designation. Under the present Ohio Balanced Growth Program, for example, Planning Partnerships at the watershed level are given responsibility for assigning priority areas. They can make relative assessments among subwatersheds on their own watershed using the methods in this paper. However, there is no way of comparing the impact of developments within different watersheds, even though a single metropolitan area may lie in several watersheds. Using an ecological model would allow such comparisons. Not only could this lead to better watershed protection, it could also make possible changes in the structure of the Balanced Growth Program. Administration of watershed protection could then occur at the metropolitan, Lake Basin, or even state level rather than watershed level. Questions of equity in assignment of protection might then be raised, as it may turn out that some areas require far more protection than others. Achieving balanced growth could become a difficult tradeoff between ecological health and equity in economic growth.

**Acknowledgments** This work was funded by EPA STAR Grant No. 8388101 and the National Center for Earthsurface Dynamics, a NSF Science and Technology Center. We thank our colleagues Justin Williams, Pearl Zheng, and Hong Li at the Johns Hopkins University and Joseph Koonce and Jon Cline at Case Western Reserve University for their suggestions and assistance with software and data.

## References

1. Aerts, J. C. J. H., Eisinger, E., & Heuvelink, G. B. M. (2003). Using linear integer programming for multi-subwatershed land-use allocation. *Geographical Analysis, 35*(2), 148–169.
2. Anderson, R. M., Hobbs, B. F., & Koonce, J. F. (2006). Modeling effects of forest cover reduction on larval Walleye survival in Lake Erie tributary spawning basins. *Ecosystems, 9*, 725–739.
3. Arnold, J. G., Srinavasan, R., Muttiah, R. S., & Williams, J. R. (1998). Large area hydrologic modeling and assessment—Part I: Model development. *Journal of the American Water Resources Association, 34*(1), 73–89.
4. Bernhardt, E. S. (2005). Synthesizing U.S. river restoration efforts. *Science, 308*, 636–637.
5. Binational Lake Erie LaMP Committee. (2000). *Lake Erie Lakewide Management Plan (LaMP)*, Ohio EPA, Columbus, OH (viewed 7/7/2007), www.epa.gov/glnpo/lakeerie/lamp2000/.
6. Chuvieco, E. (2005). Integration of linear programming and GIS for land-use modeling. *International Journal of Geographical Information Science, 7*(1), 71–83.
7. Cohon, J. L. (1976). *Multiobjective programming and planning*. New York: Academic Press.
8. Greenberg, H. J. (1995). Mathematical programming models for environmental quality control. *Operations Research, 43*(4), 578–622.
9. Guldmann, J.-M., & Shefer, D. (1977). Centralized air-pollution treatment and the optimal location of industries. *Environment and Planning A, 9*(10), 1121–1142.
10. Inamdar, S. (2004). *Sediment Modeling for the Buffalo River Watershed*. Report (viewed 06/30/2007), Buffalo State College, Buffalo, NY, www.glc.org/tributary/models/documents/BuffaloFinalReport_000.pdf.
11. Kaur, R., Srivastava, R., Betne, R., Mishra, K., & Dutta, D. (2004). Integration of linear programming and a watershed-scale hydrologic model for proposing an optimized land-use plan and assessing its impact on soil conservation - A case study of the Nagwan watershed in the Hazaribagh district of Jharkhand, India. *International Journal of Geographical Information Science, 18* (1), 73–98.
12. Kim, J. B., Hobbs, B. F., & Koonce, J. F. (2003). Multicriteria Bayesian analysis of lower trophic level uncertainties and value of research in Lake Erie. *Human and Ecological Risk Assessment, 9*, 1023–1057.
13. Migdalas, A., Varbrand, P., & Pardalos, P. M., (Eds.) (1998). *Multilevel optimization: Algorithms and applications*. Boston: Kluwer Academic Press.
14. Neitsch, S. L., Arnold, J. G., Kiniry, J. R., Srinivasan, R., & Williams, J. R. (2002). *Soil and Water Assessment Tool Users Manual Version 2000*. Texas Water Resources Institute, Chapter 33.
15. Nidumolu, U. B., van Keulen, H., Lubbers, M., & Mapfumo, A. (2007). Combining interactive multiple goal linear programming with an inter-stakeholder communication matrix to generate land use options. *Environmental Modelling & Software, 22*(1), 73–83.
16. Ohio Lake Erie Commission (2006). *Linking land use and Lake Erie: A planning framework*, (viewed 03/15/2007), www.epa.state.oh.us/oleo/bg1/documents/planningframeworklinking.pdf.
17. Tang, Z., Engel, B. A., Lim, K. J., Pijanowski, B. C., & Harbor, J. (2005). Forecasting land use change and its environmental impact at a watershed scale. *Journal of the American Water Resources Association, 41*(6), 1347–1360.
18. US General Soil Map. (2006). (viewed 05/11/2007), NRCS STATSGO, http://soildatamart.nrcs.usda.gov/USDGSM.aspx.
19. Williams, J. C., Revelle, C. S., & Levin, S. A. (2004). Using mathematical optimization models to design nature reserves. *Front. Ecol. Environ., 2*(2), 98–105.
20. Wright, J., ReVelle, C., & Cohon, J. (1983). A multiobjective integer programming model for the land acquisition problem. *Regional Science and Urban Economics, 13*(1983), 31–53.
21. Yeo, I. Y., & Guldmann, J. M. (2006). Land-use optimization for controlling peak flow discharge and nonpoint source water pollution. *Environment and Planning B: Planning and Design, 33*(6), 903–921.