Optimal TMDL Development using a Watershed Scale Simulation-Optimization Approach: a Los Angeles County Case Study

Youn Sim[1], Rui Zou[2], **John Riverson[2*]**, Clary Barreto[2]
Jenny Zhen[2], Ryan Murphy[2], Stephen Carter[2]

1. Los Angeles County Public Works, Los Angeles County Flood Control District: YSIM@dpw.lacounty.gov
2. Water Resource Center, Tetra Tech, Fairfax, VA.
   *** Presenting Author**: (e-mail: john.tiverson@tetratech.com)
   10306 Eaton Place, Suite 340
   Fairfax, VA 22030

ABSTRACT

Several Total Maximum Daily Loads (TMDL) have been developed for multiple river segments for pollutants (including nutrients, metals, and bacteria) within the Los Angeles County regional watershed area, with urban runoff and stormwater as the primary source. Managing stormwater quality is complex because it involves many aspects that must be considered collectively to make informed decisions that are cost-effective and meaningful. To address these challenges, the Los Angeles County Flood Control District through a joint effort with United States Environmental Protection Agency has developed the Watershed management Modeling System (WMMS) that identifies cost effective water quality improvement projects through an integrated, watershed based approach. The WMMS encompasses the Los Angeles County's coastal watersheds of approximately 3,100 square miles, which is composed of more than 80 incorporated cities and unincorporated County areas.

Traditional TMDL developments typically rely on iterative trial-and-error modeling approaches for testing compliance. Considering the tremendous implementation costs within this highly urbanized context, a key objective of the WMMS was to develop TMDL implementation options that are both environmentally compliant and financially efficient. As a result, the model development included mapping climate and land cover variability, BMP treatment opportunities, and a range of viable options at a high degree of spatial resolution (2,655 subwatersheds), with water quality targets at 166 unique TMDL compliance points within the instream network. Because simulation-optimization problems at this scale have been an unsolvable problem for decades, this study applied a new algorithm named Nonlinearity-Interval Mapping Scheme (NIMS) developed during this study, which was used to optimize management under various risk tolerance levels for achieving TMDL compliance with minimum BMP implementation cost. The results of this study show a promising trend for future watershed scale optimal TMDL development and implementation plan formulation.

KEYWORDS

TMDL, Optimal, BMP, Watershed Scale, Simulation-Optimization, NIMS, Implementation, Planning

INTRODUCTION

The Total Maximum Daily Loads (TMDL) developed for Los Angeles County watersheds require comprehensive implementation plans that strategically evaluate and identify specific BMPs that meet the required pollutant load reductions. The selection and sizing of these BMPs are contingent on the hydrologic conditions requiring treatment. This analysis involves:

- Characterizing hydrology and pollutant sources in the watershed
- Determining BMP sizing requirements for TMDL compliance
- Identifying the most cost-effective actions for structural BMP implementation.

The Methodology section describes the key components of the Los Angeles County Flood Control District's regional Watershed Management Modeling System (WMMS) and explains how each component was integrated to establish the analytical platform for this study. The Watershed Scale Optimization Platform section describes how the individual analytical components presented in the Methodology section was integrated and applied for watershed scale optimization planning, while addressing questions of risk and uncertainty in the overall analysis. The Results section presents a summary of model results and highlights compliance cost as a function of both distributed and centralized BMP selection. Finally, the paper concludes with a summary discussion of the results and presents a few of the potential implications of Los Angeles County's management decisions that were discovered by this study.

METHODOLOGY

The WMMS for Los Angeles County included specific changes that have been implemented to create a truly regionalized modeling approach that takes advantage of the strengths of previous modeling efforts, addresses identified weaknesses, and builds on the collective efforts and advances of the past few years. Tetra Tech performed a detailed evaluation of all the previous modeling efforts to evaluate and characterize similarities and differences. The key analytical concepts and analytical components defined below include: (1) Land Use Representation, (2) Weather Data Representation, (3) Management Categories, (4) Management Levels, and (5) Degree of Practice. These components work together to constitute the watershed scale simulation-optimization platform applied in this study.

Land Use Representation: Available spatial data were further refined to account for potential differences in soil hydrologic group and slope. The unique combination of land use, soil type, and slope represents a Hydrology Response Unit (HRU) for watershed modeling. The HRU approach simplifies the selection of model parameters and provides a clear physical basis for parameter assignment. Figure 1 is a map of the HRU distribution throughout the study area.

Weather Data Representation: The Flood Control District maintains a network of a few hundred rainfall gages that are part of an early flood warning system. Of these gages, 148 high-quality stations were selected and processed for the watershed model, as shown in Figure 2.

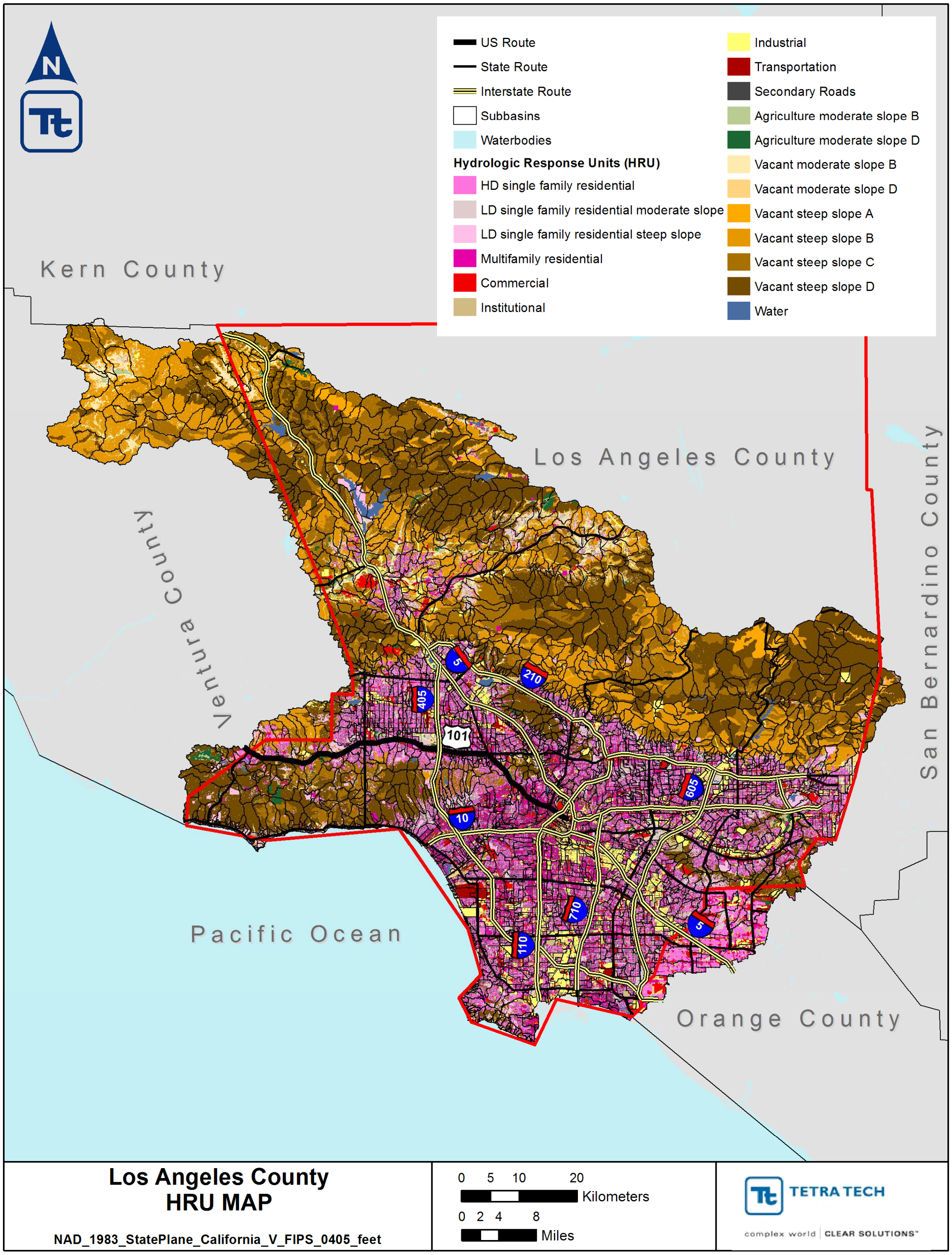

Figure 1. Hydrologic Response Unit representation in Los Angeles County regional watersheds.

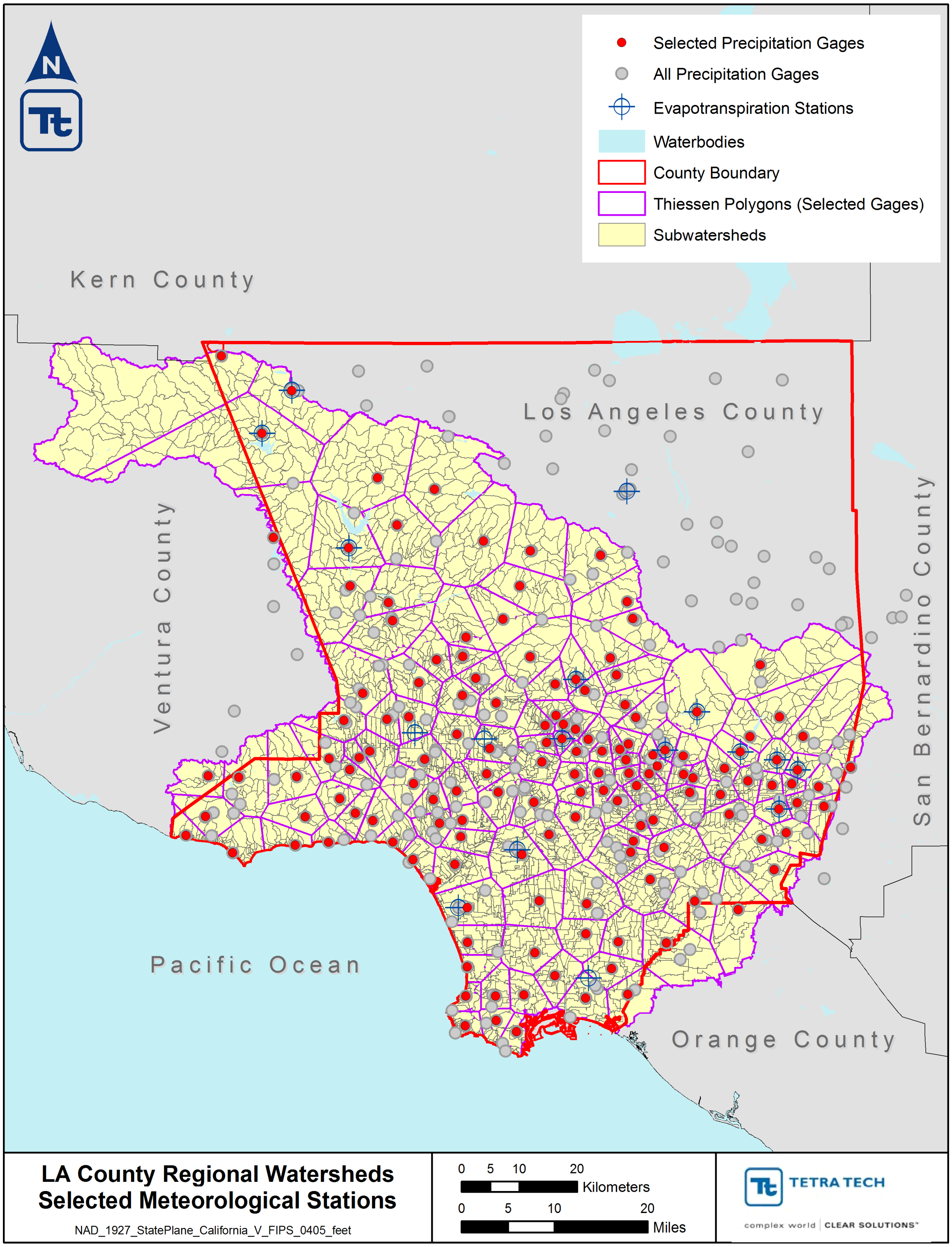

Figure 2. Precipitation gage network for the Los Angeles County regional watersheds.

Management Categories: Watershed-based "Management Categories" were identified for planning BMP activities as a function of physiographic characteristics. While HRUs represent the hydrologic response for individual land features, Management Categories describe the physiographic features such as impervious cover configuration and slope of a subwatershed. Management categories are assigned within hydrologic boundaries (subwatersheds) because the associated factors that govern the selection and placement of structural BMPs within subwatersheds are hydrologic. These factors include (1) total impervious area, (2) impervious density (dispersed or concentrated), (3) average slope of urban areas within the subwatershed (less than or greater than 10 percent) and (4) average road density (high or low). Table 1 is a summary of Management Categories for the modeled subwatersheds. Figure 3 shows the total area distribution by management category. Most of the modeled county area is classified as of Management Category C, meaning urban-concentrated impervious cover on moderate slope land with low road density. On the other hand, the Management Category covering the largest area is H, steep sloped, dispersed impervious cover, with low density. These areas are non-urban, undeveloped mountainous subwatersheds, with small pockets of impervious cover.

Table 1. Summary for Management Categories for modeled subwatersheds

ID	Impervious cover	Impervious configuration	Road density	Slope	Area	Percent Impervious
A	Urban	Concentrated	High road density	Moderate	91,205	68.5%
B	Urban	Concentrated	Low road density	Steep	94,089	30.4%
C	Urban	Concentrated	Low road density	Moderate	387,883	56.8%
D	Urban	Dispersed	Low road density	Steep	261,973	18.4%
E	Urban	Dispersed	Low road density	Moderate	138,740	37.5%
F	Non-Urban	Concentrated	Low road density	Steep	65,830	1.5%
G	Non-Urban	Concentrated	Low road density	Moderate	2,545	1.1%
H	Non-Urban	Dispersed	Low road density	Steep	895,064	0.8%
I	Non-Urban	Dispersed	Low road density	Moderate	56,375	0.4%

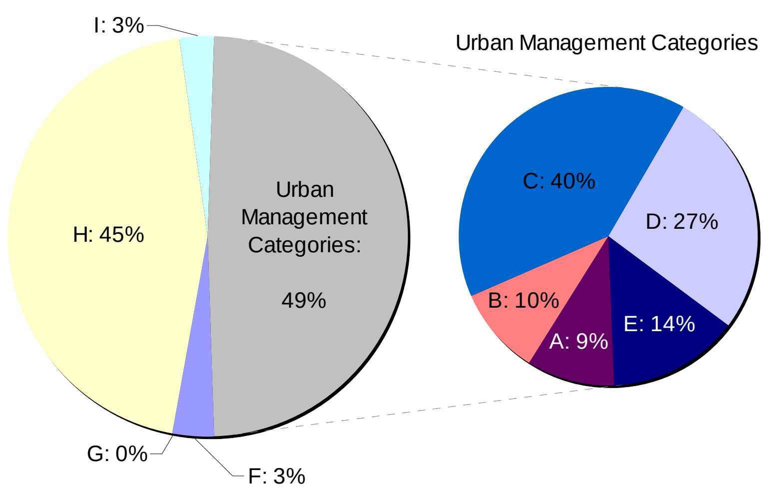

Figure 3. Total area distribution by Management Category.

Management Levels: The "Management Levels" concept was established as a way to characterize the cost-benefit relationship with increasing degrees of distributed BMP implementation. The product of this analytical component was a series of cost-effectiveness curves for every subwatershed in the study area. A cost-effectiveness curve represents the highest expected pollutant reduction benefit at each lowest-cost interval. EPA's System for Urban Subwatershed Treatment and Analysis Integration (*SUSTAIN*) was used to model BMP performance and cost-benefit optimization for this analysis using the aggregate BMP approach (EPA 2009). BMP sizing varied as a function of upstream impervious area. A schematic of possible treatment pathways for the Management Categories is presented in Figure 4. Figure 5 is an example of a cost-effectiveness curve for a hypothetical subwatershed derived using five Management Level intervals.

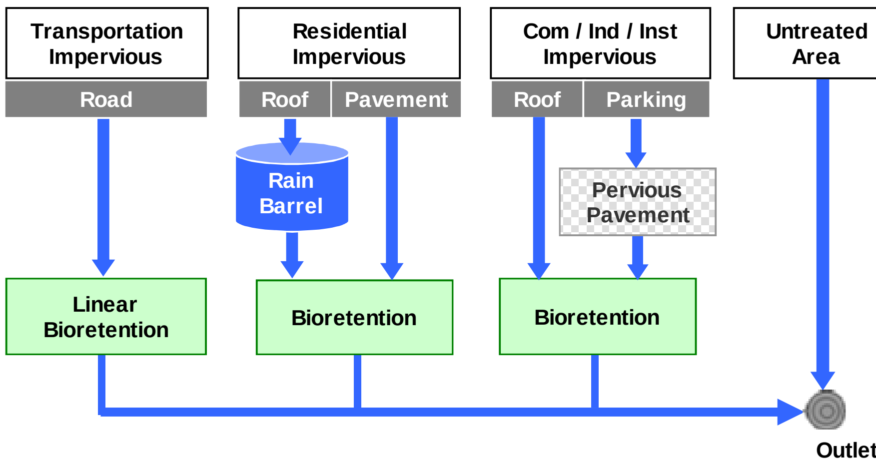

Figure 4. Generalized treatment pathways framework for defining Management Levels.

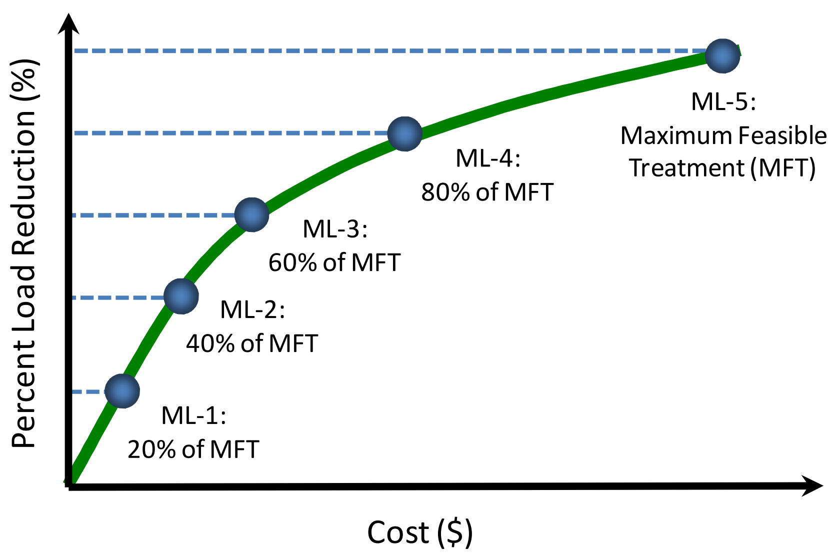

Figure 5. Example of a cost-effectiveness curve derived using five Management Level intervals.

Management Level 5 represents the maximum feasible treatment that can be achieved using distributed BMPs within a given subwatershed. Management Levels 1 through 4 represent 20 percent intervals of the maximum feasible treatment defined by Level 5. Figure 5 is typical of what is seen in cost-effectiveness curves derived using actual data. Note that each point along the curve represents an optimized set of BMP sizes and locations within a subwatershed. Although load reduction percentages are at equal intervals, implementation cost increases non-linearly with increasing reduction. In other words, marginal cost (in terms of dollars per mass of pollutant removed) increases with increasing load reduction.

Degree of Practice: TMDL targets are specified as in-stream concentrations. Given the dynamics of the concentration values and the considerable, often elusively quantifiable uncertainty involved in watershed simulation models, it was important to have a way of measuring sensitivity of the modeled results for standard compliance. Degrees of Practice was a concept established to provide a risk-cost relationship for standard compliance, which differed slightly from the cost-effectiveness relationship previously established with the Management Levels. Five Degrees of Practice were defined for this analysis. Table 2 defines the wet-weather allowable exceedance (risk tolerance) and TMDL compliance values associated with the five Degrees of Practice.

Table 2. Degree of Practice wet-weather allowable exceedance and compliance

Degree of Practice	Wet-weather allowable exceedance (percent of time)	Wet-weather TMDL compliance (percent of time)
I	25%	75%
II	15%	85%
III	10%	90%
IV	5%	95%
V	0%	100%

At the watershed scale, the model was formulated to obtain compliance using a combination of distributed BMPs (Management Levels), with supplemental centralized BMPs where distributed BMPs were inadequate to achieve the aspired compliance target associated with a given Degree of Practice. As Degree of Practice increased (enforcing a higher in-stream percent wet-weather compliance), cost was expected to increase exponentially, as conceptualized in Figure 6. At the watershed planning scale, this information is being used to both (1) target and prioritize TMDL implementation areas and (2) serve as a platform for identifying a cost-effective Degrees of Practice that define the most cost-effective practice.

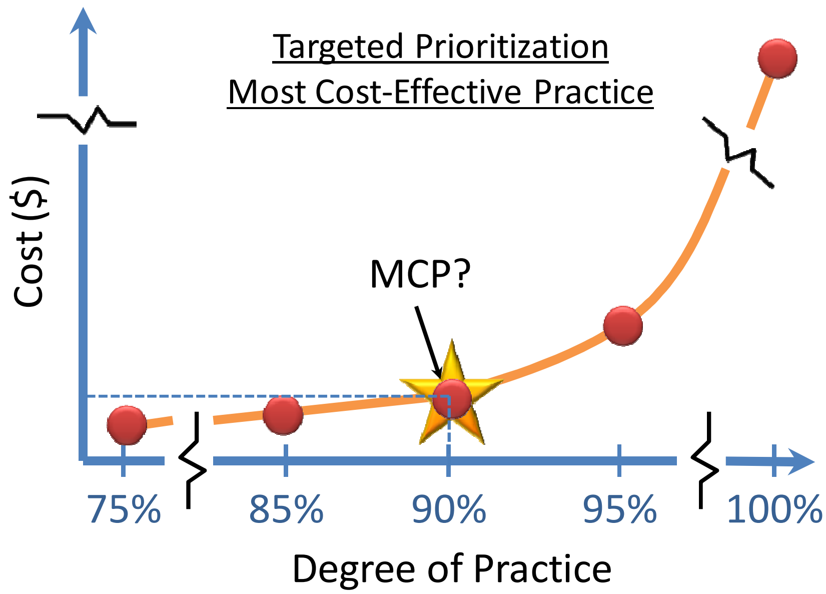

Figure 6. Theoretical graph of cost versus Degree of Practice for targeted prioritization and defining MCP.

WATERSHED SCALE OPTIMIZATION PLATFORM

Each of the analytical building blocks has been presented in the Methodology section. All of these components were integrated to form a simulation-optimization modeling platform for evaluating the range of management options throughout the county. The continuous simulation and optimization BMP design approach can be divided into two steps: (1) small-scale BMP optimization to derive Management Levels and (2) large-scale optimization of Management Levels based on TMDL compliance. Figure 7 is a conceptual illustration of this approach, and is outlined as follows:

Small-Scale Analysis:

1. Organize subwatersheds into Management Categories according to unique watershed characteristics that most influence the type of management that will be selected.
2. Identify potential BMP opportunity (volume = area x depth) and tabulate associated costs. Cost functions for were developed from local sources (CASQA, 2003, Cutter et al. 2008)
3. Derive Management Levels for each Management Category: Use cost-benefit optimization to derive a cost-effectiveness curve of the BMP opportunity space (maximum reduction at minimum-cost intervals). Each Management Level has a fixed BMP treatment capacity.

Large-Scale Analysis:

1. Determine the existing condition concentrations and water quality standards at each compliance point (by location and pollutant combination).

2. Set desired Degree of Practice for water quality compliance. This is an allowable wet-weather exceedance criterion (risk tolerance) for each water quality standard for each location.
3. Determine the optimum Management Level required to satisfy compliance at the specified Degree of Practice.
4. The resulting Management Level for each subwatershed can be translated into BMP treatment capacity (BMP size).

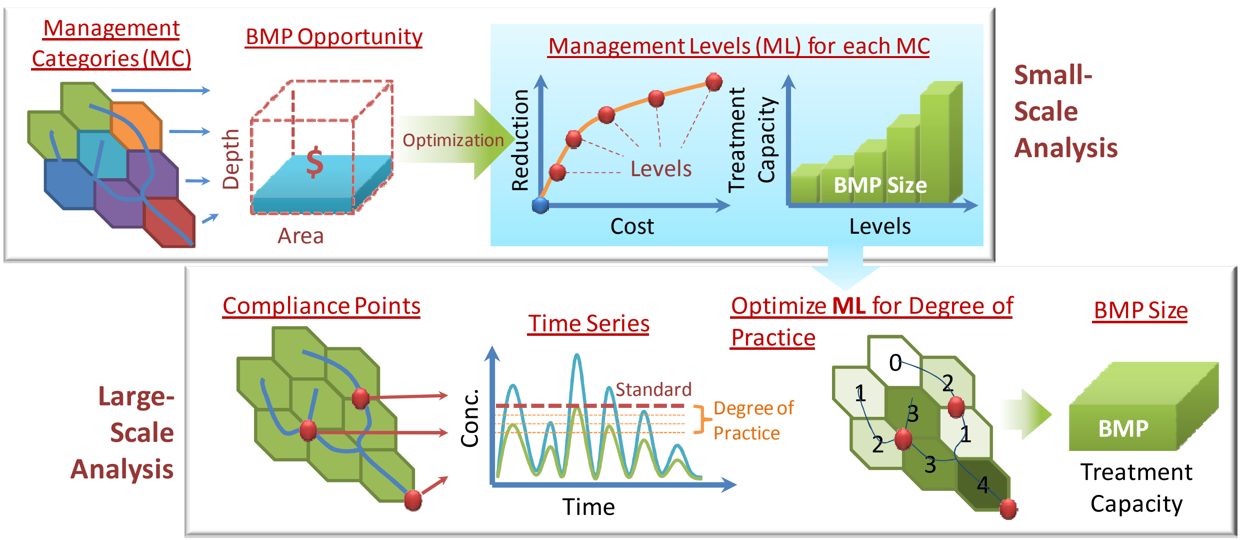

Figure 7. Continuous simulation and optimization BMP design approach for deriving BMP treatment capacity.

The large-scale watershed optimization model was formulated on the basis of the dynamic watershed simulation model for the Los Angeles County regional watersheds. The purpose of the optimization model is to find the optimal distribution of BMP treatment capacity within each of the 2,655 subwatersheds such that the TMDL targets for total nitrogen, total phosphorus, total copper, total lead, and total zinc are simultaneously met at over 166 uniquely identified TMDL compliance points throughout the County's rivers and tributaries, for the lowest possible BMP implementation cost. This platform successfully establishes a numeric linkage between TMDL targets and BMP performance measures.

A new algorithm named Nonlinearity-Interval Mapping Scheme (NIMS), which was developed during this study (Zou et al. 2010), is being used to strategically target individual subwatersheds for management. While the *SUSTAIN* optimization approach was used to develop the cost-effectiveness curve relationships during small-scale analysis, this technique is being used to determine the most cost-effective combination of Management Levels at the large-scale throughout the drainage area that leads to instream compliance at a specific Degree of Protection or risk tolerance level. Below is a simplified narrative description of the objective function and constraints:

- Minimize the total TMDL implementation cost within the study area, subject to
- Attainment of every target reduction for each listed pollutant, achieved by

- Spatially varying Management Levels within subwatersheds, until
- Each non-compliance point within the network comes into compliance.

The Results section will (1) present a pilot study application of the NIMS solution technique for a small subset of the study area, and (2) describe the preliminary efforts underway for setting up and applying this approach to the entire Los Angeles County regional watersheds study area.

RESULTS

Simulation-Optimization Pilot Study Application

Before embarking in the full-scale watershed optimization, the algorithm was tested using a small set of subwatersheds. The main purpose of this testing was to assess the feasibility of the process and to resolve the specifics of how the large-scale optimization would be performed. A representative set of subwatersheds was selected, using the following guidance criteria:

- Manageable number of subwatersheds, between 15 and 30 subwatersheds
- Subwatersheds with a mix of HRUs
- Subwatersheds that encompass a variety of Management Categories

Figure 8 presents a schematic of the routing network for this example watershed with instream compliance points highlighted, while Figure 9, Figure 10, and Figure 11 show location and HRU distribution, Management Categories, and instream compliance point locations, respectively.

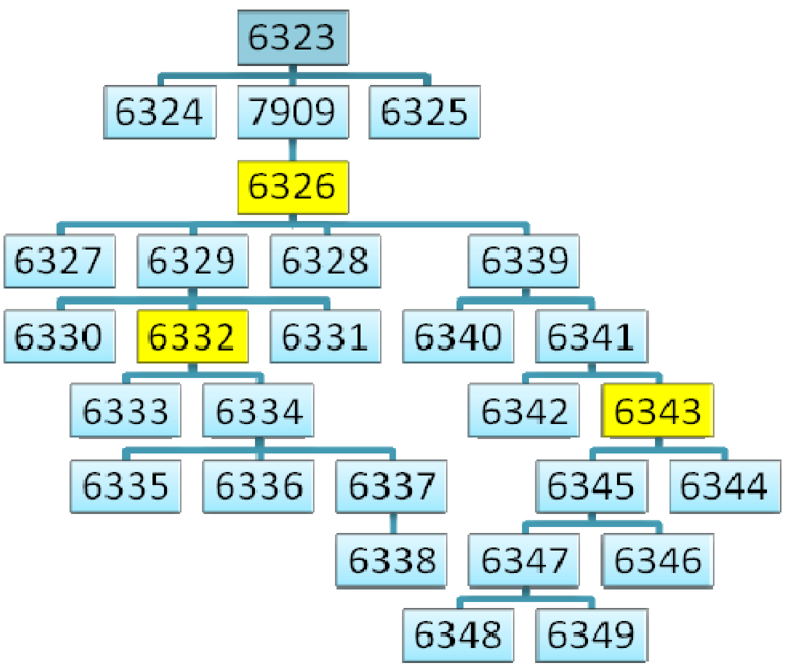

Figure 8. Routing network schematic for the example watershed.

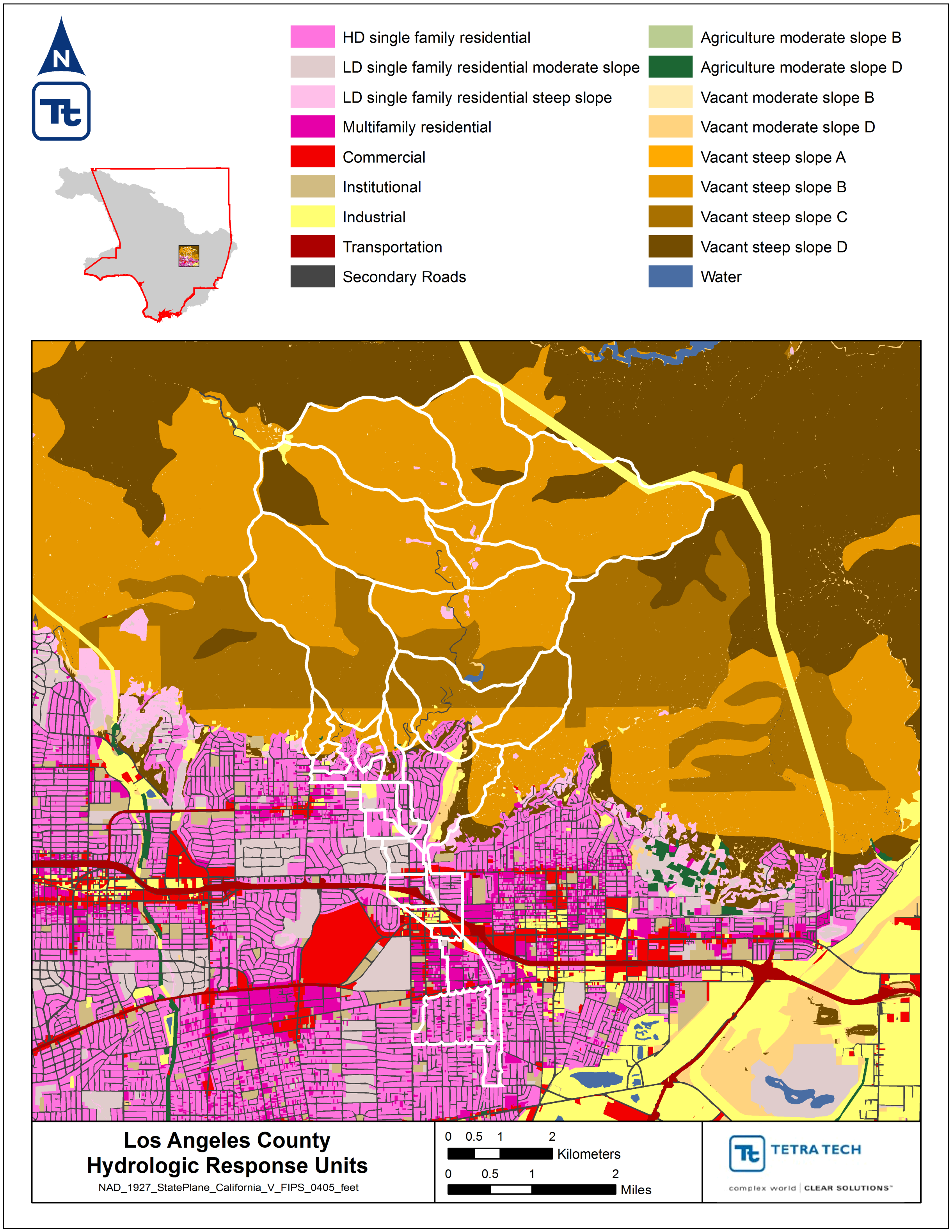

Figure 9. Location and HRU distribution map for the example watershed.

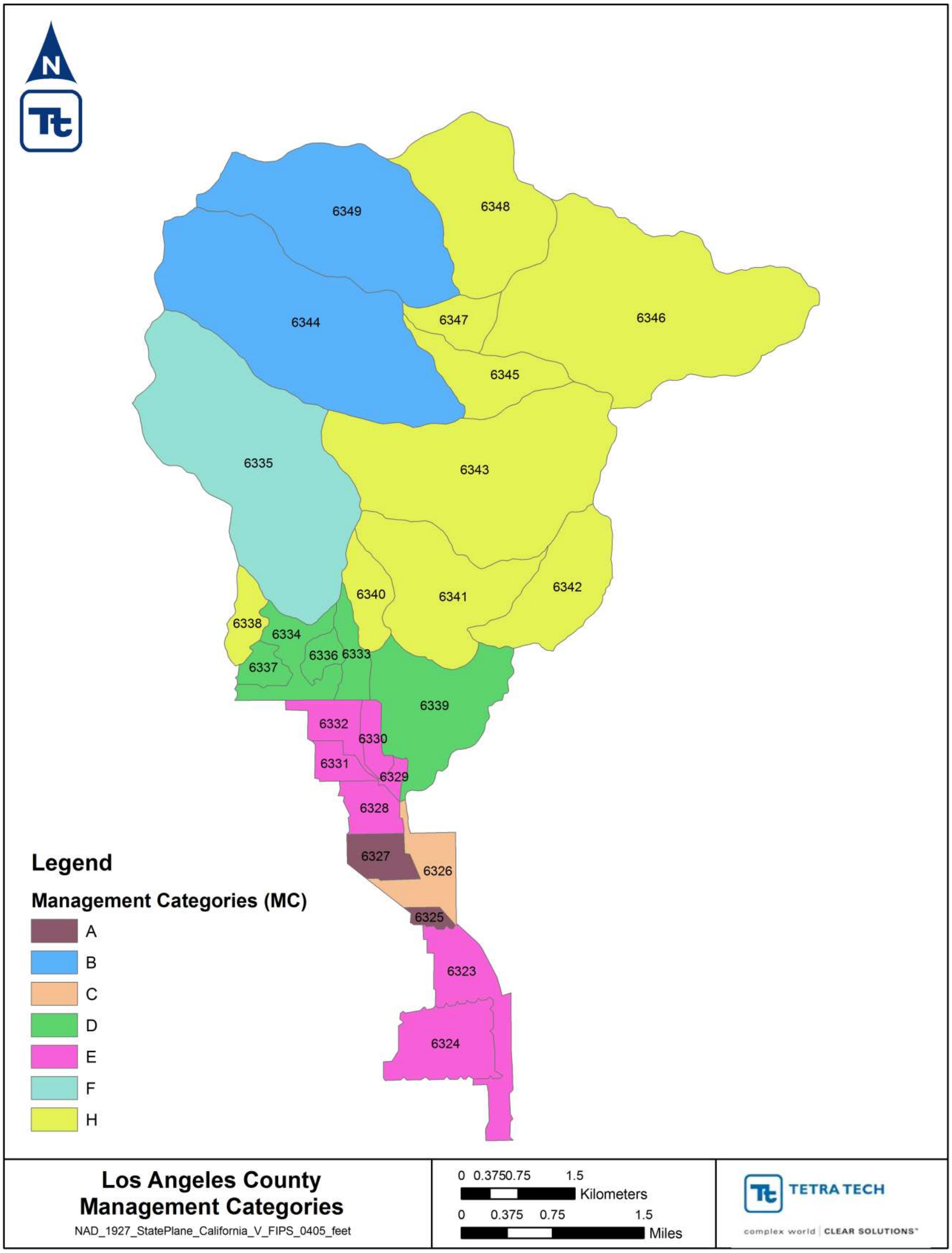

Figure 10. Management Categories of the example watershed.

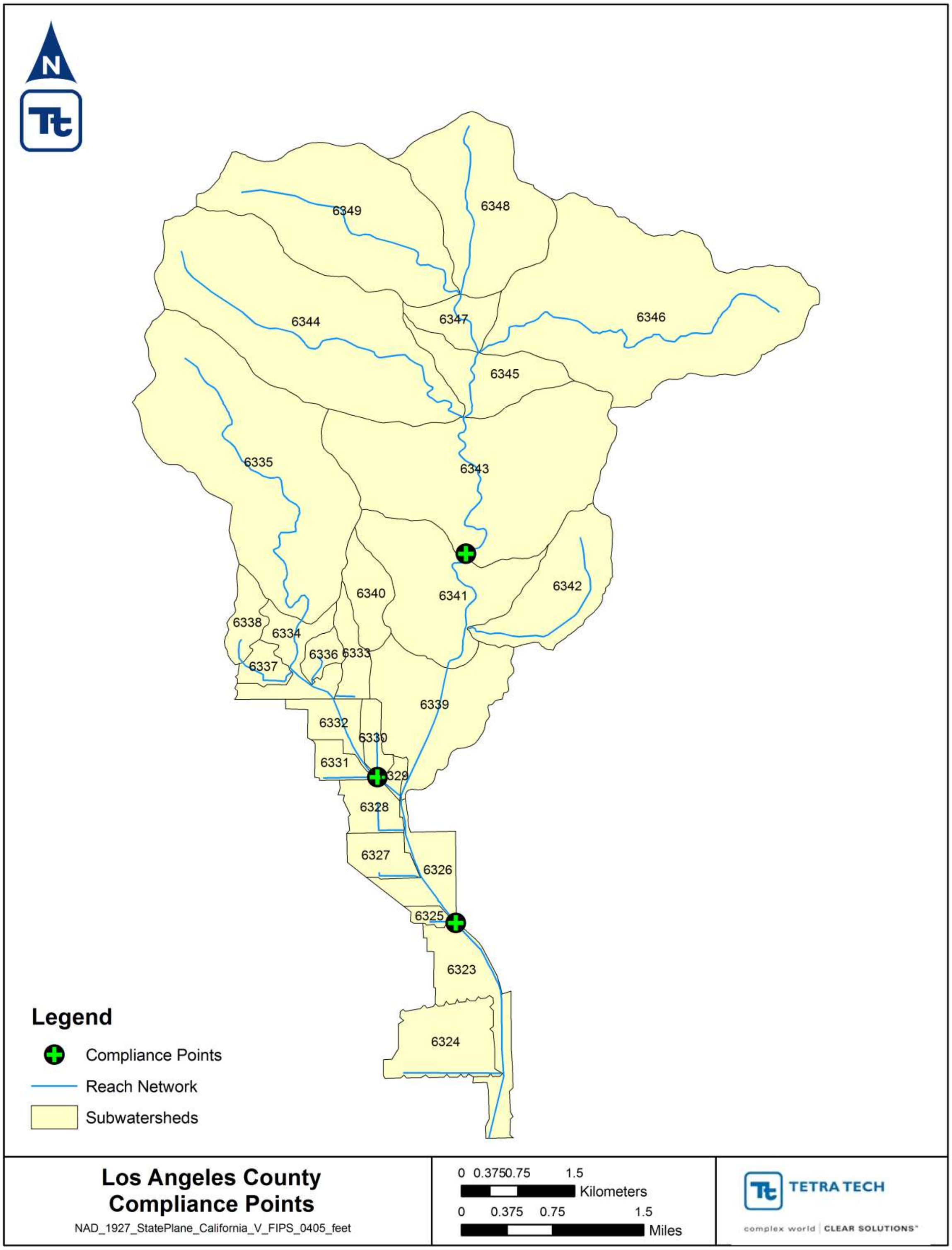

Figure 11. Reach network and location of compliance points for the example watershed.

Three nested compliance points (CP) were selected, at the outlets of reaches 6343, 6332, and 6326 (as shown in Figure 11, and previously highlighted in the Figure 8 routing schematic). Two different loading target scenarios were created, as shown in Table 3 and Table 4

Table 3. TMDL targets at the three compliance points—Scenario 1

Pollutant Load (lb/yr)	Compliance Points		
	6326	6332	6343
TN	8,360	1,870	4,901
TP	4,840	1,126	2,465
Cu	29.40	7.52	5.16
Pb	18.88	5.28	1.29
Zn	204.40	54.12	21.68

Table 4. TMDL targets at the three compliance points—Scenario 2

Pollutant Load (lb/yr)	Compliance Points		
	6326	6332	6343
TN	9,823	1,700	4,715
TP	5,687	1,024	2,370
Cu	34.55	6.84	4.97
Pb	22.18	4.80	1.25
Zn	240.17	49.20	20.85

As previously described for Management Levels, *SUSTAIN* was used to generate small-scale cost-effectiveness curve relationships for each of the 24 subwatersheds. At the large watershed scale, the objective function was formulated to minimize TMDL implementation cost, subject to constraints of spatially variable pollutant load reduction targets for the five pollutants. The NIMS-based simulation-optimization formulation for the pilot area was solved for both Scenario 1 and Scenario 2. The two simulation-optimization solutions were also compared against two conventional (manual trial-and-error) methods as described below:

1. Uniform management Level reduction in each subwatershed until the target reduction at all three compliance points was achieved. This is similar to the approach taken to map the upper limit of the optimization search space.
2. Apply the same average Unit Area Loading (UAL) reduction per subwatershed until the target reduction at all three compliance points was achieved. This results in different Management Levels among subwatersheds because of land use variation.

The optimal NIMS reduction as well as the two conventional TMDL reduction are shown in Figure 12 for Scenario 1. Similarly, Scenario 2 was analyzed using the same optimization approach. However, for Scenario 2 it was possible to apply a rough spatially variable manual reduction because the targets at the upstream compliance point 6332 were significantly more stringent than the downstream point 6326 and the parallel point 6343. Therefore, it was natural to reduce more load from the sources of 6332 to meet the target there, which minimized the need for additional reductions at the other two compliance points. The same two approaches for the uniform reduction and the UAL-based manual reduction were implemented for this scenario. The resulting manual reduction and optimal reductions are shown in Figure 13. Table 5 compares the total cost of implementation for Scenarios 1 and 2, and confirms that the NIMS-based targeted simulation-optimization approach shows a notable savings in TMDL implementation cost relative to the two conventional allocation approaches.

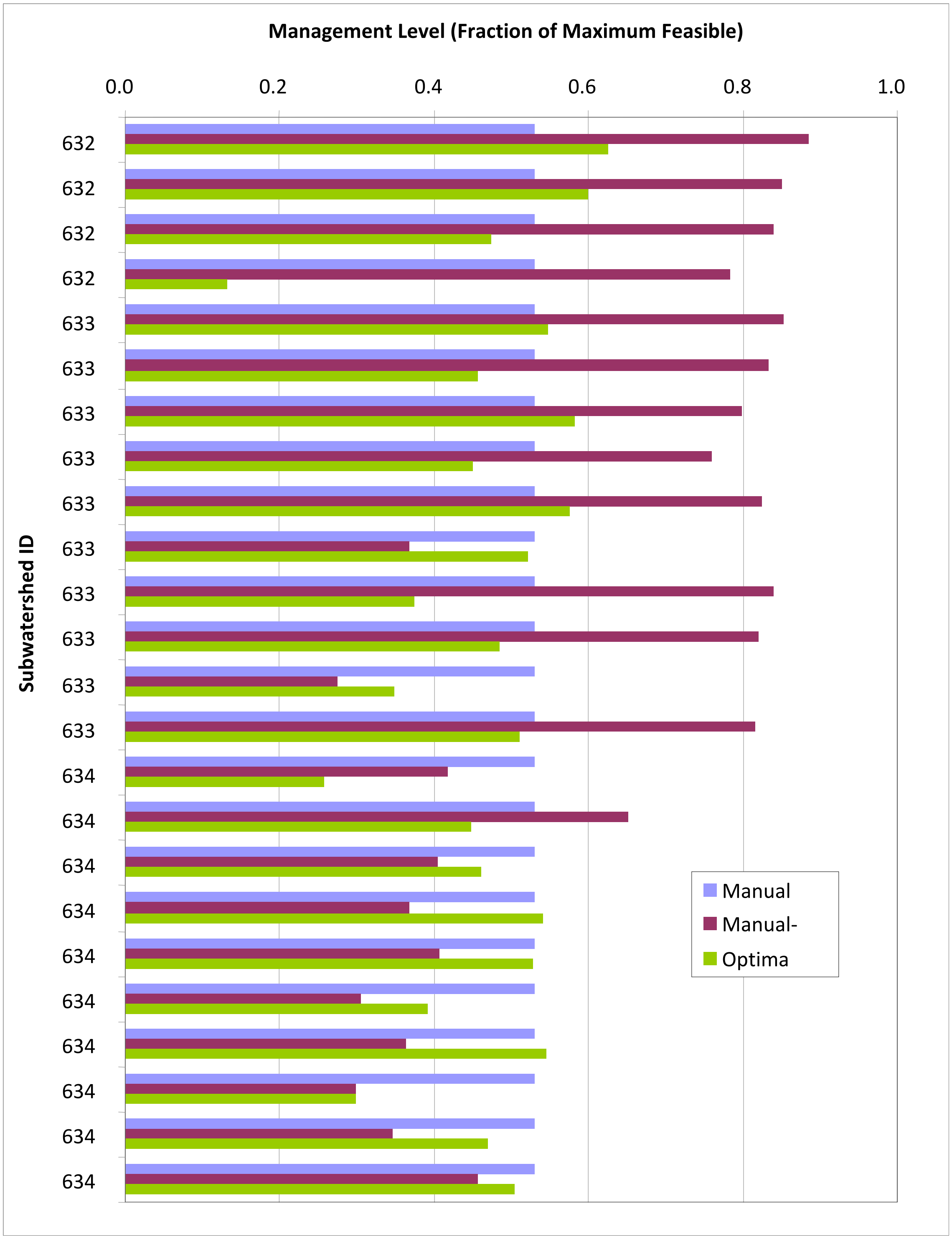

Figure 12. Comparison of manual and optimal reduction ratio distribution across subwatersheds for Scenario 1.

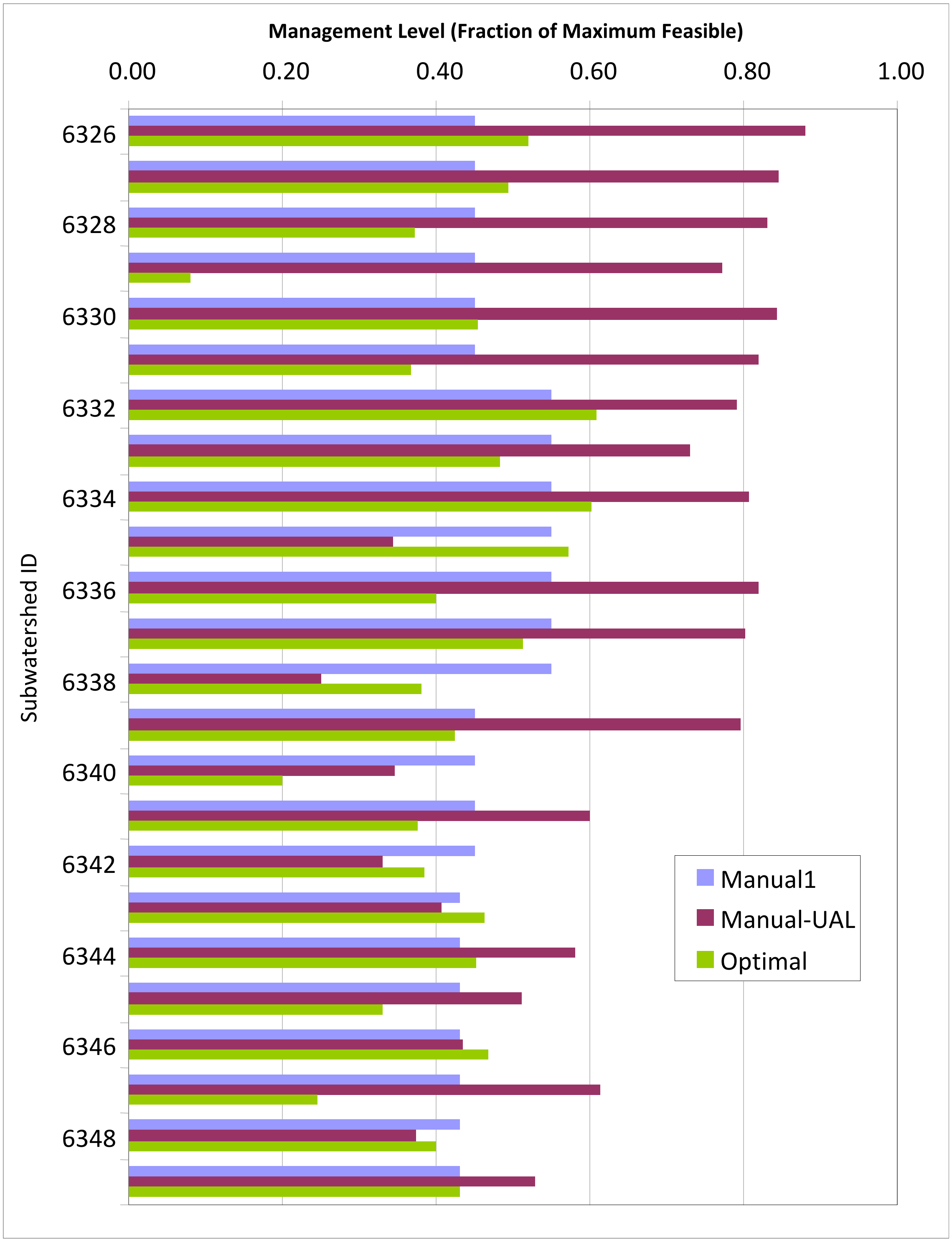

Figure 13. Comparison of manual and optimal reduction ratio distribution across subwatersheds for Scenario 2.

Table 5. TMDL implementation cost by scenario

TMDL Allocation Approach	Scenario 1 ($ Million)	Scenario 2 ($ Million)
Uniform Management Level	$97.0	$78.3
Uniform Unit-Area Load Reduction	$116.0	$122.3
Simulation-Optimization Solution (NIMS)	$92.0	$76.6

The pilot watershed is a relatively small system, and the target values were specified in a relatively simple way to allow for easy manual reduction analysis. When applied to the entire Los Angeles County watersheds area, the scale is much larger (2,655 sub-watersheds), and the TMDL targets are specified at 166 unique compliance points corresponding to individual stream outlets along listed stream segments. At the small scale, the NIMS solution technique arrived at a solution within a matter of minutes. The efficiency of this simulation-optimization approach will be truly realized at the larger watershed scale both in terms of computation speed and cost savings associated with the derived solutions, which is expected to be in the order of billions of dollars.

Large Scale County-Wide Application

In order to test the sensitivity of compliance associated with the full range of management actions performed in the watershed, five Uniform Management Level distributed BMP scenarios were modeled and evaluated for compliance at each of the five Degrees of Practice. These scenarios were configured assuming uniform application of each of the five Management Levels across all subwatersheds, similar to the first conventional approach applied in the pilot study. Each of these five scenarios was applied at each of the five Degrees of Practice. For a given compliance point, if distributed BMPs were inadequate to achieve compliance at the specified Degree of Practice, centralized BMPs were applied to meet the compliance objective. Watershed scale estimated costs were spatially aggregated by Management Level and Degree of Practice, resulted in a total of 25 combinations. Figure 14 is a three-dimensional rendering of total compliance cost for uniform application of distributed and centralized BMPs by both Management Level and Degree of Practice on the perpendicular axis. As expected, TMDL implementation cost generally increases with increasing Management Level and Degree of Practice; however, upon examining at the interplay between both of these axes suggests that competing factors that should be further evaluated for insights.

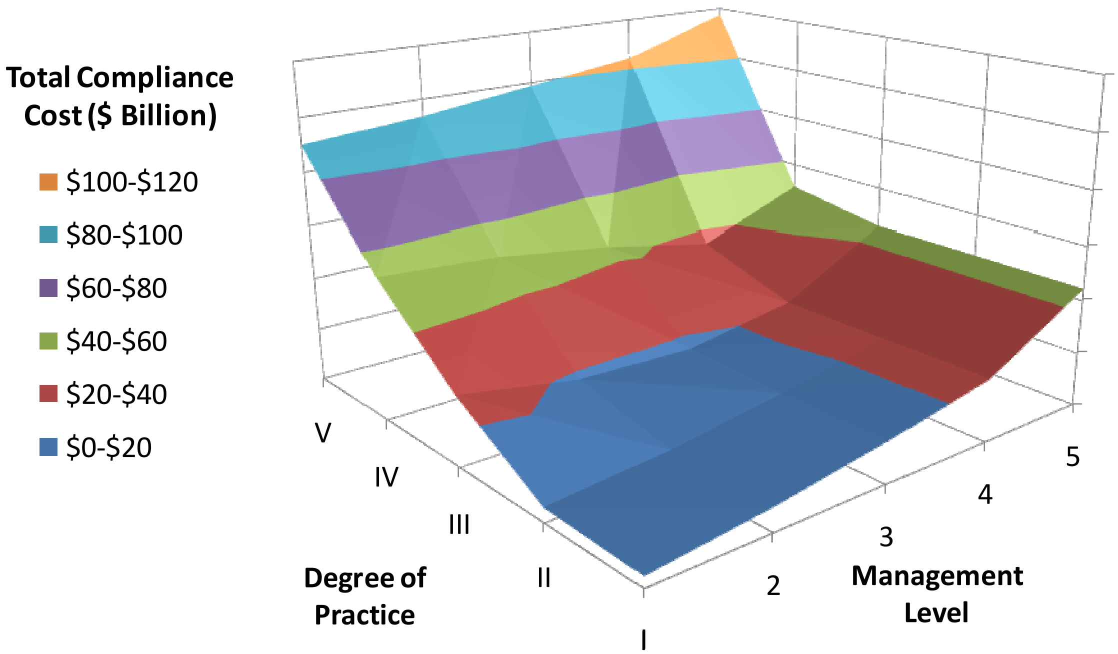

Figure 14. Total compliance cost for uniform application of distributed and centralized BMPs by Management Levels and Degrees of Practice.

In two-dimensional space, the "knee of the curve" is typically used to identify the most cost-effective point in the search space above which marginal cost increases dramatically. Because we are measuring cost-effectiveness as a function of two variables that form a cost-effectiveness plane instead of a curve, the "bowl of the plane" is conceptual counter-part to the "knee of the curve." Additional analysis is currently underway to numerically identify any notable depressions in the plane which might suggest manageable implementation targets for prioritization in the decision making process.

In the pilot study application, the uniform Management Level approach produced solutions which were slightly more expensive than the optimal solution. Treatment Levels for some of the subwatersheds in Figure 12 and Figure 13 both suggest that they were managed more aggressively than necessary under the uniform Management Level solution versus the optimal NIMS solution. In the same way, the plane shown in Figure 14 represents the upper bound of the simulation-optimization search space. It is expected that when NIMS is applied to the entire study area, optimal solutions that strategically target certain subwatersheds at different Management Levels will plot in the space beneath the upper surface of the search domain.

CONCLUSIONS AND NEXT STEPS

The high model resolution associated with the HRU and weather data representation provides a modeling platform that is able to characterize the high degree of variation found in the natural environment within this study area. Furthermore, by dividing the analytical approach into manageable components such as Management Categories, Management Levels, and Degree of

Practice, it is possible to test the sensitivity of each of these components in terms of compliance load reduction and implementation cost.

The integrated continuous simulation and optimization BMP design approach provides many advantages for comprehensive watershed scale analysis. First, the long-term continuous simulation allows for a robust testing and understanding of BMP effectiveness under a wide range of conditions. Second, using the compliance target as a requirement that drives the BMP sizing ensures that the final result has taken into consideration the need to address existing TMDL objectives. Finally, the use of optimization techniques provides opportunities to identify cost-effective combinations of management strategies that are spatially optimized to ensure the highest likelihood of TMDL compliance at the lowest cost. Using this simulation-optimization solution technique to strategically target individual subwatersheds for management also represents a promising approach that may change the way practitioners plan and implement TMDL management activities.

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