# Evaluating Management Scenarios in the Croton Watershed

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***Abstract***

*The Croton Watershed is the oldest portion of New York City's drinking water supply system and is undergoing continued development. To achieve water quality goals, a GIS-based risk assessment methodology was developed to help the New York City Department of Environmental Protection (NYCDEP) optimize watershed management efforts and focus limited resources on critical areas to achieve maximum water quality benefits.*

*The methodology was implemented using GIS raster processing and compiled in a Decision Support Tool (DST) to assist the NYCDEP in evaluating different management alternatives. With this tool, NYCDEP can systematically prioritize its watershed monitoring, protection, and restoration efforts, provide local stakeholders with technical information for their own watershed programs, and track development and mitigation projects in the watershed.*

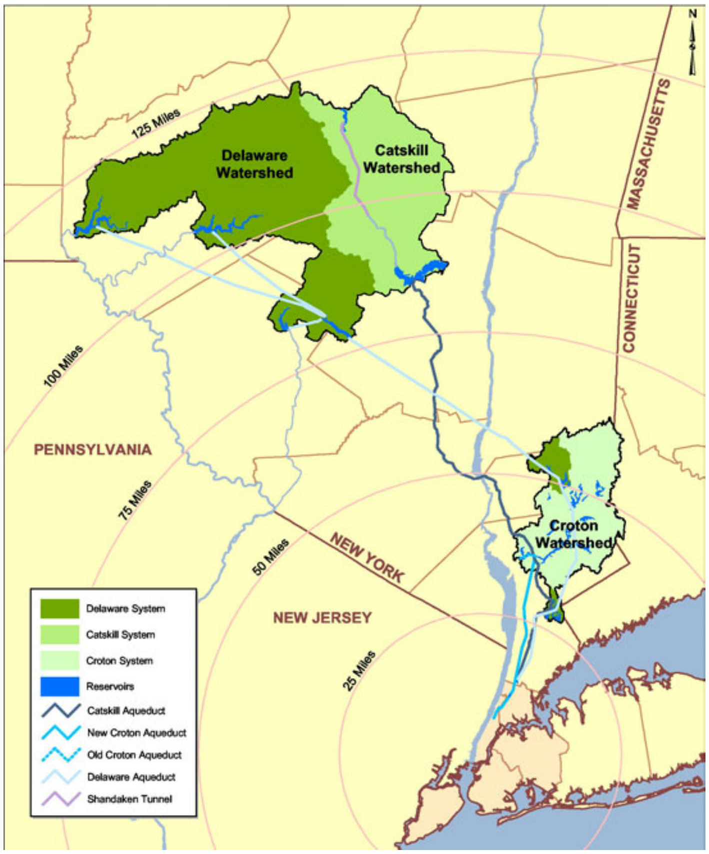
## Introduction

The New York City water supply system provides approximately 1.3 billion gallons of high quality drinking water to almost nine million New Yorkers every day — eight million city residents and a million residents of Westchester, Putnam, Orange and Ulster Counties — plus the millions of tourists and commuters who visit the City throughout the year. The source of this superior water supply is a network of 19 reservoirs in a 1,969 square-mile watershed that extends 125 miles north and west of New York City.

The Croton System is the oldest of New York City's three surface water systems. It supplies approximately 10 percent of New York City's fresh water from 10 reservoirs and three controlled lakes in Putnam and Westchester Counties. The other 90 percent of New York City fresh water comes from two reservoirs in the northwest corner of the Croton Watershed and six reservoirs in the Catskill/Delaware system, located in Delaware, Greene, Schoharie, Sullivan and Ulster Counties, west of the Hudson River. (NYCDEP, 2002) (Figure 1)

To ensure that New Yorkers will enjoy high quality water well into the 21st century, the New York City Department of Environmental Protection (NYCDEP) developed a comprehensive long-range watershed protection program. The program incorporated a multifaceted strategy to protect and improve water quality for decades to come. The program was started in 1989, and

**Figure 1**
**New York City Water Supply System**



enabled New York City to receive from the United States Environmental Protection Agency a series of waivers of the federal requirement that it filter water from its Catskill/Delaware supply. (NYCDEP, 2002)

Currently, the city is in the process of siting, designing, and building a filtration plant for treating water from the ten reservoir Croton System. The current deadline for the filter plant is 2010. Despite the construction of a filtration plant, New York City still has an interest in protecting the quality of Croton water and of the contributing watershed. Protecting Croton water quality will reduce operating costs for the treatment plant and may enable some Croton water to be combined, unfiltered, with Catskill and Delaware water in times of severe water shortage. Ensuring the long-term ecological health of the watershed is also critical for this rapidly developing area.

In 2001, the NYCDEP produced a comprehensive assessment of watershed and water quality protection efforts entitled New York City's 2001 Watershed Protection Program Summary, Assessment and Long-term Plan. (NYCDEP, 2002) This document notes that the Croton Watershed Strategy assessment was contracted with the aim of assessing, at a subbasin scale, potential sources of water quality impairment. Results from this study are intended to assist with prioritized allocation of watershed protection efforts.

**Study Site**

The Croton Watershed includes 12 primary reservoirs, the drainage areas of which are referred to as the Croton Watershed Basins. Basins are divided into between 1 and 15 subbasins, each of which drains to a major junction in its basin's drainage network. In all, there are 74 subbasins in the Croton Watershed. Water from upstream reservoirs flows to downstream reservoirs through natural streams rather than through aqueducts or tunnels. New Croton Reservoir is the terminal reservoir for the Croton Watershed. Water extracted from the New Croton Reservoir is discharged into the City's distribution system via the New Croton Aqueduct.

**Figure 2**
**Croton Watershed**


The Croton Watershed is developing rapidly, more so than any other region connected with New York City's drinking water supply. Population changes resulting from natural growth, immigration, and smaller lot sizes drive this development.

Over the last decade, almost all subbasins in the watershed have experienced significant population growth, some by as much as 40 percent or more. According to the 2000 Census, the Croton Watershed supports a total population of 189,912. Town centers and lake communities tend to be the densest areas of development in the watershed. Towns that fall mostly within the watershed all have their town centers and most of their dense communities within the watershed.

Existing land use data indicate that approximately 80 percent of the total land area in the watershed is already in use. Of the land still available for development in the watershed, 40 percent is subject to development restrictions because of steep slopes, wetlands, and riparian buffers. Conversely, only 28 percent of currently developed land is subject to the same restrictions. As development pressures increase, the risks to these sensitive features of the landscape also increase.

The watershed has several specific water quality concerns resulting from both natural sources and extensive development. These concerns include increased nutrient loading of the reservoirs, risk of spill related problems, and storm water runoff pollution. From a drinking water perspective, these problems can result in unacceptable color, taste and odor. In addition to a thorough assessment of existing conditions in the watershed, the Croton Watershed Strategy includes an assessment of potential future impacts to water quality that may be associated with further development of the watershed. This future impact assessment is intended to assist in prioritization of protective watershed programs.

## Purpose and Approach

The purpose of the Croton Watershed Strategy assessment is:

- To identify subbasins within the Croton Watershed that currently, or that may in the future, represent a potential risk of water quality impairment relative to other subbasins in the watershed;
- To develop and prioritize a set of watershed management strategies to address current and future water quality concerns within the watershed.

The Croton Watershed Strategy assessment developed a methodology that identified point and non-point sources of pollution within the Croton Watershed subbasins and assigned values to reflect the relative risk that those sources might pose to water quality. The methodology was applied for current watershed conditions, as well as for potential future conditions as determined by a build-out scenario.

The methodology was implemented using Geographic Information Systems (GIS), capitalizing on the wealth of spatial data developed by the NYCDEP and other sources. The GIS allows the methodologies to incorporate different kinds of spatial data such as the locations of point sources and the wide distribution of various land uses. The GIS provides the data processing tools used in the analysis and helps to generate graphical representations of the spatial distribution of "high-risk" areas. The methodologies are tailored to make effective use of the GIS capabilities. In addition, a GIS-based Decision Support Tool (DST) was developed to assess changing conditions, enhance the analysis with new data as they become available, evaluate future watershed management scenarios, and track ongoing development and management practices within the watershed.

## Methodology

### *Introduction*

The analysis is intended to assess the current and future potential for water quality impairment from four critical variables:

- total phosphorus
- total suspended solids
- pathogens
- toxic chemicals

The input of these variables in excess amounts poses a risk to the watershed's use as a source of drinking water and to its ecological health. Each of these variables is delivered to the streams, lakes and reservoirs from multiple sources throughout the watershed including runoff from a variety of different land uses, septic systems, and point sources. Specific areas within each subbasin of the watershed may have a greater potential for water quality impairment than other areas and so may be identified as areas of concern.

The analysis serves two purposes: to estimate the current and future potential for water quality impairment and to identify areas of concern within each subbasin; to facilitate the comparison of subbasins, under both current and future conditions, via scores representative of a subbasin's overall potential for water quality impairment. The identification of areas of concern within each subbasin and the scoring of each subbasin's relative potential for water quality impairment allows for the development, implementation, and prioritization of management strategies to mitigate water quality impairment.

***Literature Review***

A literature review was conducted to determine the management strategies currently used by other municipalities that also administer large surface drinking water supply systems. However, a brief assessment of major metropolitan areas and their water supplies found that the needs of the Croton Watershed Strategy are largely unique.

While many water supply systems of large cities rely on surface water, most draw from reservoirs in uninhabited areas, or from constantly flushed systems such as rivers. Furthermore, nearly all municipalities employ filtration. Within the United States, few other water supply systems attempt to collect a similar volume of unfiltered water from watershed of such heterogeneous use. The only somewhat similar reservoir system is that of the Quabbin and Ware reservoirs, serving the city of Boston. However, these reservoirs are in a much more rural and undeveloped area in which greater than 50 percent of the watershed land is owned by the Boston municipal authority. (MDC, 2000) In the Croton Watershed, only about 6 percent of the total land area is currently designated city-owned water supply land.

While few analyses have been developed specifically for large drinking water supply systems, numerous methods to aid in analyzing watersheds and making management decisions have been developed. Of the studies reviewed, many attempted to simulate watershed conditions and correlate them to water quality but few expected to directly inform management decisions. A mechanistic simulation generally requires a large amount of data and is calibrated for a specific watershed. Most quantitative analyses address a single land use or a small number of simplified land uses, further complicating the selection of management strategies. In some cases, analyses attempt to identify very localized areas where water bodies do not support their designated uses (e.g. swimming, fishing, drinking water supply). In the case of the Croton Watershed, however, reservoir management may be more focused on the cumulative impact of a total drainage area on the overall health of a reservoir rather than on localized impairment within the reservoir or its tributaries. Few analyses attempt to determine the most cost-effective and reasonable management plans or to weigh the myriad combinations of management strategies available. Only one study (Dreher et al, 2000) of the 30 investigated considered the ability to implement as well as the degree of improvement associated.

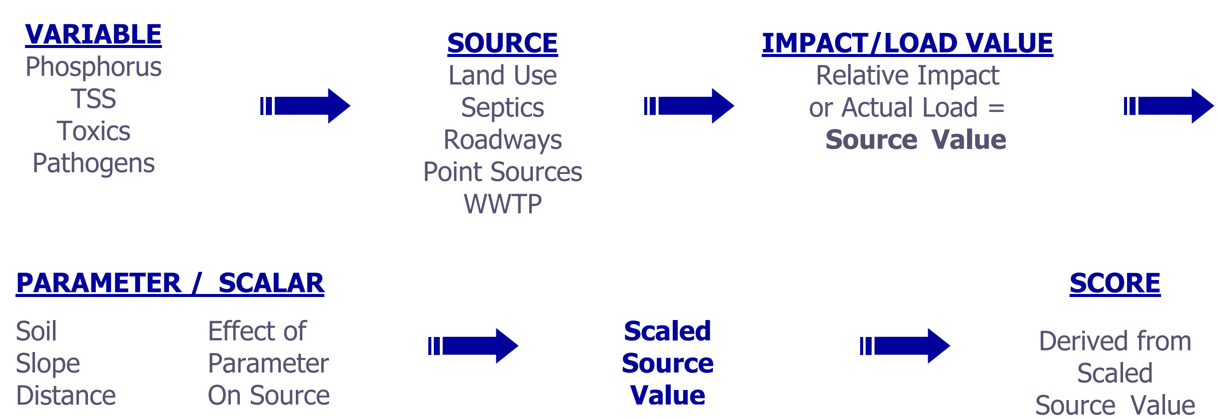
***Concept***

Achieving the NYCDEP's goals for the Croton Watershed Strategy requires a means to evaluating current and future potential risks of water quality impairment. While established water quality models such as HSPF or SWMM can predict water quality, applying these tools to the Croton Watershed engenders multiple problems. First, developing a mechanistic model for a 375 square mile heterogeneous watershed is unrealistic. The Croton Watershed contains 12 controlled and interconnected reservoirs, and the reactions within these reservoirs may dominate water quality. Developing a mechanistic model must take into account the in-reservoir dynamic, and would de-emphasize the land-based component critical to watershed management. This is contrary to the emphasis of this study, which is to provide a tool and method to support watershed management through a focus on point and non-point impacts. Second, loads for some water quality variables (such as pathogens) are not readily available. Without load information, a model cannot simulate the effect of a source on water quality. With these limitations in mind, a GIS-based risk ranking methodology, described in this paper, was developed for the Croton Watershed Management Strategy.

Applying a customized risk ranking methodology rather than more traditional water quality models acknowledges the difficulties of land-based watershed management and the NYCDEP's available water sampling data. The customized methodology differs from traditional models in two ways: first, rather than trying to predict water quality it is designed to indicate and rank potential contributions to water quality problems; second, it is not directly calibrated to measured water quality data. While a trend analysis should indicate a correlation between the results of the methodology and measured water quality, the methodology assumes no direct relationship between results and measured concentrations. The methodology is a tool to evaluate different constituents in the watershed with respect to their potential to impair water quality, not to predict their actual impact on water quality.

The methodology includes several basic modeling principles. For example, the principle of defined sources is used. The source behaves as the independent variable driving the risk ranking scheme. Of additional importance are parameters affecting transport from the source to surface water bodies. Figure 3 presents a conceptual flow chart of the risk ranking methodology.

**Figure 3**
**Risk Ranking Methodology Overview**



The methodology applies "source values" and "scalars" to determine relative scores for subbasins. For each water quality variable, contributing sources are identified. Sources include land-based, septic, and point sources. "Source values" are determined based on literature sources and are comparable to pollutant loads. A single value is determined for each source, which represents the average source value, or load generated by each source. In reality, variations in pollutant generation and transport may be caused by land characteristics such as soil type, soil erodability, slope, or proximity to receiving waters. These varying factors are incorporated through the use of scalars. Scalars are used to lower the source value under mitigating conditions, such as greater distance from receiving water, or increase the source value under enhancing conditions, such more impermeable-than-average soils.

***Data***

Information played both an enabling and a limiting role in the project. While an abundance of electronic data enabled the use of GIS for analysis, persistent questions of data suitability were also an issue of concern. In developing the methodology, all data limitations had to be considered.

The initial phase of the project included a significant effort to collect data from the NYCDEP, the New York State Department of Environmental Conservation (NYSDEC), the Connecticut Department of Environmental Protection (CTDEP), and the 22 towns and 4 counties intersecting the watershed. Information was collected in both hard copy and electronic formats. Because many of the data were acquired from different sources, the quality, format, and availability of data varied across the watershed.

The initial data development followed a two-step approach: first, identifying the data requirements of the analysis methodology, and second, identifying appropriate data sources or data gaps. Ultimately, the data development and the analysis methodology development became an iterative process, where the capabilities of the GIS analysis tools and available data supported opportunities for a more detailed analysis than initially planned, while limitations in data forced revisions in the analysis approach.

To support the analysis methodology, the project team identified several "key data sets" required for determining sources of point and non-point impacts and loading factors, modifying scalars, and determining build-out potential. These data included land use, land cover, point sources, surface hydrology, roads, soils, topography, septic/sewer areas, zoning, and regulatory restrictions to development. Additional data were required to characterize the basins in terms of background setting, socioeconomic conditions, natural resources, and surface water quality. Supporting data included stream classifications, wetlands, wetland loss trends, natural resources, aquatic habitats, reservoir operations, census, and water quality sampling results.

While many supporting data sets were available, sometimes from multiple sources, a number of data limitations caused us to adjust analysis methods or adapt alternative methods of deriving data. The primary issues encountered included inconsistent non-point loading factors across variables and land uses, incomplete spatial coverage (i.e. cadastral parcels), incomplete or inconsistent data attributes across the study area (i.e. Connecticut vs. New York parcels; development restrictions between municipalities), unavailable data sets (i.e. buried infrastructure; impervious surface; land cover), and spatial differences between data from multiple sources (i.e. NYCDEP vs. state hydrology layers).

The land use data set was critical to the analysis. Land use provides the land-based source load of each variable, and is the changing factor between the pristine, current, and build-out scenarios. Literature documentation on loading factors grouped land uses differently between the variables under study, and so the supporting land use data needed to be broad enough to support these variations.

Of the available spatial data, which included classified land cover from remote sensing, infrared aerial photography, and parcel data, the parcel data was deemed to be the most useful coverage for developing land use. At the start of the project, the parcel coverage was complete for all but one of the New York municipalities, and much of the parcel data included an attribute field that linked each parcel to the New York Office of Real Property (ORPS) database. This link provided a detailed land use classification of nine major land use categories and nearly 300 sub-categories, more than sufficient to support the different classifications required for each study variable. In addition, the parcel divisions could be used to develop septic source loads for phosphorus and pathogens on a per-lot basis. The availability of parcel data also meant that build-out and management scenarios could be modeled at a level more detailed than the subbasin scale indicated by the project scope. This cadastral data were assembled, merged, and assessed for data quality in GIS. GIS was indispensable in spatially meshing these data and establishing a master cadastral database of consistent quality.

In developing the future-condition scenario, the GIS synthesis of parcel-based land use and cadastral zoning was instrumental. The future-condition scenario was developed for the maximum build-out allowed under current zoning conditions and development restrictions. The build-out assessment used minimum lot sizes, as documented in the zoning codes for each municipality within the watershed, to determine the maximum number of potential parcels within undeveloped or under developed areas. Undeveloped parcels were determined through the selection of specific ORPS codes representing vacant land; underdeveloped parcels were determined through selecting ORPS codes likely to be converted to other uses (i.e. Agriculture and estates) or which were larger than the zoning restrictions allowed and therefore candidates for subdivision. Development restrictions, such as proximity buffers to streams and wetlands and steep slope restrictions, were superimposed on the parcels to realistically reduce the number of potential future lots. The use of GIS was crucial in obtaining accurate overlays of these restrictions on a per-lot basis for each of the more-than 70,000 parcels in the watershed. Land use under the future scenario was assigned for potentially developable parcels based on current zoning. Using this method and the available GIS vector overlay tools, we were able to assign land use, for future land-based loading, and dwelling unit density, for future septic loading, objectively and consistently.

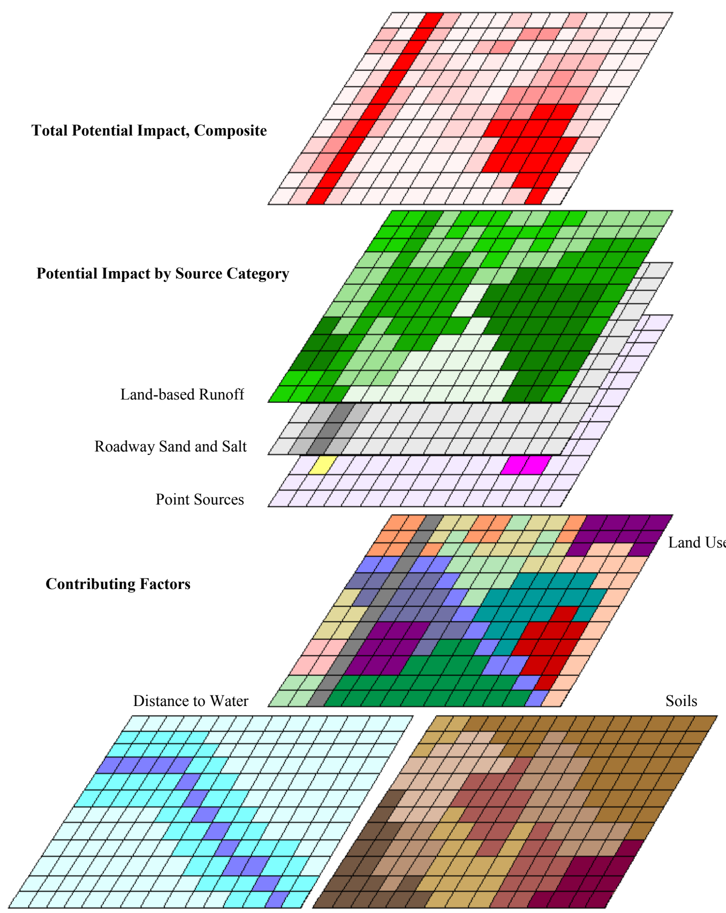
Two other key data sets used to modify the land-based source values were land cover and impervious surface. Land cover was used in combination with soils data to develop a runoff factor, an indicator of the magnitude of potential pollutant transport to receiving waters. Impervious surface was used as an indicator of potential flow volume within a subbasin, correlated to potential stream erosion. At the time of the study, land cover and impervious surface coverages were under development by the NYCDEP from recent aerial photography of the watershed, but were not available in time for inclusion in the study. As a substitute, land cover and impervious surface data were derived from the parcel/land use data using the Soil Conservation Service curve number look-up table to derive the runoff factor and Anderson land use categories to estimate impervious cover for various land uses.

### *GIS Implementation*

In conducting the point and non-point source watershed assessment, the spatial distribution of data was key. Some watersheds drain to a single distribution and control point, in which case a tabular analysis of watershed components may be sufficient for assessing water quality risks for the single terminal point. The Croton Watershed, however, has 12 reservoirs, each with separate drainage basins. In an extreme operational scenario, operational changes could be made to individual basins – taking some “off-line” or connecting some to the Delaware System instead of the Croton System. In such a discrete system, it was crucial to understand exactly *where* in the watershed a feature was located and which of the 12 reservoirs might be impacted by that feature. For this reason, as noted above, GIS was instrumental in compiling sufficient base data.

Due to the spatial distribution and variety of sources and the effects of multiple physical characteristics affecting the risk assessment, the risk ranking methodology itself was also applied in GIS. GIS provides the framework for the data processing that yields aggregate subbasin scores and it allows for enhanced graphical representation of the scored subbasins. This graphical representation provides a visual indication of the distribution of “high-risk” subbasins across the watershed. The GIS also provides sufficient detail to identify localized areas of concern on a parcel basis. The analysis for this project was largely conducted with GIS raster processing tools, as represented in Figure 4. A base layer such as land use was converted to a grid with grid cell values corresponding to each land use’s source value. For a total suspended solids analysis, for example, an area of commercial land use would have higher grid values than a forested area because of the larger quantities of silt, dust, and other suspended solids that run off impervious surfaces during rain storms. Such parameters as the soil underlying a given area or the area’s distance to the nearest water body might also contribute to the potential for water quality impairment. Raster processing and grid algebra allows each of these contributing layers to be combined into single layers representing potential impacts. Potential impacts could be summarized by source category, separate layers for risks from land use, roads, and point sources, for example. Potential impacts could also be composited in a single layer representing the total risk to water quality from a single variable – total suspended solids, for example. The key function of the GIS is to enable the quantitative synthesis of many different types of information (layers) without losing resolution on the spatial variability of each datum.

**Figure 4**
**Raster Processing Overview**



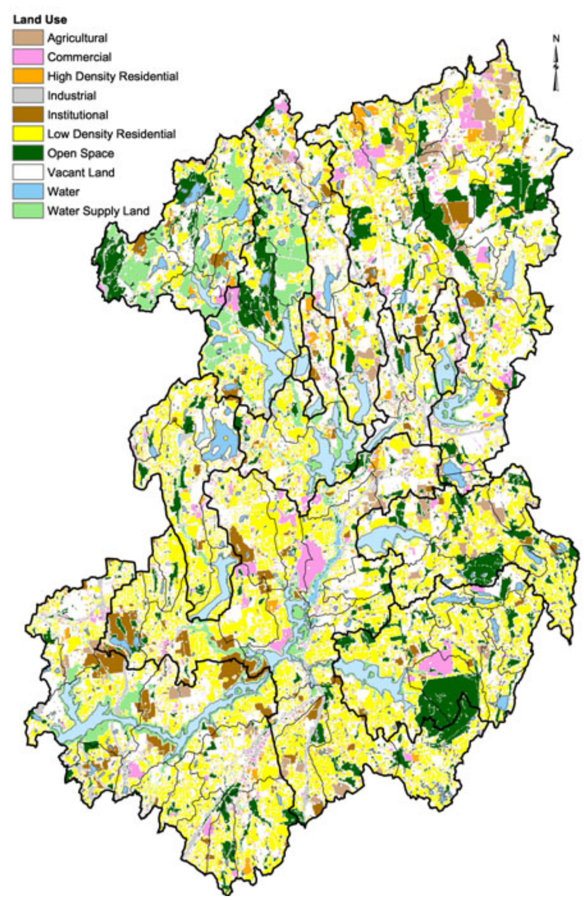
## *Procedure*

### Sources

For the purposes of the methodology, a source is a watershed characteristic that contributes to the risk of impairment of water quality by a specific variable. For example, sources of phosphorus in the watershed are wastewater treatment plants, septic systems, and the land itself. A source may include many contributing factors: "land," for example, is understood to include distributed pesticide applications, atmospheric dry deposition, and rain-deposited pollutants. A *point source* is a discrete location with the potential to discharge into the watershed such as a tank containing toxic chemicals or a wastewater treatment plant's effluent pipe. A *non-point source* is a dispersed or diffuse source such as land-based runoff. Additionally, sources may be *continuous*, releasing small but constant levels of pollutants, or *episodic*, at risk for a sudden massive release of pollutants.

Many sources are dependent on land use and may also be dependent on the stage of development. Each of the land uses may contribute to more than one source and may pose different magnitudes of risk to water quality from different variables. In fact, the land uses employed in this methodology are aggregate categories of 187 unique property classes, each of which is considered independently in the methodology. The overall categories considered are illustrated in Figure 5. Land use is not the only input to the methodology; also included are the wastewater treatment systems which give rise to the failed septics' washout, wastewater treatment plant, pump station, and broken sewer sources. The other point sources are a third major data input to the methodology. These point sources include Connecticut Municipal Waste Sites, New York State Department of Transportation Salt and Sand Storage Sheds, Toxic Release Inventory (TRI) sites, Comprehensive Environmental Response Compensation and Liability Information System (CERCLIS) sites, Hazardous Waste Sites, Connecticut Underground Storage Tanks, Chemical Bulk Storage (CBS) sites, Petroleum Bulk Storage (PBS) sites, NYCDEP East-of-Hudson Wastewater Treatment Plants, New York State Pollution Discharge Elimination System (NYSPDES) sites, Resource Conservation and Recovery Information System (RCRIS) sites, Connecticut Leaking Underground Storage Tanks, and NY Leaking Underground Storage Tanks. Points were also included that were the centroids of tax parcels the land use of which was thought likely to provide a toxics point source. Gas stations, pesticide retailers, pest control services, and gardening and landscaping suppliers and services listed in the yellow pages for the region were also geocoded and included.

**Figure 5**
**Land Use Categories**



**Source Values**

The relative potential for water quality impairment from each of the variables is based on scaled source values determined for each source of each variable in each subbasin. The methodology is intended to help make informed management decisions using limited information. For instance, the methodology ranks sources on a relative scale based on the assumption that differences between sources can be approximated more confidently than the absolute impact of each source on water quality. However, a degree of uncertainty is still involved in the process. In particular, the risk ranking is only as accurate as the scientific data on which it is based. This level of uncertainty differs across variables since more extensive information is available for certain variables than for others. For example, the generation and transport of phosphorus, total suspended solids, and toxics such as metals have been extensively studied and modeled by numerous scientists and engineers. In contrast, a standardized laboratory process for detecting the pathogen Cryptosporidium is still being settled upon by the scientific community, and there is limited field data linking the pathogen to landscape conditions. Similarly, the scores associated with continuous pollutant sources are generally more certain than episodic pollutant sources since actual empirical data is available for estimating continuous sources, but the effect of episodic sources must be surmised. For this reason, most episodic toxic sources were simply inventoried instead of assigned scores. Table 1 lists the source components and source values for one source: land-based phosphorus runoff.

**Table 1**

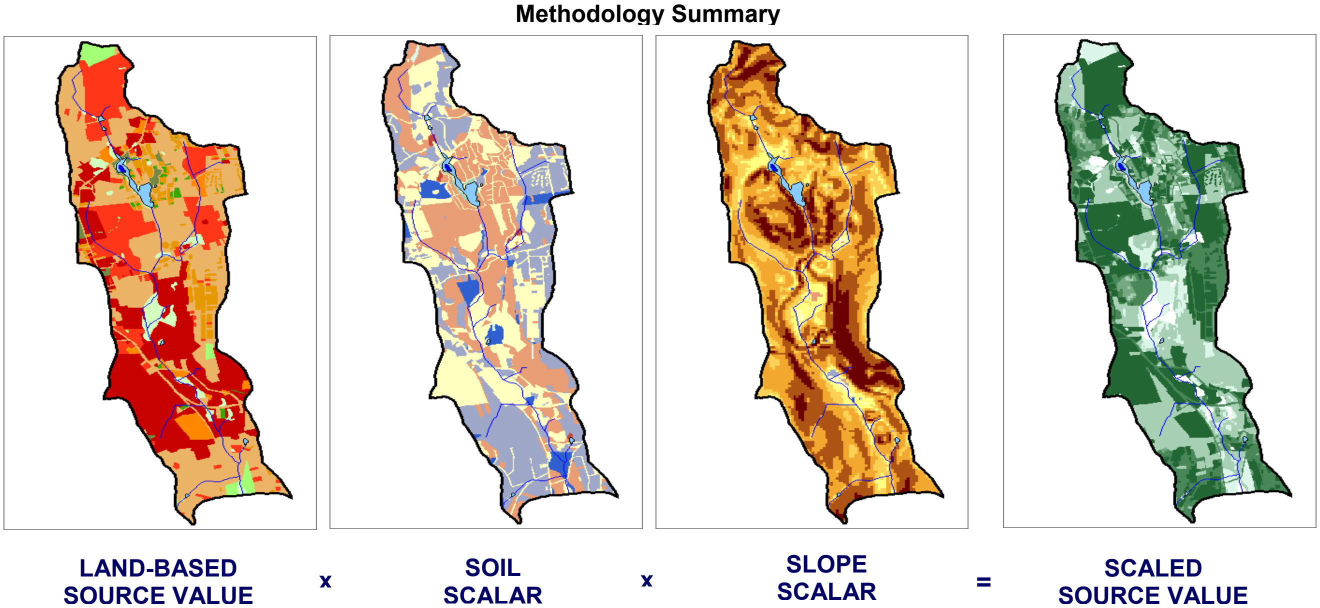
<table>
<tr><th rowspan="2"></th><th colspan="4">Source Information</th><th colspan="3">Parameter Information</th></tr>
<tr><th>Sources</th><th>Source Components</th><th>Source Component Values</th><th>Unit Source Values (per cell or point)</th><th>Parameters</th><th>Scalars</th><th>Scalar Values</th></tr>
<tr><td rowspan="14">Non-Point Sources</td><td rowspan="14">Land-Based Phosphorus Category (average source delivered by storm water runoff)</td><td>Agricultural - Livestock</td><td>5 kg/yr/ha</td><td>0.05 kg/yr/cell</td><td rowspan="5">Soil</td><td rowspan="5">Surface Runoff Calculation</td><td rowspan="14">Combined, range based on 2 Standard Deviations from 1</td></tr>
<tr><td>Commercial</td><td>2.5 kg/yr/ha</td><td>0.025 kg/yr/cell</td></tr>
<tr><td>Agricultural - Row Crops</td><td>2 kg/yr/ha</td><td>0.02 kg/yr/cell</td></tr>
<tr><td>High Density Residential</td><td>2 kg/yr/ha</td><td>0.02 kg/yr/cell</td></tr>
<tr><td>Industrial</td><td>1.75 kg/yr/ha</td><td>0.0175 kg/yr/cell</td></tr>
<tr><td>Medium Density Residential</td><td>1.5 kg/yr/ha</td><td>0.015 kg/yr/cell</td><td rowspan="5">Slope</td><td rowspan="5">Velocity Calculation</td></tr>
<tr><td>Roadways</td><td>1 kg/yr/ha</td><td>0.01 kg/yr/cell</td></tr>
<tr><td>Low Density Commercial</td><td>1 kg/yr/ha</td><td>0.01 kg/yr/cell</td></tr>
<tr><td>Low Density Residential</td><td>1 kg/yr/ha</td><td>0.01 kg/yr/cell</td></tr>
<tr><td>Low Intensity Agricultural</td><td>0.5 kg/yr/ha</td><td>0.005 kg/yr/cell</td></tr>
<tr><td>Managed Lawns</td><td>0.5 kg/yr/ha</td><td>0.005 kg/yr/cell</td><td rowspan="4">Percent Imperviousness</td><td rowspan="4">Percent Imperviousness</td></tr>
<tr><td>Undeveloped</td><td>0.1 kg/yr/ha</td><td>0.001 kg/yr/cell</td></tr>
<tr><td>Forested</td><td>0.08 kg/yr/ha</td><td>0.0008 kg/yr/cell</td></tr>
<tr><td>Water</td><td>0 kg/yr/ha</td><td>0.0 kg/yr/cell</td></tr>
</table>

Using the GIS platform for implementation of a standardized analysis ensures that source values were applied consistently and objectively throughout the watershed. Furthermore, the GIS environment facilitates comparison of values in different spatial locations, as well as watershed-wide statistics. The analysis for the Croton Watershed Strategy assessment was conducted on a relative basis – each grid cell in the watershed was scored for a particular variable relative to the watershed's average condition with respect to that variable. For this purpose the available data were sufficient and the methodology perfectly suited.

**Parameters and Scalars**

All locations in the watershed are not equal with respect to their potential to transmit pollutants to surface water bodies. Sources may vary in intensity depending on local physical site characteristics. Such characteristics, or parameters, as soil permeability and slope may affect the magnitude of a source's potential to impair water quality. For example, the delivery of land-based runoff due to a rainfall event is affected by the soil and slope on which the precipitation lands. This effect is quantified in a *scalar value*. The methodology assigned all land uses of the same type, such as commercial properties, the same initial source value. Less permeable and more steeply sloped properties are expected to contribute more runoff to surface water bodies than the average site in the watershed, and so are assigned soil and slope scalars greater than one. Regions with more permeable soil and less slope than the watershed average were assigned soil and slope scalars less than one. Using the grid capabilities of GIS, each of the source value and scalar layers could be maintained as separate grids and multiplied using map algebra to produce a single *scaled source value* results grid. This process is illustrated for a single subbasin in Figure 6.

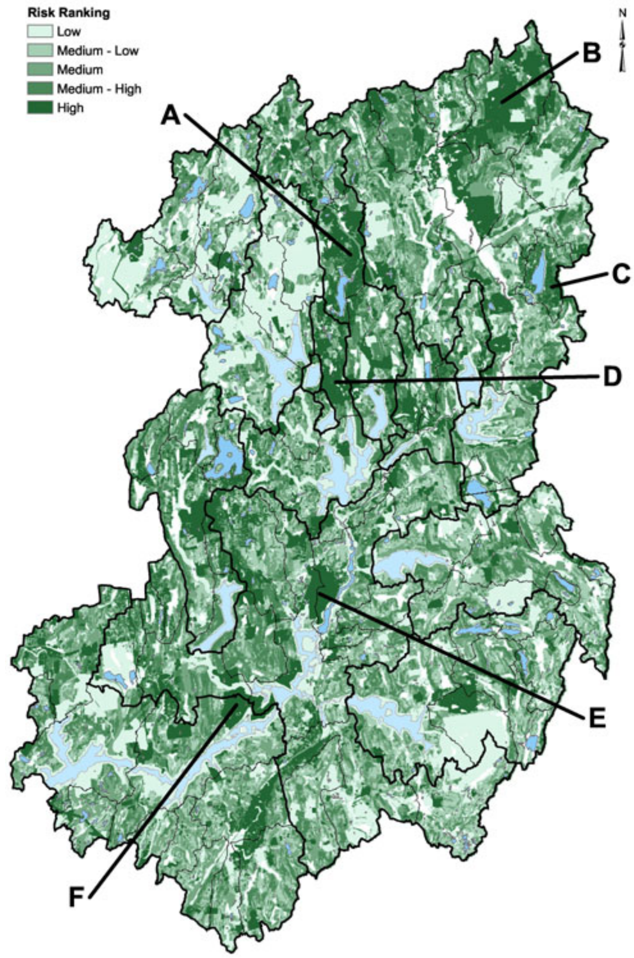
**Figure 6**
**Methodology Summary**



### Scoring and Subbasin Ranking

This methodology, and the resulting scaled source value grids, enables three analyses: estimation of the potential for water quality impairment in a given subbasin, identification of potential areas of concern for acute water quality impairment, and comparison of the potential for water quality impairment among all subbasins.

Figure 7
Sample Risk Ranking and Areas of Concern



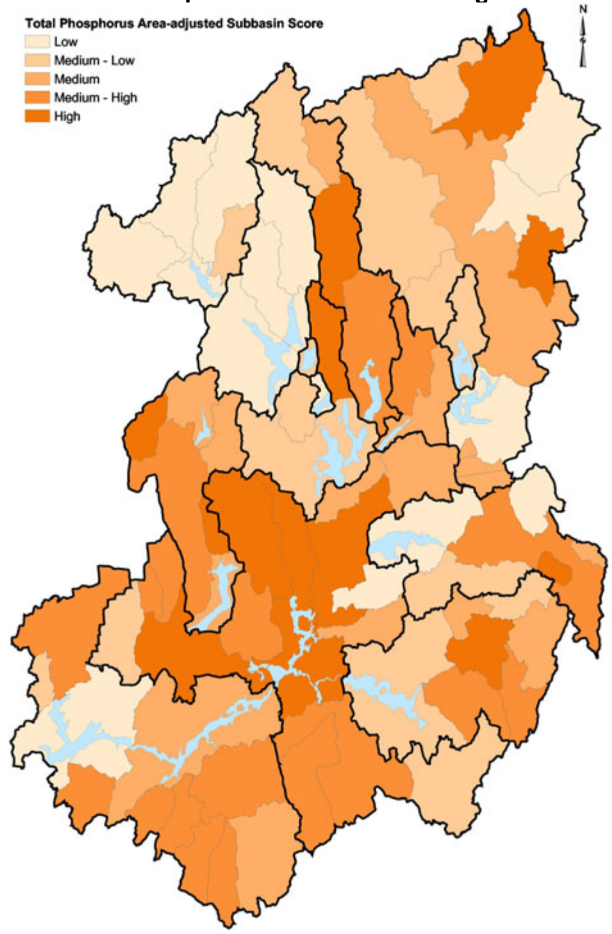

The spatially-distributed scaled source values for a particular source within a basin are ranked according to magnitude in ascending order. The ranked values are divided into five indices representing the risk they pose to water quality. (Figure 7) With the presentation of these indicators on a map, areas of concern are easily identified as those regions with a relatively high overall indicator value. Areas of concern may be small and localized areas in the high-density index or may be large areas ranking in the low-density index but aggregating to a high overall impact from their large total area. Sample areas of concern are called out in Figure 7.

The spatially-distributed scaled source values are also summed for each variable in each subbasin, yielding the source score for a given source (e.g. the land-based runoff total phosphorus score for subbasin X). Summing the source scores for all sources in a subbasin yields the total subbasin score for the variable under consideration (e.g. the total phosphorus score for subbasin X, which includes land-based runoff, septic runoff, and wastewater treatment plant discharge). Total subbasin scores are also ranked and grouped to facilitate comparison between subbasins.

### *Extension of Methodology – Future Condition*

In addition to evaluating the current conditions of the watershed, this project includes analyses of two other basic scenarios used to establish the minimum and maximum limits to water quality impairment potential: "fully built-out" conditions and "pristine" conditions. The fully built-out analysis used zoning information, socio-economic data, and other indicators of development and land use to identify the potential future land-use for all currently undeveloped or underdeveloped lands. By assuming that all land reaches this fully developed condition, the build-out analysis creates an extreme scenario to identify the areas with the highest potential to have an impact on water quality in the future. Conversely, the pristine analysis assumed a pre-development watershed of predominantly forested land. This analysis provides a baseline for the opposite extreme: virgin water quality prior to modern development.

Figure 8
Example: TSS Subbasin rankings




These analyses were particularly suited to the GIS framework. The ability to quickly and consistently reclassify any of the input layers, changing land uses, soil permeabilities, point source magnitudes, is built-in to GIS. Achieving future or pre-development conditions in non-spatial platform would have been a much more daunting task.

## Results and Discussion

The scaled source values are summed to produce total subbasin scores for each variable. To account for differing subbasin areas that might inaccurately weight large subbasins as large sources, total subbasin scores were divided by total subbasin area, yielding an area-adjusted total subbasin score. Based on these area-adjusted scores, the subbasins were bracketed for each scored variable into quintiles such that the first quintile was the lowest fifth of the subbasin scores and the fifth quintile the highest fifth. Figure 8 is and example of these subbasin rankings for total suspended solids. Subbasins highlighted in the darkest color are expected to contribute the most risk to water quality due to TSS.

Bracketing subbasin scores into quintiles also allows for aggregating relative subbasin scores. The simplest way to do this is to assign each subbasin the number of the quintile into which it falls for each variable, and the sum the variables' quintile scores to obtain an overall subbasin index. The six variables assessed by quintile were total phosphorus, total suspended solids, continuous toxics – pesticides, continuous toxics – other, continuous pathogens, and episodic pathogens. With a maximum possible quintile score of 5 for each of these 6

Figure 9
Overall Subbasin Rankings
Existing Conditions

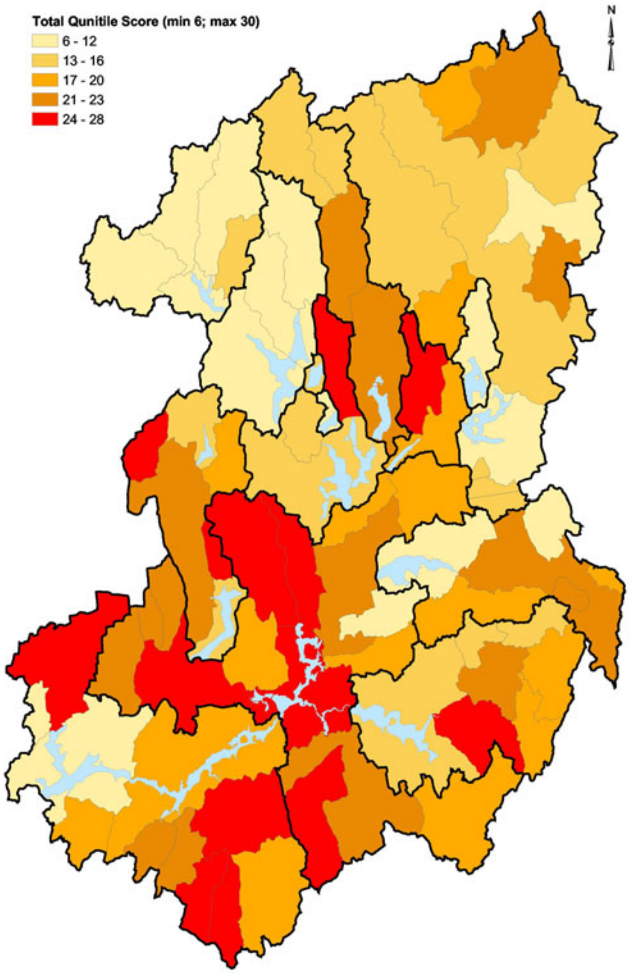
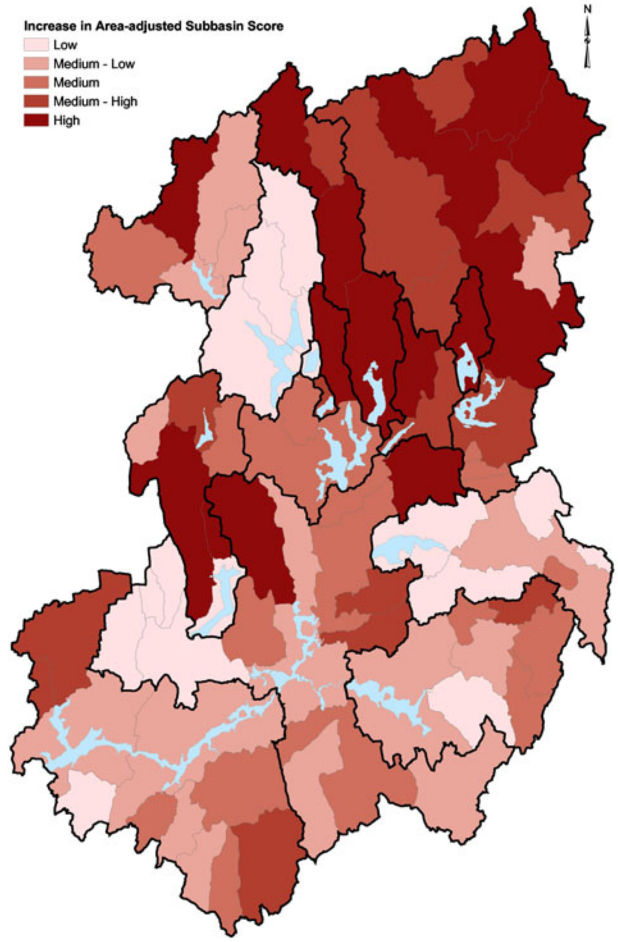


Figure 10
Increase in Area-Adjusted Score
with Full Build-Out




variable categories, the maximum total subbasin score is 30. It should be noted that this method weights each variable equally. The top-scoring subbasins are illustrated in Figure 9.

Those subbasins listed in Figure 10 as having high score increases in the future are expected to see the greatest growth in their potential to impair water quality. This also loosely translates to mean that these subbasins are expected to see the most conversion of low-intensity land use into high-intensity land use since high-intensity land uses greatly increase the subbasin scores for each variable. This result is reasonable as the southern and western portions of the watershed are already much more developed than the northeast section, here indicated as having the most potential growth in water quality impairment. The future analysis that was conducted is only one potential outcome of future development, however, as it assumed that all land was completely built-out according to its current zoning. Additionally, this method of estimating build-out does not take into account the pattern of development, only the end result. It is likely that areas close to transportation corridors and business centers will be the first to develop new commercial properties, and that vacant areas near lakes and open space will be the most desirable residential properties.

These maps of subbasin scores are one means to compare relative impacts across the watershed. Over such a large area as the whole watershed, however, there are other factors that might affect prioritization of management strategies. Five such factors were considered in a subsequent watershed-wide analysis:

- Water Supply System Section Priority: Areas closer to a water distribution uptake (basins of terminal reservoirs) are considered higher priority than distant headwater subbasins.
- 60-Day Travel Time: A 60-day travel time buffer is commonly used for pathogens in particular to allow for natural degradation and die-off. Waters calculated to be within a 60-day travel time of a primary water are of much higher concern than those with greater-than 60-day travel time.
- Phosphorus Restricted Basins: The NYCDEP has determined that some basins exceed the New York State guidance value for phosphorus. Though phosphorus itself does not usually impair water quality, in a phosphorus limited environment excess phosphorus may lead to *eutrophication*, or excess biological activity including algal blooms and other such effects that may impair water quality.
- Trout Streams: Trout streams are important to the watershed not only as a natural resource, but also because trout are a good indicator of overall stream quality. If

streams become too sedimented or have poor water quality the trout populations may be negatively impacted.

- Wetlands and Other Sensitive Ecologies: Wetlands are key natural resources, concentrated centers of biodiversity and natural filters of surface water. Typical wetland functions affecting water quality include the detention of flood and storm waters, maintenance of base flows to streams and rivers, and the provision of discharge or recharge for groundwater. These areas were highlighted for special water quality consideration.

**Figure 12**
**Areas of Concern for Habitat and Sensitive Species**

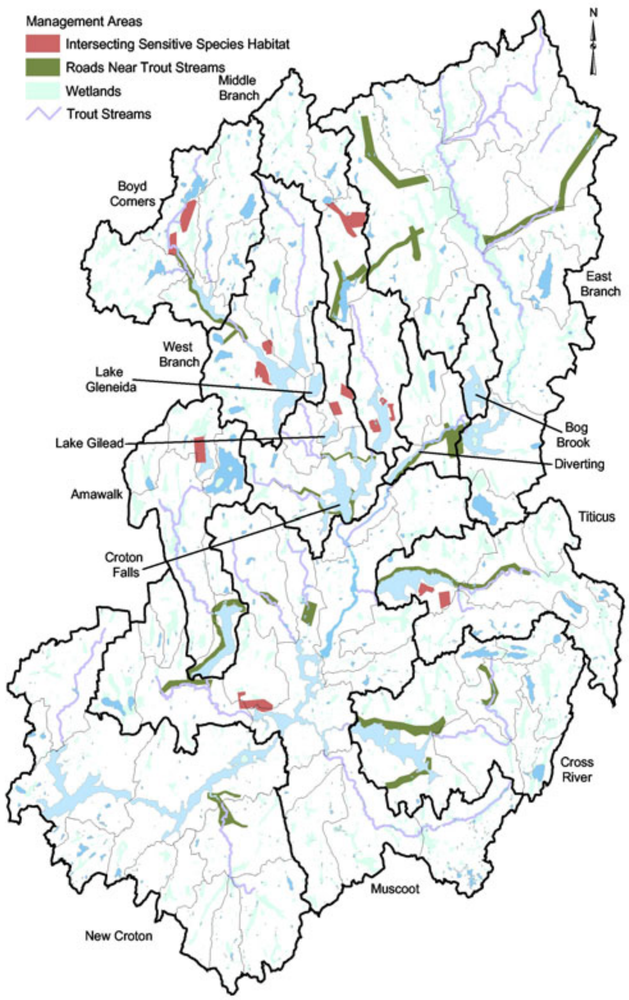
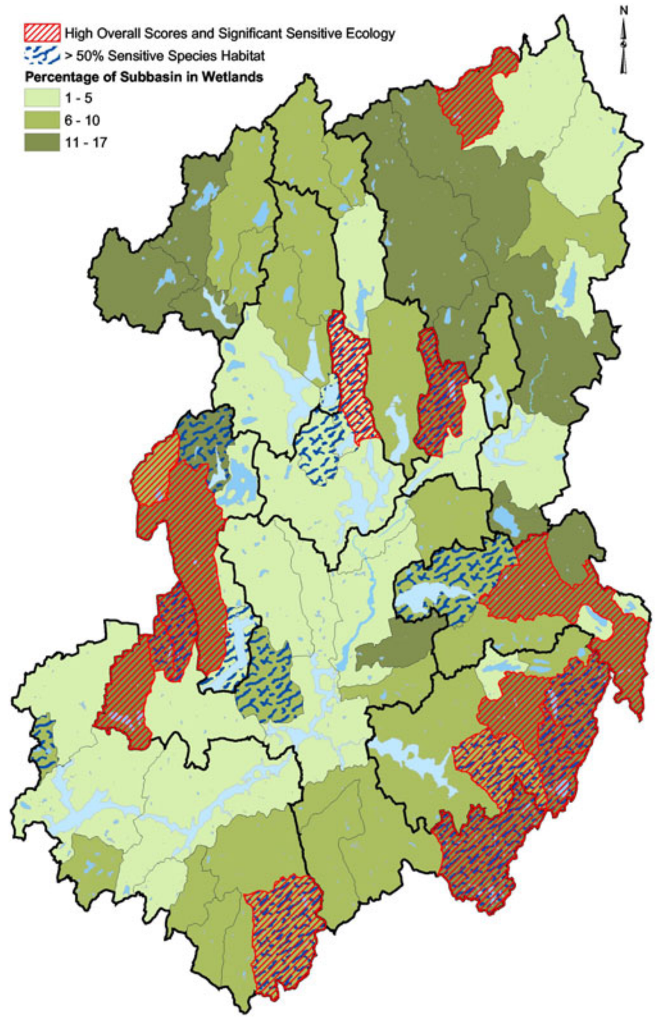



**Figure 11**
**Potential Impacts on Wetlands and Sensitive Species**




As illustrated in Figure 11 and as is evident in comparing Figures 9 and 11, some areas that have high overall scores on the purely objective scale (Figure 9) may not be of as high priority if the primary management aim is protection of habitat and species. Figure 11 highlights the areas that might pertain to this management focus. Similar graphics were developed for each of the five watershed-wide factors mentioned above.

Finally, combining the areas of concern identified via the scaled source values (Figure 7), the overall subbasin contributions to potential reservoir water quality (Figure 9), and the watershed wide factors (e.g. Figure 11), the methodology enabled prioritization of particular management areas. For example, the roads near trout streams identified in green in Figure 12 and the management areas that intersect sensitive species habitat identified in red in Figure 12 were identified as the key areas of concern for a management strategy focused on habitat and sensitive species. Other key areas were identified for each variable considered in the analysis, as well as for focuses on toxics and spills, aggregate loading reduction, and source water buffer protection.

**Future Steps**

The Croton Watershed Strategy assessment resulted in a series of reports, for each basin in the watershed and for the watershed as a whole. A Decision Support Tool (DST) application was developed to package the methodology for future use within the ArcGIS platform. With the results of the Croton Watershed Strategy assessment and the DST, the NYCDEP will be able to prioritize its watershed monitoring, modeling, protection and restoration efforts as well as provide local stakeholders with technical information for their own watershed programs. The types of watershed strategies expected to be employed in the DST are open space preservation, storm water management, wastewater management, road drainage improvements, and agricultural management. The DST also includes the ability for users to prioritize areas of concern based on user-defined factors such as sensitive habitats, development trends, or alternative system operational scenarios.

Ultimately, the DST is just one component of a project tracking and reporting tool. Already in place in the Croton Watershed are programs to address storm water pollution from construction and new developments, tertiary treatment of wastewater treatment plant effluent, agricultural runoff, and storm water management for the basin linked to the Delaware System. Additionally, several federal regulations that may eventually influence actions within the watershed. The two primary programs are Total Maximum Daily Loads (TMDLs) and Phase II Storm Water Regulations. As further projects and regulatory demands develop for the watershed and the situation becomes more complex, the NYCDEP must be able to maintain the same level of analysis currently implemented by the methodology.

The most critical benefits of the Croton Watershed Strategy assessment and the DST may yet to be seen. Some planned applications of the methodology include:

- Project Tracking: The Tracking System will utilize the datasets and modeling tools developed as part of the first phase of Croton Watershed Strategy and will essentially be an additional component to the DST. This provides the NYCDEP a means by which to track ongoing remedial efforts as well as to evaluate proposed projects in the context of subbasin sensitivity, as determined by the DST system, and in the broader context of other on-going activities within the watershed.
- Annual Progress Reporting: The NYCDEP must comply with various reporting requirements including the 2002 Filtration Avoidance agreement with the USEPA. Regular status reports on the effects of non-point and point source activities is a monumental task that cannot be adequately addressed without automated reporting capabilities. To assist with the reporting requirements, the DST will auto-generate maps, quantify benefits, and summarize annual trends for inclusion with the Filtration Avoidance Determination reports.

## Conclusions

Development of the Croton Watershed Management Strategy was part of a two-year project, which has been extended into a third year. The first part of this program was designed to develop an analytical methodology to identify areas of concern within the watershed and a mechanism to develop preliminary management strategies. The second phase will refine the initial methodology with new data and develop additional tools to support on-going watershed management activities.

The results of the analysis are used in a comprehensive watershed-wide management strategy. This strategy, along with the basin reports, forms the foundation for managing the resource in the future. While the NYCDEP is tasked with managing the resource from a drinking water perspective, other stakeholders, including the counties and municipalities that are located with the watershed, have different needs and goals for the resource. Each county is in the process of developing a watershed management plan that will incorporate local priorities. The NYCDEP management strategy along with the individual county plans provide an opportunity for these stakeholders to work together to implement programs to protect the resources associated with the watershed.

The methodology was initially designed in a way that could support refinements to loading and land use data resulting from supplemental analyses, new user-defined criteria, and updated spatial data. During the second phase of this program, refinement activities are being conducted, and the Decision Support Tool is being supplemented with additional tracking and reporting functions. This approach has proved to be an effective method to assess watershed quality at a time when evaluation methods within the industry are continuing to evolve and watershed-specific details are refined.

Application of this approach has value to any group tasked with evaluating the effects of land-side development on water quality. Although the Croton System is a relatively large water supply system, the risk ranking methodologies provide a framework for managing much smaller systems.

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