ABSTRACT

Kuterdem, Can Ali. Integrated Watershed Management Using a Genetic Algorithm-Based Approach (Under the direction of Dr. Ranji S. Ranjithan)

Watershed management requires consideration of a multitude of factors affecting water quality at the watershed-scale while integrating point and non-point sources of pollution and control. While the existing water quality modeling systems and associated quantitative tools can assist in some aspects of Total Maximum Daily Load (TMDL) development for a watershed, their abilities to assist in determining efficient management strategies are limited. Typically, the best a user can do is employ these tools manually to explore the solution space via a trial-and-error process, which is inefficient for finding management strategies that consider water quality as well as a multitude of other design issues simultaneously. Recent implementation of the STAR (STrategy, Analysis, and Reporting) system incorporates a set of systems analytic tools to assist decisions-makers explore and identify alternative management strategies. The main engine of the STAR system is a genetic algorithm-based optimization technique, which is coupled with additional tools such as an uncertainty propagation tool, a solution reporting system, and an incremental strategy development system to form a decision support framework. This paper describes some of the capabilities of this framework through several illustrative scenarios for the Yellow River watershed in Gwinnett County, Georgia, which conducted a comprehensive, countywide TMDL investigation to assess the current water quality conditions. The STAR system's capabilities are employed to identify ways to achieve minimum total phosphorous (TP) levels via point and nonpoint source controls, as well as characterize the implications of future urban development on TP levels. Noninferior tradeoffs between urban development and TP levels at different degrees of point source controls are generated. The range of uses of the STAR system in considering the integrated effect of point and non-point sources in watershed management is demonstrated throughout these illustrative scenarios.

Integrated Watershed Management Using a Genetic Algorithm-Based Approach

by

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BIOGRAPHY

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1. INTRODUCTION

Traditionally, water quality problems in surface water systems have been addressed through managing point sources only. While controlling point source pollution has been successful in improving water quality in many cases, chronic water quality problems still exist. Non-point sources are more diffuse and are harder to identify, isolate, and control than point sources. It has been well documented that non-point source pollution such as nutrient runoff and atmospheric deposition contribute significantly to water quality problems (Jarrell 1999). Also, US EPA estimates that only 10 percent of impaired water bodies are attributed to point source pollution alone. Watershed scale management now requires an integrated approach that considers basin-wide water quality impacts of point and non-point source pollution and associated controls. This is reflected in US EPA's requirement for development of a total maximum daily load (TMDL) and a plan to achieve it in impaired watersheds. Basin-wide TMDL development and implementations are required to ensure that the water quality of a given watershed will not deteriorate in response to growth or other anthropogenic uses. Although many advances have been made in computing technology and state-of-art water quality modeling, identifying proper pollution reduction strategies for watershed management still remains to be a daunting challenge for environmental managers. Numerous studies have been reported in the last decade that describe improvements to methods and tools for watershed management (e.g., Yeh and Labadie, 1997; Cox and Madramootoo, 1998; Gu and Dong, 1998; Dupont et. al., 1998; Mailhot et. al., 1998; Chen et. al., 1999; Coburn, 1999; Xinhao et. al., 2000).

To assist states in their watershed management activities, US EPA is continuing to develop the software system Better Assessment Science Integrating Point and Nonpoint Sources (BASINS), which integrates hydrologic and environmental databases with water quality models within a geographic information system (GIS) (Lahlou et al., 1998). BASINS provides a framework for developing total maximum daily loads (TMDLs) at a watershed scale, enabling simulation of water quality using watershed models, such as Hydrological Simulation Program FORTRAN (HSPF) (Bicknell, 1997), and Soil and Water Assessment Tool (SWAT) (Arnold, 1997). Although BASINS facilitates specification of alternative pollutant loading scenarios and evaluation of resulting water quality, the search for good management strategies that specify pollutant reduction allocations among the sources and the associated need for best management practices (BMPs) requires a trial-and-error approach. In addition, systematic consideration of other implications, most importantly the costs of watershed-scale pollution reduction strategies, is not supported.

Mathematical modeling is used to represent the search problem for which the solution characterizes a feasible set of decision variable values that meet the objectives and constraints embedded in the model. Depending on the structure of that model and the types of functions used to describe the problem, different solution approaches, or algorithms, are used to determine the optimal solution. The watershed management problem can be represented via such a model, which requires representation of the pollution transport and chemical transformation processes that are typically non linear. Further, any realistic watershed management problem has a large number of feasible solutions, making trial-and-error search procedures inefficient. Systematic search via a formal algorithm is needed. The nature of the mathematical functions used to define this problem generally renders traditional search algorithms poorly applicable. Emerging contemporary optimization procedures, such as genetic algorithms (GA's), simulated annealing (SA), ant colony algorithm, and particle swarm optimization, offer alternative means for solving optimization models that are inherently discontinuous and non-linear (Michalewicz, 1996). These heuristic techniques allow integration of the complex simulation models that include nonlinear and discontinuous relationships directly into the optimization process. In the case of watershed management, a comprehensive water quality model like HSPF could be used instead of relying on their reduced-form mathematical representations. Several studies describe the utilization of such search algorithms for solving environmental management problems (e.g., Harrell and Ranjithan, 1998; Matthews et. al., 1999; Murray, 2000; Loughlin et. al. 2000).

The existing watershed management capabilities within BASINS are extended using a set of decision support tools that are implemented within the STAR (STrategy, Analysis, and Reporting) system (Dorn et al., 2001). A genetic algorithm-based search procedure forms the primary engine of the STAR system. This is coupled with additional tools, including an uncertainty propagation tool, solution reporting system, and an incremental strategy development system, to form a highly interactive decision support framework. The STAR system facilitates a systematic approach for developing watershed management strategies for point and nonpoint source controls to meet specified watershed-scale water quality targets while enabling consideration of cost and uncertainty. Murray (2000) demonstrated the applicability of the STAR system in developing TMDL's through a realistic illustrative case study. The focus of this study was identifying appropriate future land use allocations with nonpoint source controls for the Suwanee Creek watershed in Gwinnett County, Georgia under different water quality targets. The point source control capabilities were not explored or tested. The purpose of the work presented in this paper is to demonstrate the applicability of the STAR system in studying a realistic watershed management problem that requires the consideration of both point and nonpoint source controls. Data from a recent EPA TMDL study for the watersheds in the Gwinnett County, Georgia were used to construct an array of illustrative watershed management scenarios, which are then solved using the capabilities of the STAR system.

2. BACKGROUND

The STAR system consists of the following major components: a set of input graphical user interfaces (GUIs) for defining the watershed management problem; a systematic search procedure using genetic algorithms (GAs); uncertainty propagation procedures; a flexible linkage of these procedures to watershed water quality models; a set of GUIs for solution display; and an interactive interface for incremental what-if analysis. These components are implemented using the Java programming language, and are embedded within the STAR system. In addition to being able to function in a stand-alone mode, a version of STAR is also integrated with BASINS such that a user could employ the HSPF watershed model available within BASINS. Detailed descriptions of this framework are provided by Parandekar (1999).

In this study, STAR's GA-based search capabilities along with the GUIs for problem definition and solution display, as well as the incremental strategy development capabilities, were utilized. The GUIs enabled the definition of the range of watershed management scenarios that considered nonpoint source control via riparian buffer strips, multiple instream water quality parameters, and changes in land use allocation to accommodate growth. The general structure of the search (optimization) procedure is shown in Figure 1. The HSPF model was coupled with this search procedure to determine the water quality parameter values.

HSPF is a continuous, lumped parameter model, which simulates the hydrology over pervious and impervious land segments, and the physical and chemical processes within a stream (Bicknell, 1997). HSPF consists of three types of zones: pervious land segments (PERLND), impervious land segments (IMPLND), and reaches (RCHRES). Each zone produces outflow, which is evaluated at a node. The area between two nodes is defined as a reach (Bicknell, 1997). Runoff and pollutant loading from the land area in each reach is attributed to the corresponding node. Each reach has inflows from the associated land segments and any upstream reaches. The processes modeled within the reach affect outflows from a reach. HSPF usually models long continuous simulations, sometimes over a few years, although it is capable of simulating storm events.

HSPF is effective in modeling the water quality for existing and future conditions. If the resulting water quality, however, violates the given water quality standard, the effectiveness of pollution reduction strategies could be simulated using HSPF. Along with point source controls, nonpoint source pollution is often curbed using BMPs, including detention ponds, buffer zones, and alternative agricultural crop management practices. Through appropriate land use planning, nonpoint source pollution can be controlled so that future water quality is not put at risk. HSPF's capabilities collectively enable modeling of water quality impacts due to changes in land use allocations within each subwatershed, facilitating investigations of development plans considering BMPs and water quality at a watershed scale. Similarly, controls on point source pollution could be incorporated. According to a given treatment or pollution reduction efficiency, the loading from the point source is appropriately discounted during the water quality simulations. By specifying different treatment efficiencies at the various point sources, different point source control scenarios can be simulated to study their impacts on water quality.

Coupling of HSPF with a systematic search procedure as shown in Figure 1 allows the user to define an array of water quality and land use development goals. For example, values of pollutant concentrations modeled within HSPF can be minimized or the area of urban land use types can be maximized. Constraints can also be imposed to achieve required water quality or development targets, enabling the user to examine tradeoffs among competing objectives. For example, water quality can be constrained to a desired level while determining the maximum allowable development in a watershed. Alternatively, constraints can be imposed to limit the amount and type of development, either for any subwatershed, or for the entire watershed. The first type of land use constraints can be used to restrict conversion of an area from one type of land use to another. For example, the user may prevent development in any natural wetlands. The second type of land use constraints can be used to prevent unreasonable growth or depletion of a certain land use. For example, urban land in the future development plan may be limited to a maximum percentage of the watershed. Similarly, constraints can be imposed on point source controls to ensure a certain level of reduction in discharge at any point source.

These capabilities of the STAR system were utilized to implement the scenarios considered in this study, and to solve them using the GA-based search procedure embedded within it.

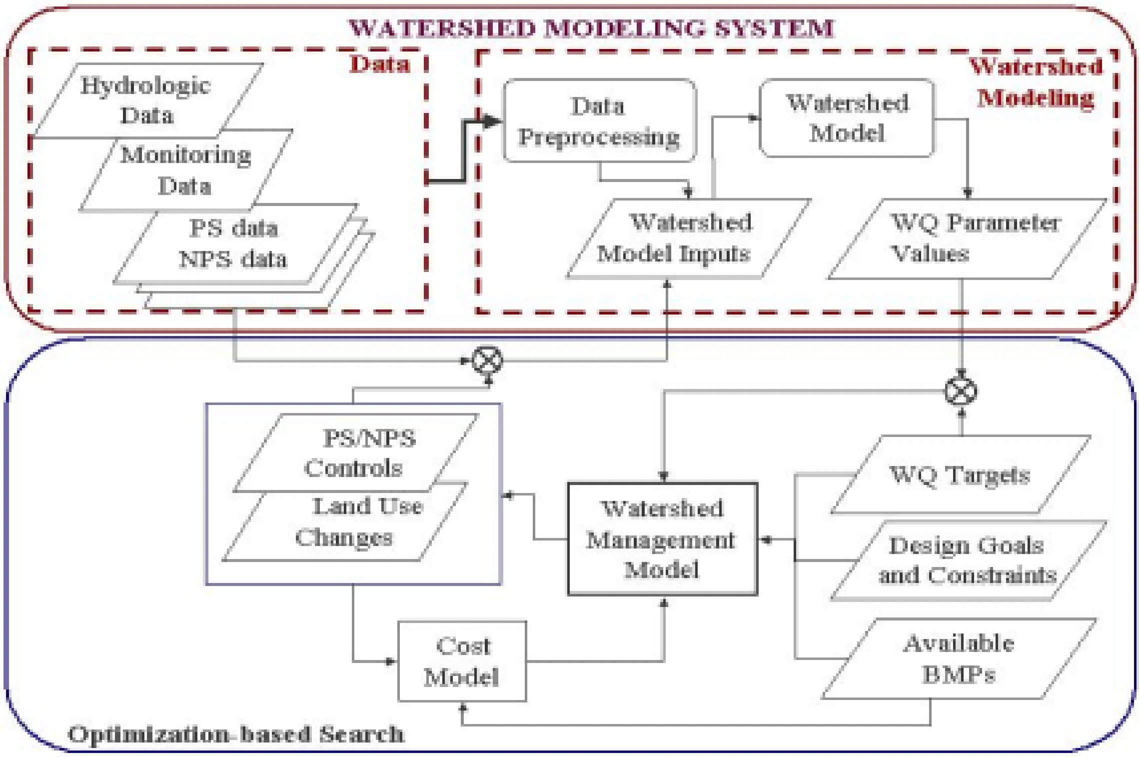

Figure 1 – A schematic diagram of the optimization component within the STAR System for watershed management. Current implementation links the HSPF model.

3. THE STUDY AREA

To illustrate the integrated watershed management capabilities of the STAR system, a case study for the Northwest portion of the Yellow River watershed was conducted with the help of a calibrated HSPF watershed model for this area. The Yellow River watershed, which is a part of Ocmulgee River Basins, was modeled as a part of a countywide watershed assessment and modeling study to evaluate water quality in all major stream systems in the Gwinnett County, Georgia (Tetra Tech, Inc., 1999). This county expects urbanization in the next 20 years, potentially increasing the nutrients and total suspended sediments (TSS) loadings that are currently of concern in this watershed. Identifying strategies that preserve the water quality while sustaining the development was one of the main goals of the work presented here.

The study area includes the drainage basin covering the Northwest portion of the Yellow River system starting from Beaver Ruin Creek and extending to Sweetwater Creek, Jackson Creek (Dekalb Co.) till Jackson Creek at Arcado Rd. (Figure 2). The study by TetraTech, Inc. calibrated the HSPF model for flow, temperature, sediments, dissolved oxygen, biochemical oxygen demand, nutrients and metals. The calibration data was based on monitoring information for the period January 1993 to December 1998. The study area includes approximately 44,460 acres (68 square miles) located northeast of metropolitan Atlanta, and it is subdivided into five sub basins. Three point sources are located within these five sub basins (Figure 2).

Although the model characterizes an array of pollutants, the current study focuses on TSS and total phosphorous (TP), the pollutants for which TMDL development is currently underway. Based on recent studies, a loading rate of 1,600 lbs/ac/yr of TSS in each sub basin has been identified as an acceptable target to meet desired TSS levels in the stream.   Although no specific loading rate for TP is set yet, the goal is to minimize the TP loading as well as to study the variation of TP loading with different urban growth levels.

To represent the non point source loading from the land cover in the basin, the study area was characterized by 17 different land use types (Table 1). The data for this characterization was produced from the 1995 ARC land use coverage and the 1997 Gwinnett County land use coverage developed by Gwinnett DOT (Tetra Tech, Inc., 1999). In the illustrative study presented in this paper, land use types of similar characteristics were grouped together to form a reduced set of eight land types (Table 1). Two new land use types were also introduced to represent future urban areas (namely high density residential and office parks) with buffer strips as BMPs for nonpoint source control. In all scenarios analyzed here, urban development is represented by the sum of the acreages allocated to the following land use types: high-density residential, low-density residential, office parks, roads, high-density residential w/ buffer and office parks w/ buffer. Table 1 shows the original acreages of the land uses in each subwatershed as well as the total acreages at the watershed level.

Discharges from three point sources (Figure 2) are modeled in this study. The Gwinnett Co. Beaver/Sweetwater wastewater treatment plant and the Jackson Creak wastewater treatment plant discharge TSS and phosphorous, as well as CBOD, fecal coliform, ammonia, and zinc. The third point source, the technical alloy company, has no reported pollutant discharge.

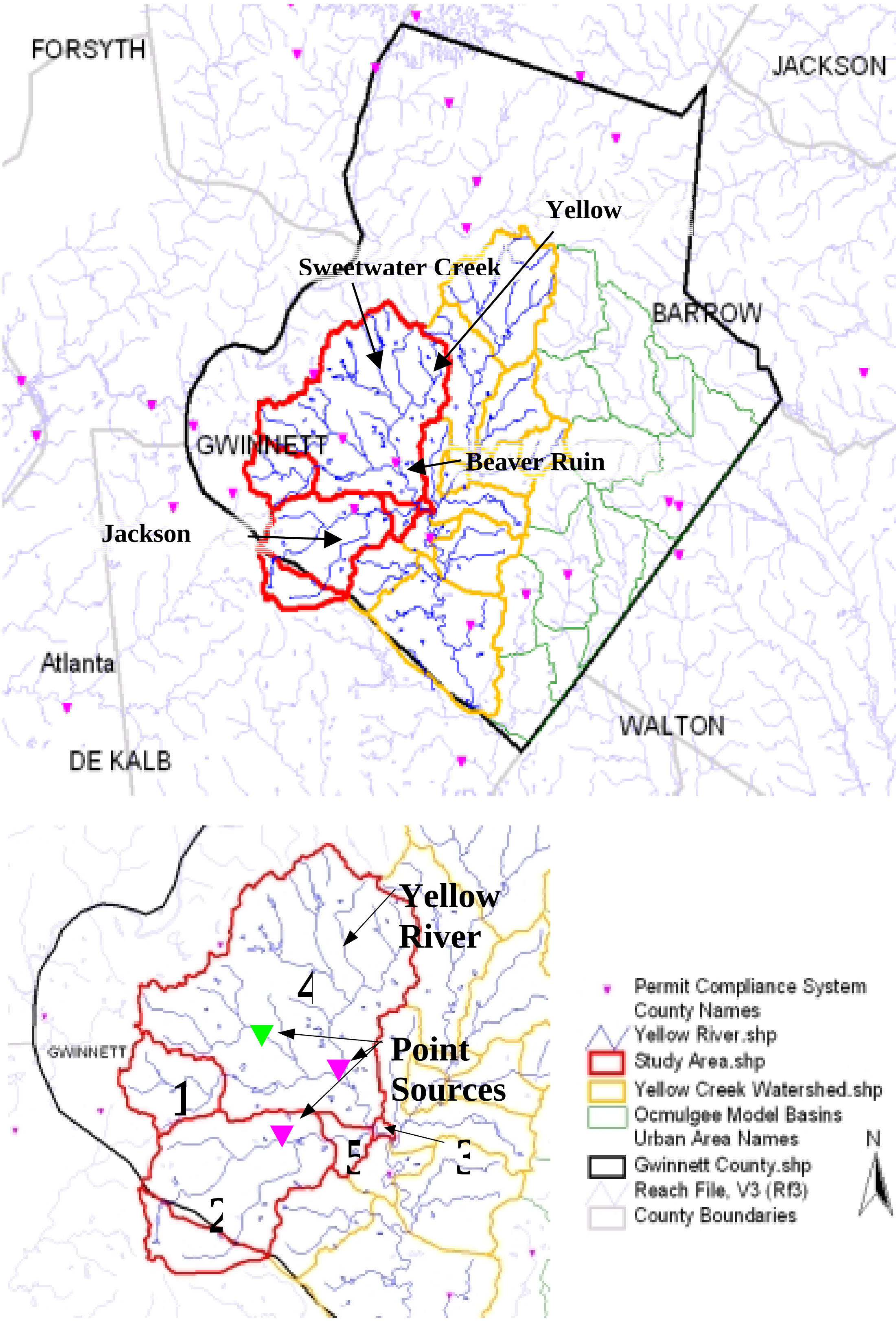

Figure 2 - Yellow Creek Watershed

Table 1 - Land use allocations

Land Use Types		Subwatershed Areas (ac)					Total Area (ac)	% of Watershed
Considered	Existing	1	2	3	4	5		
Agricultural	Agricultural	0	71	0	16	0	87	0
Vacant	Vacant	627	3344	13	5657	124	9764	22
High Density Residential	High Density Residential	206	494	0	1062	0	1761	4
Estate Residential	Estate Residential	10	522	8	2713	80	3332	7
Low Density Residential	Low Density Residential, Middle to Low Density Residential and Middle Residential	906	5238	95	8125	428	14793	33
Office Parks	Commercial, Heavy Industrial, Institutions and Public Uses, Light Industrial, Multi and Mix Use Industrial, Office Parks	1202	1329	2	5016	231	7780	17
Parks and Recreation	Parks and Recreation	44	303	34	728	9	1118	3
Roads	Pavement, Transportation, Communication and Utilities	703	1391	38	3516	179	5827	13
Total	Total	3699	12692	190	26830	1051	44462	100

4. CASE STUDY SCENARIOS

As stated in the Gwinnett County Watershed Protection Plan, development is expected in residential and commercial sectors within the next 20 years. It is evident that development and growth have adverse effects on the water quality due to increase in point and non-point source loadings. Scenarios were constructed to identify point and nonpoint source pollution control strategies that would facilitate increased urban development while meeting the water quality goals in the watershed. As TSS in the Yellow River watershed is already identified as a critical pollutant and associated loading targets have been set, the scenarios analyzed here were constrained to meet those targets. The recent Watershed Protection Planning study specifies a countywide TSS loading target of 1600 lbs/ac/yr. The corresponding in-stream allowable TSS amounts at the outfall of each subwatershed were estimated using the calibrated HSPF model (Table 2). When calculating the allowable amounts within a subwatershed, the loading associated with drainage from upstream subwatersheds into that watershed is appropriately added. As an example, subwatershed 1 in the study area contributes to the annual sediment loading at the outlet of the subwatershed 4. Thus, the TSS target for the subwatershed 4 is calculated by accounting for the TSS loading from the contributing areas in subwatersheds 1 and 4. A comparison of current and allowable TSS amounts (Table 2) indicates that reductions in TSS loadings are necessary. In the following scenarios, these allowable instream TSS amounts were imposed as constraints when identifying point and nonpoint source control strategies.

Table 2 - Current and allowable instream TSS amounts

Subwatershed	Area (ac)	Annual Allowable Instream TSS Amounts (tons/yr)	Original TSS Loadings (tons/yr)
1	3699	2959	3017
2	12692	10154	11268
3	190	35569	36288
4	26830	24423	24787
5	1051	10994	11604

Although no specific TP loading target is identified for this watershed, it is assessed that current loadings (Table 3) are higher than what could be sustained at downstream locations. The scenarios described in the following sections attempt to improve upon current loading rate and minimize TP loading at the outfall of the study area, i.e., at the outlet of subwatershed 3, from future urban development. These scenarios are also used to examine the tradeoff among urban development, TP loading, and point and nonpoint source reductions. Buffer strips as BMPs in new urban areas and treatment technologies to reduce point source loadings are considered.

Table 3 - Current instream total phosphorous amounts

Subwatershed	Area (ac)	Original Total Phosphorous Loadings (lbs/yr)
1	3698.8	4123
2	12692.0	18226
3	189.9	46142
4	26830.1	26781
5	1050.7	19220

4.1 Watershed Management Strategies to Minimize Total Phosphorous

To set a benchmark for the lowest TP at the outfall (subwatershed 3) of the study area, the optimization capability of the STAR system was applied to identify a watershed management strategy that considers only retrofitting existing urban areas with buffer strips. To ensure realistic land use changes and future land use allocations, land use conversion restrictions were imposed. This prevented conversion of developed land areas to be converted back to undeveloped areas (e.g., residential areas cannot be converted to forest land). Additionally, limits on allowable percentage of land use areas in each subwatershed were imposed as shown in Table 4. Also, to avoid excessive conversion of existing low density residential areas to high density with buffer, the acreage for low density residential was not allowed to decrease below 50% of the existing acreage for low residential land use type. Constraints on TSS amounts at the outlet of each subwatershed (as shown in Table 2) were also imposed. Maximum treatment efficiencies at the point sources were set at the following discrete levels: 0%, 30%, 60%, and 90% reduction.

Table 4 - Allowable maximum percentages of land use development

	Subwatershed					
Land Types	**1**	**2**	**3**	**4**	**5**	**Total Area**
Agriculture	3	3	3	3	3	3
Vacant	20	30	20	30	20	29
HDR	25	25	25	25	25	25
Estate	15	15	15	15	15	15
LDR	50	60	70	50	60	53
Office Parks	50	30	15	30	30	32
Parks	2	10	30	10	10	9
Roads	30	30	30	30	30	30
HDR Buffer	25	25	25	25	25	25
OP Buffer	25	25	25	25	25	25

4.1.1 Minimizing TP w/o Point Source Controls

In the first scenario, TP was minimized using only retrofit of existing urban land areas allocated to high density residential and office parks land use types. No point source controls were considered. This represents the scenario that attempts to improve the TP amounts via nonpoint source controls only. The resulting land use allocation is summarized in Table 5 and is illustrated in Figure 3. As expected, higher TSS and TP loadings from low-density residential land areas are reduced by converting those areas to high density residential and office park areas with buffers. This behavior was expected because the buffers curb the phosphorous loadings by reducing the initial phosphorous storage capacity of impervious land and allowing less TSS, as well as the attached phosphorous, to runoff into the stream network over the pervious land. The Figure 4 presents the resulting allocation with respect to the original development.

Table 5 - Land use allocation for minimizing total phosphorous

	Original Allocation		Land Use Allocation for Minimizing TP w/o Point Source Controls		
Land Type	**Acreage of Watershed Area**	**Percent of Watershed**	**Acreage of Watershed Area**	**Percent of Watershed**	**Percent Change**
Agriculture	87	0	43	0.1	-51
Vacant	9764	22	9706	21.8	-1
HDR	1761	4	1282	2.9	-27
Estate	3332	8	2815	6.3	-16
LDR	14793	33	7957	17.9	-46
Office Parks	7780	18	6715	15.1	-13
Parks	1118	3	874	2.0	-22
Roads	5827	13	5874	13.2	1
HDR Buffer	0.0	0.0	5269	11.9	NA
OP Buffer	0.0	0.0	3928	8.8	NA

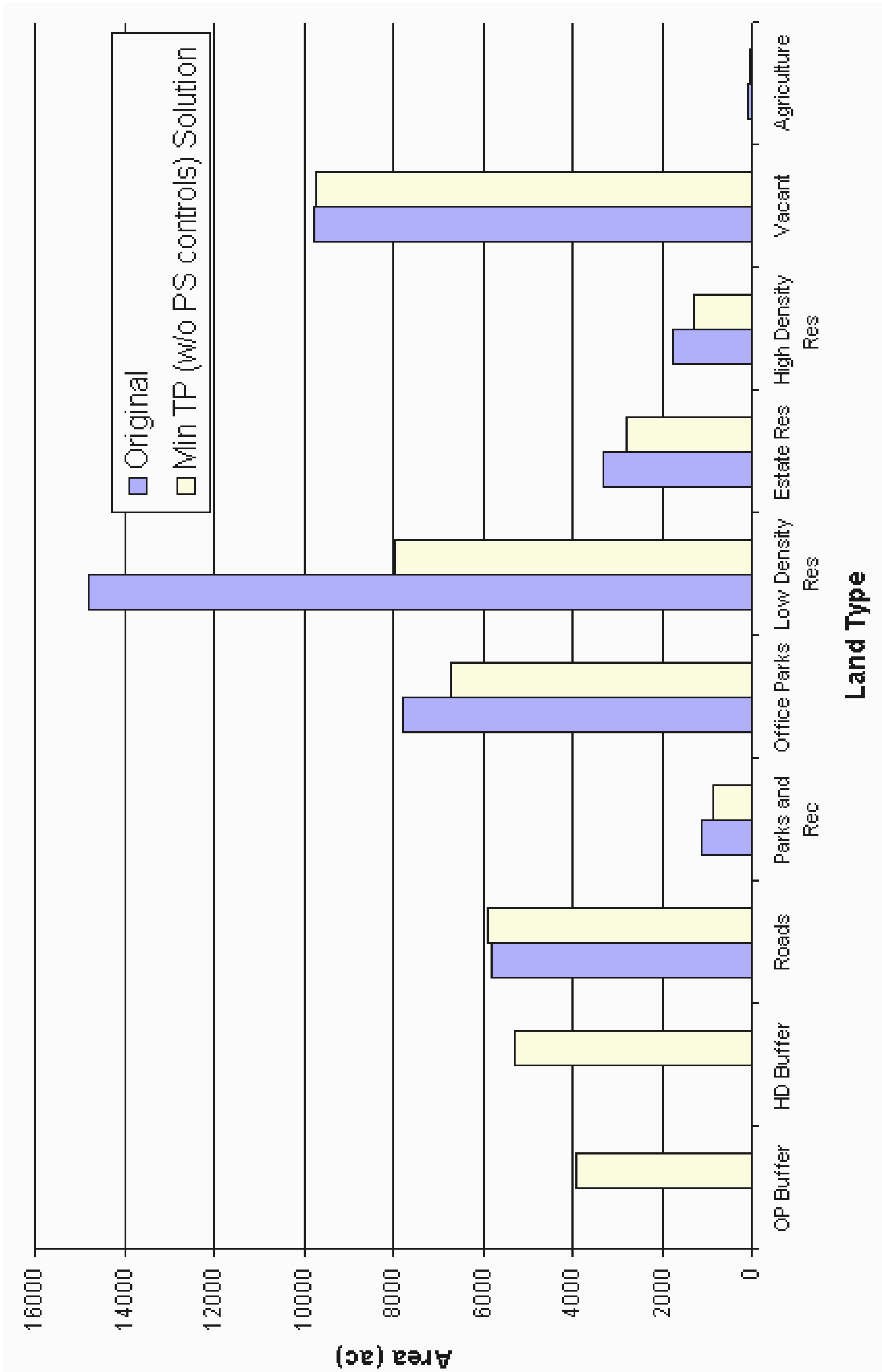

Figure 3 - Land use allocation for minimizing TP w/o point source controls

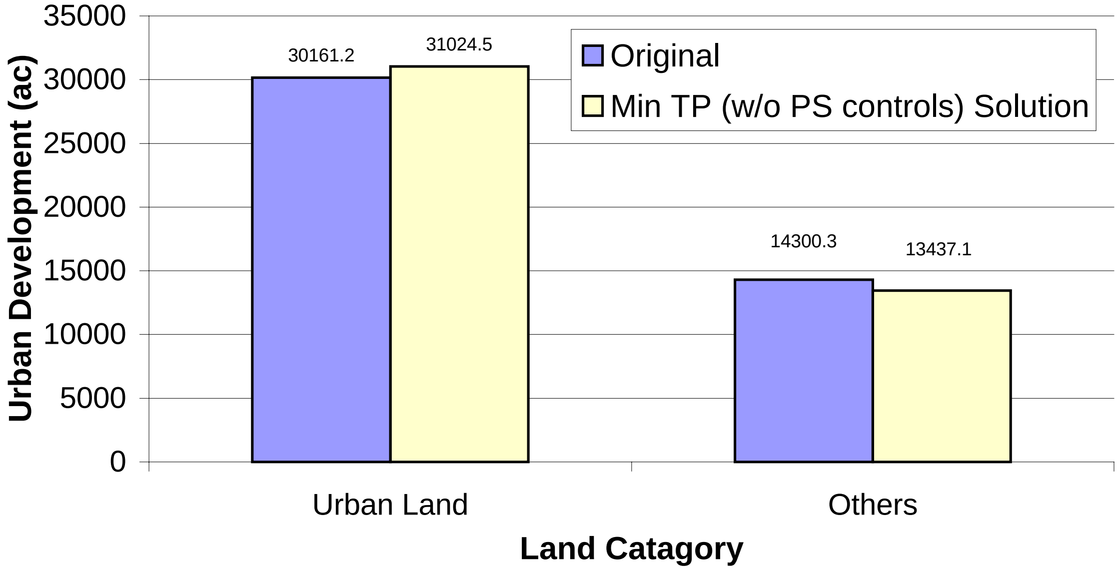

Figure 4 - Urban development when minimizing TP w/o point source controls

4.1.2 Minimizing TP with Point Source Controls

The previous scenario that identified the nonpoint source control options without any point source controls to minimize TP was extended to study the improvements in TP that may be achieved via increased point source controls. The previous model was modified by adding a new constraint that required the point source controls to be applied at varying (discrete) levels—30%, 60%, 90%—of phosphorous treatment at all point sources. Again, the optimization capability of the STAR system was used to solve these updated models. The results are summarized in Figure 5. As anticipated, the results show a diminishing rate of return in TP improvement with increasing point source controls. This behavior could be explained by the non-linear instream chemistry of the phosphorous related to algae uptake and decay coefficients. The best achievable instream phosphorous amount (at the outfall of subwatershed 3) is 28,215 lbs/yr. This value along with the corresponding value (i.e., 46,142 lbs/yr) under current loading conditions (Table 3) define the range of TP targets to be achieved in the urban development scenarios described below.

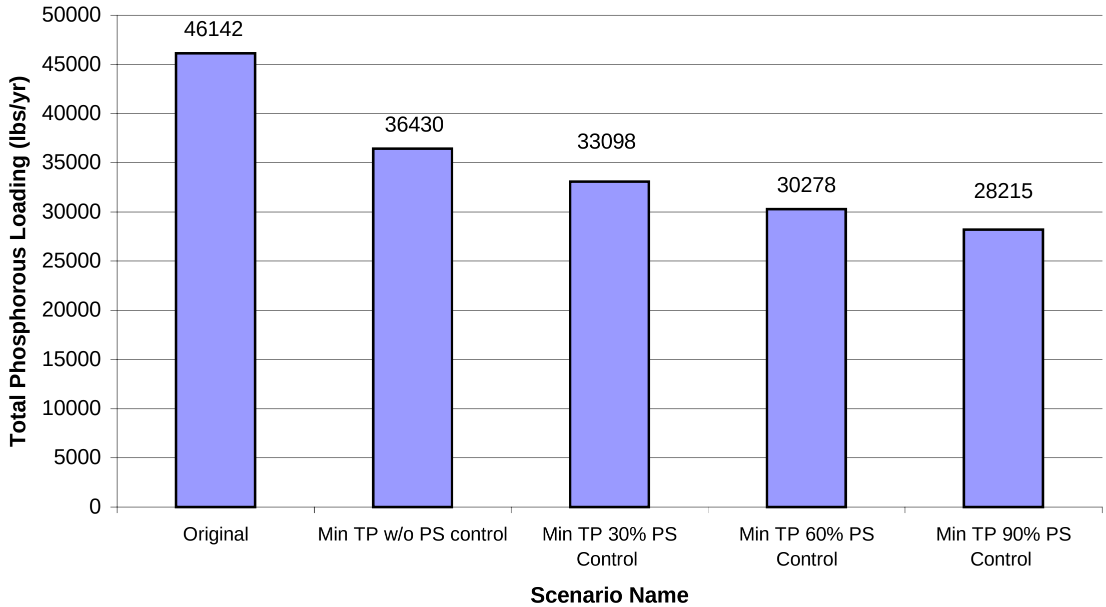

Figure 5 - Minimum achievable TP at the outlet with varying PS treatment levels

4.2 Watershed Management Strategies under Urban Development Scenarios

To provide insight into how much urban development could be allowed and how that affects TP at the outfall, a series of scenarios was defined. In these scenarios, while ensuring the TSS targets and land use conversion constraints, the urban areas are maximized under varying point source control levels and TP amount at the outfall. Land types that contribute to the urban category are high-density residential, low-density residential, office parks, roads, high-density residential with buffer and office parks with buffer. Using the results from the results discussed in Section 4.1, discrete TP levels, as shown in Figure 5, were used to define different scenarios. Similarly, the point source control levels were set at different discrete levels (30%, 60% and 90% treatment efficiencies). Different combinations of these discrete levels were used to define different models, and their solutions describe the tradeoff between urban development and TP amount at the outfall.

4.2.1 Maximizing Urban Development to Meet a TP Target of 36,430 lbs/yr

In this scenario, urban development plans at different point source treatment levels were identified, and the results are summarized in Figure 6. As indicated by the tradeoff in these results, the rate of increase in urban development with increasing point source treatment levels diminishes.

The land allocations for these three scenarios are plotted in Figure 7. In general, as more point source treatment is allowed, the conversion of low density residential area to office parks with buffer and high-density residential with buffer decreases. Although the overall urban areas change in the desired direction, the high-density residential allocation for the scenario at 60% point source treatment does not follow a trend (Figure 7). This specific case was examined further using the incremental analysis component of the STAR system. An alternate land allocation that uses 1000 acres less of high-density residential area (and correspondingly 1000 acres more of low-density residential area) was identified. The associated change in the TP loading was approximately 1%, indicating the presence of alternative urban development plans that meet the modeled water quality targets within reasonable limits. A formal technique like modeling to generate alternatives (MGA) approach could be employed to explore such alternative solutions.

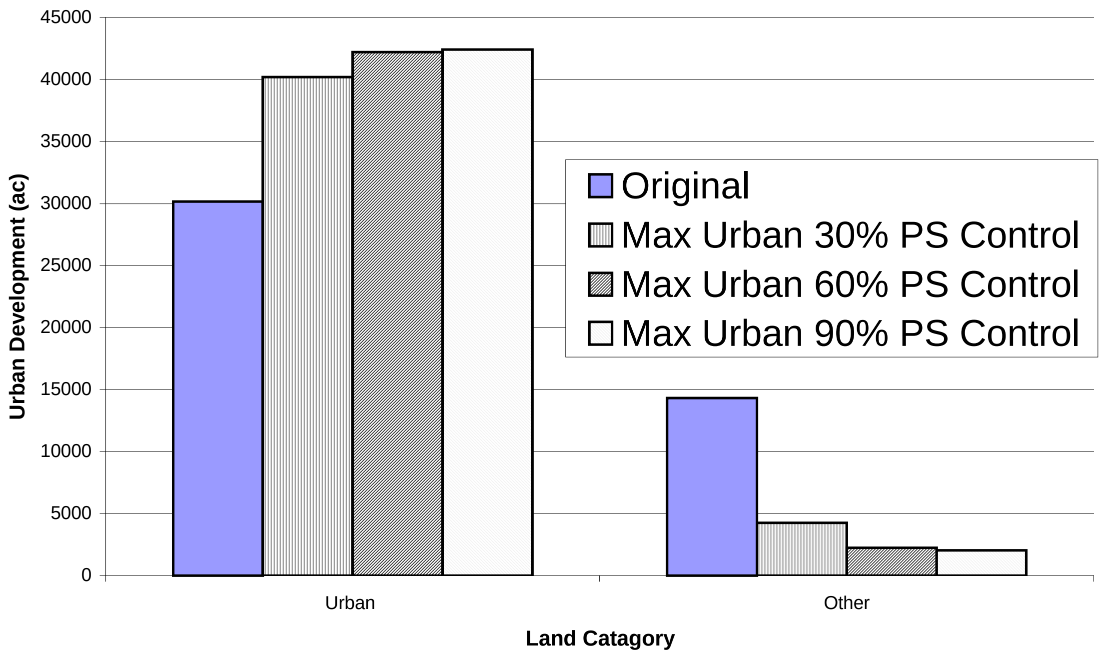

Figure 6 - Urban development under various point source treatment efficiencies at the TP target of 36,430 lbs/yr

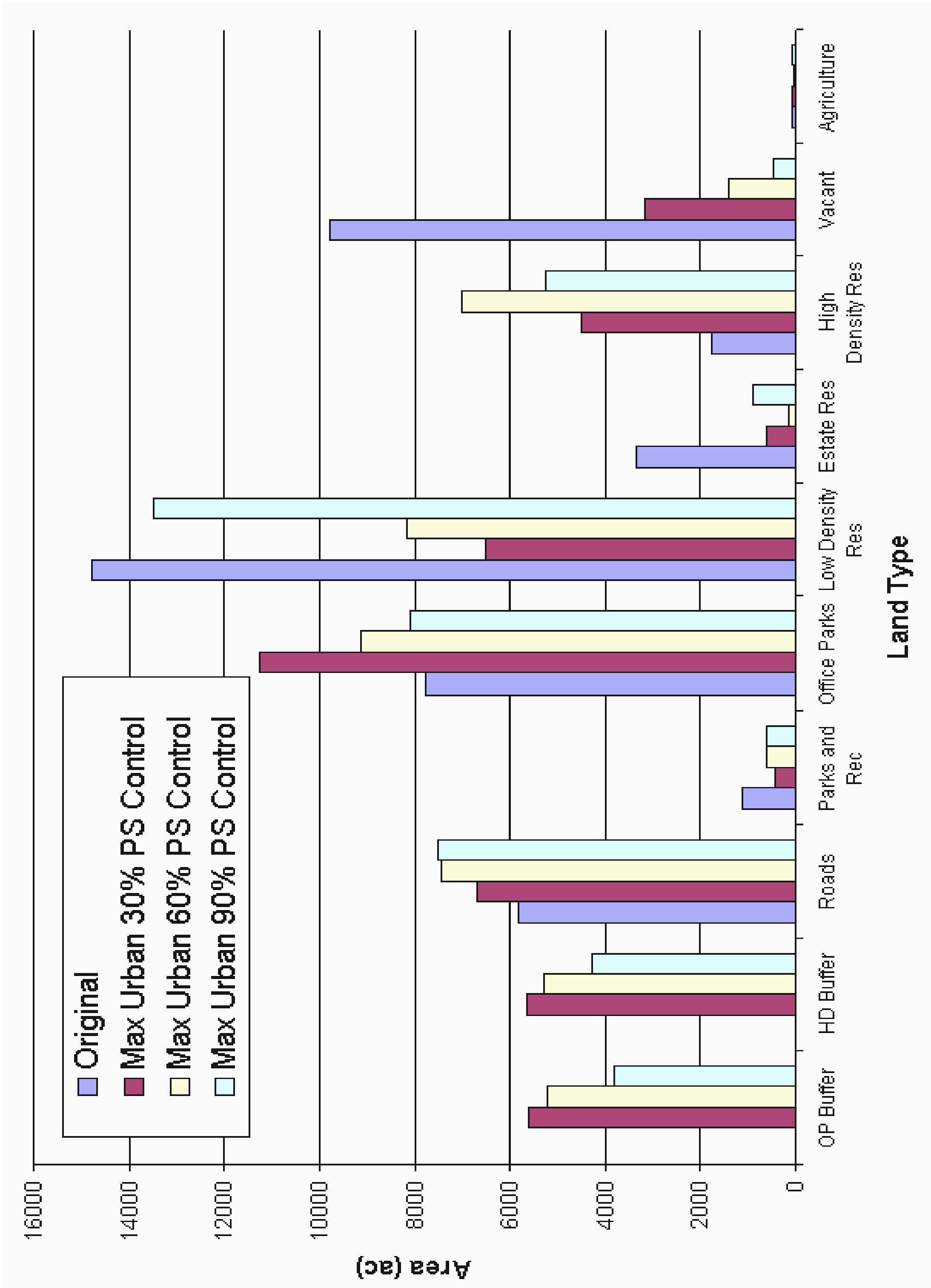

Figure 7 - Land allocation for maximize urban land at TP target of 36,430 lbs/yr under various treatment options

4.2.2 Maximizing Urban Development to Meet Different TP Targets

The previous set of scenarios was repeated for different TP targets to identify the urban development vs. TP tradeoff at varying levels of point source treatment. The results are summarized in Figure 8. For all total phosphorous targets, approximately 10,000 to 10,300 acres of urban development is allowed by introducing 30% more point source treatment. For example, Max Urban 90% PS Controls under TP target of 30,278 lbs/yr scenario shows that 10,335 more acres of urban development could be achieved by increasing the point source treatment from 60% to 90%. The maximum urban development that could be achieved is 42,425 acres, which is 40% over the existing urban areas. The summary results in Figure 8 show that the incremental improvement in urban development diminishes rapidly with tighter TP target at all point source treatment levels.

More points on this tradeoff curves could be obtained by solving additional scenarios at intermediate TP targets. Although sparse, the tradeoff curves summarized in Figure 8 represent valuable information for a decision maker. A line drawn horizontally will indicate the amount of point source treatment required to meet different TP targets while achieving a specific urban development level. For example, to achieve 42,000 acres of urban land, 90% point source treatment is required to achieve a TP target of 32,550 lbs/yr, or 60% point source treatment for a TP target of 35,500 lbs/yr. Similarly a line drawn vertically will identify different levels of urban development that could be achieved with different point source treatment levels for a given TP target. In addition, this figure can also help identify the tradeoff between urban development and TP target for a given point source treatment level. Combining these different sets of information with cost (of point source and nonpoint source controls) and benefits (from increased urban development and water quality improvement), a decision maker is now able to make more informed decisions.

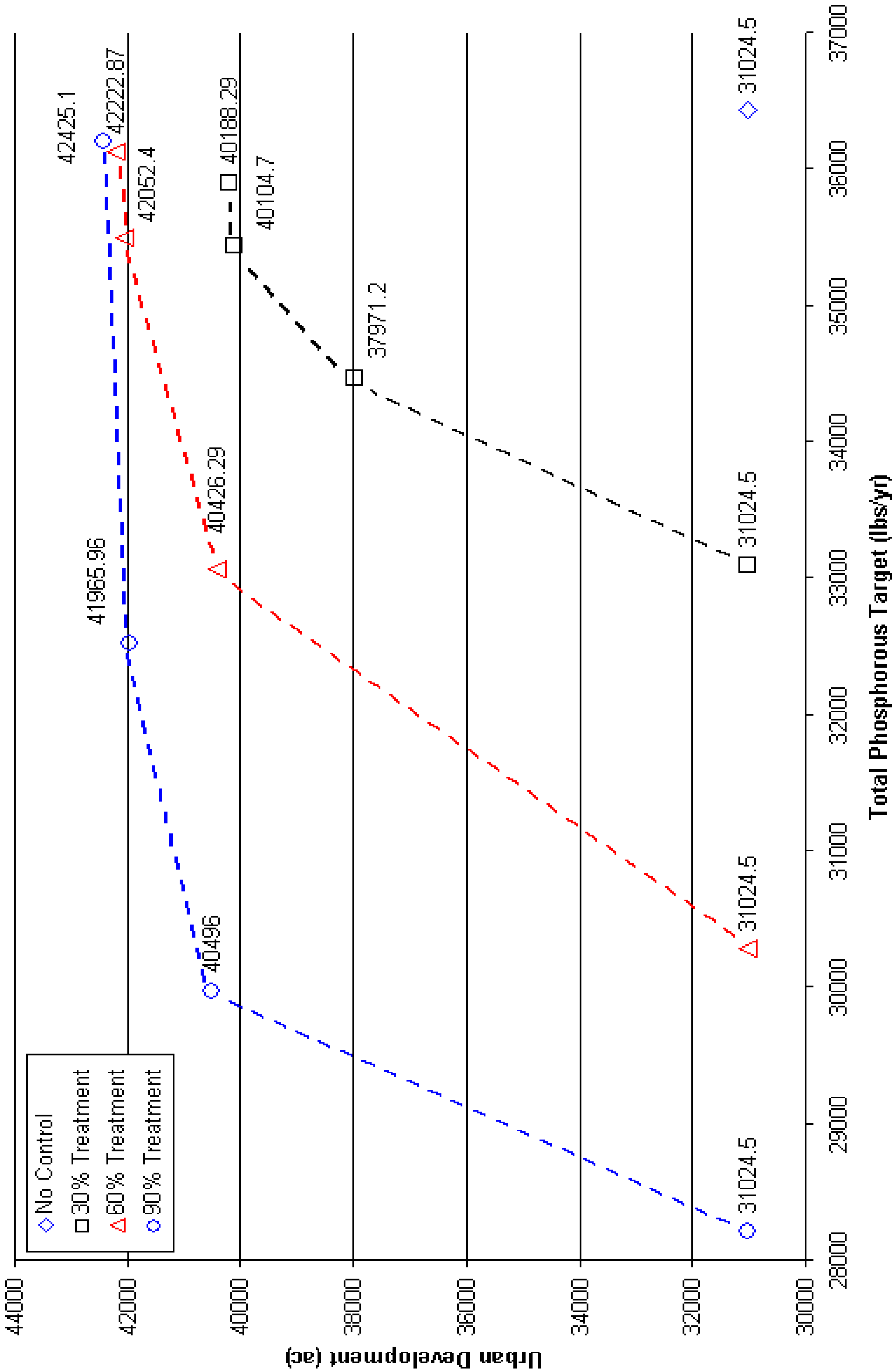

Figure 8 - Tradeoff between point source treatment versus urban development and point source treatment versus water quality

5. SUMMARY AND CONCLUSIONS

This paper presents an application of the STrategy, Analysis and Reporting (STAR) system to an illustrative but realistic case study for the Yellow River Watershed in Gwinnett County, Georgia. Two sets of scenarios were studied to demonstrate the applicability of the STAR system to integrated watershed management. While TSS targets are well established for this watershed, no phosphorous target is yet specified. Thus, the first set of scenarios focused on identifying the best total phosphorous levels that could be achieved at the outlet of the watershed. This was explored by considering point and nonpoint source control options. As Gwinnett County expects to grow in the next 20 years, another set of scenarios were designed to identify future growth and associated land use allocation plans that meet water quality targets. These scenarios help determine the tradeoff between future urban development and TP levels. Again, point and nonpoint source controls were applied at varying levels in generating this tradeoff information. The incremental strategy development capabilities of the STAR system was also applied to examine selected solutions and to identify alternatives.

The results indicate that considerable improvement in TP levels could be achieved while meeting current targets on TSS. The degree of improvement in TP levels from different levels of point source controls, as well as nonpoint source control via requiring buffer strips for new urban land areas, are characterized. The set of tradeoff curves generated in this study provides rich information on how to achieve different urban development levels via different degrees of point source treatment, as well as on how to achieve a specific TP level through urban development management at different point source treatment levels. Such information that is made possible by employing the capabilities of the STAR system can assist a user in exploring alternative strategies and in understanding the available choices in watershed management.

The illustrative scenarios examined in this paper show the integrated effect of point and non-point sources on the water quality. The tools within the STAR system offer a convenient way to define watershed management problems, identify solutions to those problems by a systematic search procedure and allow manipulation of the results to get better solutions. The resulting solutions are expected to serve as good starting points for further manual trial-and-error search, enabling an iterative watershed management decision-making process.

6. REFERENCES

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