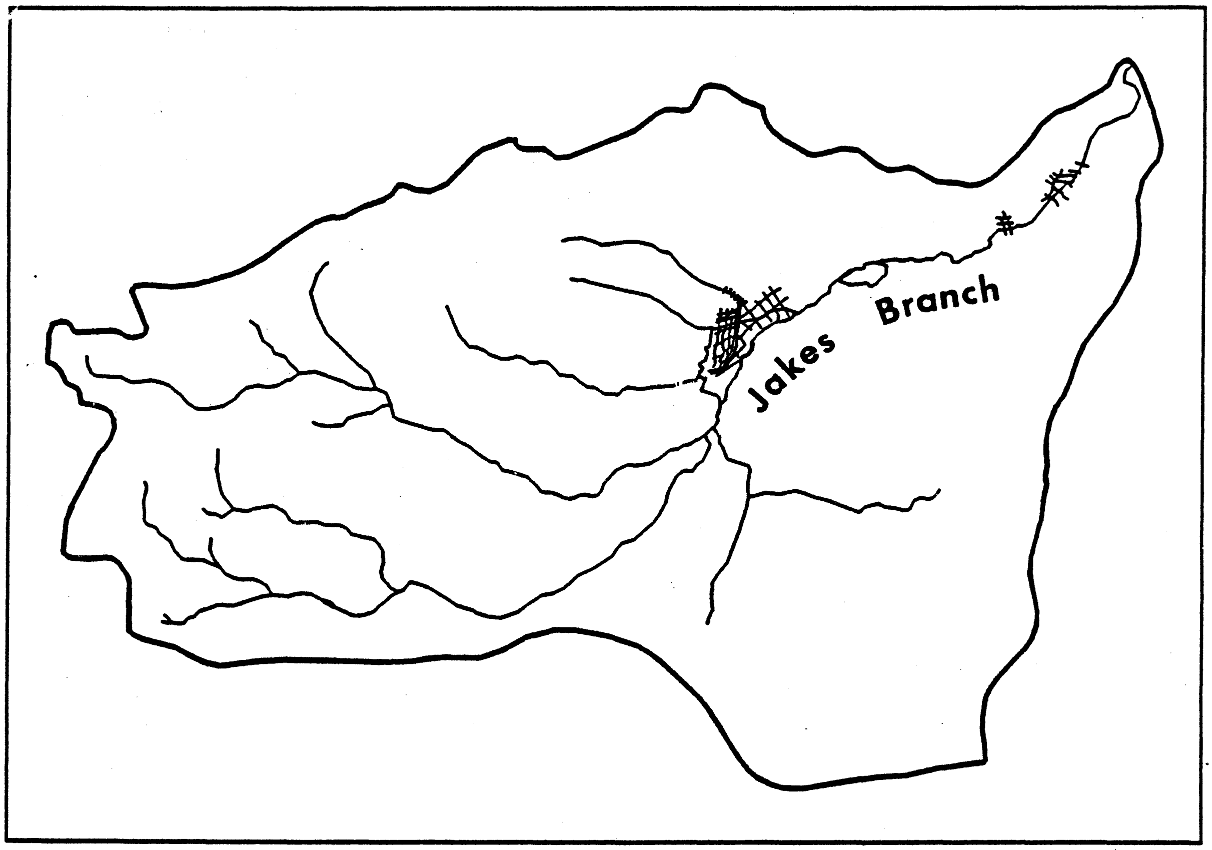
A WATERSHED-BASED WETLAND ASSESSMENT METHOD FOR THE NEW JERSEY PINELANDS

Robert A. Zampella, Richard G. Lathrop,
John A. Bognar, Lyda J. Craig, and Kim J. Laidig



PINELANDS COMMISSION
1994

A Watershed-Based Wetland Assessment Method for the New Jersey Pinelands

Prepared by

Robert A. Zampella, Richard G. Lathrop,
John A. Bognar, Lyda J. Craig, and Kim J. Laidig

December 1994

Pinelands Commission
New Lisbon, New Jersey

ABSTRACT

Sustaining the long-term ecological integrity of Pinelands wetlands is the ultimate goal of the Pinelands Commission's wetland protection program. One technique used to accomplish this goal is the establishment of upland buffer zones based on an assessment of wetland quality and potential development-related impacts. We present a geographic information system (GIS) based watershed-level landscape approach for assessing watershed and wetland systems along ecological integrity and future potential impact gradients. Several GIS-based landscape indexes of wetland quality and impact are developed along with a drainage basin ranking system. Landscape indexes used to evaluate watershed integrity include developed and agricultural land cover, soils with a high potential for ground water contamination, surface water quality, major water supply withdrawals, and biological diversity. Future land use patterns, upland soils with high water tables, and watershed and wetland dimensions are used to evaluate potential impacts effecting the long-term sustainability of these systems. A modified weighted factor procedure is used to rank drainage areas. Several policy options for establishing buffer distances based on the results of the watershed evaluation method are briefly discussed. For demonstration purposes, we present results obtained by applying the methodology in several Pinelands basins.

ACKNOWLEDGMENTS

We gratefully acknowledge and thank those individuals who contributed to the completion of this study. John Stokes, Kathy Swigon, Donna McBride (Pinelands Commission), Robert Nicholson (U.S. Geological Survey), Charles Roman (U.S. National Biological Survey), Joan Ehrenfeld (Rutgers University), Lawrence Niles (N.J. Department of Environmental Protection) and Ralph Tiner (U.S. Fish and Wildlife Service) reviewed the draft report. Audrey Moore (U.S. Environmental Protection Agency) managed the project for the EPA. Eric Vowinkel (U.S. Geological Survey), Nicholas Zripko, Lawrence Thornton, Thomas Breden (N.J. Department of Environmental Protection), and Daryl Lund (U.S. Soil Conservation Service) provided information used in this study. Madhuri Tummalapalli and Lisa Marie Windham (Rutgers University) assisted with data collection and John Bunnell (Pinelands Commission) assisted with the preparation of the final report. This project was funded through a U.S. Environmental Protection Agency Wetlands Protection Development Program Grant. The Pinelands Commission provided additional support.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF COLOR PLATES

LIST OF APPENDICES

PART 1. INTRODUCTION

Background

Wetlands comprise about one-third of the 927,000 acre Pinelands Area (Figure 1) and represent a substantial component of New Jersey's wetland inventory. The values and functions of Pinelands wetlands are well documented (Roman and Good 1983). Outstanding natural attributes include ground and surface waters of exceptional quality, indigenous fish and amphibian communities that are tolerant of the region's highly acidic waters, a rich diversity of rare plant and animal species, and characteristic Pinelands plant communities such as pitch pine lowlands and Atlantic white cedar swamps.

The Pinelands Commission employs a variety of techniques, including regulation and acquisition, to protect the region's wetlands. These programs are implemented through a comprehensive management plan (Pinelands Commission 1980, Collins and Russell 1988). Wetland related activities are strictly regulated. Development of wetlands is generally prohibited and direct wetland loss is minimal.

A major focus of the Pinelands wetlands program is the establishment of upland buffer zones to minimize the adverse effects of development occurring adjacent to wetlands. Since 1985 the Pinelands Commission has used a method developed by Roman and Good (1985, 1986) for guidance in assigning wetland buffers. The objective of the Roman and Good model is to provide a reliable and reproducible approach to determining appropriate buffer widths.

Briefly, the Roman and Good model considers both the relative quality of wetlands located adjacent to proposed development and the potential impacts associated with the development to assign buffer distances. Specific buffer distances are assigned to special cases such as septic systems and sand mines. Although regional factors such as local zoning and downstream impacts are considered, the project-specific approach does not adequately address the overall value of affected wetland systems and the potential cumulative impact of existing and future projects on these systems. Cumulative impact assessment has the advantage of evaluating the collective function of all wetlands in a watershed rather than the contribution of a single wetland area (Johnston et al. 1990).

Purpose

We present a geographic information system (GIS) and watershed-based landscape approach for assessing watershed and wetland integrity and potential impacts effecting the long-term sustainability of wetland systems (Figure 2). The watershed-based approach was developed to enable the Pinelands Commission to complete a comparative assessment of all watersheds and associated wetlands in the Pinelands. Once completed, this regional assessment can provide guidance for policy and regulatory decisions concerning site-specific wetland buffers.

As a prelude to the methodology, we summarize the important ecological characteristics of Pinelands wetlands, the effects of land use activities on these systems, and the role of wetland buffers. For demonstration purposes, we present results obtained by applying the methodology in several Pinelands basins located in Ocean County (Figure 1).

PART 2. ECOSYSTEM CHARACTERISTICS AND HUMAN IMPACTS

Selecting appropriate ecological indicators and assessing the effects of human activities on these attributes is essential for the effective management of human-dominated systems such as the Pinelands (Lubchenco et al. 1991). The Pinelands ecosystem has long been the subject of scientific study and the resulting literature on the region's natural history, ecosystem

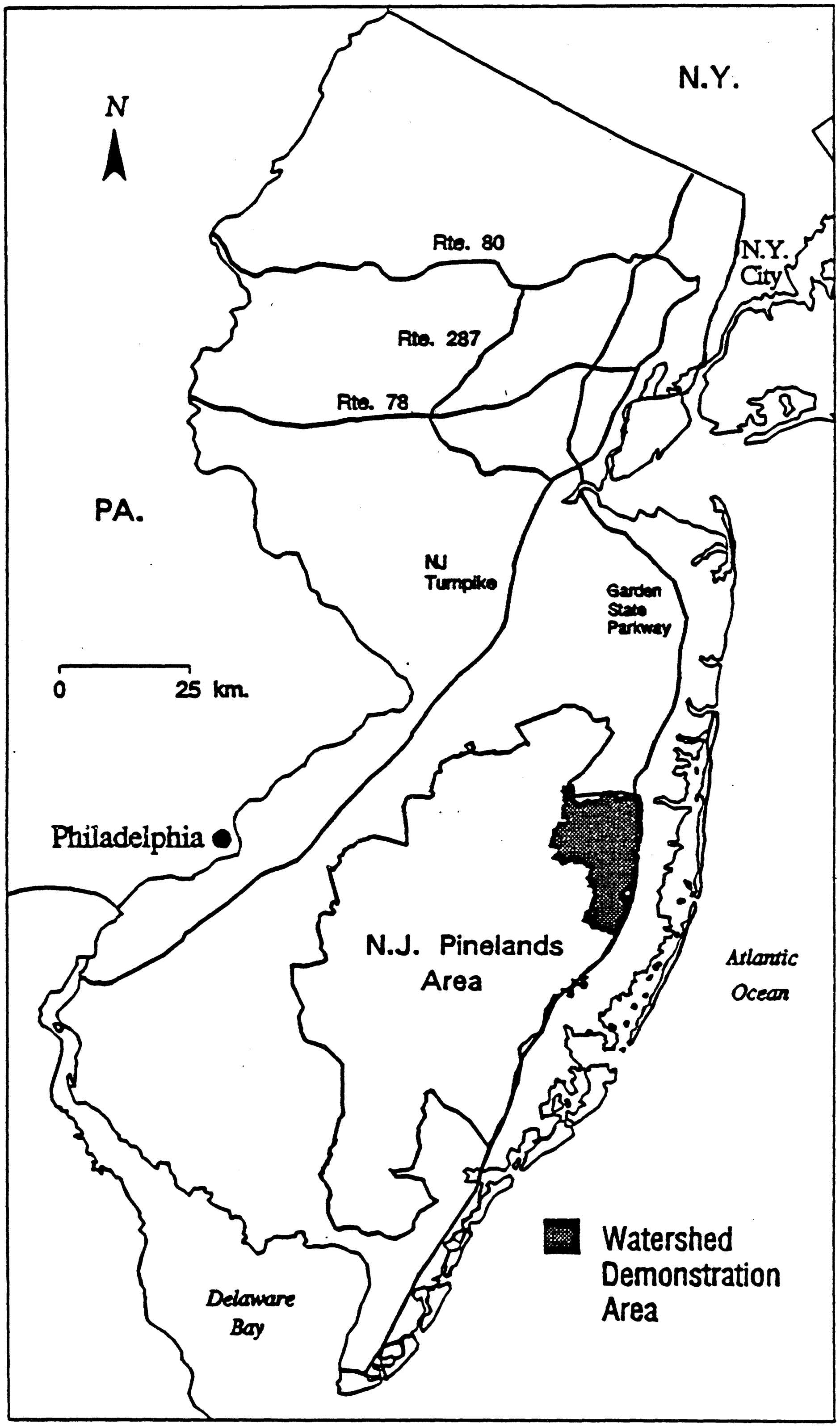


Figure 1. New Jersey Pinelands Area and location of watershed demonstration area.

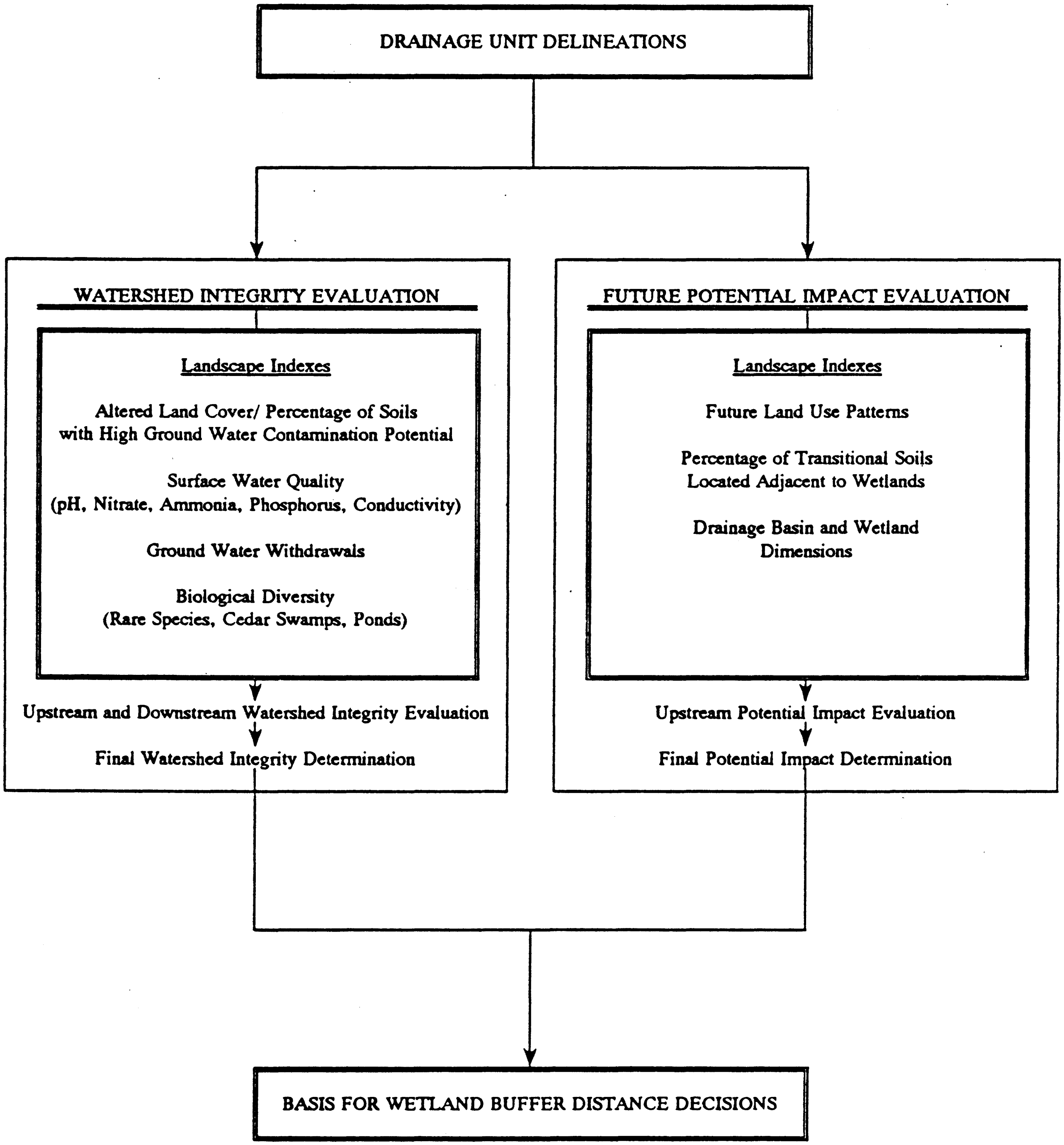


Figure 2. The watershed-based wetland assessment method.

processes, and human impacts is relatively extensive (Buchholz and Good 1982, Gemmell et al. 1989). The purpose of this part is to briefly characterize the important features of Pinelands wetlands and describe what is known of the effects of modern-day land use activities on these systems.

Few areas in the Pinelands have been unaffected by human interference in natural processes (Wacker 1979). Eighteenth, nineteenth, and early twentieth century resource exploitation, including timber harvesting, charcoal-making, mining, impoundment of waters, resource based industry, and agriculture have left a visible mark on the landscape. Ironically, the devastation wrought by this early exploitation has contributed substantially to the creation of many present-day habitats and landscape patterns considered characteristic of the region.

The long-term effect of modern day real estate development, intensive agricultural activities, and large scale mining on the Pinelands will be substantially different from that of the transitory resource exploitation of the past. The ecological consequences of more permanent landscape changes and chemical alteration of ground and surface water associated with present-day land uses may be irreversible.

Hydrology and Water Quality

Hydrology

Nearly all of the New Jersey Pinelands occur on the Outer Coastal Plain. The principal aquifer is the Kirkwood-Cohansey, a water-table reservoir dominated by quartzose sands and gravels (Rhodehamel 1979a, 1979b). This aquifer exerts considerable influence on the structure and function of the Pinelands ecosystem (Ballard 1979, Whittaker 1979). The region's upland and wetland ecosystems operate as a single hydrologic unit that is characterized by a largely unidirectional flow of water down elevational gradients (Ballard 1979).

Rhodehamel's (1979b) annual hydrologic budget for the Pinelands provides a simple model (Table 1) which relates precipitation to stream discharge. Total discharge equals 57.2 cm or 1,563.5 $m^3/day/km^2$ and represents 50% of precipitation. Ground water discharge alone accounts for 89% of annual stream discharge. This relationship is similar to that developed for the Great Egg Harbor River basin by Watt and Johnson (1992). Mean annual discharge for this basin for the period 1931-1988 was 52.12 cm (20.52 inches) which represented 45 percent of mean annual precipitation (115.04 cm or 45.29 inches) measured at nearby Hammonton.

Although water yields of gaged Pinelands streams are not uniform, Rhodehamel's budget provides stream discharge estimates that are comparable to those obtained by regressing discharge and basin size of gaged streams (Figure 3) or from predictions based on correlating partial records with continuous discharge data (Watt and Johnson 1992). Gaged streams displaying the greatest difference between measured and estimated flows are Oyster Creek, Mullica River, McDonalds Branch, Middle Branch Mt. Misery, and Oswego River. In small headwater streams, such as McDonalds Branch and Middle Branch Mt. Misery Brook, a higher percentage of infiltrating precipitation may follow a regional flow path which bypasses local streams and discharges to more distant streams (Rhodehamel 1979b). It is estimated that approximately 8 to 13 cm (3 to 5 inches) of ground water recharge leaves McDonalds Branch basin in the regional flow system (Johnsson and Barringer 1993). Interbasin transfer of water from Oswego River to Oyster Creek and Westecunk Creek may account for the variation in average annual flows in these streams (Pinelands Commission 1980). Discharge in Oyster Creek is especially high but the disparity between precipitation and stream discharge in this basin is probably an exceptional case. Generally, annual stream discharge is closely related to drainage area.

Table 1. Annual hydrologic budget for the Pinelands. Stream discharge = precipitation - evapotranspiration.

Precipitation	114.3 cm	(45 in)
Evapotranspiration (ET)		
Interception	15.0 cm	(5.9 in)
ET from undrained depressions	2.3 cm	(0.9 in)
ET from soil and ground water	39.9 cm	(15.7 in)
Total water loss	57.2 cm	(22.5 in)
Stream discharge		
Direct runoff	6.4 cm	(2.5 in)
Ground water discharge	50.8 cm	(20 in)
Total discharge	57.2 cm	(22.5 in)

Rhodehamel (1979b) estimated near-surface ground water velocity in the northwestern portion of Wharton State Forest to be 36.6 to 48.8 m/year (120-160 ft/year). Because recharge in upland areas follows deeper flow patterns, ground water travel times from recharge areas in the Kirkwood-Cohansey increase with distance to stream courses (Szabo et al. 1994). Discharge to streams and wetlands is also effected by site-specific conditions. Johnsson and Barringer (1993) found differing ground water/surface water relationships along the length of McDonalds Branch. Water appeared to be draining to the shallow ground water system in sections of the stream channel and seasonal differences in recharge and discharge relationships were observed. Impervious materials beneath the stream channel may impede movement of water between the stream and ground water (Lang and Rhodehamel 1963, Johnsson and Barringer 1993).

Ground water withdrawals and stream diversions can have an impact on Pinelands hydrologic systems. Water is removed from the local ground water system by homes supplied by private wells and served by a regional sewer system. Although there is some consumptive use (e.g., lawn irrigation and loss through evapotranspiration), most of the water used by a home with a septic system is returned to the ground water system. Agricultural water demand also removes water from the Kirkwood-Cohansey aquifer system. Most types of crops in New Jersey are irrigated although consumptive use varies among crops (Clawges and Titus 1993).

Water Quality

Ground water in areas of the Pinelands not altered by human activities is generally acidic and low in dissolved solids (Rhodehamel 1979b, Johnsson and Barringer 1993, Table 2). Although surface water chemistry reflects that of ground water, intensive investigations in McDonalds Branch basin indicate that this relationship is complicated by the presence of freshwater wetlands and various hydrologic, geochemical, and biochemical processes (Johnsson and Barringer 1993).

Shallow ground water of the Kirkwood-Cohansey aquifer has been shown to be susceptible to nonpoint contamination by agricultural pesticides and nitrate contamination associated with agricultural, residential and urban land uses (Vowinkel 1991, Louis and Vowinkel 1989, Szabo et al. 1994). Vowinkel (1991) found that concentrations of nitrate in the Kirkwood-Cohansey aquifer underlying agricultural lands was higher than concentrations in ground water beneath urban and undeveloped lands, while purgeable organic compounds such as trichloroethane and benzene were detected less frequently beneath agricultural lands. Szabo et

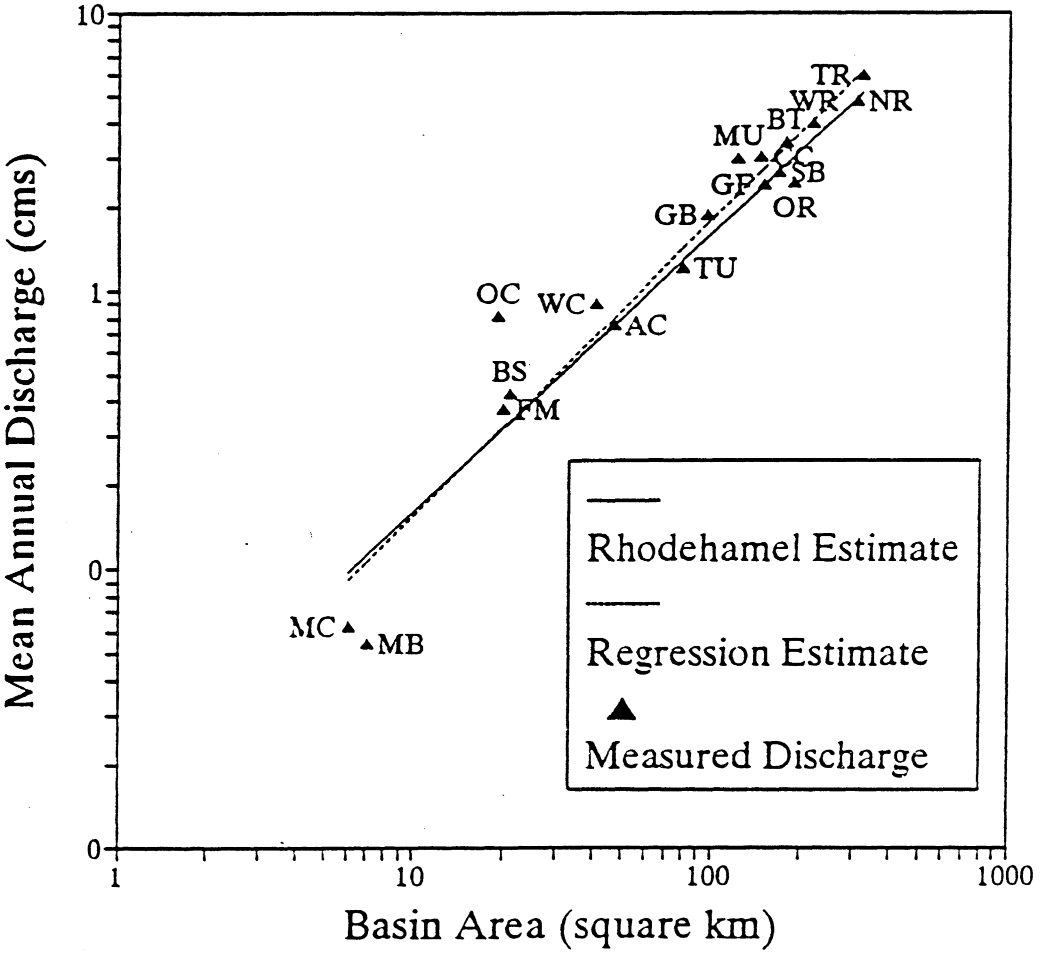


Figure 3. Stream discharge estimates based on Rhodehamel's (1979b) model and regression of mean annual discharge and basin area. Regression analysis is based on all USGS data available through 1992. Stream name abbreviations are as follows: TR (Toms River near Toms River), MU (Mullica River near Batsto), BT (Batsto River at Batsto), WR (West Branch Wading River near Jenkins), OR (Oswego River at Harrisville), BS (East Branch Bass River near New Gretna), GF (Great Egg Harbor River near Folsom), GB (Great Egg Harbor River near Blue Anchor), SB (South Branch Rancocas Creek at Vincentown), NR (North Branch Rancocas Creek at Pemberton), MC (McDonalds Branch in Lebanon State Forest), MB (Middle Branch of Mt. Misery Brook), OC (Oyster Creek near Brookville), FM (Four Mile Branch at New Brooklyn), WC (Westecunk Creek at Stafford Forge), AC (Absecon Creek at Absecon), TU (Tuckahoe River at Head of River), CC (Cedar Creek at Lanoka Harbor).

Table 2. Median values of selected properties and constituents for surface water and shallow ground water in McDonalds Branch. Surface water data are from Lord et al. (1990) and ground water data are from Johnsson and Barringer (1993).

	Surface water			Ground water							
Constituent (1)	Stream Station S1 01/85-03/86	Stream Station S9 01/85-03/86	Stream USGS gage (2) 01/85-03/86	Hardwood Swamp 01/85-02/86	Hardwood Swamp 11/86-06/88	Cedar Swamp 02/85-02/86	Cedar Swamp 11/86-06/88	Upland Site 01/85-02/86	Upland Site 11/86-05/88	Upland Site 01/85-02/86	Upland Site 11/86-06/88
Temperature (C)	7.0	12.0	9.5	9.8	9.6	10	10.6	11	11.1	10.5	11.8
Field pH (units)	3.7	4.5	4.4	3.9	3.91	4.8	4.72	4.9	4.77	4.5	4.49
Field sp.cond. (uS/cm)	114	32	32	77	80	30	37	36	39	48	48
DO (mg/l)	3.8	3.1	4.1	0.3	0.4	1.5	1.9	8.2	8.9	8.4	9.4
DOC (mg/l)	19	1.7	2.6	18	26	0.7	1	0.8	1.2	1.3	1.4
Calcium (mg/l)	0.8	0.37	0.41	0.4	0.41	0.7	0.93	1.8	1.7	1.30	1.1
Magnesium (mg/l)	0.5	0.41	0.47	0.25	0.22	0.70	0.92	0.70	0.56	0.40	0.35
Sodium (mg/l)	2.6	1.9	2	2.2	1.95	1.8	2	1.9	1.9	2	2.1
Potassium (mg/l)	1.8	0.3	0.3	0.16	0.14	0.34	0.4	0.29	0.3	0.17	0.17
Ammonium (mg/l)	0.023	0.012	0.013	-	-	-	-	-	-	-	-
Aluminun (ug/l)	880	50	60	1100	949	140	185	190	430	975	1000
Iron (ug/l)	580	41	72	3100	3250	6.5	7.5	11.5	12.5	20	11
Manganese (mg/l)	20	9	7	11	15	23	34	84	97	86	86
Sulfate (mg/l)	16	3.2	3.7	11	6.3	4.8	6.7	7.3	8.1	10	9.8
Chloride (mg/l)	5.7	3.4	3.6	5.8	4.6	3.2	3.3	3.3	3.3	3.6	3.8
Silica (mg/l)	4.9	4.3	4.2	5.3	5.6	3.8	4.1	2.8	2.9	2.3	2.3

(1) Nitrate and phosphate were not included because values were less than the reporting limit.

(2) USGS gaging station 01466500.

al. (1994) also indicated that pesticides and elevated nitrate concentrations in ground water were associated with agricultural land in the southwestern portion of the Kirkwood-Cohansey aquifer system. Watt and Johnson (1992) reported elevated nitrate and magnesium concentrations in water samples from wells located on agricultural land in the upper Great Egg Harbor River basin. They suggested that the relatively high concentrations of these constituents may be due to leaching of agricultural lime or fertilizer or leachate from feedlots or septic systems.

Because ground water is the primary source of stream flow, it is probably a major source of surface water contamination in the New Jersey Coastal Plain (Vowinkel and Siwiec 1991). Yuretich et al. (1981) suggested that higher concentrations of calcium and magnesium in several Pinelands rivers may be attributed to human influence including development and agriculture. Morgan and Good (1988) indicated that watershed disturbance had a substantial effect on Pinelands stream water chemistry. They found elevated pH and concentrations of nitrate, calcium, magnesium, potassium, and sulfate in streams draining watersheds disturbed by residential development and agriculture.

Zampella (1994a) described a gradient of increasing pH, specific conductance, and concentrations of nitrate, ammonia, phosphorus, calcium, and magnesium in Pinelands surface waters that paralleled a gradient of increasing land use intensity (percent developed and agricultural land) and waste water flow associated with each drainage area. Median pH in undisturbed streams was less than 4.5 and median nitrate-nitrogen and ammonia-nitrogen concentrations were less than 0.10 mg/l. Watt and Johnson (1992) found that watershed disturbance in the upper portions of the Great Egg Harbor River basin effected stream water chemistry. Specific conductance and concentrations of dissolved solids, including calcium, total phosphorus, and to a lesser degree, magnesium and total nitrite plus nitrate decreased downstream. They attributed this trend to a decrease in human disturbance and to increased stream discharge which dilutes dissolved materials transported from upstream areas.

Although sewage treatment plant discharges historically represented an important point source of pollution within certain Pinelands stream systems (Pinelands Commission 1980, Fusillo 1981, Schornick and Ram 1978), recent regionalization of some existing systems and the prohibition of new stream discharges has reduced their effects. However, on-site waste water disposal systems (septic systems) remain an important nonpoint source of ground water contamination in the region.

Stormwater runoff from developed areas is also recognized as a major source of nonpoint pollution. The level of nonpoint pollution associated with stormwater runoff is generally related to the percentage of impervious surface within a drainage area (Hammer 1976, Rimer et al. 1978). Although the relationship between land use and nonpoint pollution has not been well documented for the Outer Coastal Plain of New Jersey, examples of pollutants that may be contained in stormwater runoff from both impervious surfaces (roads and parking lots) and pervious surfaces (residential lawns, golf courses, and agricultural areas) within the region include phosphorus, nitrogen, suspended solids, petroleum hydrocarbons, synthetic organic chemicals, and heavy metals (Cahill Associates 1989).

Biological Diversity

Plant Communities

The composition of Pinelands wetland plant communities has been extensively studied and described. Most of the descriptive studies have been reviewed and summarized by Roman and Good (1983), Tiner (1985), and Zampella (1991). Following McCormick's (1979) concise and widely used classification of the many possible community types, wetlands include Southern or Atlantic white cedar swamp forests (Little 1950, 1951, Olsson 1979, Roman et al. 1990, Ehrenfeld and Schneider 1991), broadleaf or hardwood swamp forests (Olsson 1979, Bernard 1963, Ehrenfeld and Gulick 1981), pitch pine lowland and pine transition forests

(Olsson 1979, Roman et al. 1985, Zampella et al. 1992), shrubby wetland communities (Olsson 1979), and herbaceous wetland communities, including both submerged and emergent vegetation (Olsson 1979, Morgan and Philipp 1986).

The unique character of Pinelands flora is widely recognized (Christensen 1988). Pinelands wetlands support a large portion of the region's floral biodiversity, including many rare plant species (Fairbrothers 1979, Snyder and Vivian 1981, Roman and Good 1983). Although forested wetlands are dominated by a few tree species, including red maple (*Acer rubrum*), Atlantic white cedar (*Chamaecyparis thyoides*), blackgum (*Nyssa sylvatica*), and pitch pine (*Pinus rigida*), more than twenty shrub species are found in the understory. Biologically significant species occurring in wetlands include endemics such as New Jersey rush (*Juncus caesariensis*) and sand myrtle (*Leiophyllum buxifolium*), peripheral and disjunct southern species such as turkeybeard (*Xerophyllum asphodeloides*) and false asphodel (*Tofieldia racemosa*), and curly grass fern (*Schizaea pusilla*), a northern peripheral species (Fairbrothers 1979). The federally endangered swamp-pink (*Helonias bullata*) and Knieskern's beakrush (*Rhynchospora knieskernii*) are also found in Pinelands wetlands.

Present day Pinelands vegetation patterns reflect intense wildfire and cutting histories and soil moisture regimes (Little 1979, Whittaker 1979). The synergistic effects of hydrology and disturbance are responsible for the patchiness and prominence of early successional wetland communities that characterize the Pinelands landscape. Fire is recognized as an extremely important landscape shaping factor (Little 1979). Large wildfires have decreased in frequency since the advent of modern forest fire prevention and this trend may have important landscape consequences (Forman and Boerner 1981, Buchholz and Zampella 1987). Because of the need to protect improved property, development of forest land will permanently alter the role of fire in shaping the ecosystem. A decrease in timber harvesting will also affect succession and landscape patterns. Accurate estimates of the area affected by timber harvesting are unavailable but it is most probable that there has been a decrease during this century and the level of harvesting that occurred during the previous two centuries will never be repeated.

Watershed disturbance associated with development and agriculture has been shown to affect species composition of Pinelands wetlands. Ehrenfeld (1983) compared the species composition of forested Pinelands wetlands located within developed and agricultural watersheds to that of undisturbed basins. There was a loss of characteristic herbaceous species in developed basins which was accompanied by the establishment of non-native species. The result was a higher species richness in disturbed basins compared to undisturbed basins.

Ehrenfeld and Schneider (1991) studied the hydrology, water quality, and community composition and structure of Pinelands cedar swamps along a suburbanization gradient. Suburbanization had a significant effect on water chemistry (Table 3). Compared to cedar swamps in undisturbed watersheds, ammonia levels in surface and ground waters of swamps located adjacent to residential development using septic systems or similar sites with direct stormwater discharges to the wetlands were substantially higher. Elevated orthophosphate concentrations were also found in both ground and surface waters of swamps receiving stormwater runoff. Chloride and lead also increased along the disturbance gradient.

Changes in plant species composition due to the occurrence of non-native species and the loss of indigenous species was associated with increases in ammonia, orthophosphate, chloride, and lead in surface and ground waters of the cedar swamps observed along the disturbance gradient. These changes involved species occurring at low frequencies and low cover. Little change in woody plant species composition and structure was observed. Therefore, Ehrenfeld and Schneider (1991) concluded that they would probably not have any impact on functional properties such as nutrient dynamics and productivity. One important change that could affect the long term sustainability of cedar swamps was a decrease in *Sphagnum* and cedar reproduction observed along the disturbance gradient.

Table 3. Mean water quality of surface and ground water in cedar swamps along a gradient of suburban development reported by Ehrenfeld and Schneider (1991). Ammonia, orthophosphate, and lead concentrations are given in ug/l (1 ug = 0.001 mg).

		Cedar Swamp Type			
		Control[a]	Near[b]	Developed[c]	Runoff[d]
Surface Water					
Ammonia	April-October	3.9	2.2	141.3	229.4
(ug/l)	November-March	0	8.7	0	124.4
Orthophosphate	April-October	14.4	12.5	7.6	55.0
(ug/l)	November-March	4.5	17.1	7.2	7.3
Chloride	April-October	4.71	6.25	6.93	12.99
(mg/l)	November-March	3.96	3.5	1.35	12.53
Groundwater					
Ammonia	April-October	42.1	98.4	506.2	583.3
(ug/l)	November-March	49.6	103.2	429.4	330.2
Orthophosphate	April-October	11.0	12.7	30.9	68.0
(ug/l)	November-March	2.7	16.5	6.8	9.3
Chloride	April-October	4.93	7.04	16.4	15.4
(mg/l)	November-March	4.15	3.87	11.22	14.97
Lead	Dryweather	2.5	4.0	15.8	99.1
(ug/l)	Wetweather	1.3	1.9	1.1	5.6

Cedar swamp types include swamps: (a) in undisturbed watersheds; (b) in undisturbed watersheds but bisected by roads; (c) adjacent to residential development with septic systems; (2) adjacent to residential development with septic systems and receiving stormwater runoff.

Morgan and Philipp (1986) also found that altered surface water chemistry effected wetland species composition. In their study of six Pinelands streams, polluted streams were distinguished from unpolluted streams primarily by elevated nitrate-nitrogen and pH. Mean nitrate-nitrogen in polluted streams was 426 ug/l (0.426 mg/l) compared to 19 ug/l (0.019 mg/l) for unpolluted streams. Mean pH values for polluted and unpolluted streams were 5.1 and 4.1, respectively. The elevated pH and nutrients in the polluted streams was associated with a slight increase in species richness and replacement of native plants by non-native species. An increase in periphyton species richness was also associated with disturbance in the same streams, and species characteristic of undisturbed Pinelands streams appeared to be replaced by species that are peripheral or non-indigenous to the region (Morgan 1987).

Water table level is also a major determinant of wetland vegetation patterns in the Pinelands. Relatively distinct forest communities are associated with narrow ranges of water levels (Ehrenfeld and Gulick 1981, Roman et al. 1985, Ehrenfeld 1986, Stoltzfus 1990, Ehrenfeld and Schneider 1991, Zampella et al. 1992). The drier end of the forested wetland gradient is dominated by transitional pine forests on mineral soils while hardwood and cedar swamps underlain by organic soils occupy the wetter end of the hydrologic continuum.

If a cone of depression created by ground water pumping in an unconfined aquifer intersects a wetland, the lowered hydraulic head will cause seepage from the wetland (Winter 1988). Because of the integral relationship between ground water and surface water in the Pinelands, it is generally assumed that pumping will affect water levels in wetlands and stream discharge even if the pumping center is a distance from the wetland. Although the assumption has a sound theoretical basis, the empirical evidence needed to quantify the relationship is generally lacking. The potential for such impacts was demonstrated by a pump test along the Mullica River in Wharton State Forest (Lang and Rhodehamel 1963). After about six days of pumping, water levels declined in swamps located on both sides of the river.

Hydrologic and water quality impacts associated with development may exert a greater influence on Pinelands wetland vegetation than patch size and continuity, but fragmentation created by upland land uses may also have an effect. Landscape fragmentation results when human-altered habitats are created within a previously continuous community or ecosystem (Schonewald-Cox and Beuchner 1992). Due to the high degree of patchiness, ecotones (areas of transition from one habitat to another) are a dominant feature of the undeveloped Pinelands landscape. Stoltzfus (1990) studied the effects of swamp size on the species composition and community structure of mature cedar swamps within undisturbed Pinelands watersheds. He found that hydrology and past disturbance history were important determinants of composition and structure and that fragmentation resulting from fire and timber harvesting had relatively little effect on these two attributes. There is, however, an important distinction between fragmentation and edge effect created by moisture gradients and human-related disturbances such as fire and timber harvesting and that resulting from real estate development and agricultural activities.

Gibson et al. (1988) found the density, diversity, and richness of saplings and trees to be higher in Pinelands upland oak-pine fragments bordered by agriculture or developed land compared to continuous forest stands. Sassafras (*Sassafras albidum*) was particularly abundant in the forest fragments and several species including red cedar (*Juniper virginiana*) and saplings of gray birch (*Betula populifolia*), Virginia pine (*Pinus virginiana*), and black cherry (*Prunus serotina*) were unique to the fragments. Although Gibson et al. (1988) did not note it, all are edge or early successional species that are relatively common in well established residential and agricultural landscapes within the Pinelands. Proximity of seed source and edge effect, as well as lower regional fire frequency, may have contributed to their importance in forest fragments.

Ehrenfeld and Schneider (1991) propose that because species introductions tend to increase with the rate of human visitation to an area, developed areas may provide a potentially large source of non-native species. Line corridors associated with human habitation, such as roads and roadsides, railroads, dikes, ditches, and power lines are also dominated by edge species (Forman and Godron 1986). Malanson (1993) suggests that riparian zones are particularly accessible to wind-dispersed and animal-dispersed plant species where edge habitat is extensive and that wide riparian zones may present a barrier to the wind-dispersed seeds of upland plant species. It is possible that the establishment of transitional or upland species as well as exotic species may be more pronounced along the drier edge of Pinelands wetlands exposed to upland land uses and that this effect may be enhanced by hydrologic changes associated with development.

Animal Communities

The unique combination of hydrologic, biogeographic, and landscape characteristics and processes in the Pinelands is also reflected in the region's faunal biodiversity. Pinelands waters support an acid tolerant fish fauna comprised of 13 characteristic species including banded sunfish (*Enneacanthus obesus*), blackbanded sunfish (*Enneacanthus chaetodon*), bluespotted sunfish (*Enneacanthus gloriosus*), pirate perch (*Aphredoderus sayanus*), swamp darter (*Etheostoma fusiforme*), and yellow bullhead (*Ameiurus natalis*) (Hastings 1984). Peripheral and introduced species such as pumpkinseed (*Lepomis gibbosus*), golden shiner (*Notemigonus chrysoleucas*), brown bullhead (*Ameiurus nebulosus*), bluegill (*Lepomis macrochirus*), and largemouth bass (*Micropterus salmoides*) generally occur in modified waters where pH is higher than about 5.5 (Hastings 1984). Graham and Hastings (1984) suggested that the absence of pumpkinseed and bluegill sunfish from dystrophic Pinelands waters may be due to trophic limitations rather than intolerance of low pH. Unlike native *Enneacanthus* sunfish, young bluegills and pumpkinseeds are primarily pelagic planktivores, a dietary niche which is generally absent in Pinelands waters. Altered water chemistry has also been shown to adversely affect characteristic Pinelands zooplankton and macroinverterbrate communities (Morgan 1985, 1986, Dougherty and Morgan 1991).

A varied herpetofauna is also found in the Pinelands (Conant 1979). Characteristic Pinelands amphibians include Pine Barrens treefrog (*Hyla andersonii*), carpenter frog (*Rana virgatipes*) and southern leopard frog (*Rana utricularia*). Species such as the New Jersey chorus frog (*Pseudacris triseriata kalmi*), bullfrog (*Rana catesbeiana*), and pickerel frog (*Rana palustris*) may enter the central Pinelands where habitats have been disturbed by humans or where conditions are especially suitable for their survival (Conant 1979). Due to their dependency on wetland habitats, the region's characteristic amphibian communities are susceptible to changes in hydrology and water quality associated with watershed disturbance. The inability of the border entrant species, such as bullfrog, to establish viable populations in undisturbed areas has been attributed to the high acidity of surface waters, among other factors (Gosner and Black 1957, Freda and Dunson 1986). Freda and Morin (1984) found that bullfrogs replaced carpenter frogs in waters where the pH was greater than 4.5.

Many of the wetland dependent amphibians and reptiles are highly mobile and use upland habitats. Sustaining these species requires protecting adjacent uplands as well as hydrologic and water quality integrity. In the central Pinelands, timber rattlesnakes (*Crotalus horridus*) rely primarily on upland forests for summer foraging but hibernate in wetlands (Reinhart and Zappalorti 1988a, 1988b). Tiger salamanders (*Ambystoma tigrinum tigrinum*) are primarily found in Cumberland and Cape May counties. This endangered species typically breeds in ponds surrounded by oak dominated forest and moves into the uplands following breeding (Zappalorti 1980). Like other peripheral species, the tiger salamander enters typical Pinelands habitats under exceptional conditions (Conant 1979). The absence of tiger salamander in the central Pinelands may be due to its sensitivity to low pH since the species generally fails to reproduce in waters where the pH is less than 4.5 (Freda and Morin 1984). Thus, protection of a complex of upland and wetland habitats rather than acid water conditions is probably more important where this species is found in the region.

Using radioactive tags, Freda and Gonzalez (1986) tracked the movement of eight Pine Barrens treefrogs captured at a seepage pond surrounded by a narrow shrub wetland in the Pine Plains. Seven individuals remained within 70 m (230 ft) of the breeding site and one frog moved 106 m (348 ft) from the pond. Microhabitat descriptions suggest that most of the recaptures occurred in uplands. Based on observations of tagged, toe clipped, and undisturbed treefrogs, they found that in late July most individuals heard calling were more than 100 m from the pond. Movement of Pine Barrens treefrog into an upland Pine Plains habitat is especially significant because the xeric conditions found in this forest type contrasts sharply with that of wetland habitats (Good et al. 1979, Whittaker 1979).

Studies in other parts of the country have also highlighted the need to preserve a complex of upland and wetland habitats to sustain amphibian populations. Buhlmann et al. (1993) often captured amphibians such as green frog (*Rana clamitans*) and southern leopard frog (*Rana utricularia*) in upland sites adjacent to forested wetlands in the Coastal Plain of Virginia. They concluded that protection of wetland fauna requires the protection of surrounding upland habitat. Forester (1993) considers habitat fragmentation to be a serious problem effecting the perpetuation of amphibian populations through isolation and inbreeding. He views patch continuity to be more important than patch size and suggests that riparian buffers facilitate dispersal between isolated patches.

Bird diversity in the Pinelands is generally considered to be limited (McCormick 1970, Leck 1979, Kerlinger 1984). It is this characteristic rather than any unique biogeographic attribute that distinguishes Pinelands bird fauna from that of other regions. Birds do, however, contribute substantially to the region's biological diversity since the total number of species typically found in the Pinelands is greater than that of any other vertebrate group. The area also supports several rare species.

Brush (1987) found that most birds within his central Pinelands study area switched between and among upland and lowland habitats seasonally. He concluded that no one habitat was sufficient to allow all species to coexist and that a mosaic of contiguous vegetation types must be preserved to maintain the full diversity of Pinelands birdlife. Kerlinger (1984) also recommended that to maintain a characteristic Pinelands avifauna, a mosaic of successional habitats that reflect the region's dynamic disturbance regimes must be maintained. He indicated that the Pinelands should be managed to maintain the low diversity of avian species that characterize the ecosystem. Wander (1981) surveyed breeding birds in Pinelands cedar swamps. Based on his observations that ecotones between habitats supported a higher diversity of birds and that birds moved among and between habitats, he recommended that protection of cedar swamps include a band of upland.

Studies of terrestrial birds in habitat islands in other areas have contributed greatly to our present understanding of the relationship of habitat area and landscape fragmentation to the preservation of regional biota. Many studies have indicated that neotropical bird species are especially sensitive to forest island size and their recent decline has been attributed to habitat loss and fragmentation (Forman et al. 1976, Whitcomb et al. 1981, Ambuel and Temple 1983, Howe 1984, Blake and Karr 1984, Robbins et al. 1989) among other factors such as changes beyond the breeding range (Whitcomb et al. 1981, Ambuel and Temple 1982, Hall 1984), cowbird nest parasitism (Whitcomb 1977, Brittingham and Temple 1983) and nest predation (Wilcove 1985, Böhning-Gaese et al. 1993, Andren and Angelstam 1988) in the breeding range.

Edge may increase overall wildlife diversity but it can have negative consequences for forest interior birds (Yahner 1988). In a comparative study of New York (Long Island and Albany) and New Jersey upland Pine Barrens habitats, Kerlinger and Doremus (1981) associated changes in bird community structure in the New York barrens with edge effects created by greater reductions in habitat area and dissection by roads and developments. They identified fire suppression as another habitat altering factor effecting avian community structure.

Keller et al. (1993) studied the relationship between riparian forest width and bird species composition in agricultural landscapes of the Delmarva Peninsula. They found that several area-sensitive neotropical migrant species were encountered more frequently in wider riparian forests. They recommended that riparian corridors at least 100 m (328 ft) wide be provided to function as habitat for forest interior birds. They recognized that wider corridors would be preferable and indicated that the widest corridors should be targeted for preservation since they are most likely to provide habitat for forest interior birds and have less forest edge.

Fragmentation of the forest landscape may be an especially important concern for some raptors such as barred owl (*Strix varia*) and red-shouldered hawks (*Buteo lineatus*). The barred owl is a wide-ranging species that uses large, contiguous tracts of mature upland forests and hardwood swamps for breeding (Karalus and Eckert 1973). It is one of the more reclusive and sedentary owl species. Survey work in southern New Jersey has elicited vocal responses from this species in oak-pine uplands, hardwood swamps, pitch pine lowlands, and Atlantic white cedar swamps (Sutton 1988, Laidig 1992). In New Jersey, breeding red-shouldered hawks are primarily limited to the deciduous lowland swamp forests in the far south (Dowdell and Sutton 1993) and moist lowlands in the north (Leck 1984). Dowdell and Sutton (1993) suggest that increased forest fragmentation in southern New Jersey may lead to the replacement of red-shouldered hawks by red-tailed hawks (*Buteo jamaicensis*) and increased predation pressure from great horned owls (*Bubo virginianus*).

Suburbanization has effects other than fragmenting the landscape. In their study of an upland site in Connecticut which had become progressively suburbanized, Butcher et al. (1981) reported that although species diversity remained high, densities of forest birds declined quite precipitously. They concluded that in addition to destroying forest habitat and isolating the study site from similar habitat, development reduced the buffer of low-density human use, creating disturbance from construction, noise, lights, and other human activities. Whitcomb (1977) suggested that human impacts, such as trampling, may have a greater effect on neotropical birds than on other species because they nest on or near the ground.

In Virginia, Aldrich and Coffin (1980) found a larger total breeding bird population and a greater number of bird species after suburbanization but several neotropical species which were present earlier were absent. The increase in species richness was due to the establishment of suburban birds such as blue jay (*Cyanocitta cristata*), northern mockingbird (*Mimus polyglottos*), European starling (*Sturnus vulgaris*), northern cardinal (*Cardinalis cardinalis*), and song sparrow (*Melospiza melodia*). In the Pinelands, species that are common near developed areas include the American robin (*Turdus migratorius*), European starling, chipping sparrow (*Spizella passerina*), rock dove (*Columba livia*), house sparrow (*Passer montanus*), and northern mockingbird (Leck 1979, Brush 1987). Suburbanization can also directly affect predation. Wilcove (1985) found that nest predation was more intense in woodlots surrounded by residential development compared to similar woodlots surrounded by agricultural land. He attributed the higher predation to higher densities of nest predators such as Blue Jay, raccoon (*Procyon lotor*), dogs, and cats near suburban developments.

Common mammal species such as raccoon, eastern gray squirrel (*Sciurus carolinensis*), opossum (*Didelphis marsupialis*), whitetail deer (*Odocoileus virginianus*), and striped skunk (*Mephitis mephitis*) may coexist and sometimes benefit from suburban development. Generalizations can be made about the effect of upland activities on such common mammals but little is known about the distribution and status of less common species including many of the small mammals. Although few mammal species can be considered to be characteristic Pinelands species, two wetland dependent small mammals, red-backed vole (*Clethrionomys gapperi*) and bog lemming (*Synaptomys cooperi*) are of biogeographic interest (Rhoads 1893, Stone 1893, Rhoads 1903, White 1961, Craig and Dobkin 1993). Beaver (*Castor canadensis*), another wetland dependent species, have become relatively common since being reintroduced to the Pinelands.

PART 3. THE ROLE OF WETLAND BUFFERS

Scientific Uncertainty

Establishing upland buffers between development and wetlands is one of the means employed by the Pinelands Commission to minimize the adverse effects of adjacent development. However, our ability to assign buffers with a high degree of certainty that they will ensure the long-term ecological integrity of Pinelands wetlands is limited. Scientists and resource managers always confront uncertainty when attempting to determine how ecological systems respond to resource exploitation and habitat destruction (Ehrlich and Daily 1993, Hilborn and Ludwig 1993). Due to the nature of the regulatory process, managers must often base decisions on limited data and generalizations concerning wetland functions and sensitivities (Kusler 1986).

Although science may not be able to provide precise conclusions regarding ecological sustainability, decisions based on available data and sound scientific principles are generally superior to those based on guesswork (Ehrlich and Daily 1993). Since resource management decisions may be influenced by one's viewpoint, it is important that a distinction be made between scientific facts and value judgments and that the uncertainties and the possible outcomes of those uncertainties be identified (Mangel et al. 1993).

The regulatory community (both the regulators and the regulated) often expects to directly observe cause and effect relationships between impacts and ecological responses. Although catastrophic events such as direct destruction of wetland habitat, dissolved oxygen depletion in surface waters, and stream channelization have dramatic effects on resident biota, the impacts associated with many current land uses on the Pinelands ecosystem are subtle and cumulative and their effect can only be measured over decades. Because our knowledge of thresholds in assessing cumulative effects on wetlands function is limited (Preston and Bedford 1988), determining the long-term ecological effects of a single house or a subdivision on adjacent wetlands and the adequacy of buffers must be based on sound scientific judgment and intuition.

Protection of Water Resources and Wetland Dependent Communities

We know that upland land uses such as development and agriculture alter the quality of Pinelands ground and surface waters and that these changes affect the composition of characteristic wetland plant and animal communities, including a loss of characteristic species and the establishment of non-indigenous species. The relationship between wetland forest community composition and water table levels is also fairly well documented. The effect of ground and surface water diversions on wetland hydroperiods has not been well documented but studies of undisturbed Pinelands wetlands suggest that wetland communities respond to subtle changes in water table level.

Muscutt et al. (1993) held that there are no generally accepted methods of designating buffer zones to improve water quality. He suggested that buffers may directly affect water quality by removing land from uses that generate pollution. Xiang (1993), who emphasized the need for quantitative approaches for determining riparian buffers, employed a buffer width model based on runoff-borne pollution detention time. Although this approach may appear to be more scientifically justifiable, such a singular approach does not address the full range of wetland values and functions and may be of little relevance where ground water flow is the major contaminant pathway.

Hydrologic models are important quantitative tools for determining the subsurface flow of contaminants. However, they may be of limited use for determining variable buffer widths within the narrow range ($\leq$92 m or 300 ft) employed by the Pinelands Commission for several reasons including: 1) the variability of ground water and surface water interactions; 2) the range of land uses regulated under the Pinelands plan; 3) the cumulative effect of additional contaminant loadings along the same flow path; 4) uncertainty regarding biodegradation of contaminants, such as nitrate-nitrogen; and 5) the data, expertise, and time needed to accurately calibrate and apply these models.

Septic systems are considered an important source of ground water contamination in the Pinelands. Canter and Knox's (1985) attempts to apply the Konikow and Bredehoeft (1978) solute transport model to assess the impact of septic systems on ground water were unsuccessful due to their inability to calibrate the model. Their difficulty was attributed to inadequate aquifer characterization information and input data. They concluded that the utility of solute transport models to assess septic system problems may be outweighed by their data requirements.

Generalizations can be derived from other modeling and field studies. Based primarily on a Pinelands ground water flow model developed by Harlukowicz and Ahlert (1978) and the work of Walker et al. (1973), Roman and Good (1985) indicated that a buffer of at least 300 ft between septic leach fields and wetland boundaries is justified to prevent ground water plume nitrate-nitrogen concentrations greater than 2 mg/l from reaching surface water and wetlands.

Robertson et al. (1991) conducted a detailed investigation of septic systems serving two single family homes on shallow unconfined sand aquifers in Ontario. At one 12 year old site, a distinct 130 m (426 ft) plume with a uniform 10 m (33 ft) width was observed. Nitrate concentrations at the end of the plume were 50 percent of the source concentration. After 1.5 years of use, the plume from the second system began discharging to a river located 20 m (66 ft) from the tile field. Almost complete nitrogen attenuation, which was attributed to denitrification, occurred within 2 m (6.5 ft) before discharge to the river. Based on their field results and modeling, Robertson et al. (1991) estimated that a plume with a source concentration of 33 mg/l nitrate-nitrogen must travel 170 m (558 ft) for nitrate concentrations to reach 10 mg/l. Approximately 2 km (1.2 miles) would be required to reduce the source nitrate-nitrogen concentration to 2.5 mg/l. Given the extremely low concentrations of nitrate and other constituents in natural Pinelands ground and surface waters, it is doubtful that a 300 ft buffer between a septic system and a wetland would prevent "a change in the natural chemistry of the ground or surface water in the wetland" if dilution is the only attenuation process.

As indicated by Robertson et al. (1991), biodegradation may occur at the upland/wetland interface. Most studies of the role of riparian buffers in attenuating nutrients are concerned with agricultural lands (Malanson 1993). These studies suggest that nitrogen may be lost through plant uptake or denitrification upon passing through a wetland, although its ultimate fate is somewhat uncertain and varies among sites. Jacobs and Gilliam (1985) observed a substantial decrease in nitrate-nitrogen as subsurface agricultural drainage water traveled through a densely vegetated riparian buffer strip. They attributed a substantial part of these losses to denitrification in the saturated soils and reported that riparian buffer strips of <16 m were effective in removing nitrates before they reached the adjacent stream.

Peterjohn and Correll (1984) suggested uptake by vegetation and denitrification as two possible mechanisms to account for substantial decreases in ground water nitrate concentrations they observed in a Maryland riparian forest located adjacent to a cornfield. Plant uptake can provide short-term removal of nitrogen and phosphorus from wetland waters and peat and sediment accumulation can provide long-term removal but only denitrification allows permanent removal of nitrogen (Hemond and Benoit 1988). Phillips et al. (1993) indicated that the primary effect of wetlands on ground water nitrate concentrations on the Delmarva Peninsula is through dilution and denitrification and that this role varied according to local conditions such as topography and hydrology which determine whether ground water passes through anoxic or oxic zones. Similarly, levels of phosphorus retention by wetlands may be influenced by the soil characteristics and the depth at which the phosphorus laden ground water flows (Walbridge and Struthers 1993). Omernik et al. (1981) concluded that although forested buffer strips may temporarily alleviate sediment related transport of nitrogen and phosphorus, the long-term effect may be negligible due to subsurface flow of nutrients.

Protection of Landscape Matrixes and Forest Ecotones

Our understanding of the consequences of watershed disturbance on Pinelands wetland biota is greater than our knowledge of the effects of landscape fragmentation and development encroachment. We know that many wetland dependent animal species range far beyond wetland boundaries and that their continued maintenance requires that a landscape matrix of upland and wetland Pinelands habitats be protected. Edge associated with human habitation can affect plant and animal community composition through the introduction of non-indigenous species, an increase in the abundance of common animal species, and, in the case of forest interior birds, increased parasitism and predation. Forman and Godron (1986) note that riparian buffers should be wide enough for the movement of upland forest interior plant and animal species along the stream system but provide only vague buffer criteria, indicating that the upland buffer should be wide enough to prevent an edge effect.

For protection of wide ranging species, such as the tiger salamander, timber rattlesnake, and barred owl, which use wetlands for only part of their habitat needs, management of upland and wetland matrixes rather than establishment of wetland buffers is probably a more important issue. Preserving large blocks of wetland and upland forest, continuity among wetland patches as well as between wetlands, streams, and upland forest are important goals where maintenance of watershed and landscape integrity depend on maintaining forest area and pattern (Lee and Gosselink 1988).

Home range data are available for many Pinelands species and this information may be used to delineate a buffer area around a documented sighting or habitat for species which use both uplands and lowlands. This approach affords some protection to the species of concern but it has a few limitations. First, the geometry of the buffer area may be difficult to determine. For example, the home range of the barred owl is usually an irregularly shaped patch that follows natural and manmade landscape features (Nicholls and Warner 1972). Secondly, a home range based buffer may protect an individual or group of individuals for a period of time but may not ensure the long-term maintenance of a population.

Robbins (1979) and Robbins et al. (1989) estimated minimum areas of contiguous forest required to sustain viable populations of area-sensitive forest birds based on the point at which population levels begin to decline. Robbins et al. (1989) suggested that 3000 ha is the minimum area needed to retain all species of forest-breeding birds in the Middle Atlantic States. Although this approach is useful and indicates that large tracts are required to protect a region's avifauna, it does not consider the potential longevity of the affected populations Shaffer (1981).

The minimum area required to maintain viable populations of all species comprising the regional species pool is an important concern. An understanding of the relationship of population size to area and extinction probabilities is needed to determine this area (Shaffer 1981, Shaffer 1985, Soule and Simberloff 1986). These relationships are species specific, empirical, and poorly known for virtually all species (Simberloff and Abele 1982). The issue of minimum area is further complicated by the need to maintain genetic variation within and between populations of plants and animals. The evidence regarding the effectiveness of riparian zones as pathways for the diffusion of genetic information is sparse although this may be due to a lack of research on the topic rather than effect (Malanson 1993).

A few generalizations regarding wetland buffers can be derived from habitat island studies, species-area relationships, and home range information. Upland buffers zones serve to increase the total area associated with wetland complexes, reduce edge effect and perimeter impacts, and provide some habitat for those species dependent on upland areas. However, the long-term protection of many animal species requires more than just protecting delineated wetlands and a band of upland buffer.

Wetland Integrity and Potential Impact Gradients

Schneider and Ehrenfeld (1987) indicated that a gradient of disturbance from different levels of development causes a gradient of response in Atlantic white cedar swamps. They suggested that any change in upland land use is likely to cause a change in adjoining wetlands. This statement is theoretically valid yet it would be nearly impossible to accurately measure the effect of individual upland disturbances on adjacent wetlands. What it implies is that preservation of the unique characteristics of high quality Pinelands wetlands requires that the entire associated drainage basin be protected. Obviously, this is not accomplished merely by requiring a 300 ft buffer to developed lands.

There is no simple formula that can be used to establish upland buffers. Within a regulatory context, the 300 ft buffer requirement has been shown to be a workable wetland protection strategy. Arguments for larger or smaller buffers can be made but the only definitive conclusion that can be reached is that they offer either more or less protection to adjacent wetlands than that provided by a 300 ft buffer.

There are some practical considerations. For example, since it is not unusual for backyards of single family homes to be expanded to include cleared land, lawns, or pools, a 300 ft buffer to human disturbance may actually be substantially reduced following initial approval of a permitted development. The probability of such encroachments decreases with increasing buffer width. Regarding larger buffers, at some point prohibiting development within a buffer becomes an upland zoning issue where assigning lower development densities rather than requiring wider buffers may be a more effective strategy.

As previously indicated, the Roman and Good model evaluates both the relative quality of wetlands located adjacent to proposed development and the potential impacts associated with the development to determine buffer distances. The model is not quantitative. It is based on generalizations regarding the values and functions of wetlands and development impacts and assigns wetland buffers according to a sliding distance scale that takes both factors into account. We employ a similar approach at the watershed level to evaluate wetlands along watershed integrity and potential impact gradients.

PART 4. EVALUATION OF WATERSHED INTEGRITY AND POTENTIAL IMPACTS EFFECTING THE LONG-TERM SUSTAINABILITY OF PINELANDS WETLANDS

Landscape Approach

Borrowing from Lee and Gosselink (1988), three assumptions underlay our landscape approach to cumulative wetland impact assessment in the Pinelands: 1) cumulative impacts are usually landscape-level phenomena; 2) a landscape focus can conserve valued attributes that are not manageable at a finer scale; and 3) landscape conservation also conserves the valued functions and biota of smaller subsystems. This strategy presumes that the ecological integrity of individual sites will be preserved by preserving an appropriate landscape pattern (Lee and Gosselink 1988, Gosselink et al. 1990). Naiman et al. (1993) indicate that the need for a landscape perspective to maintain species and ecological processes pertains especially to riparian systems. Similarly, Franklin (1993) suggests that emphasis on species-based approaches rather than ecosystem and landscape level approaches may not conserve the majority of existing biological diversity. A practical consideration is that regional land use planning may be more effective than site-specific regulation in protecting important Pinelands resources such as rare species (Zampella 1986).

A landscape approach to wetland assessment addresses a range of values and functions. A shortcoming is that although it may encompass most wetland attributes, it may not adequately address the needs of individual plant or animal species. Ideally, the coarse landscape approach should be complemented by a species-based approach. Given our current understanding of the ecological and genetic requirements of individual species and our ability to translate the available information into practical management programs, a landscape approach to wetland assessment offers a means of implementing consistent regulatory and planning policies intended to protect the basic fabric of Pinelands wetland habitats.

We developed our watershed-based landscape approach to wetland assessment with the objective of ranking wetland systems along regional quality and future potential impact gradients. The approach is based on an evaluation of the ecological integrity of watersheds and associated wetland systems and factors effecting their long-term sustainability (Figure 2). Developed and agricultural land cover, soils with a high potential for ground water contamination, surface water quality, major water supply withdrawals, and biological diversity are used to evaluate existing watershed integrity. Future land use patterns, non-hydric soils with a high water table, and watershed and wetland dimensions are used to evaluate potential impacts effecting the long-term sustainability of these systems. The methodology is an attempt to translate this information into a consistent and logical means of assessing wetland values and impacts. The rankings can serve as the basis for policy and regulatory decisions regarding the level of protection to be afforded to specific Pinelands wetland systems.

Goal Setting

Conservation of landscape patterns requires goal-setting (Lee and Gosselink 1988, Gosselink et al. 1990). The goals of the Pinelands comprehensive management plan wetlands program are explicit and are established through regulation. As stated in the purpose: "This program is deemed to be the minimum standards necessary to protect the long-term integrity of wetlands."[1] Upland development must maintain a 300 ft buffer to wetlands unless it can be demonstrated that the development will not result in a significant adverse impact on the wetland.

A significant adverse impact[2] is considered to exist if one or more wetland alterations result in an irreversible effect on the ecological integrity of the wetland and its biotic components including, but not limited to, threatened or endangered plant and animal species. These modifications include:

1) an increase in surface water runoff discharging into a wetland;
2) a change in the normal seasonal flow patterns in a wetland;
3) an alteration of the water table in the wetland;
4) an increase in erosion resulting in increased sedimentation in the wetland;
5) a change in the natural chemistry of the ground or surface water in the wetland;
6) a loss of wetland habitat;
7) a reduction in wetland habitat diversity;
8) a change in wetland species composition; or
9) a significant disturbance of areas used by indigenous and migratory wildlife for breeding, nesting, or feeding.

The regulations also require that the cumulative modifications associated with both the proposed development and any other existing or potential development be considered when determining whether a significant adverse impact exists. It is apparent that sustaining the long-term ecological integrity of Pinelands wetlands, including their hydrologic, water quality, and habitat functions, is the ultimate goal of the Pinelands comprehensive management plan program.

Study Boundaries: Delineating Drainage Units

Mitsch and Gosselink (1993) consider hydrology to be the most important factor controlling the structure and function of wetlands. Although disturbance regimes, such as timber harvesting and fire, and biogeographical considerations are critical factors, maintaining intact wetland systems and their characteristic water quality and hydrologic regimes is primary to preserving Pinelands wetland communities. Maintenance of water quality and hydrologic

---

[1] NJAC 7:50-6.1

[2] NJAC 7:50-6.7

regimes requires a watershed approach. Because the watershed is the appropriate focus for the study of hydrologic and water quality functions of wetlands (Preston and Bedford 1988), we have selected drainage areas as our basic study unit.

Velnich (1982, 1984) provides an inventory of drainage areas in New Jersey. Because generally only named streams appearing on 1:24,000 scale United States Geological Survey (USGS) quadrangles and unnamed tributaries with drainage areas greater than 5 square miles are included, the resulting stream hierarchy is highly variable both within and between major Pinelands stream basins and the number of small drainage areas is greatly underestimated. We used the following approach to define and delineate drainage units:

1) include all permanent and intermittent streams depicted on USGS 1:24,000 scale quadrangles;
2) include all wetlands depicted on 1:24,000 scale United States Fish and Wildlife Service National Wetland Inventory maps or 1:12,000 scale N.J. Department of Environmental Protection (NJDEP) Freshwater Wetland maps that do not parallel a USGS depicted stream but which are connected directly to one;
3) delineate drainage areas for these streams and wetlands using the ten foot contour lines depicted on USGS quadrangles; and
4) divide the main stem of high order ($\geq$ 3rd order) streams at its confluence with lower order streams or along human-made divides, e.g., roads and railroad grades.

This method provides a consistent and easily duplicated method of delineating a finite number of drainage units, including discrete small ones. An example is shown in Figure 4. The total number of drainage units delineated is directly related to the level of mapping detail provided by USGS quadrangles and either of the two widely used wetland maps. These drainage units provide the basic study unit for evaluating watershed and wetland integrity and potential impacts to these systems.

Landscape Indexes

Development of landscape pattern indexes that characterize ecological processes at the landscape scale can simplify regional risk assessment and facilitate the development of effective models (Hunsaker et al. 1990). Leibowitz et al. (1992) present several function and value related landscape indexes for assessing cumulative impacts and relative risk to wetlands. Actual data or measurements, referred to as landscape indicators, are used to provide a first-order approximation of these indexes, e.g., agricultural area can be used as an indicator of nonpoint source nitrate loadings. We developed several GIS-based landscape indicators along with a ranking system that can be used to evaluate both existing ecological integrity of watersheds and associated wetland systems and potential impacts effecting their long-term ecological sustainability (Table 4). In the following sections we describe each index and present its rationale. We then show how each of the indexes is applied to rank drainage units.

Watershed Integrity Indexes

Land Use and Associated Soils

Development and agricultural activities affect the ecological integrity of wetlands by fragmenting the landscape, altering adjacent upland habitats, and degrading ground and surface waters. Percent cover of altered lands, i.e. non-forest land, provides a measure of landscape integrity that encompasses all the hydrologic and ecological consequences associated with these

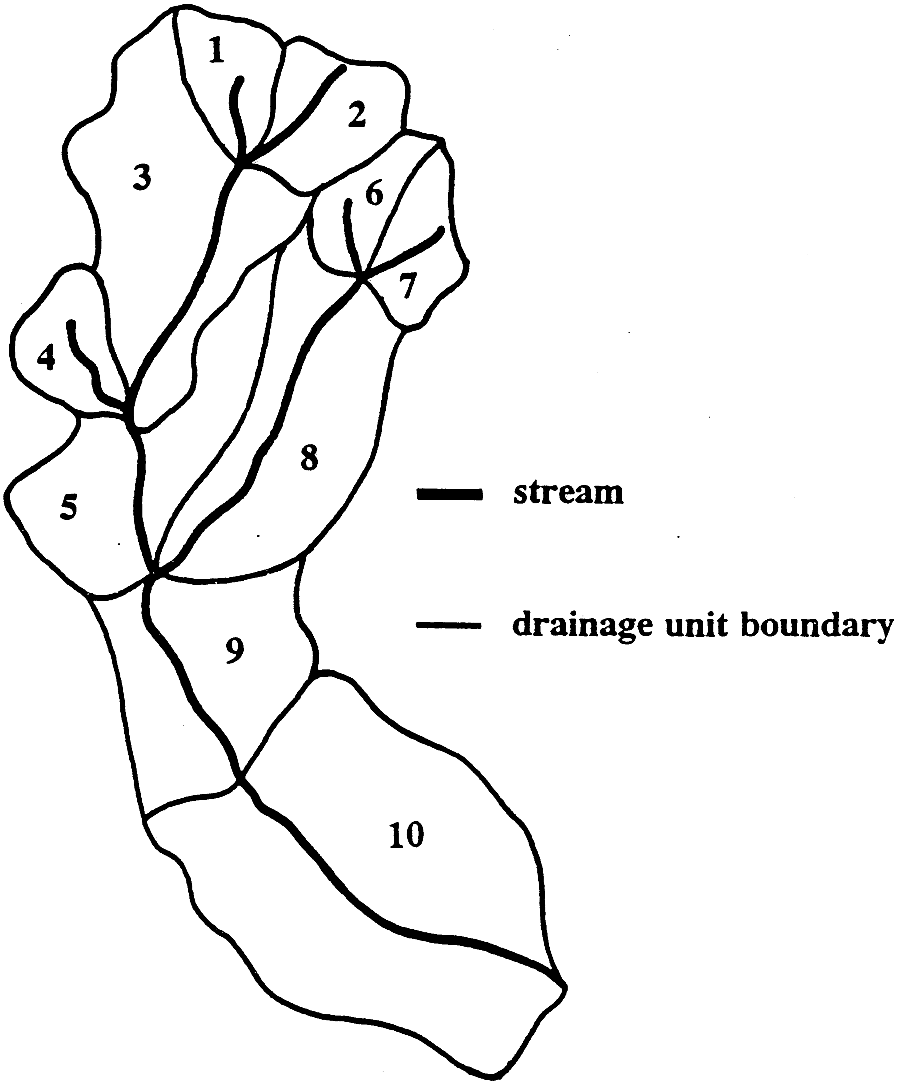


Figure 4. Delineation of drainage unit boundaries.

land uses. The NJDEP'S integrated terrain unit (ITU) mapping system includes digitized land use, land cover, and soils data. Because the NJDEP's freshwater wetland maps offer more detailed wetlands information, these data should be merged with the ITU coverage. National Wetlands Inventory maps provide a secondary source of wetlands mapping.

Table 4. Landscape indexes used to assess watershed integrity and potential impacts effecting the long term sustainability of wetlands.

Watershed Integrity

land use and associated soils
surface water quality
ground water withdrawals
biological diversity

Potential Impacts

future land use patterns
transitional soils
watershed and wetland dimensions

The classification system used by the NJDEP is derived from Anderson et al. (1976). We combined urban land, agriculture, extractive mining, waste disposal areas, and transitional areas as one class referred to as "altered land" (Table 5). Although each of these altered land use categories generates different impacts effecting the integrity of wetland systems, it is difficult to rank them when evaluating a wide range of wetland values and functions. For example, urban land represents a more permanent alteration of the landscape than crop land but nitrate contamination of ground water is probably greater on the agricultural land. Sanitary landfills have the potential to adversely impact wetlands through the migration of contaminants (Lambou et al. 1990) but the available data do not allow an assessment of this impact to be made for Pinelands landfills.

Table 5. Land use and land cover classes included as "altered lands".

residential
commercial and services
military reservations
industrial
transportation/communication/utilities
industrial and commercial complexes
mixed urban or built-up land
other urban or built-up land
recreation land
community recreation areas/athletic fields
cropland and pastureland
orchards, vineyards, nurseries, and horticultural areas
confined feeding operations
other agriculture
extractive mining
solid waste disposal areas
dredge material disposal sites
transitional areas where development site preparation has begun

The potential for wetland degradation is higher where altered land is located on soils with a high potential for ground water contamination. Vowinkel and Siwiec (1991) identified several factors that may be used to assess ground water contamination potential. Included among these are mappable surface features such as topography, drainage basin divides, rivers and lakes, soils, recharge rate, and depth to water. Using two soil factors, hydrologic group and organic matter content, Goss (1988) developed an algorithm to rank soils for potential loss of pesticides to leaching. Hydrologic soil groups indicate runoff potential under similar storm, slope, and cover conditions.

Soils are placed in four hydrologic soil groups based on infiltration rate, depth to water, and permeability (Table 6). In the Pinelands, these same soil properties can be used to evaluate the potential for leaching of contaminants to ground water. The first three hydrologic soil groups (A, B, and C) represent an upland gradient of coarse to fine textured soils and decreasing infiltration rate, soil drainage, and permeability. Thus, hydrologic groups A, B, and C also represent a gradient of decreasing potential for ground water contamination in upland areas. All group D Pinelands soils are poorly drained or very poorly drained hydric soils. A range of textural characteristics is found within this group, and a high water table is the primary reason for their association.

Table 6. Hydrologic soil groups.

Group A. Soils having high infiltration rates even when thoroughly wetted and consisting of deep, well-drained to excessively drained sands or gravels. These soils have a high rate of water transmission.

Group B. Soils having moderate infiltration rates when thoroughly wetted and consisting chiefly of moderately deep to deep, moderately well drained to well drained soils with moderately fine to moderately coarse textures. These soils have a moderate rate of water transmission.

Group C. Soils having slow infiltration rates when thoroughly wetted and consisting chiefly of soils with a layer that impedes downward movement of water, or soils with moderately fine to fine texture. These soils have a slow rate of water transmission.

Group D. Soils having very slow infiltration rates when thoroughly wetted and consisting chiefly of clay soils with a high swelling potential, soils with a permanent high water table, soils with a claypan or clay layer at or near the surface, and shallow soils over nearly impervious material. These soils have a very slow rate of water transmission.

With few exceptions, soil leaching potential ratings for group A and B Pinelands soils derived using Goss' (1988) algorithm correspond directly to hydrologic soil group due to the thin surface horizon or low organic matter content found in these soils. In New Jersey, a limitation of the Goss (1988) model is that depth to water table is not considered when assessing hydrologic group C and D soils. The potential for leaching in these two groups is given as nominal, regardless of organic matter content, even though shallow depth to water table poses a high threat for ground water contamination. We modified this approach and classified all A, C, and D soils and B soils with a high water table (<1.5 m or 5 ft) as having a high potential for ground water contamination when associated with altered land. Soils not assigned to any hydrologic soil group are classified as having a high potential through default. Classification of Ocean County soils using this approach is shown in Table 7.

Table 7. Potential for ground water contamination: Ocean County soils.

Soil Name	Symbol	Hydrologic Soil Group	Depth to Water (ft)	Contamination Potential[1]	Hydric Soil Classification
Adelphia	AdA	C	1.5-4.0	High/wt	Non-Hydric
Atsion	At	D	0-1.0	High/wet	Hydric/Mineral
Atsion	Aw	D	0-1.0	High/wet	Hydric/Mineral
Aura	AxB	B	>6.0	Moderate	Non-Hydric
Berryland	BF	D	0-0.5	High/wet	Hydric/Mineral
Berryland	Be	D	0-0.5	High/wet	Hydric/Mineral
Collington	CoA	B	>6.0	Moderate	Non-Hydric
Collington	CoB	B	>6.0	Moderate	Non-Hydric
Collington	CoC	B	>6.0	Moderate	Non-Hydric
Downer	Do	A	>6.0	Moderate	Non-Hydric
Downer	DpA	B	>6.0	Moderate	Non-Hydric
Downer	DpB	B	>6.0	Moderate	Non-Hydric
Downer	DrB	B	>6.0	Moderate	Non-Hydric
Evesboro	EvB	A	>6.0	High	Non-Hydric
Evesboro	EvC	A	>6.0	High	Non-Hydric
Evesboro	EvD	A	>6.0	High	Non-Hydric
Fripp	FtB	A	>6.0	High	Non-Hydric
Hammonton	HaA	B	1.5-4.0	High/wt	Non-Hydric
Hammonton	HcA	B	1.5-4.0	High/wt	Non-Hydric
Humaquepts	HU	variable	0.5-2.5	High/wet	Hydric/Mineral
Keyport	KeA	C	1.5-4.0	High/wt	Non-Hydric
Klej	KlA	B	1.5-2.0	High/wt	Non-Hydric
Kresson	KrA	C	1.0-1.5	High/wt	Non-Hydric
Lakehurst	LhA	A	1.5-3.5	High/wt	Non-Hydric
Lakehurst	LmA	A	1.5-2.5	High/wt	Non-Hydric
Lakewood	LwB	A	>6.0	High	Non-Hydric
Lakewood	LwC	A	>6.0	High	Non-Hydric
Manahawkin	Ma	D	+1.0-0	High/wet	Hydric_Organic
Mullica	Mr	D	0-0.5	High/wet	Hydric/Mineral
Mullica	Mu	D	0-0.5	High/wet	Hydric/Mineral
Psamments	PN	-	---	High	Non-Hydric
Psamments	PO	-	---	High/d	Variable
Psamments	PW	-	---	High/d	Variable
Pemberton	PeA	A	1.0-4.0	High/wt	Non-Hydric
Phalanx	PhB	B	>6.0	Moderate	Non-Hydric
Phalanx	PhC	B	>6.0	Moderate	Non-Hydric
Pits	Pm	A	---	High	Non-Hydric
Sulfaquents	SS	D	+1.0-0	High/wet	Hydric/Mineral
Sulfihemists	SS	-	---	High/wt	Hydric_Organic
Sassafras	SaB	B	>6.0	Moderate	Non-Hydric
Shrewsbury	Sh	D	0-1.0	High	Hydric/Mineral
Tinton	TnB	A	>6.0	High	Non-Hydric
UrbanLand	UL	-	---	High/d	N/A
UrbanLand	UP	-	---	High/d	N/A
Woodmansie	WoB	B	>6.0	Moderate	Non-Hydric
Woodmansie	WoC	B	>6.0	Moderate	Non-Hydric

[1] High contamination potential due to A, C, or D hydrologic soil classification, high water table (wt), including hydric soil conditions (wet), or through default (d).

Surface Water Quality

Surface water quality provides a measure of both the impact of watershed disturbance and the ecological integrity of Pinelands aquatic and wetland systems. Five factors are used in the water quality index. These are pH, specific conductance, and nitrate, ammonia, and phosphorus concentrations. Due to the relationship between water quality and associated communities, in-stream nutrient concentration measures rather than loadings are more appropriate as a measure of biological integrity (Osborne and Wiley 1988).

Nitrate and pH are the two primary water quality factors. Nitrate is generally considered to be limited in Pinelands waters and pH has been shown to be a major factor effecting species composition. Total phosphorus, ammonia, and specific conductance are considered secondary factors. Total phosphorus and ammonia concentrations are usually low even in moderately disturbed streams. High concentrations are generally indicative of substantial watershed disturbance including domestic waste water discharges (Fusillo 1981, Schornick and Ram 1978, Zampella 1994a). Specific conductance of Pinelands water is correlated with concentrations of dissolved constituents including calcium and magnesium concentrations and thus provides another measure of watershed disturbance.

Ground Water Withdrawals

Ground water withdrawals provide a measure of a basin's hydrologic integrity and use related hydrologic changes that are of a similar magnitude should generally have a greater impact on the hydrologic budget of small basins relative to large basins. For example, assuming a one to one relationship between ground water recharge and discharge, a one million gallon per day water supply well would totally deplete the estimated annual contribution of ground water recharge to stream runoff within a one square mile basin. The same withdrawal would represent approximately 10% of ground water recharge in a 10 square mile basin. The actual effect will depend on local hydrogeologic conditions and the location of the water withdrawal, that is, whether wells are located near a discharge area, a divide, or distributed throughout the basin.

Biological Diversity

Biological diversity provides an additional measure of ecological integrity. Biological diversity encompasses a wide range of Pinelands attributes including a richly patterned landscape comprised of a variety of vegetation communities, endemic and disjunct species, species at the limit of their geographic range, acid water animal communities, and rare species. As a general rule, areas of important biological diversity are associated with watersheds displaying a high degree of landscape and water quality integrity. The Wading River ecosystem (McCormick 1970) and other areas within the Mullica River basin are prime examples of this. Several biodiversity attributes, including threatened and endangered species and special habitats such as cedar swamps and ephemeral ponds, can be used to further refine an assessment of watershed integrity based on land use and water quality characteristics.

Risser et al. (1982) indicate that rare species are not likely to be good ecosystem indicators and that managing for ecosystem sustainability in the Pinelands is not the same as managing for rare species. This may generally be true, yet some species such as the Pine Barrens treefrog are probably good indicators of important wetland properties such as water quality and hydrology. Even though the importance of individual rare species in ecosystem management continues to be debated (Franklin 1993, Tracy and Brussard 1994), it is valid to conclude that threatened and endangered Pinelands species (Appendix 1) represent an important wetland value and most definitely contribute to the overall biological diversity of Pinelands wetlands.

The occurrence of particular wetland community types or habitats can also provide a measure of potential biological diversity. Selecting appropriate indicators is relatively subjective since there is no satisfactory method of ranking the importance of different Pinelands wetland habitats. We judge Atlantic white cedar swamps to be significant landscape elements that contribute to the region's characteristic biological diversity. Cedar swamps are generally recognized as an especially important wetland type which has declined in extent due to wildfire, harvesting, and succession to hardwood swamp (Roman et al. 1987).

Small stream impoundments, shrubby wetlands occurring in small depressions, and ephemeral ponds are mappable cover types that represent important habitats for amphibians such as tiger salamander, Pine Barrens treefrog, and southern gray treefrog (Zappalorti 1980, Freda and Morin 1984, Zappalorti and Dowdell 1991, Zappalorti and Vargas 1991). Some ephemeral ponds also support a diverse flora. We make no distinction between natural and human-made ponds or shrubby depressions such as small abandoned cranberry bogs and borrow pits since habitat differences between the two are often too subtle to note either through remote sensing or on the ground.

Potential Impact Indexes

Future Land Use Patterns

Lee et al. (1992) suggest that a landscape ecology approach aimed at ecological sustainability should consider projected changes in regional land use and land cover patterns. These projections are based on transitional probabilities which incorporate socioeconomic factors such as markets, institutional, natural, and locational attributes and landowner characteristics. Our assessment of impacts associated with future land use patterns relies on Pinelands management area designations as a landscape index.

The Pinelands regional planning and land allocation program divides the Pinelands into several management areas within which land uses of varying intensities are permitted (Pinelands Commission 1980, Collins and Russell 1988). The greatest land use restrictions are placed on management areas within the Preservation Area which represents the core of the Pinelands Area. This core is surrounded by the Protection Area where a greater variety of lands uses are allowed. Management area designations were based on existing natural features and land uses as well as socioeconomic factors such as proximity to job centers, available infrastructure, and land transaction and development approval activity.

In the order of increasing permitted development intensity and potential for impacts effecting long-term sustainability, Pinelands management areas are Preservation Area District, Forest Areas, Special Agricultural Production Areas (blueberry and cranberry agriculture in the Preservation Area), Rural Development Areas, Agricultural Production Areas, Infill Areas, Pinelands Villages, Pinelands Towns, and Regional Growth Areas. Another management area, referred to as the Military and Federal Installation Area, includes military bases such as Fort Dix and other federal facilities such as the Federal Aviation Administration and Technical Center. The intensity of land uses within these federal facilities is variable.

Transitional Soils

Pinelands vegetation reflects the effects of disturbance and subtle topographic, water table, and soil gradients. From an ecological perspective, the distinction between uplands and wetlands shown on soils and vegetation maps is an arbitrary one since environmental and vegetational gradients often exist as a continuum. Soils and vegetation of the Lakewood catena provide an example of the transitional nature of upland to wetland gradients (Tedrow 1979, Roman et al. 1985, Zampella et al. 1992, Zampella 1994b).

Somewhat poorly drained to moderately well drained soils such as Lakehurst and Hammonton generally occur in an intermediate position between well drained upland and wetland soils. To reflect the upland to wetland continuum and the uncertainty of wetland boundary conditions, we assume that the potential for development impacts to wetlands increases as the percentage of somewhat poorly drained soils occurring adjacent to delineated wetlands increases.

Basin and Wetland Dimensions

We assume that water quality and hydrologic changes of a similar magnitude should generally have a greater impact on wetlands in small basins relative to large basins. Due to higher surface and ground water discharges in large basins, the impact of depletive water use is less and dilution of contaminants is greater than in small basins. We also assume that wetlands in basins with a high percentage of wetlands are less affected by hydrologic and ecological impacts that originate in the upland portion of the drainage area. Because the potential for impact probably increases as the amount of wetland edge exposed to upland development increases, we also use the amount of wetland perimeter relative to wetland area as a potential impact factor.

Evaluating Drainage Units

General Approach

The scoring method developed for the watershed integrity and potential impact assessments allows a drainage unit to be ranked according to its individual attributes as well as those of both upstream and downstream drainage units (Figure 2, Table 8). Several steps requiring calculations based on weights and rating schedules are involved. First, landscape index scores are calculated. These scores are then used to calculate primary drainage unit watershed integrity scores (WIS^o) and potential impact scores (PIS^o). Calculation of final wetland integrity scores (WIS) and potential impact scores (PIS) is the last step of the evaluation method. Primary drainage unit wetland integrity scores of upstream and downstream drainage units are considered when calculating a final wetland integrity score (WIS) for a particular drainage unit. Only upstream conditions are used to calculate a final potential impact score (PIS). The contribution of other units to a drainage unit's final watershed integrity or potential impact score is based on its area and relative position in the drainage system. A detailed description of the scoring method is given in the following sections.

Table 8. GIS-based evaluation of watershed integrity and potential impacts.

Step I. Delineate drainage units.

Step II. Evaluate watershed integrity.

A. Calculate primary drainage unit wetland integrity score (WIS^o).
  1) Calculate Land Use Score (LUS).
    a) Delineate 100 m wide concentric upland zones.
    b) Weight zones according to drainage area and position relative to wetlands.
    c) Rate concentric zones using land use rating schedule (percentage of altered land and percentage of soils with a high potential for ground water contamination).
    d) Calculate land use score by summing weighted ratings of each concentric zone.
  2) Calculate water quality score (WQS).
    a) Determine if location of water quality monitoring station is appropriate for rating primary drainage unit.
    b) Use water quality rating schedules to determine nitrate, pH, ammonia phosphorus, and specific conductance ratings.

c) WQS = 0.33 (nitrate rating) + 0.33 (pH rating) + 0.11 (ammonia + phosphorus + specific conductance ratings).
d) If necessary, adjust WQS and LUS weights to account for missing water quality data.

3) Calculate ground water withdrawal score (GWS).
a) Estimate zone of recharge associated with drainage unit.
b) Determine percentage of drainage unit's water budget depleted by water withdrawal.
c) Determine GWS using ground water withdrawal rating schedule.

4) Calculate biodiversity score (BDS).
a) Develop biodiversity rating schedule by ranking rare species occurrences, number of ponds, and percentage of cedar swamp within each drainage unit.
b) BDS = 0.75 (rare species rating) + 0.20 (cedar swamp rating) + 0.05 (pond rating).

5) Calculate primary watershed integrity score (WIS^{o}).
a) WIS^{o} = 0.70 (LUS) + 0.20 (WQS) + 0.10 (GWS) + 0.25 (BDS).
b) Addition of the biological diversity score may result in a WIS^{o} > 10.

B. Calculate final watershed integrity score (WIS).

1) Calculate the target drainage unit's upstream watershed integrity score (WIS^{u}) by summing its area weighted WIS^{o} and the area weighted WIS^{o} of all upstream drainage units.
2) Compare the target unit's WIS^{u} to that of the adjacent downstream drainage unit. The downstream unit's score is referred to as the target unit's WIS^{d}.
3) If $WIS^{u} > WIS^{d}$, then $WIS = WIS^{u}$.
4) If $WIS^{u} < WIS^{d}$, then $WIS = (WIS^{u}+WiS^{d})/2$.

Step III. Evaluate Potential Impacts

A. Calculate primary drainage unit Potential Impact Scores (PIS^{o}).

1) Calculate Future Land Use Pattern Score (LPS).
a) Delineate 100 m concentric upland zones.
b) Weight zones according to drainage unit position and area.
c) Rate each concentric zone using percent cover of each management area and management area rating schedule.
d) Calculate LPS by summing weighted ratings of each concentric zone.

2) Calculate Transitional Soils Score (TSS).
a) Determine percentage of transitional soils within first 100 m upland zone.
b) Determine TSS using transitional soils rating schedule.

3) Calculate Basin and Wetland Dimension Score (WDS).
a) Develop wetland dimension score rating schedule.
1. Rank upstream watershed area (WA).
2. Rank percentage of wetland in upstream watershed (WW).
3. Rank percentage of wetland in drainage unit unit (DW).
4. Rank wetland perimeter in drainage unit (WP).
b) WDS = 0.4 (WA) + 0.3 (WW) + 0.2 (DW) + 0. 1 (WP).

4) Calculate primary drainage unit potential impact score (PIS^{o}).
a) PIS^{o} = LPS + 0.01 (LPS) (TSS) + 0.01 (LPS) (WDS).
b) Because scores > 10 will occur, the PIS^{o} of all drainage units must be rescaled from 1 to 10.

B. Calculate the target drainage unit's final Potential Impact Score (PIS) by summing its area weighted PIS^{o} and the PIS^{o} of all upstream drainage units.

Step IV. Develop wetland buffer options based on the watershed integrity and potential impact evaluation.

Developing Landscape Index Rating Schedules and Weights

A modified weighted factor procedure (Anderson 1987) is used to calculate scores for each of the landscape indexes. A rating schedule, expressed on a scale of 1 (low integrity and low impacts) to 10 (high integrity and high impacts), and a relative weight, expressed as a percentage, was established for each index. In its simplest form, an index score is calculated by multiplying the rating by the weight. Rating schedules and the weights represent subjective judgments based on available scientific information rather than hard quantitative data.

The detailed ratings assigned to each of the landscape indexes are not intended to provide a false sense of scientific accuracy. The rating schedules represent rankings of measured data, such as area of developed land or pH, and reflect the accuracy of those data. Although coarser ranking systems with fewer categories (e.g., high, medium, and low) may eliminate the appearance of unwarranted certainty, they do not recognize that wetland qualities and impacts exist along a continuum. The coarser the ranking system, the more arbitrary the established thresholds become. This is especially true because our knowledge of ecological thresholds is limited.

Wetland regulators are required to consider many factors when making decisions regarding wetland quality and impacts. Weights merely provide a means of describing the relative importance of each factor. In some cases they also indicate the amount of certainty that is associated with a factor. For example, nitrate and and pH are better indicators of watershed disturbance than ammonia, phosphorus, and specific conductance. This general statement does not provide the basis for a consistent and repeatable evaluation method. Assigning a weight of 0.33 to both pH and nitrate and 0.11 to each of the other three factors is a means of indicating that pH and nitrate are judged to be equally important and that each one is thought to be more important than the other factors. This numerical statement is more tangible and, in application, no less arbitrary than a general statement provided that the subjectivity and intent of this approach are clearly indicated. Use of a numerical ranking system should not belie the fact that the ratings and weights represent opinions based on available information.

Calculating Drainage Unit Index Scores

Land Use Score (LUS)

The land use rating schedule (Figure 5 and Appendix II) is based on both altered land cover and the percentage of upland soils that have a high potential for leaching and lie beneath the altered land. The integrity of associated wetlands decreases as the percentage of existing altered land within a basin increases and where development and agriculture are located on soils with a high potential for ground water contamination. For example, a rating of 10 is assigned to a drainage unit where 5% of the land is altered but where less than 25% of the altered land occurs on soils with a high potential for ground water contamination. In contrast, a rating of 9.25 is assigned to a drainage unit with the same percentage of altered land but where a greater percentage (> 75%) of the altered land occurs on soils with a high potential for ground water contamination.

An underlying assumption of the evaluation scheme is that hydrologic and ecological impacts associated with upland development and agriculture generally decrease with increasing distance from wetlands. We have applied this assumption by: 1) calculating land use scores for separate 100 m concentric zones surrounding the wetlands within a drainage unit (Figure 6); 2) weighting the scores for each zone according to its area and relative position to the wetlands; and 3) summing the weighted scores for each 100 m zone to derive a drainage unit land use score. Two examples are given in Table 9. In the first example, all 100 m zones are of equal area. The second one provides a more realistic case of variable zone areas.

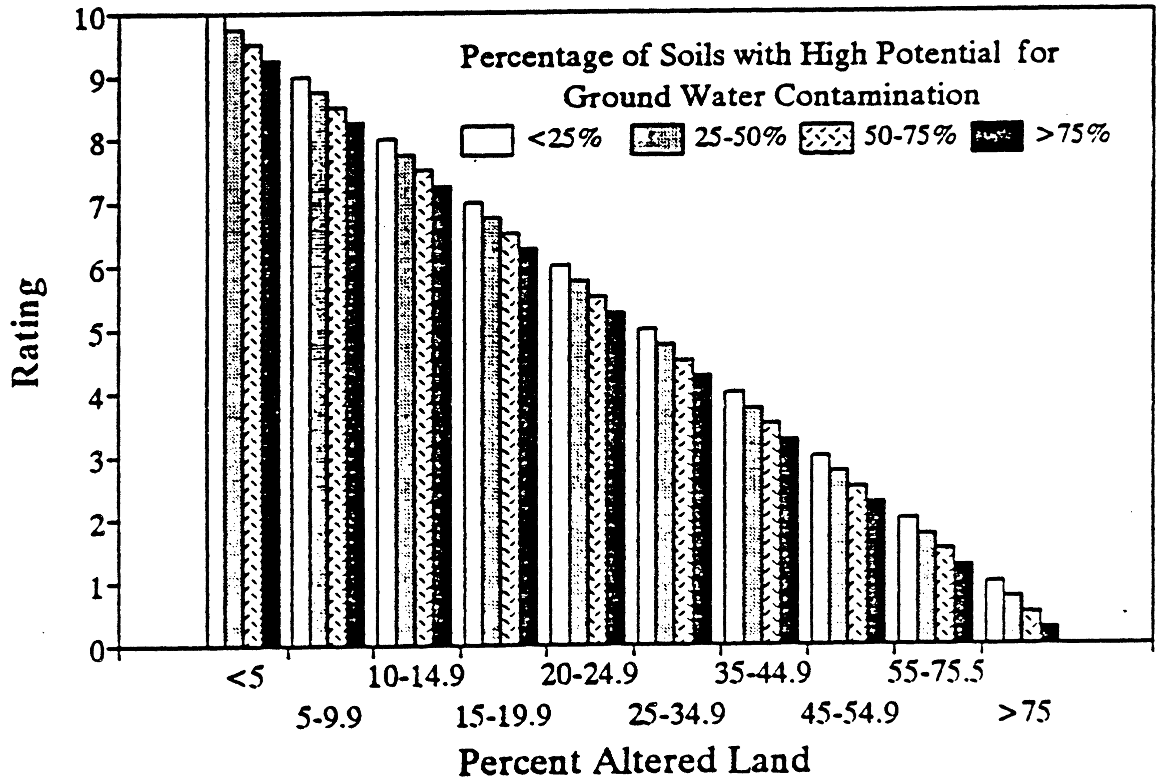


Figure 5. Land use rating schedule.

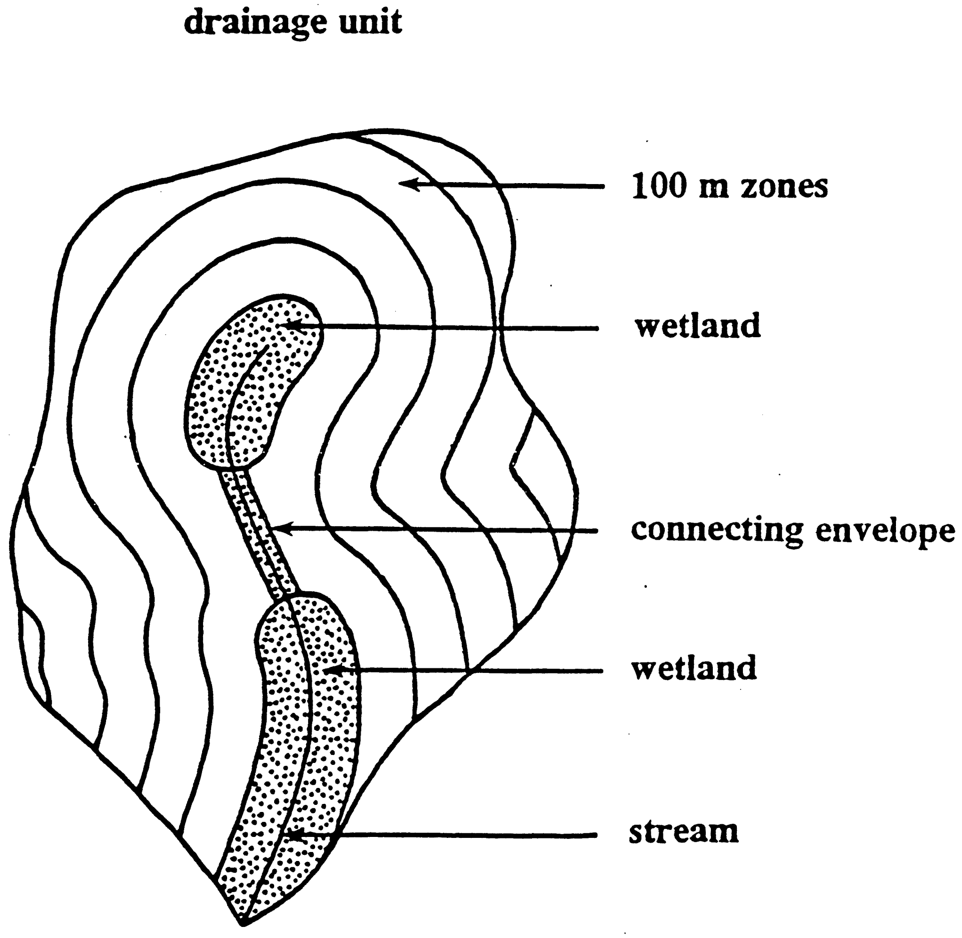


Figure 6. Delineation of buffer zones and creation of a contiguous wetland polygon.

Table 9. Calculating drainage unit land use scores.

Example 1

	Zone (m)				
	0-100	100-200	200-300	300-400	400-500
Zone Area (ha)	100	100	100	100	100
Zone Land Use Rating[1]	10	9	8	6	5
UpgradientArea(ha)[2]	500	400	300	200	100
Zone Weights	0.33	0.27	0.20	0.13	0.07
Weighted Zone Score	3.30	2.43	1.60	0.78	0.35

Land Use Score (Sum of Weighted 100 m Zone Scores) = 8.46

Example 2

	Zone (m)				
	0-100	100-200	200-300	300-400	400-500
Zone Area (ha)	33	67	100	133	167
Zone Land Use Rating[1]	10	9	8	6	5
Upgradient Area (ha)[2]	500	467	400	300	167
Zone Weights	0.27	0.26	0.22	0.16	0.09
Weighted Zone Score	2.70	2.34	1.76	0.96	0.45

Primary Land Use Score (Sum of Weighted Zone Scores)= 8.21

[1] Hypothetical ratings based on Figure 5.
[2] The area upgradient from the lower boundary of the respective zone.

The first example in Table 9 offers a simple explanation of how the zone weights are calculated for each zone. Each of the hypothetical zones is 100 ha. The downgradient boundary of the first concentric zone coincides with the wetland/non-wetland boundary. The drainage unit area located upgradient from this boundary is 500 ha. The drainage unit area occurring upgradient from the lower boundary of the 100-200 m zone is 400 ha, etc. The weights are derived by dividing the area upgradient from the lower boundary of each zone by the sum of the values for all zones (Table 10).

Because the zones in the first example are the same size, the weights are identical to those that would be derived if each zone were ranked according to its relative position. The zone located closest to the wetland (0-100 m) is weighted five times that of the farthest zone. As can be seen in the second example given in Table 10, the weights are also affected by a zone's area.

To facilitate a GIS application of this method separate wetland polygons located along the same stream are connected (Figure 6). An envelope is created around the wetland polygons and the stream connecting them. Because developed and agricultural land may be captured in this wetland envelope, two separate land use scores are calculated and averaged to obtain a final land use score. The first land use score is derived using the wetland envelope as the first zone. The second is calculated using the adjacent 100 m upland zone as the first zone.

Table 10. Deriving buffer zone weights.

Example 1

Zone	Upgradient Area	Weight
0-100 m	500 ha	500/1500 = 0.33
100-200 m	400 ha	400/1500 = 0.27
200-300 m	300 ha	300/1500 = 0.20
300-400 m	200 ha	200/1500 = 0.13
400-500 m	100 ha	100/1500 = 0.07
	Sum 1500 ha	1.00

Example 2

Zone	Upgradient Area	Weight
0-100 m	500 ha	500/1834 = 0.27
100-200 m	467 ha	467/1834 = 0.26
200-300 m	400 ha	400/1834 = 0.22
300-400 m	300 ha	300/1834 = 0.16
400-500 m	167 ha	167/1834 = 0.09
	Sum 1834 ha	1.00

Surface Water Quality Score (WQS)

The surface water quality score is a composite score derived from pH, specific conductance, nitrate, phosphorus, and ammonia ratings and weights (Figure 7, Table 11). Nitrate-nitrogen and pH are weighted more heavily because they are the primary water quality factors. The ratings were based on the watershed disturbance gradient described by Zampella (1994a). Stream stations along McDonalds Branch, Bass River, Oswego River, and Wading River represent regional reference sites (Hughes et al. 1986). Reference sites are stream stations in undisturbed drainage areas with landscape features, such as forest type, soils, and geology, that characterize a region. These reference sites are useful for classifying streams and setting ecological criteria. Hammonton Creek, at the extreme opposite end of the gradient, represents a severely disturbed Pinelands stream.

Using water quality values for three USGS reference sites, examples of how the water quality score is calculated are given in Table 11. If data for one or more of the secondary factors are not available, the weights assigned to those factors should be added to pH and nitrate as shown in Table 12. As shown in Table 12, when acceptable data for one or both of the primary factors are not available the water quality index weight should be reduced and the land use index should be increased. If the location of a sampling station does not adequately characterize upstream conditions, the water quality index should not be used and its weight should be added to the land use index. This determination is ultimately a subjective one.

Ground Water Withdrawal Score (GWS)

The location and pumping rate of ground water wells can be determined from NJDEP water allocation and well records. The relative impacts of these diversions within a drainage unit are rated by comparing the well withdrawal rate to estimated recharge at that point in the watershed. A well's zone of influence may cross drainage divides. To account for this, we al-

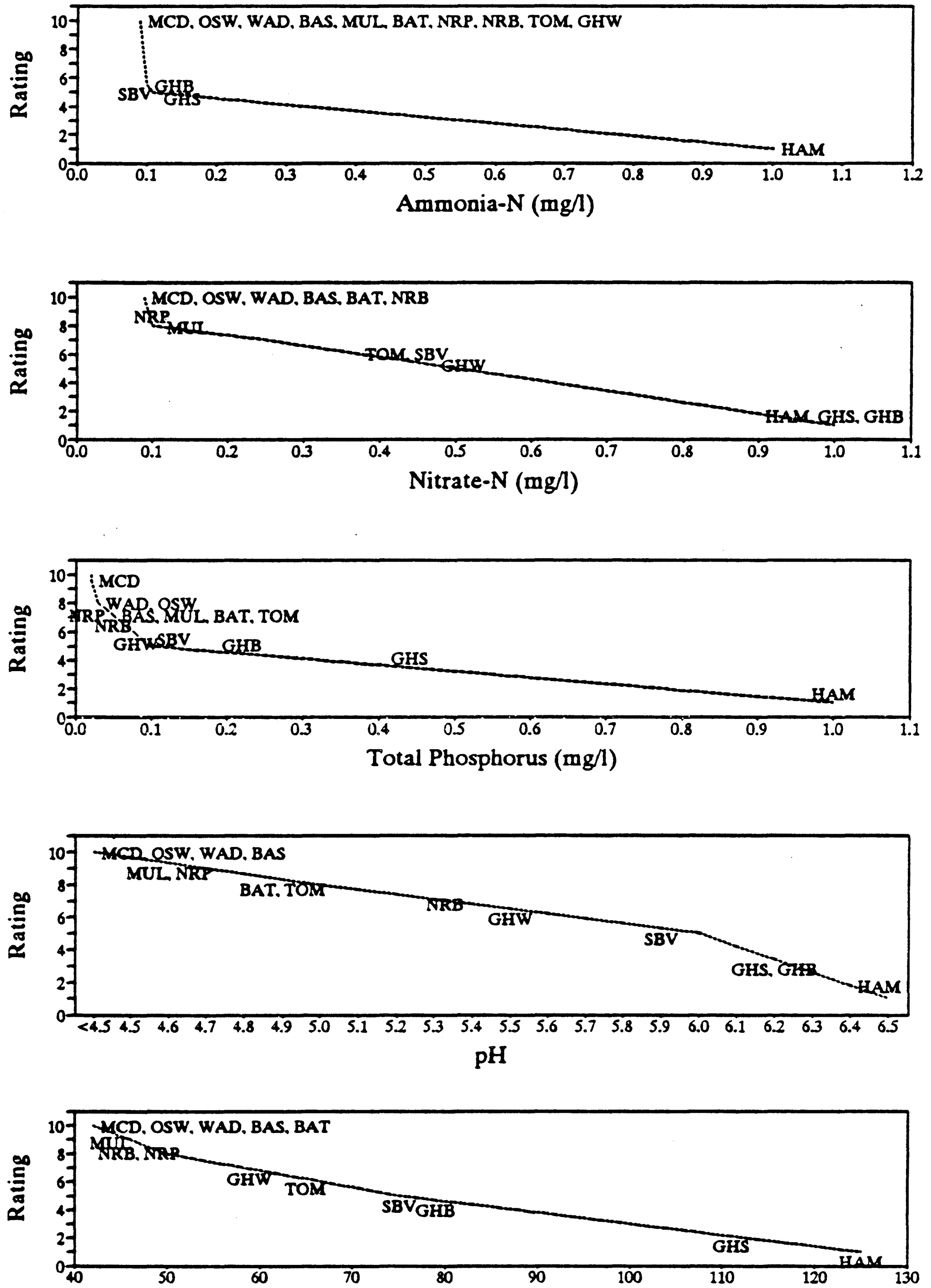


Figure 7. Surface water quality rating schedules. Stream name abbreviations are as follows: TOM (Toms River near Toms River), MUL (Mullica River at Atsion Lake outlet), HAM (Hammonton Creek at Wescoatville), BAT (Batsto River at Batsto), WAD (West Branch Wading River at Maxwell), OSW (Oswego River at Harrisville), BAS (East Branch Bass River near New Gretna), GHS (Great Egg Harbor River near Sicklerville), GHB (Great Egg Harbor River near Blue Anchor), GHW (Great Egg Harbor River at Weymouth), SBR (South Branch Rancocas Creek at Vincentown), NRP (North Branch Rancocas Creek at Browns Mills), MCD (McDonalds Branch in Lebanon State Forest), NRB (North Branch Rancocas Creek at Pemberton).

Table 11. Calculating water quality scores.

McDonalds Branch

Factor	Median	Rating	x	Weight		Score
pH	4.2	10.0	x	0.33	=	3.3
NO_3-N (mg/l)	<0.10	10.0	x	0.33	=	3.3
NH_3-N (mg/l)	<0.10	10.0	x	0.11	=	1.1
Spec.Cond.	42	10.0	x	0.11	=	1.1
Total P (mg/l)	<0.02	10.0	x	0.11	=	1.1
Final Score:						10.0

TomsRiver

Factor	Median	Rating	x	Weight		Score
pH	4.9	8.3	x	0.33	=	2.7
NO_3-N (mg/l)	0.37	6	x	0.33	=	2.0
NH_3-N (mg/l)	<0.10	10	x	0.11	=	1.1
Spec.Cond.	65	6.2	x	0.11	=	0.7
Total P (mg/l)	0.03	8.0	x	0.11	=	0.9
Final Score:						7.4

Hammonton Creek

Factor	Median	Rating	x	Weight		Score
pH	6.4	1.8	x	0.33	=	0.6
NO_3-N (mg/l)	1.62	1.0	x	0.33	=	0.3
NH_3-N (mg/l)	1.29	1.0	x	0.11	=	0.1
Spec.Cond.	136	1.0	x	0.11	=	0.1
Total P (mg/l)	1.06	1.0	x	0.11	=	0.1
Final Score						1.2

Table 12. Adjusting water quality factor weights and land use index weights when water quality factors are missing.

Number of Factors		Factor Weight		Water Quality	Land Use
Primary	Secondary	Primary	Secondary	Index Weight	Index Weight
2	3	0.33	0.11	0.20	0.70
2	2	0.39	0.11	0.20	0.70
2	1	0.44	0.11	0.20	0.70
2	0	0.50	0.00	0.20	0.70
1	3	0.50	0.17	0.10	0.80
1	2	0.67	0.17	0.10	0.80
1	1	0.83	0.17	0.10	0.80
1	0	1.00	0.00	0.10	0.80

locate withdrawals according to the area within an estimated zone of influence. There are numerous mathematical models of varying complexity that may be used to estimate the zone of influence associated with a water supply well. In the absence of detailed well and aquifer property information, a simple mass balance model can be used to estimate the surface area needed to capture the volume of recharge equal to the withdrawal rate of a water supply well. It is expressed as: zone of influence = well withdrawal rate/recharge rate. This approach assumes that: 1) the zone of recharge associated with a well is a circular area; 2) all of the precipitation that falls within the estimated recharge area flows to the well; and 3) ground water depletion within a basin is proportional to the estimated zone of recharge. The rating schedule for ground water withdrawals is shown in Figure 8 and Appendix III. The watershed area includes the area of a drainage unit and all upstream drainage units. Water budget depletion (%) = (zone of influence or recharge/watershed area) X 100. An example of its application is given in Table 13.

Table 13. Application of ground water withdrawal rating schedule. A water supply well is located in drainage unit 4. Total watershed area includes a drainage unit and all upstream drainage units.

Drainage Unit[1]	Unit Area (ha)	Watershed Area (ha)	Water Budget Depletion (%)	Rating
1	25	25	0	10.0
2	40	40	0	10.0
3	80	145	0	10.0
4	30	30	50	3.3
5	80	225	14	8.8
6	20	20	0	10.0
7	25	25	0	10.0
8	105	150	0	10.0
9	70	475	3	9.4
10	230	705	2	9.6

[1] Refer to Figure 4.

Biological Diversity Score (BDS)

The Natural Heritage Program GIS database (Breden et al. 1990) is the primary data source for rare species data. Cedar data can be derived from NJDEP freshwater wetland maps although these maps are not currently available for the entire Pinelands. Delineation of ephemeral ponds and shrubby wetlands requires original photointerpretation. Rare species locations included in the Natural Heritage Program data base are indicated using rectangles representing seconds and minutes (longitude and latitude) precision. Species occurrences with seconds precision are more accurate and are mapped using rectangles which are four seconds on each side. Those with minutes precision are assigned rectangles that are one minute on a side. The method provides the user with an indication of the precision of the data but it also results in a much larger area being associated with less accurate locations. To ensure that species occurrences are actually associated with a particular drainage unit, only data with seconds precision are used in the watershed assessment.

There are two additional limitations that should be recognized when using the Natural Heritage Program data base. Because multiple species occurrences are enclosed in irregularly shaped polygons, individual sightings and the criteria used to create the polygon are not known to the user. Unlike the information used for other landscape indicators (e.g. land cover, soils,

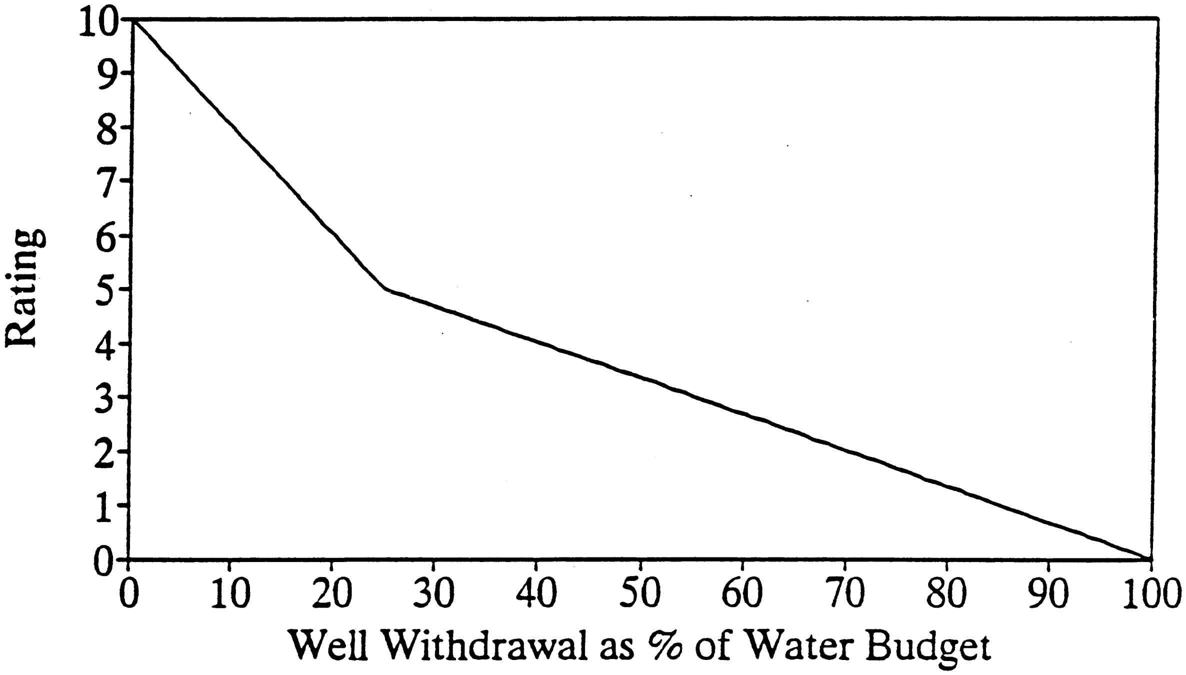


Figure 8. Ground water withdrawal rating schedule.

wetlands), data included in the Natural Heritage database are generally not based on systematic surveys. Thus, the absence of a rare species in an area does not necessarily indicate that it is not found there. It may merely mean that a site was not surveyed.

The rating system for the three biological diversity factors and the calculation of biological diversity scores should be based on a relative ranking of all drainage units in the Pinelands. An example is given in Table 14. First, the following values must be calculated for each drainage unit: 1) the number of threatened and endangered species per drainage unit area; 2) the number of herbaceous or shrub ponds per drainage unit area; and 3) the percentage of drainage unit comprised of cedar swamps. Next, a rating schedule for each biodiversity attribute is based on a ranking of positive occurrences which is converted to a scale of one to ten. Finally, a primary drainage unit biological diversity score (BDS) is calculated by adding the weighted ratings of the three biological attributes.

Table 14. Developing rating schedules for biological diversity factors and calculating primary drainage unit biological diversity scores (BDS). BDS = 0.75 (threatened and endangered species rank) + 0.20 (cedar cover rank) + 0.05 (pond rank).

Basin	T/E Species		Cedar Swamps		Ponds		BDS
Unit[1]	No./km^2	Rating	Percent	Rating	No./km^2	Rating	
1	4.0	8.5	3	2.5	4.0	6.5	7.2
2	2.5	4.5	4	4	2.5	1	4.2
3	2.5	4.5	3	2.5	5.0	9.5	4.4
4	3.3	6	7	8	3.3	4	6.3
5	3.8	7	5	5.5	3.8	5	6.6
6	5.0	10	12	10	5.0	9.5	10.0
7	4.0	8.5	2	1	4.0	6.5	6.9
8	1.9	3	8	9	4.8	8	4.5
9	1.4	1	5	5.5	2.9	3	2.0
10	1.7	2	6	7	2.6	2	3.0

[1] Refer to Figure 4.

The other three watershed integrity landscape indexes (land use, water quality, and water withdrawals) characterize drainage units along a disturbance gradient under the assumption that human disturbance degrades the ecological integrity of wetlands. Unlike the land use factors, which adversely affect watershed and wetland integrity, the biological attributes contribute to the overall value of a wetland. This positive aspect of biological diversity is recognized in the ranking method by using biological data to increase the rating of a drainage unit (Table 8). Thus, intact drainage basins are not penalized due to the absence of rare species.

Future Land Use Pattern Score (LPS)

The management area rankings shown in Table 15 provide a coarse, relative estimate of land use projections and potential threats to long-term sustainability of Pinelands wetlands. Because the proportion of potentially developable land relative to the area designated as Military and Federal Installation Area varies considerably among facilities, this management area is assigned a variable rank. All facilities in the Pinelands Protection Area and developed portions of facilities within the Preservation Area are assigned the same rating as Regional Growth Areas. Because the projected uses of undeveloped portions of Fort Dix and other facilities within the Preservation Area are uncertain they are assigned the same rating as Forest Areas.

Public conservation lands comprise more than one-third of the Pinelands. Acquisition of land to develop a system of representative and self-maintaining ecological reserves is a major component of the Pinelands protection program (Zampella 1988). Because the potential for long-term ecological sustainability is greatest for publicly owned lands, these areas are ranked higher than private lands in the Preservation Area District.

With one additional measure, future land use pattern scores are calculated using the same method previously employed to compute primary drainage unit land use scores (Tables 9 and 10). Because several land management areas may occur within the same drainage unit, a composite future land use pattern score must first be calculated for each of the 100 m concentric zones surrounding the wetland (Table 16). The percent cover of each management area within a zone is multiplied by the appropriate rating (Table 15) and these products are added to derive a future land use pattern score for each concentric zone. Future land use pattern scores are then derived by summing scores for the 100 m, weighted zones surrounding the wetlands within a drainage unit (Table 17).

Table 15. Potential for impacts associated with Pinelands management area designations.

Management Area Category	Rating
Public Conservation Lands	1 Low Impact Potential
Preservation Area District	2
Forest Area	3
Special Agricultural Production Area	4
Rural Development Area	5
Infill Area	6
Agricultural Production Area	7
Pinelands Village	8
Federal Installation Area	V
Pinelands Town	9
Regional Growth Area	10 High Impact Potential

Table 16. Calculating future land use pattern scores for individual zones within a drainage unit.

Management Area	Rating	Percent Cover	Product
Rural Development Area	5	49	2.45
Agricultural Production Area	7	40 51	3.57
Zone Score			6.02

Transitional Soils Score (TSS)

The transitional soils index assumes that the potential for development impacts to wetlands increases as the percentage of somewhat poorly drained soils within a 100 m zone adjacent to delineated wetlands increases. The rating schedule for transitional soils is based on percent cover values for these high water table upland soils (Table 18).

Table 17. Calculating drainage unit future land use pattern scores. A composite score must be calculated for each zone as shown in Table 16.

Example 1

	Zone (m)				
	0-100	100-200	200-300	300-400	400-500
Zone Size (ha)	100	100	100	100	100
Zone Future Rating	3	4	5	6	7
Upgradient Area (ha)[1]	500	400	300	200	100
Zone Weights	0.33	0.27	0.20	0.13	0.07
Weighted Zone Score	0.99	1.08	1.00	0.78	0.49

Future Land Use Pattern Score (Sum of Weighted Zone Scores) = 4.34

[1] The area upgradient from the lower boundary of the respective zone.

Example 2

	Zone (m)				
	0-100	100-200	200-300	300-400	400-500
Zone Size (ha)	33	67	100	133	167
Zone Future Rating	3	4	5	6	7
Upgradient Area (ha)[1]	500	467	400	300	167
Zone Weights	0.27	0.26	0.22	0.16	0.09
Weighted Zone Score	0.81	1.04	1.10	0.96	0.63

Future Land Use Pattern Score (Sum of Weighted Zone Scores) = 4.54

[1] The area upgradient from the lower boundary of the respective zone.

Table 18. Transitional soils rating schedule.

Transitional Soils (%)	Rating
100	10.0
95	9.5
90	9.0
85	8.5
80	8.0
75	7.5
70	7.0
65	6.5
60	6.0
55	5.5
50	5.0
45	4.5
40	4.0
35	3.5
30	3.0
25	2.5
20	2.0
15	1.5
10	1.0

Basin and Wetland Dimension Score (WDS)

The following factors are derived for each primary drainage unit: 1) watershed area (WA); 2) percentage of the watershed comprised of wetlands (WW); 3) percentage of the target drainage unit comprised of wetlands (DW); and 4) the ratio of perimeter to wetland area within the target drainage unit (WP). The watershed represents the entire upstream drainage area associated with a drainage unit. Each of these factors is ranked separately and the ranks are scaled from one to 10. A primary drainage unit's basin/wetland dimension score (WDS) is derived by adding the weighted ranks of the individual factors (Table 19). Factor weights represent the relative importance assigned to each of the dimension variables and are simply based on rank order.

Table 19. Calculating basin and wetland dimension scores (WDS). WDS = 0.4 (WA rank) + 0.3 (WW rank) + 0.2 (DW rank) + 0.1 (WP rank).

Drainage Unit[1]	Watershed Data		Drainage Unit Data		
	Area(ha)	%Wetland	% Wetland	Perimeter	Area (ha)
1	25	10	10	0.20	25
2	40	12	12	0.25	40
3	145	13	15	0.10	80
4	30	10	10	0.15	30
5	255	14	18	0.15	80
6	20	12	12	0.05	20
7	25	13	13	0.10	25
8	150	18	20	0.30	105
9	475	17	25	0.22	70
10	705	20	26	0.12	230

Drainage[1] Unit	Watershed Ranks		Drainage Unit Ranks		WDS
	Area	% Wetland	% Wetland	Perimeter	
1	8.5	9.5	9.5	7	8.85
2	6	7.5	7.5	9	7.05
3	5	5.5	5	2.5	4.90
4	7	9.5	9.5	5.5	8.10
5	3	4	4	5.5	3.75
6	10	7.5	7.5	1	7.85
7	8.5	5.5	6	2.5	6.50
8	4	2	3	10	3.80
9	2	3	2	8	2.90
10	1	1	1	4	1.30

[1] Refer to Figure 4.

Calculating Drainage Unit Watershed Integrity and Potential Impact Scores

Watershed Integrity Scores

The primary watershed integrity scores (WIS^o), which reflect local conditions within individual drainage units, are calculated by adding the respective weighted index scores (Table 20). For unit 1 in Table 20, WIS^o = 0.70 (10.00) + 0.20 (10.00) + 0.10 (10.0) + 0.25 (7.20) = 11.8. For unit 4, WIS^o = 0.70 (8.50) + 0.20 (7.65) + 0.10 (3.3) + 0.25 (6.30) = 9.4. Addition of the biological diversity score (BDS) can result in a $WIS^o > 10$.

Table 20. Calculating primary (WIS^o) and final (WIS) drainage unit watershed integrity scores. $WIS^o = 0.70\ (LUS) + 0.20\ (WQS) + 0.10\ (GWS) + 0.25\ (BDS)$.

Drainage Unit[1]	Area Ha1	Ha2	LUS	WQS	GWS	BDS	WIS^o	WIS^u	WIS^d	WIS
1	25	25	10.00	10.00	10.0	7.20	11.8	11.8	11.1	11.8
2	40	40	9.75	10.00	10.0	4.20	10.9	10.9	11.1	11.0
3	80	145	10.00	10.00	10.0	4.40	11.1	11.2	10.4	11.2
4	30	30	8.50	7.65	3.3	6.30	9.4	9.4	10.4	9.9
5	80	255	8.00	7.65	8.8	6.60	9.7	10.5	9.7	10.5
6	20	20	10.00	-	10.0	10.00	12.5	12.5	9.9	12.5
7	25	25	10.00	-	10.0	6.90	11.7	11.7	9.9	11.7
8	105	150	7.50	7.65	10.0	4.50	8.9	9.9	9.7	9.9
9	70	475	7.25	7.65	9.4	2.00	8.0	9.9	9.3	9.9
10	230	705	7.00	7.65	9.6	3.00	8.1	9.3	-	9.3

[1] Refer to Figure 4.

Ha1 = Drainage unit area. Ha2= Upstream watershed area.
WIS^u = WIS of drainage unit without consideration of downstream units.
WIS^d = WIS of downstream drainage unit(s).

The final drainage unit watershed integrity score (WIS) is meant to reflect both upstream and downstream conditions. From a hydrologic perspective the flow of water and energy is largely downgradient and wetland integrity is determined primarily by upstream and local watershed conditions. Because maintenance of water quality and hydrologic regimes is the major focus of the watershed integrity evaluation, upstream conditions are given greater importance than downstream conditions. When assessing a particular drainage unit, consideration of downstream conditions is limited to an assessment of adjacent downgradient drainage units.

For each drainage unit, an upstream watershed integrity score (WIS^u) is derived by summing the weighted WIS^o scores of that unit and all upstream drainage units. The unit weights used in the calculation are merely the percentage of the upstream watershed contributed by each unit. The upstream watershed represents the entire upstream drainage area associated with a drainage unit. For example, the upstream watershed area given for drainage unit 3 in Table 20 is 145 ha. It includes drainage units 1 (25 ha), 2 (40), and 3 (80 ha). Thus, the contribution of each drainage unit to drainage unit 3's upstream drainage area is: unit 1 (25/145 = 17%); unit 2 (40/145 = 28%); and unit 3 (80/145 = 55%). For drainage unit 3, $WIS^u = 0.17\ (11.8) + 0.28\ (10.9) + 0.55\ (11.1) = 11.2$. Because drainage units 1 and 2 are associated with first order headwater streams, there are no upstream units and $WIS^o = WIS^u$.

The WIS^u represents a drainage unit's final watershed integrity score (WIS) unless the drainage units located immediately downstream have a higher WIS^u. Downstream drainage units include those units that comprise 100 ha of downstream area. The downstream watershed integrity score associated with each drainage unit is referred to as its WIS^d. When more than one unit falls within the 100 ha area their scores are weighted according to their contribution to the 100 ha. If a drainage unit's WIS^u is less than its WIS^d, the two values are averaged to obtain a final watershed integrity score (WIS). Two examples are given here using drainage units 1 and 2 from Table 20.

Upstream watershed integrity scores (WIS^u) for units 1 and 2 are 11.8 and 10.9, respectively. Unit 3 (80 ha) and 5 (80 ha) represent 80% and 20%, respectively, of the 100 ha area located downstream from units 1 and 2 (Figure 4). The WIS^u's for units 3 and 5 are 11.2 and 10.5. Thus, WIS^d for both unit 1 and unit 2 = 0.80 (11.2) + 0.20 (10.5) = 11.1. For unit 1, $WIS^u > WIS^d$ and WIS^u represents the final watershed integrity score (WIS). For unit 2, $WIS^u < WIS^d$ and $WIS = (WIS^u + WIS^d)/2$.

Potential Impact Scores

As with the primary watershed integrity scores (WIS^o), the primary potential impact scores (PIS^o) reflect local conditions within individual drainage units. They are calculated by adding the respective weighted index scores (Table 21). For unit 1 in Table 21, PIS^o = 10 + 0.01(10)(7.0) + 0.01(10)(8.85) = 11.6. Multiplying the transitional soils and basin/wetland dimension scores by a fraction of the future land use pattern score when calculating the PIS^o allows the importance of the two physical factors to be proportional to potential land use impacts. Both indexes become more important as the potential for impact increases.

Because primary drainage unit potential impact scores > 10 may result from adding the transitional soils score (TSS) and basin/wetland dimension score (WDS) to the land use pattern score (LPS), the PIS^o of all drainage units in a project area are rescaled from 1 to 10 to obtain final primary drainage unit potential impact scores (PIS^r).

Only upstream conditions are considered when calculating a final drainage unit potential impact score (PIS) (Table 21). The approach is similar to that used to calculate an upstream watershed integrity score (WIS^u). A PIS is derived by summing the weighted PIS^r scores of that unit and all upstream drainage units. The unit weights used in the calculation are the percentage of the upstream watershed contributed by each unit. Because drainage units 1 and 2 are associated with first order headwater streams, there are no upstream units and PIS = PIS^r. For drainage unit 3 in Table 21, PIS = 0.17 (10.0) + 0.28 (7.7) + 0.55 (8.2) = 8.4.

Table 21. Calculating primary (PIS^o) and final (PIS) drainage unit potential impact scores. PIS^o = future land use patterns score + 0.01 (future land use patterns score) X (transitional soils score) + 0.01 (future land use patterns score) X (basin/wetland dimension score). PIS^r is derived by rescaling PIS^o from 1 to 10.

Drainage Unit[1]	Area Ha1	Ha2	LPS	TSS	WDS	PIS^o	PIS^r	PIS
1	25	25	10.0	7.0	8.85	11.6	10.0	10.0
2	40	40	8.0	4.5	7.05	8.9	7.7	7.7
3	80	145	9.0	1.0	4.90	9.5	8.2	8.4
4	30	30	4.0	10.0	8.10	4.7	4.1	4.1
5	80	255	5.0	8.5	3.75	5.6	4.9	6.8
6	20	20	1.0	3.0	7.85	1.1	1.0	1.0
7	25	25	3.0	8.0	6.50	3.4	3.0	3.0
8	105	150	2.0	6.5	3.80	2.2	2.0	2.0
9	70	475	1.0	5.0	2.90	1.1	1.0	4.4
10	230	705	10.0	2.0	1.30	10.3	8.9	5.9

[1] Refer to Figure 4.

Ha1 = Drainage unit area. Ha2 = Upstream watershed area.

Relating Wetland Integrity and Potential for Impacts to Buffers

Establishing guidelines for wetland buffers is basically a policy decision that must consider both the level of protection to be afforded wetlands in general and the variable watershed integrity and potential impacts displayed by the region's wetlands. A regional wetland assessment can provide a basis for such guidelines. The watershed integrity evaluation method offers a means of ranking drainage basins along a regional gradient of increasing wetland quality. The gradient derived from the potential impact methodology evaluates future land use projections and the resiliency of wetlands to upland impacts. Together, they can be used to identify high quality wetlands where factors effecting their long-term maintenance are of little consequence or where conflicts between existing integrity and projected land use patterns exist.

Wetland integrity and potential impact scores can be translated into a range of buffer distances to consider when evaluating site-specific development projects. Use of the future land use pattern index assumes average conditions which mostly reflect residential development unit densities. Because densities vary within each of the management areas, buffer decisions based on the potential impact evaluation should be flexible to allow for this variability. As previously indicated, areas of important biological diversity are often associated with watersheds displaying a high degree of landscape and water quality integrity. However, there will be situations where the use of the watershed assessment to assign buffers may not adequately protect a rare plant or animal species. Resolution of such conflicts is site-specific and species-specific.

Decisions based on results of a watershed evaluation of potential impacts are most appropriate for Pinelands residential development and small scale commercial establishments. They are not appropriate for special cases including resource extraction operations and large commercial projects, such as major shopping malls, which generate greater impacts than those assumed in the watershed methodology. The wetlands sustainability assessment does not adequately address the future potential impact of resource extraction operations within the Preservation Area District and Forest Areas. Although these management areas are assigned a low future land use pattern score, the potential for extensive surface mining exists within some areas of the region. Roman and Good (1985) recommend that a 300 ft buffer be maintained between resource extraction areas and wetlands because of the potential for severe environmental impacts associated with mining activities.

Several buffer policy options regarding wetland buffers can be pursued. A few are briefly discussed. Each has different goals and affords varying levels of protection to wetlands. For each case, conversion tables relating watershed integrity scores and potential impact scores to buffers must be developed. Development of conversion tables is highly subjective and the possibilities are too many to describe here.

> <u>Option 1</u>. Assign a maximum buffer to all wetlands in areas displaying high watershed integrity regardless of potential impact and reduce the buffer along the integrity gradient.
>
> <u>Option 2</u>. Assign buffers that reflect both watershed integrity and the level of potential impact.
>
> <u>Option 3</u>. Assign buffers that reflect both watershed integrity and the potential for long-term sustainability.

Option 1 affords the maximum level of protection (300 ft) to all high quality wetlands. By assigning a maximum buffer to wetlands in areas where impacts are low, it tacitly suggests that a 300 ft buffer may not prevent a substantial impact to wetlands in areas where the potential for impact is high.

Option 2 reflects the assumptions that high quality wetlands require greater buffers and that buffer width should be related to potential impact. The largest buffers would generally be assigned to high quality wetlands in Regional Growth Areas. Conversely, high quality wetlands in the Preservation Area District would receive lesser buffers than comparable wetlands in areas where potential impacts are higher.

Option 3 views the potential impact ranking differently. It suggests that the potential for long-term sustainability decreases as the potential for impact increases. Thus, it may not be warranted to afford a high level of protection to wetlands in areas designated for high density development. This option accommodates the regional planning objectives of the Pinelands Comprehensive Management Plan which directs development to Regional Growth Areas and away from areas that are generally considered to display greater ecological integrity.

PART 5. A DEMONSTRATION OF THE WATERSHED-BASED METHODOLOGY

Study Area

We applied the watershed-based wetland assessment methodology to a portion of the Pinelands in Ocean County. Six demonstration watersheds were selected for study. These are the Davenport Branch and Jakes Branch of the Toms River, Cedar Creek, Forked River, Oyster Creek, and Mill Creek basins (Figure 9). These watersheds were chosen for the following reasons: 1) they originate within the Pinelands Area and the upstream reaches fall within the jurisdiction of the Pinelands Commission; 2) they support representative Pinelands wetland communities and ecological attributes; and 3) they display a gradient of existing development intensity (land cover) and permitted land uses (Pinelands management areas). With the exception of Mill Creek, which discharges to Manahawkin Bay, all drain to Barnegat Bay. This application was completed solely for demonstration purposes. Because the drainage unit assessments are based on rankings completed only for the study area, they will change if a comparative assessment of all Pinelands wetland systems is completed.

Data Acquisition and Analysis

We acquired existing digitized data from several sources and developed some new data. Digital data preparation and processing was completed at the Rutgers University Center for Remote Sensing and Spatial Analysis using ARC/INFO and GRASS geographic information system software. Data analysis and calculation of watershed integrity and potential impact scores were completed using personal computer spreadsheets.

Drainage unit boundaries were delineated on 1:24,000 scale USGS quadrangles. These boundaries were digitized and merged with digital watershed files obtained from the USGS to create a watershed/primary drainage unit map (Figure 10). A total of 284 separate drainage units were created. A few minor mapping discrepancies resulted from errors in the USGS digital watershed files, our mapping of drainage unit boundaries, and because we combined the digital watershed files and the newer hydrography (stream line) data obtained from the NJDEP.

Digital integrated terrain unit (ITU) mapping data were obtained from the NJDEP. The appropriate land use/land cover types were combined to create altered land coverage (Plate 1). ITU soils data were grouped using the classification system shown in Table 7. This

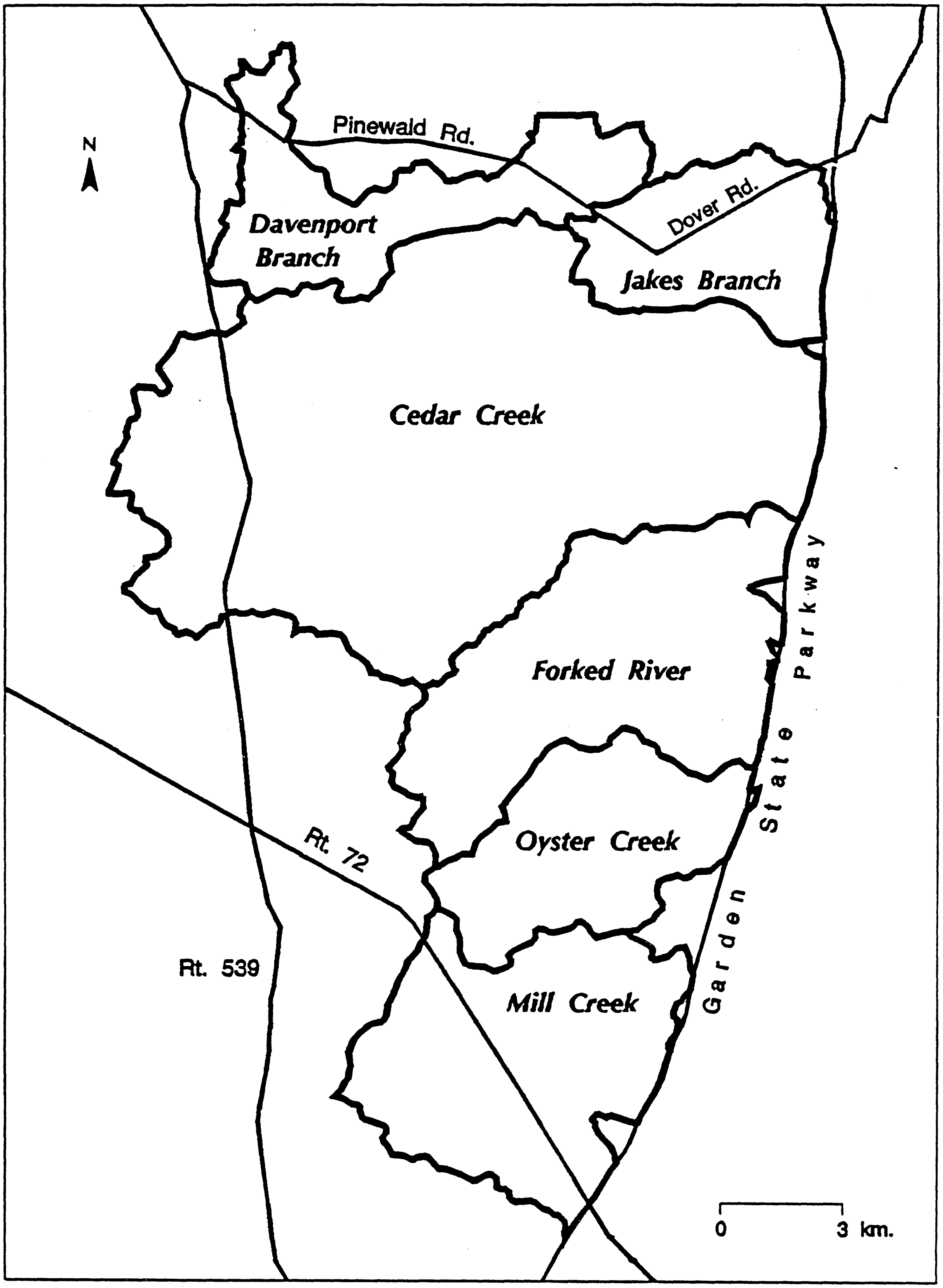


Figure 9. Demonstration watersheds.

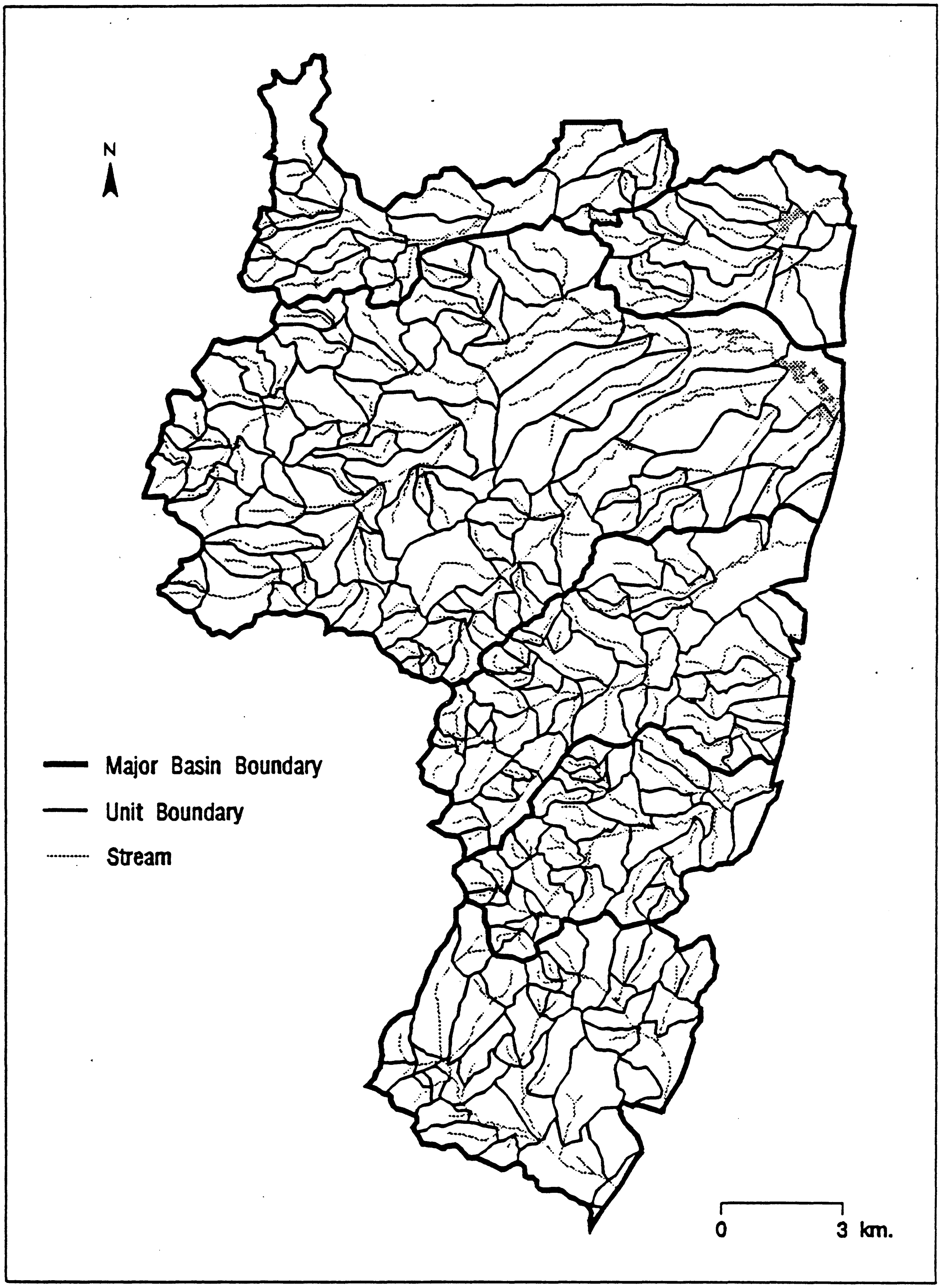


Figure 10. Major basin/primary drainage unit map.

classification system describes the ground water contamination potential of Pinelands soils (Plate 2). Most areas mapped as cranberry bog within the study area are actually abandoned bogs. Based on photointerpretation and field reconnaissance, we reclassified all but three areas as wetlands. Although there were some other minor classification problems (e.g. wildlife food plots mapped as agriculture), we attempted no further editing of the ITU land use/land cover maps.

New Jersey freshwater wetland maps were not available for the Ocean County study area. To provide wetland coverage (Figure 11), we acquired National Wetland Inventory digital data from the U.S. Geological Survey Earth Science Information Center. These wetland data were merged with the ITU coverage.

Pinelands land management area (Plate 3) and public lands data (Figure 12) were also acquired from the NJDEP. Several areas not included in the state's inventory, including a recent major land acquisition in the Mill Creek watershed, were added to this file. The locations of major water supply wells were obtained from the USGS (West Trenton, N.J.) in digital form along with ownership and pumping rate information (Table 22). All are screened in the Kirkwood-Cohansey and all withdrawals are discharged outside the study area (Zripko and Hasan 1994).

Table 22. Major ground water withdrawals within the demonstration area. Withdrawal rates are given as million gallons per year (Mgy).

Well No	WAP[1] No	Permit Name	Withdrawal Rate(Mgy)[2] Total	Study Basins
290485	5231	Crestwood Village Water Co.	41.1	35.6
290569	5301	Barnegat Water Company	335.8	16.8
290569	5301	Barnegat Water Company	335.8	24.5
290570	5060	Pinewood Estates	4.7	4.7
290571	5060	Pinewood Estates	22.7	22.7
290589	5000	TomsRiver Water Company	163.9	58.8
290721	5231	Crestwood Village Water Co.	60.3	50.6
290735	5231	Crestwood Village Water Co.	85.9	0.3
290766	5038	Stafford Township Water Co.	28.3	1.5
290766	5038	Stafford Township Water Co.	28.3	26.8
290927	5060	Brighton at Barnegat	14.4	1.7
290927	5060	Brighton at Barnegat	14.4	6.4
290927	5060	Brighton at Barnegat	14.4	3.4
290927	5060	Brighton at Barnegat	14.4	2.8
290928	5000	Toms River Water Company	264.3	162.6
290928	5000	Toms River Water Company	264.3	44.1
291093	5065	Brookdale Utilities Corp.	13.9	11.3

[1] NJDEP water allocation permit number.
[2] Study basin withdrawal rates represent the portion of the total withdrawal derived from drainage areas located within the demonstration area (Mgy = million gallons per year).

Water quality data for stations within the demonstration area (Table 23, Figure 13) were taken from Zampella et al. (1994). The water quality index was not applied to portions of the Davenport Branch (17%), Cedar Creek (14%), Forked River (24%), Oyster Creek (21%), and Mill Creek (42%) watersheds because the water quality data were not available or, as in the case of Mill Creek, were not considered appropriate for these areas. Because the Mill

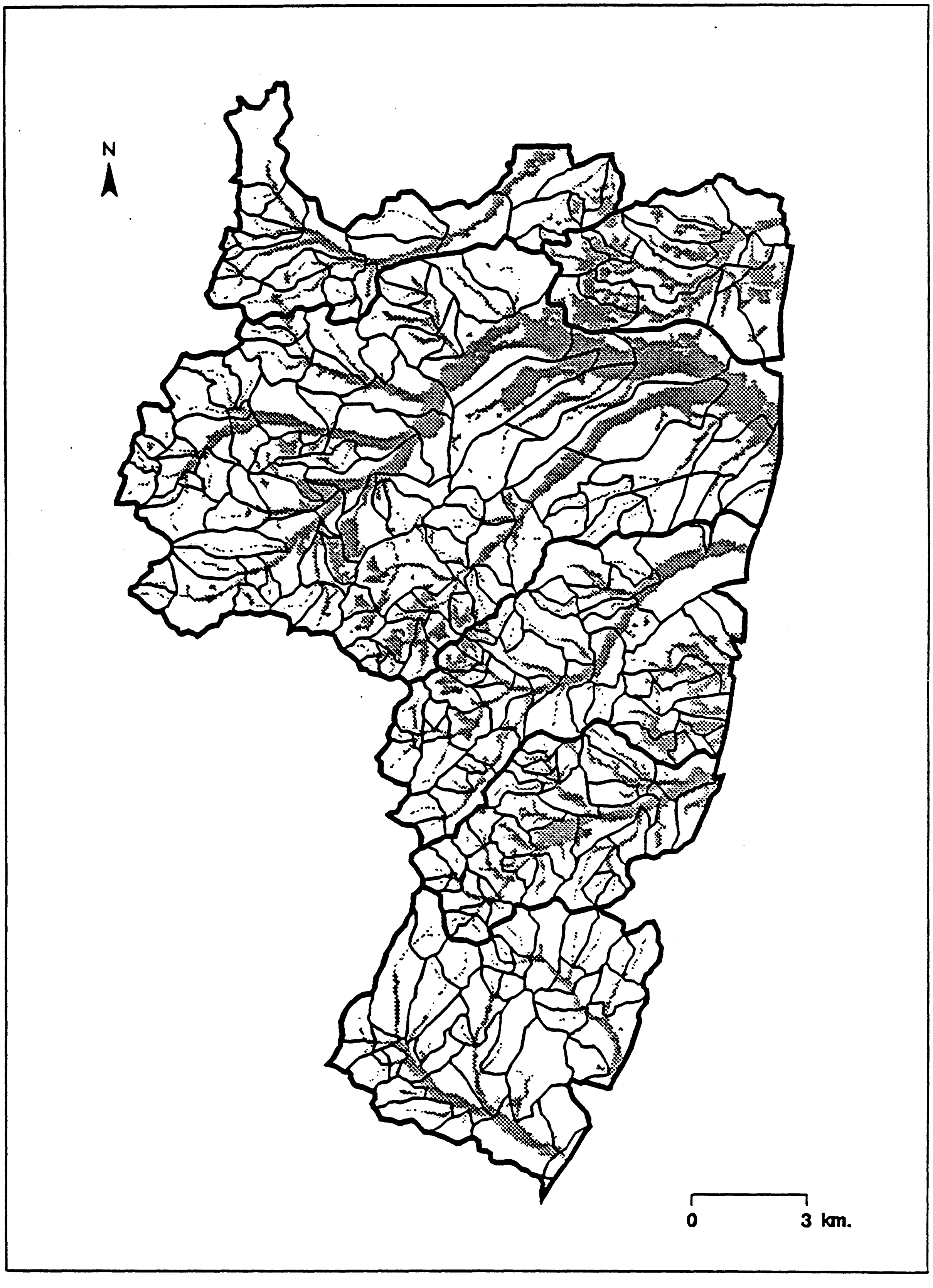


Figure 11. Wetlands.

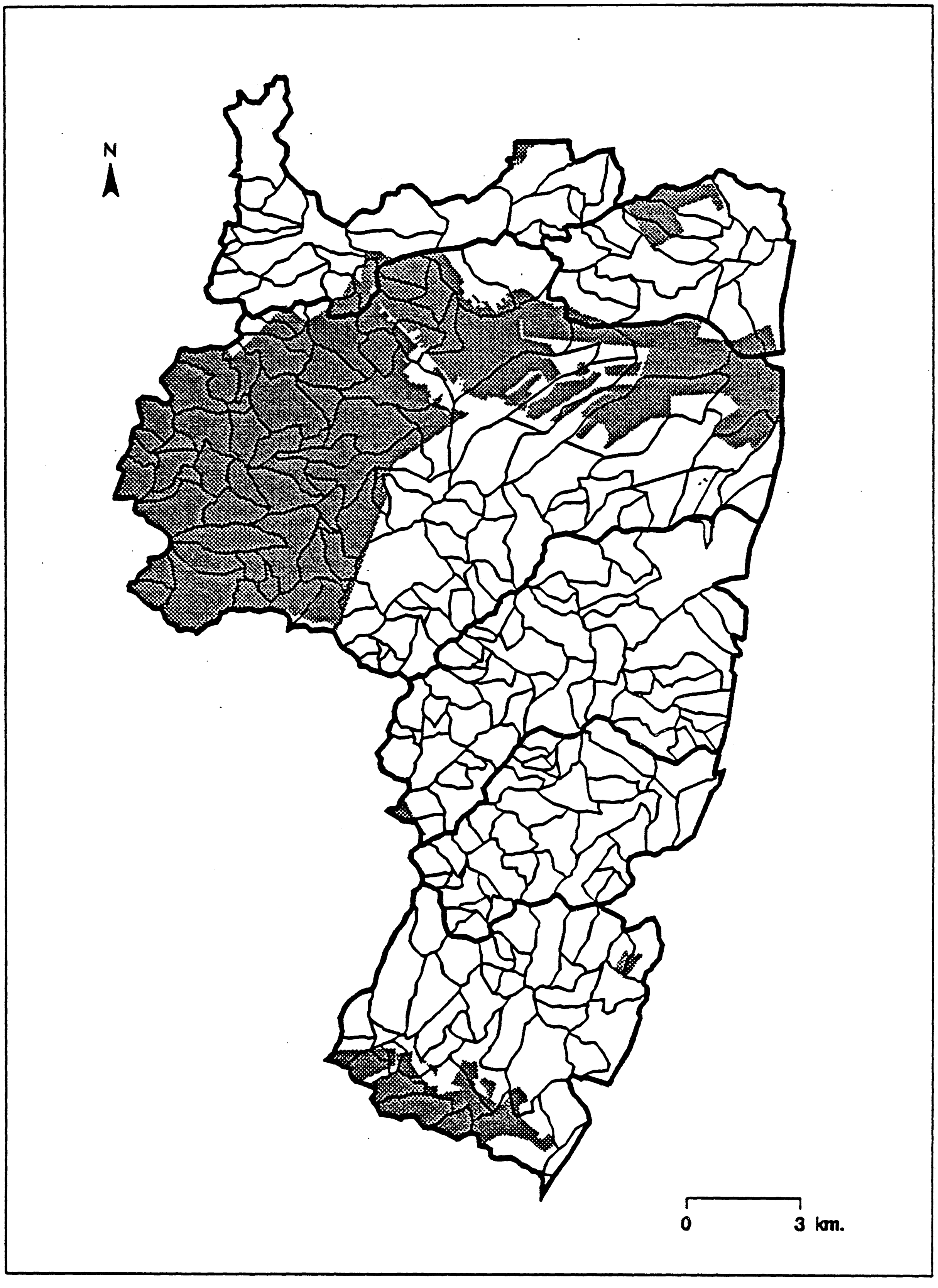


Figure 12. Public open space.

Creek station (OCN054) is located directly below a landfill and the confluence of a heavily developed tributary basin, it does not adequately reflect undeveloped conditions found in the upper reaches of the drainage system.

Table 23. Water quality characteristics of study area streams (1991-1993).

Stream	Station No.	Median Values				
		pH	NO_3-N	NH_3-N	P	Spec.Cond.
Cedar Creek	OCN045	4.7	<0.10	<0.10	<0.02	28
Cedar Creek	OCN044	4.6	<0.10	<0.10	<0.02	32
Davenport	PTR10	4.4	<0.10	<0.10	<0.02	42
Forked River	PFR4A	4.3	<0.10	<0.10	<0.02	41
Factory Branch	PCC2	4.2	<0.10	<0.10	<0.02	42
Mill Creek	OCN054	5.8	<0.10	0.31	<0.02	48
Oyster Creek	OCN051	4.5	<0.10	<0.10	<0.02	38
Four Mile Branch	PM16	4.9	0.24	<0.10	<0.02	43
Jakes Branch	OCNO32	4.3	<0.10	<0.10	<0.02	41

The NJ Heritage Program provided species occurrence information for threatened and endangered species by drainage drainage unit. During 1993 and 1994 we conducted a Pine Barrens treefrog survey within the study area and added the results to the inventory obtained from the Heritage Program (Table 24). Because New Jersey freshwater wetlands maps were not available for the entire study area, we used cedar data obtained through interpretation of Landsat TM imagery (Lathrop 1994). Cedar polygons were verified using 1:40,000 scale infrared photography flown in 1991. Ephemeral ponds were mapped using 1:12,000 scale true color photography flown in 1978 and 1979. The center point of each pond was digitized.

Due to the extensive data set used to evaluate the 284 separate drainage units, we cannot present all the information on which watershed integrity and potential impact scores are based. Major results are summarized in graphic and tabular form.

Results of the Watershed Integrity and Potential Impact Evaluations

The Forked River, Jakes Branch, Oyster Creek, and Cedar Creek basins display the highest watershed integrity scores and the lowest potential impact scores (Plates 4 and 5, Tables 25-27). The lower potential impact scores associated with the Cedar Creek basin are due both to its designation as Preservation Area District and the extensive public land holding located within its boundaries. However, these low scores belie the potential for surface mining on private lands within the basin. Watershed integrity scores displayed by the Forked River and Jakes Branch basins are generally higher than those of Cedar Creek. The slightly higher potential impact scores reflect their Forest Area designation. Of the four high quality basins, the greatest disparity between watershed integrity and potential impacts is found in the Oyster Creek watersheds. This is due to the predominance of Rural Development Area within its boundaries.

The widest range of watershed integrity and potential impact scores is found in the Davenport Branch and Mill Creek watersheds. The lower watershed integrity scores clearly reflect the greater amount of development that exists within these basins. Because of the mix of developed and undeveloped lands within these basins, there are local inconsistencies between watershed integrity and land management designations.

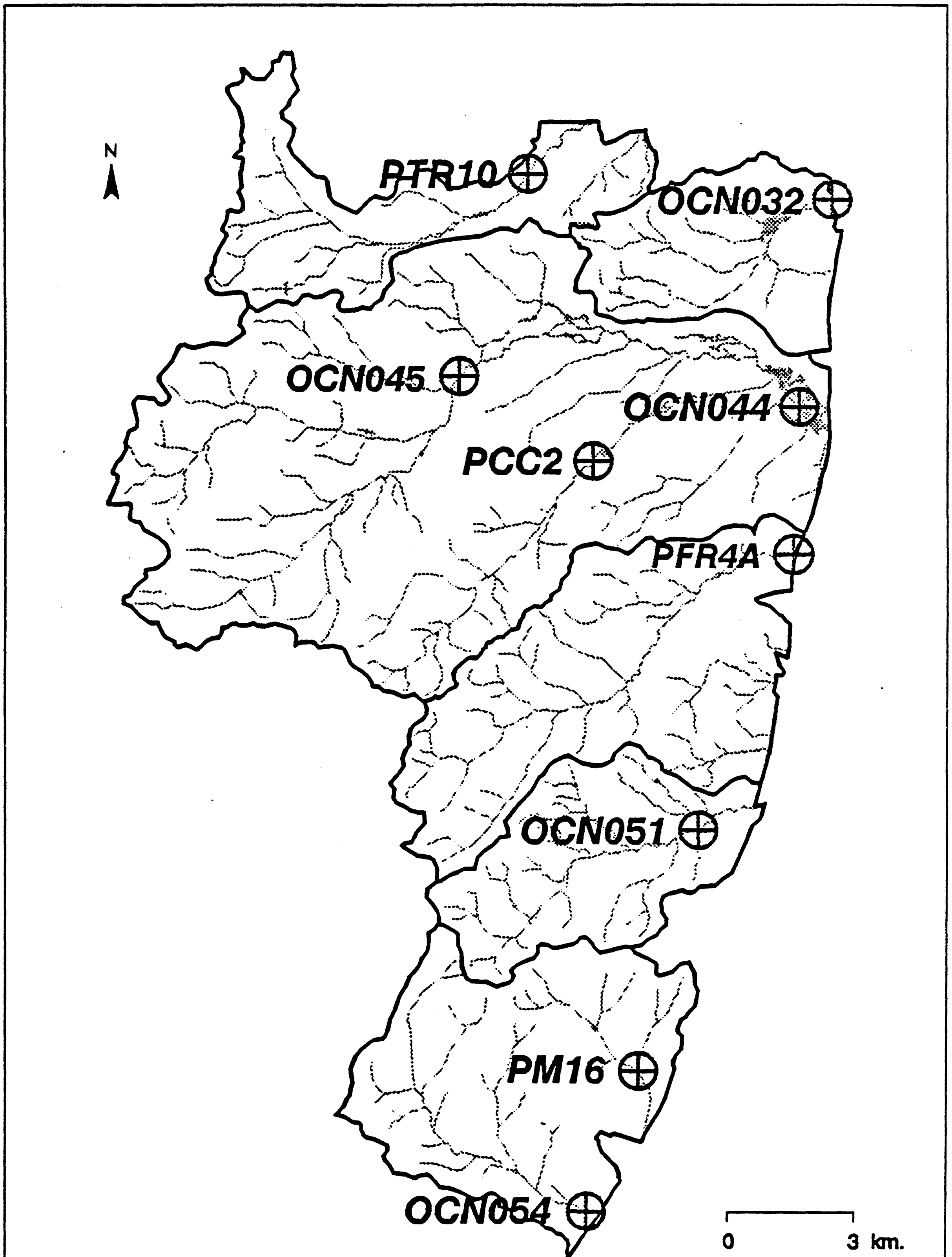


Figure 13. Surface water quality stations.

Table 24. Number of drainage units within major watersheds with threatened or endangered species occurrences. Unless noted, data are from the NJ Natural Heritage database.

Common name	Species	Watersheds (2)					
		DVP	JKE	CDR	FRK	OYS	MIL
pine barrens treefrog	*Hyla andersonii*	3	3	6	1	3	-
pine barrens treefrog (1)	*Hyla andersonii*	9	4	10	3	4	1
cooper's hawk	*Accipiter cooperii*	7	-	-	-	-	-
barred owl	*Strix varia*	-	-	-	3	-	-
wood turtle	*Clemmys insculpta*	2	-	-	-	-	-
timber rattlesnake	*Crotalus horridus horridus*	16	-	47	-	-	-
pine barrens gentian	*Gentiana autumnalis*	-	-	-	1	-	-
Barratt's sedge	*Carex barrattii*	1	-	-	-	-	-
Knieskern's beaked rush	*Rhynchospora knieskernii*	3	-	-	1	-	7
New Jersey rush	*Juncus caesariensis*	-	-	1	2	-	-
swamp-pink	*Helonias bullata*	-	-	1	1	-	7
pine barrens reedgrass	*Calamovilfa brevipilis*	1	-	1	2	-	-
pine barrens smoke grass	*Muhlenbergia torreyana*	-	-	-	2	-	-
curly grass fern	*Schizaea pusilla*	-	-	2	-	-	2

(1) Heritage data plus Pinelands Commission surveys.
(2) Codes for watershed abbreviations:

Davenport Branch: DVP
Jakes Branch: JKE
Cedar Creek: CDR
Forked River: FRK
Oyster Creek: OYS
Mill Creek: MIL

Table 25. Percentage of total area within each major watershed assigned various watershed integrity and potential impact scores.

Watershed Integrity Score

	Low									High
Watershed	1-1.9	2-2.9	3-3.9	4-4.9	5-5.9	6-6.9	7-7.9	8-8.9	9-9.9	10+
Davenport Branch	-	-	-	13	2	4	19	15	18	28
Jakes Branch	-	-	-	-	-	-	-	8	40	53
Cedar Creek	-	-	-	-	-	3	3	13	35	46
Forked River	-	-	-	-	-	-	-	-	24	76
Oyster Creek	-	-	-	-	-	-	3	5	46	47
Mill Creek	-	-	-	-	3	16	19	22	16	24

Potential Impact Score

	Low									High
Watershed	1-1.9	2-2.9	3-3.9	4-4.9	5-5.9	6-6.9	7-7.9	8-8.9	9-9.9	10+
Davenport Branch	4	8	25	2	16	5	3	21	15	-
Jakes Branch	-	41	57	-	-	-	-	-	-	-
Cedar Creek	75	25	-	-	-	-	-	-	-	-
Forked River	-	40	60	-	-	-	-	-	-	-
Oyster Creek	-	-	27	36	37	-	-	-	-	-
Mill Creek	9	11	18	7	1	5	3	20	26	1

Table 26. Percentage of total wetland area within each major watershed assigned various watershed integrity and potential impact scores.

Watershed Integrity Score

	Low									High
Watershed	1-1.9	2-2.9	3-3.9	4-4.9	5-5.9	6-6.9	7-7.9	8-8.9	9-9.9	10+
Davenport Branch	-	-	-	2	<1	4	22	20	30	21
Jakes Branch	-	-	-	-	-	-	-	2	33	65
Cedar Creek	-	-	-	-	-	<1	<1	13	48	39
Forked River	-	-	-	-	-	-	-	-	24	76
Oyster Creek	-	-	-	-	-	-	2	3	64	32
Mill Creek	-	-	-	-	<1	6	14	40	26	13

Potential Impact Score

	Low									High
Watershed	1-1.9	2-2.9	3-3.9	4-4.9	5-5.9	6-6.9	7-7.9	8-8.9	9-9.9	10+
Davenport Branch	3	6	16	4	26	13	2	23	6	-
Jakes Branch	-	46	51	-	-	-	-	3	-	-
Cedar Creek	84	16	-	-	-	-	-	-	-	-
Forked River	-	35	65	-	-	-	-	-	-	-
Oyster Creek	-	-	25	47	28	-	-	-	-	-
Mill Creek	4	24	10	18	1	7	<1	13	22	<1

Table 27. Percentage of total wetland perimeter within each major watershed assigned various watershed integrity and potential impact scores.

Watershed Integrity Score

	Low									High
Watershed	1-1.9	2-2.9	3-3.9	4-4.9	5-5.9	6-6.9	7-7.9	8-8.9	9-9.9	10+
Davenport Branch	-	-	-	3	1	5	21	19	18	33
Jakes Branch	-	-	-	-	-	-	-	3	32	65
Cedar Creek	-	-	-	-	-	1	2	12	34	52
Forked River	-	-	-	-	-	-	-	-	17	83
Oyster Creek	-	-	-	-	-	-	-	-	-	-
Mill Creek	-	-	-	-	-	-	-	-	-	-

Potential Impact Score

	Low									High
Watershed	1-1.9	2-2.9	3-3.9	4-4.9	5-5.9	6-6.9	7-7.9	8-8.9	9-9.9	10+
Davenport Branch	4	4	27	3	16	6	4	24	5	-
Jakes Branch	-	38	59	-	-	-	-	4-	-	-
Cedar Creek	73	27	-	-	-	-	-	-	-	-
Forked River	-	33	67	-	-	-	-	-	-	-
Oyster Creek	-	-	23	35	42	-	-	-	-	-
Mill Creek	10	15	19	7	1	8	1	15	24	1

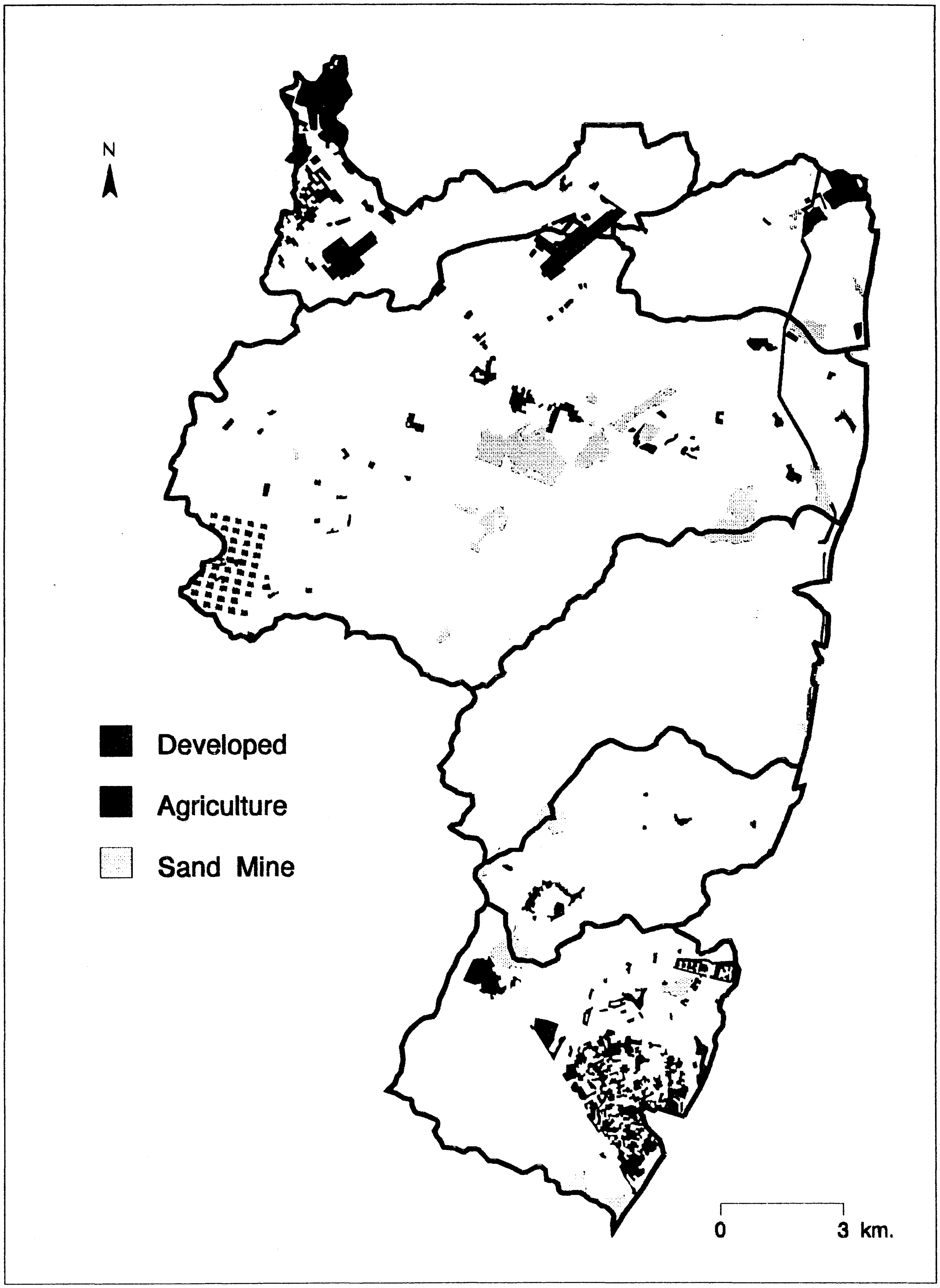


Plate 1. Altered Land

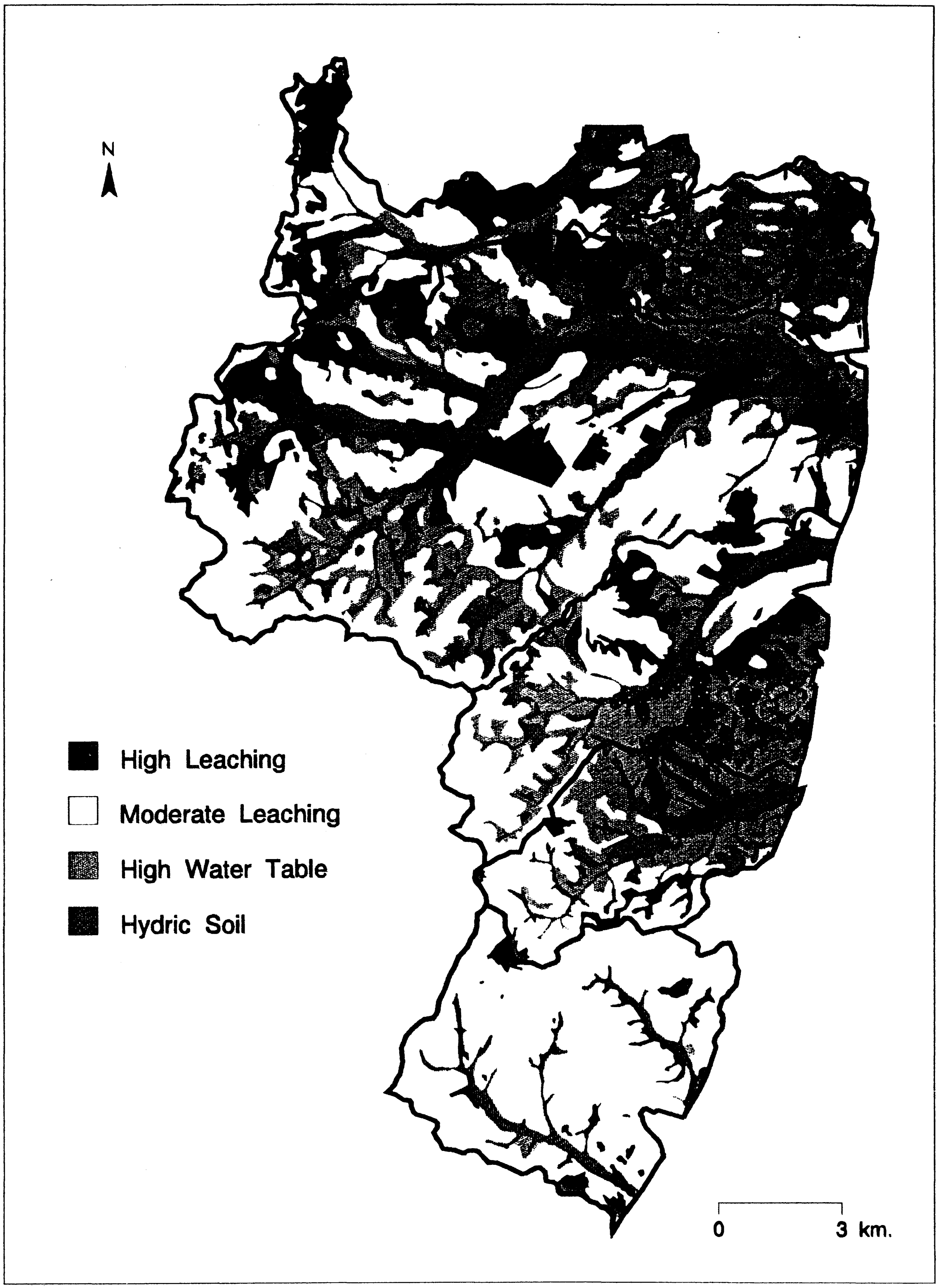


Plate 2. Groundwater Contamination Potential

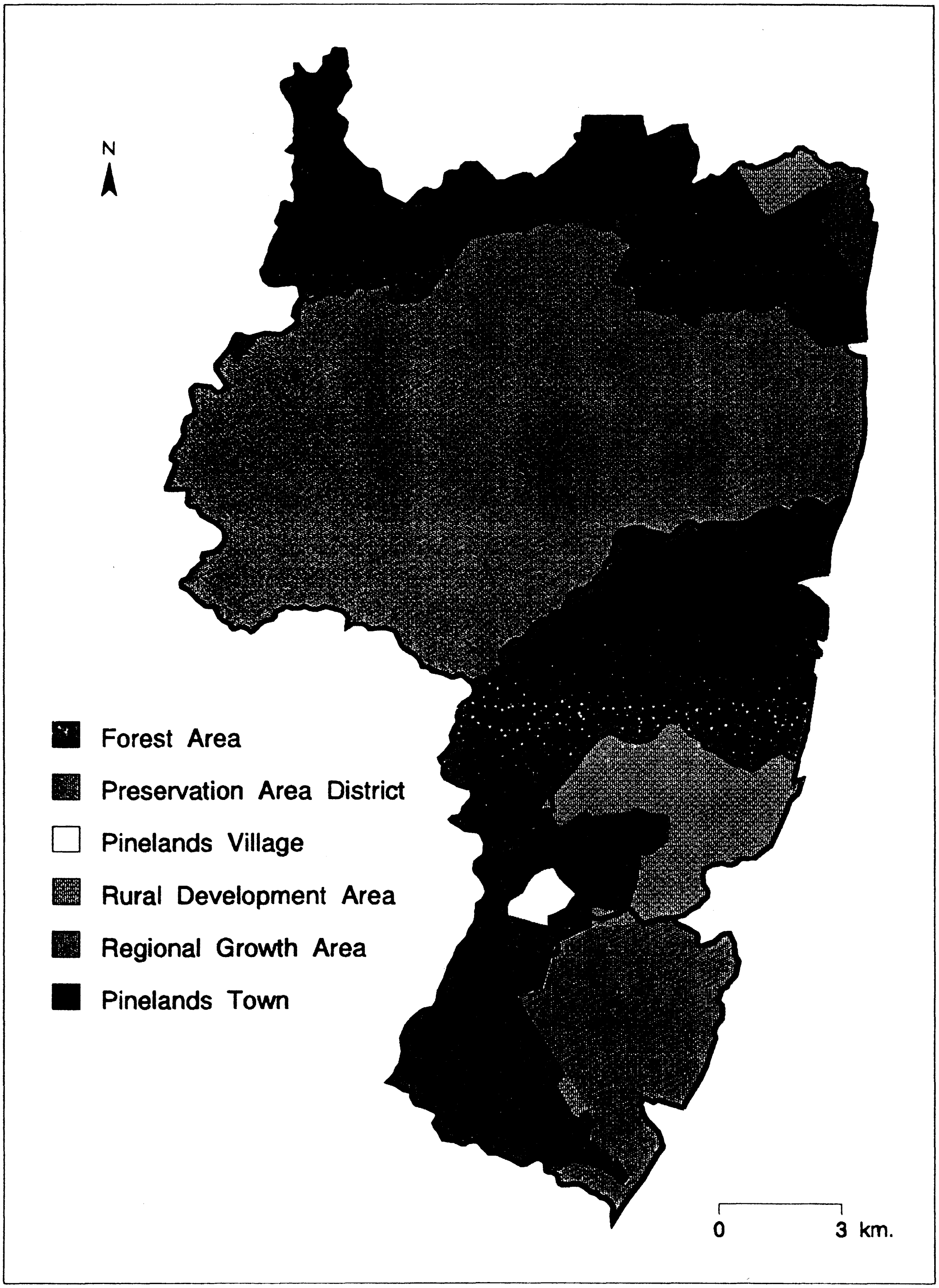


Plate 3. Pinelands Management Areas

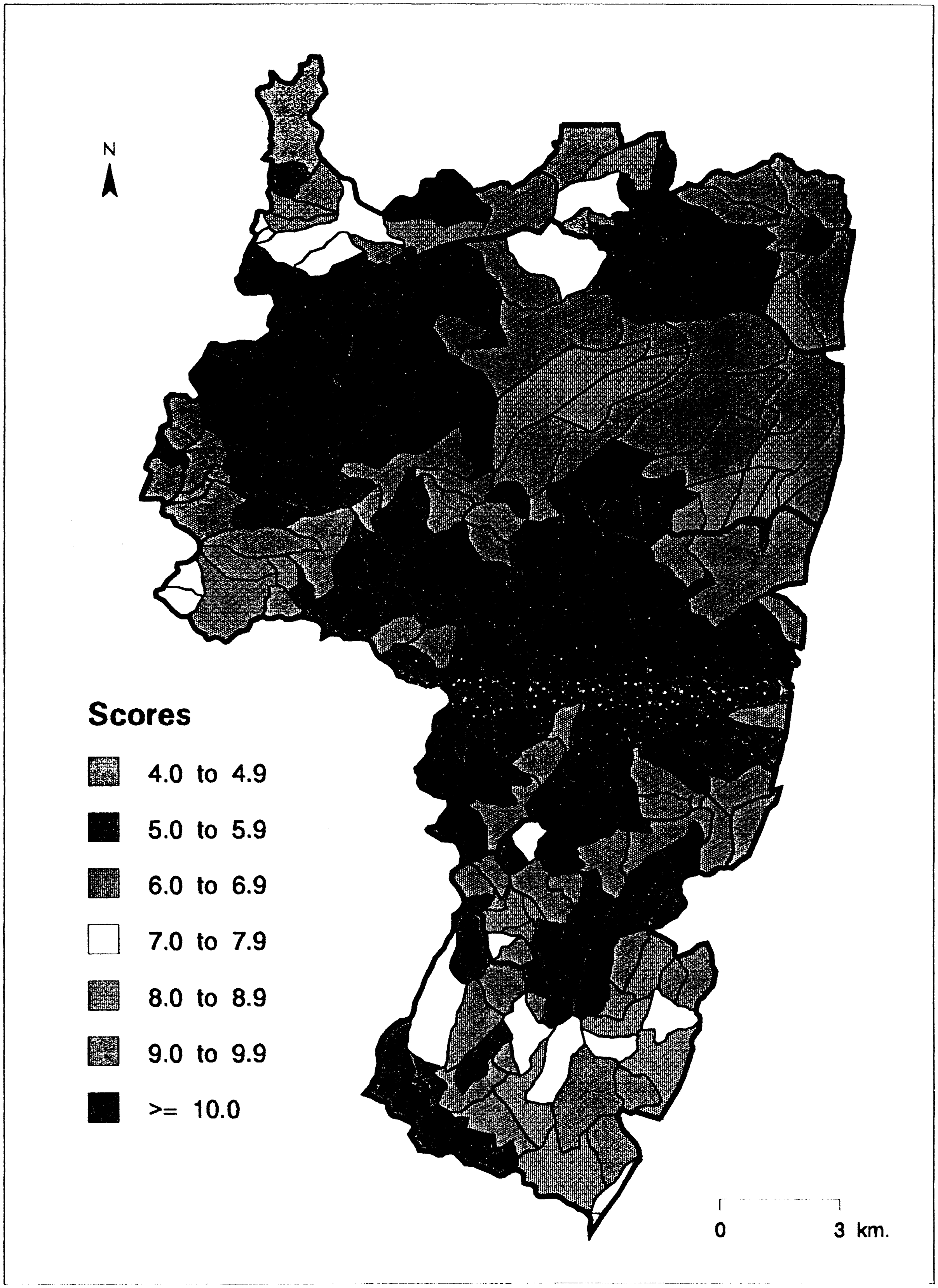


Plate 4. Watershed Integrity Evaluation

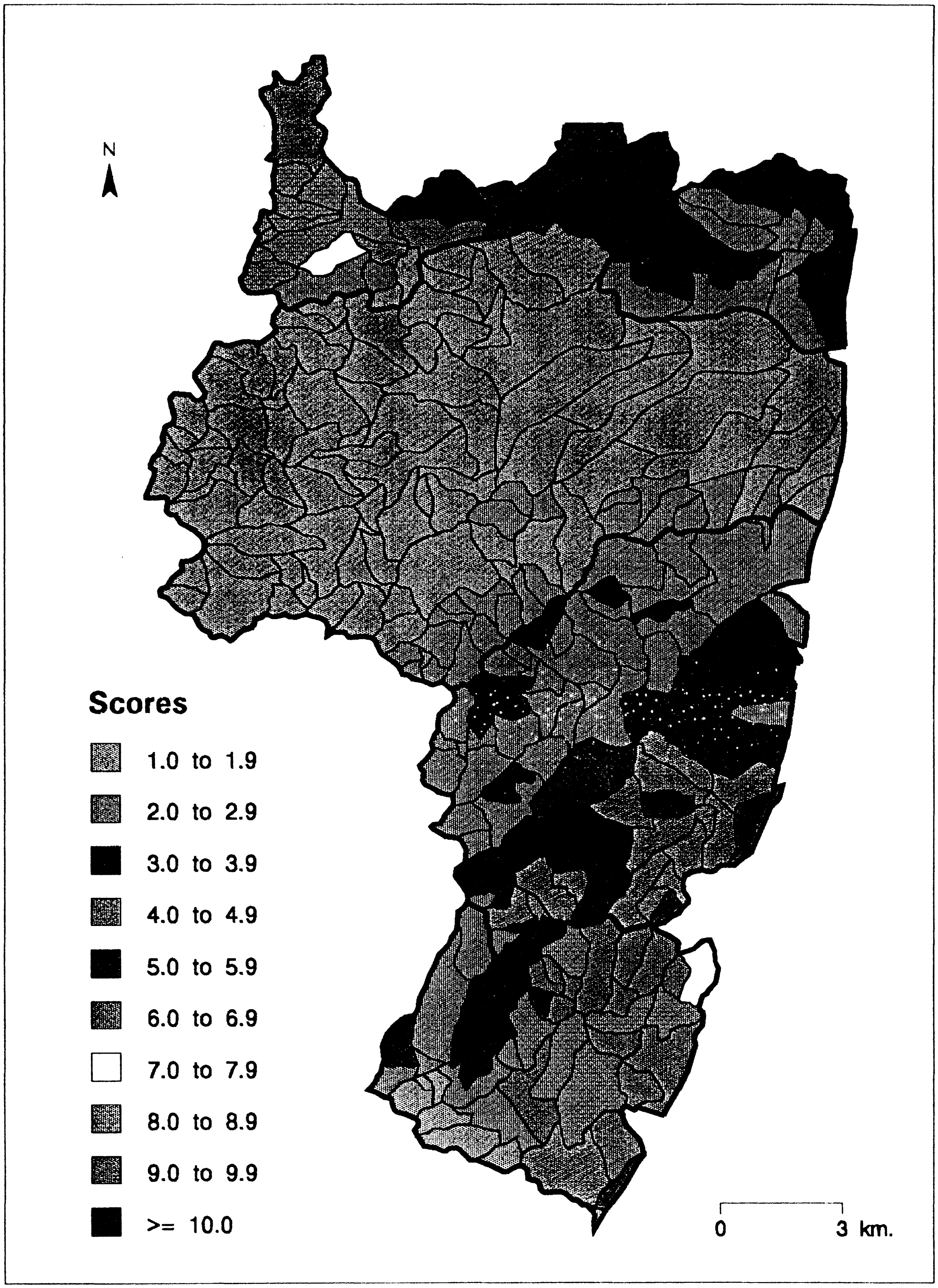


Plate 5. Potential Impact Evaluation

LITERATURE CITED

Aldrich, J. W., and R. W. Coffin. 1980. Breeding bird populations from forest to suburbia after thirty-seven years. American Birds 34:3-7.

Ambuel, B., and S. A. Temple. 1982. Songbird populations in southern Wisconsin forests: 1954 and 1979. Journal of Field Ornithology 53:149-158.

Ambuel, B., and S. A. Temple. 1983. Area-dependent changes in the bird communities and vegetation of southern Wisconsin forests. Ecology 64:1057-1068.

Anderson, J. R., E. E. Hardy, J. T. Roach, and R. E. Witmer. 1976. A land use and land cover classification system for use with remote sensor data. U.S. Geological Survey Professional Paper 964.

Anderson, L. T. 1987. Seven methods for calculating land capability/suitability. American Planning Association, Chicago, Illinois.

Andren, H. and P. Angelstam. 1988. Elevated predation rates as an edge effect in habitat islands: experimental evidence. Ecology 69:544-547.

Ballard, J. T. 1979. Fluxes of water and energy through the Pine Barrens Ecosystems. Pages 133-146 *in* R. T. T. Forman, editor. Pine Barrens: ecosystem and landscape. Academic Press, New York.

Bernard, J. M. 1963. Lowland forests of the Cape May Formation in southern New Jersey. Bulletin of the New Jersey Academy of Science 8:1-12.

Blake, J. G., and J. R. Karr. 1984. Species composition of bird communities and the conservation benefit of large versus small forests. Biological Conservation 30:173-187.

Böhning-gaese, K., M. L. Taper, and J. H. Brown. 1993. Are declines in North American insectivorous songbirds due to causes on the breeding range? Conservation Biology 7:76-86.

Breden, T. F., J. E. Saks, and J. Schooley. 1990. Attaching the New Jersey Natural Heritage Program database to a geographic information system. Pages 122-124 *in* R. S. Mitchell, C. J. Sheviak and D. J. Leopold, editors. Ecosystem management: rare species and significant habitats. New York State Museum Bulletin 471. New York State Museum, Albany, New York.

Brittingham, M. C., and S. A. Tempel. 1983. Have cowbirds caused forest songbirds to decline? BioScience 33:31-35.

Brush, T. 1987. Birds of the central Pine Barrens: abundance and habitat use. Bulletin of the New Jersey Academy of Science 32:5-17.

Buchholz, K., and R. E. Good. 1982. Compendium of New Jersey Pine Barrens literature. Division of Pinelands Research, Center for Coastal and Environmental Studies, Rutgers University, New Brunswick, New Jersey.

Buchholz, K., and R. A. Zampella. 1987. A 30-year fire history of the New Jersey Pine Plains. Bulletin of the New Jersey Academy of Science 32:61-69.

Buhlmann, K. A., J. C. Mitchell, and C. A. Paque. 1993. Amphibian and small mammal abundance and diversity in saturated forested wetlands and adjacent uplands of southeastern Virginia. Pages 1-7 *in* S. D. Eckles, A. Jennings, A. Spingarn and C. Wienhold, editors. Proceedings of a workshop on saturated forested wetlands in the Mid-Atlantic Region: the state of the science. U.S. Fish and Wildlife Service, Annapolis, Maryland.

Butcher, G. S., W. A. Niering, W. J. Barry, and R. H. Goodwin. 1981. Equilibrium biogeography and the size of nature preserves: an avian case study. Oecologia 49:29-37.

Cahill Associates. 1989. Stormwater management in the New Jersey Coastal Zone. Division of Coastal Resources, New Jersey Department of Environmental Protection, Trenton, New Jersey.

Cantor, L. W., and R. C. Knox. 1985. Septic tank system effects on ground water quality. Lewis Publishers, Inc., Chelsea, Michigan.

Christensen, N. L. 1988. Vegetation of the Southeastern Coastal Plain. Pages 317-363 *in* North American terrestrial vegetation. Cambridge University Press, Cambridge, England.

Clawges, R. M., and E. O. Titus. 1993. Method for predicting water demand for crop uses in New Jersey in 1990, 2000, 2010, and 2020, and for estimating water use for livestock and selected sectors of the food-processing industry in New Jersey in 1987. U.S. Geological Survey Water-Resources Investigations Report 92-4145.

Collins, B. R., and E. W. B. Russell. 1988. Protecting the New Jersey Pinelands. Rutgers University Press, New Brunswick, New Jersey.

Conant, R. 1979. A zoogeographical review of the amphibians and reptiles of southern New Jersey, with emphasis on the Pine Barrens. Pages 467-488 *in* R. T. T. Forman, editor. Pine Barrens: ecosystem and landscape. Academic Press, New York.

Craig, L. J. and D.S. Dobkin. 1993. Community dynamics of small mammals in mature and logged Atlantic white cedar swamps of the New Jersey Pine Barrens. New York State Museum Bulletin No. 487. The University of the State of New York, Albany, New York.

Dougherty, J. E., and M. D. Morgan. 1991. Benthic community response (primarily Chironomidae) to nutrient enrichment and alkalinization in shallow, soft water humic lakes. Hydrobiologia 215:73-82.

Dowdell, J., and C. Sutton. 1993. The status and distribution of breeding red-shouldered hawks in southern New Jersey. Records of New Jersey Birds 19:6-9.

Ehrenfeld, J. G. 1983. The effects of changes in land-use on swamps of the New Jersey Pine Barrens. Biological Conservation 25:353-375.

Ehrenfeld, J. G. 1986. Wetlands of the New Jersey Pine Barrens: the role of species composition in community function. The American Midland Naturalist 115:301-313.

Ehrenfeld, J. G., and M. Gulick. 1981. Structure and dynamics of hardwood swamps in the New Jersey Pine Barrens: contrasting patterns in trees and shrubs. American Journal of Botany 68:471-481.

Ehrenfeld, J. G., and J. P. Schneider. 1991. *Chamaecyparis thyoides* wetlands and suburbanization: effects on hydrology, water quality and plant community composition. Journal of Applied Ecology 28:467-490.

Ehrlich, P. R., and G. C. Daily. 1993. Science and the management of natural resources. Ecological Applications 3:558-560.

Fairbrothers, D. E. 1979. Endangered, threatened, and rare vascular plants of the Pine Barrens and their biogeography. Pages 395-405 *in* R. T. T. Forman, editor. Pine Barrens: ecosystem and landscape. Academic Press, New York.

Forester, D. C. 1993. The importance of saturated wetlands to the perpetuation of amphibian populations. Pages 16-23 *in* S. D. Eckles, A. Jennings, A. Spingarn and C. Wienhold, editors. Proceedings of a workshop on saturated forested wetlands in the Mid-Atlantic Region: the state of the science. U.S. Fish and Wildlife Service, Annapolis, Maryland.

Forman, R. T. T., and R. E. Boerner. 1981. Fire frequency and the Pine Barrens of New Jersey. Bulletin of the Torrey Botanical Club 108:34-50.

Forman, R. T. T., and M. Godron. 1986. Landscape ecology. John Wiley & Sons, New York.

Forman, R. T. T., A. E. Galli, and C. F. Leck. 1976. Forest size and avian diversity in New Jersey woodlots with some land use implications. Oecologia 26:1-8.

Franklin, J. F. 1993. Preserving biodiversity: species, ecosystems, or landscapes? Ecological Applications 3:202-205.

Freda, J., and W. A. Dunson. 1986. Effects of low pH and other chemical variables on the local distribution of amphibians. Copeia 86:454-466.

Freda, J., and R. J. Gonzalez. 1986. Daily movements of the treefrog, *Hyla andersoni*. Journal of Herpetology 20:469-471.

Freda, J., and P. J. Morin. 1984. Adult home range of the Pine Barrens Treefrog (*Hyla andersonii*) and the physical, chemical, and ecological characteristics of its preferred breeding ponds. Center for Coastal and Environmental Studies, Rutgers, the State University of New Jersey, New Brunswick, New Jersey.

Fusillo, T. V. 1981. Impact of suburban residential development on water resources in the area of Winslow Township, Camden County, New Jersey. U.S. Geological Survey Water-Resources Investigation 81-27. U.S. Geological Survey, Trenton, New Jersey.

Gemmell, D. J., N. F. Good, and R. E. Good. 1989. Compendium II New Jersey Pine Barrens literature. Division of Pinelands Research, Center for Coastal and Environmental Studies, Rutgers, The State University, New Brunswick, New Jersey.

Gibson, D. J., S. L. Collins, and R. E. Good. 1988. Ecosystem fragmentation of oak-pine forest in the New Jersey Pinelands. Forest Ecology and Management 25:105-122.

Good, R. E., N. F. Good, and J. W. Andresen. 1979. The Pine Barren Plains. Pages 283-295 *in* R. T. T. Forman, editor. Pine Barrens: ecosystem and landscape. Academic Press, New York.

Gosner, K. L., and I. H. Black. 1957. The effects of acidity on the development and hatching of New Jersey frogs. Ecology 38:256-262.

Goss, D. 1988. Pesticide-soil interaction: potentials for loss, original method, 1988. National Soil Survey, Soil Conservation Service, Lincoln, Nebraska.

Gosselink, J. G., G. P. Shaffer, L. C. Lee, D. M. Burdick, D. L. Childers, N. C. Leibowitz, S. C. Hamilton, R. Boumans, D. Cushman, S. Fields, M. Kock, and J. M. Visser. 1990. Landscape conservation in a forested wetland watershed. BioScience 40:588-600.

Graham, J. H., and R. W. Hastings. 1984. Distributional patterns of sunfishes on the New Jersey coastal plain. Environmental Biology of Fishes 10:137-148.

Hall, G. A. 1984. Population decline of neotropical migrants in an Appalachian forest. American Birds 38:14-18.

Hammer, T. R. 1976. Planning methodologies for analysis of land use/water quality relationships. U.S. Environmental Protection Agency, Washington, D. C.

Harlukowicz, T. J., and R. C. Ahlert. 1978. Effects of septic tank effluent on groundwater quality in the New Jersey Pine Barrens. Final report to the Rockefeller Foundation. College of Engineering, Bureau of Engineering Research, Rutgers University, New Brunswick, New Jersey.

Hastings, R. W. 1984. The fishes of the Mullica River, a naturally acid water system of the New Jersey Pine Barrens. Bulletin of the New Jersey Academy of Science 29:9-23.

Hemond, H. F., and J. Benoit. 1988. Cumulative impacts on water quality functions of wetlands. Environmental Management 12:639-653.

Hilborn, R., and D. Ludwig. 1993. The limits of applied ecological research. Ecological Applications 3:550-552.

Howe, R. W. 1984. Local dynamics of bird assemblages in small forest habitat islands in Australia and North America. Ecology 65:1585-1601.

Hughes, R. M., D. P. Larsen, and J. M. Omernik. 1986. Regional reference sites: a method for assessing stream pollution. Environmental Management 10:629-635.

Hunsaker, C. T., R. L. Graham, G. W. Suter II, R. V. O'Neill, L. W. Barnthouse, and R. H. Gardner. 1990. Assessing ecological risk on a regional scale. Environmental Management 14:325-332.

Jacobs, T. C., and J. W. Gilliam. 1985. Riparian losses of nitrate from agricultural drainage waters. Journal of Environmental Quality 14:472-478.

Johnsson, P. A., and J. L. Barringer. 1993. Water quality and hydrogeochemical processes in McDonalds Branch Basin, New Jersey, 1984-1988. U.S. Geological Survey Water-Resources Investigations Report 91-4081. U.S. Geological Survey, West Trenton, New Jersey.

Johnston, C. A., N. E. Detenbeck, and G. J. Niemi. 1990. The cumulative effect of wetlands on stream water quality and quantity: a landscape approach. Biogeochemistry 10:105-141.

Karalus, K. E., and A. W. Eckert. 1973. The owls of North America. Weathervane Books, New York.

Keller, C. M. E., C. S. Robbins, and J. S. Hatfield. 1993. Avian communities in riparian forests of different widths in Maryland and Delaware. Wetlands 13:137-144.

Kerlinger, P. 1984. Avian community structure along a successional gradient in the New Jersey Pine Barrens. Records of New Jersey Birds 9:71-78.

Kerlinger, P., and C. Doremus. 1981. Habitat disturbance and the decline of dominant avian species in pine barrens of the northeastern United States. American Birds 35:16-20.

Konikow, L. F., and J. D. Bredehoeft. 1978. Computer model of two-dimensional solute transport in ground water. Book I, Chapter 2 *in* Techniques of water-resources investigations of the United States Geological Survey. U.S. Geological Survey, Washington, D.C.

Kusler, J. A. 1986. Wetland assessment: the regulator's perspective. Pages 2-8 *in* J. A. Kusler and P. Riexinger, editors. Proceedings of the National Wetlands Assessment Symposium. Association of State Wetland Managers, Chester, Virginia.

Laidig, K. J. 1992. Population survey, habitat associations and vocalization analyses of barred owls in southern New Jersey. M.S. Thesis. Rutgers, The State University of New Jersey, Camden, New Jersey.

Lambou, V. W., J. M. Kuperberg, J. E. Moerlins, R. C. Herndon, and R. L. Gebhard. 1990. Proximity of sanitary landfills to wetlands and deepwater habitats: an evaluation and comparison of 1,153 sanitary landfills in 11 states. EPA/600/S4-90/012.

Lang, S. M., and E. C. Rhodehamel. 1963. Aquifer test at a site on the Mullica River in the Wharton Tract, southern New Jersey. Bulletin of the International Association of Scientific Hydrology 8:31-38.

Lathrop, R. G. 1994. Satellite remote sensing of Pinelands ecosystems. Bartonia 58:1-9.

Leck, C. F. 1979. Birds of the Pine Barrens. Pages 457-466 *in* R. T. T. Forman, editor. Pine Barrens: ecosystem and landscape. Academic Press, New York.

Leck, C. F. 1984. The status and distribution of New Jersey's birds. Rutgers University Press, New Brunswick, New Jersey.

Lee, L. C., and J. G. Gosselink. 1988. Cumulative impacts on wetlands: linking scientific assessments and regulatory alternatives. Environmental Management 12:591-602.

Lee, R. G., R. Flamm, M. G. Turner, C. Bledsoe, P. Chandler, C. DeFerrari, R. Gottfried, R. J. Naiman, N. Schumaker, and D. Wear. 1992. Integrating sustainable development and environmental vitality: a landscape ecology approach. Pages 499-521 *in* R. J. Naiman, editor. Watershed management: balancing sustainability and environmental change. Springer-Verlag, New York, New York.

Leibowitz, S. G., B. Abbruzzese, P. R. Adamus, L. E. Hughes, and J. T. Irish. 1992. A synoptic approach to cumulative impact assessment. U.S. Environmental Protection Agency, Corvallis, Oregon.

Little, S. 1950. Ecology and silviculture of white cedar and associated hardwoods in southern New Jersey. Yale University School of Forestry Bulletin 56:1-103.

Little, S. 1951. Observations on the minor vegetation of the Pine Barrens swamps in southern New Jersey. Bulletin of the Torrey Botanical Club 78:153-160.

Little, S. 1979. Fire and plant succession in the New Jersey Pine Barrens. Pages 297-314 *in* R. T. T. Forman, editor. Pine Barrens: ecosystem and landscape. Academic Press, New York.

Lord, D. G., J. L. Barringer, P. A. Johnsson, P. F. Schuster, R. L. Walker, J. E. Fairchild, B. N. Sroka, and E. Jacobsen. 1990. Hydrogeological data from an acidic deposition study at McDonalds Branch basin in the New Jersey Pinelands, 1983-86. U.S. Geological Survey Open-file Report 88-500. U.S. Geological Survey, West Trenton, New Jersey.

Louis, J., and E. Vowinkel. 1989. Effects of agricultural chemicals on groundwater quality in the New Jersey coastal plain. Pages 80-89 *in* D. L. Weigmann, editor. Pesticides in terrestrial and aquatic environments: proceedings of a National Research Conference. Virginia Water Resources Research Center, Virginia Polytechnic Institute and State University, Blacksburg, Virginia.

Lubchenco, J., A. M. Olson, L. B. Brubaker, S. R. Carpenter, M. M. Holland, S. P. Hubbell, S. A. Levin, J. A. MacMahon, P. A. Matson, J. M. Melillo, H. A. Mooney, C. H. Peterson, H. R. Pulliam, L. A. Real, P. J. Regal, and P. G. Risser. 1991. The sustainable biosphere initiative: an ecological research agenda. Ecology 72:371-412.

Malanson, G. P. 1993. Riparian landscapes. Cambridge University Press, Cambridge, England.

Mangel, M., R. J. Hofman, E. A. Norse, and J. R. Twiss Jr. 1993. Sustainability and ecological research. Ecological Applications 3:573-575.

McCormick, J. 1970. The Pine Barrens: a preliminary ecological inventory. Research Report No. 2. New Jersey State Museum, Trenton, New Jersey.

McCormick, J. 1979. The vegetation of the New Jersey Pine Barrens. Pages 229-243 *in* R. T. T. Forman, editor. Pine Barrens: ecosystem and landscape. Academic Press, New York.

Mitsch, W. J., and J. G. Gosselink. 1993. Wetlands, 2nd Edition. Van Nostrand Reinhold, New York.

Morgan, M. D. 1985. Photosynthetically elevated pH in acid waters with high nutrient content and its significance for the zooplankton community. Hydrobiologia 128:239-247.

Morgan, M. D. 1986. The effect of altered pH on zooplankton community structure in a disturbed New Jersey Pine Barrens pond. Journal of Freshwater Ecology 3:467-476.

Morgan, M. D. 1987. Impact of nutrient enrichment and alkalinization on periphyton communities in the New Jersey Pine Barrens. Hydrobiologia 144:233-241.

Morgan, M. D., and R. E. Good. 1988. Stream chemistry in the New Jersey Pinelands: the influence of precipitation and watershed disturbance. Water Resources Bulletin 24:1091-1100.

Morgan, M. D., and K. R. Philipp. 1986. The effect of agricultural and residential development on aquatic macrophytes in the New Jersey Pine Barrens. Biological Conservation 35:143-158.

Muscutt, A. D., G. L. Harris, S. W. Bailey, and D. B. Davies. 1993. Buffer zones to improve water quality: a review of their potential use in UK agriculture. Agriculture, Ecosystems and Environment 45:59-77.

Naiman, R. J., H. Decamps, and M. Pollock. 1993. The role of riparian corridors in maintaining regional biodiversity. Ecological Applications 3:209-112.

Nicholls, T. H., and D. W. Warner. 1972. Barred owl habitat use as determined by radiotelemetry. Journal of Wildlife Management 36:213-224.

Olsson, H. 1979. Vegetation of the New Jersey Pine Barrens: a phytosociological classification. Pages 245-263 *in* R. T. T. Forman, editor. Pine Barrens: ecosystem and landscape. Academic Press, New York.

Omernik, J. M., A. R. Abernathy, and L. M. Male. 1981. Stream nutrient levels and proximity of agricultural and forest land to streams: some relationships. Journal of Soil and Water Conservation 36:227-231.

Osborne, L. L., and M. J. Wiley. 1988. Empirical relationships between land use/cover and stream water quality in an agricultural watershed. Journal of Environmental Management 26:9-27.

Peterjohn, W. T., and D. L. Correll. 1984. Nutrient dynamics in an agricultural watershed: observations on the role of a riparian forest. Ecology 65:1466-1475.

Phillips, P. J., J. M. Denver, R. J. Shedlock, and P. A. Hamilton. 1993. Effect of forested wetlands on nitrate concentrations in ground water and surface water on the Delmarva Peninsula. Wetlands 13:75-83.

Pinelands Commission. 1980. New Jersey Pinelands Comprehensive Management Plan. Pinelands Commission, New Lisbon, New Jersey.

Preston, E. M., and B. L. Bedford. 1988. Evaluating cumulative effects on wetland functions: a conceptual overview and generic framework. Environmental Management 12:565-583.

Reinert, H. K., and R. T. Zappalorti. 1988a. Field observation of the association of adult and neonatal timber rattlesnakes, *Crotalus horridus*, with possible evidence for conspecific trailing. Copeia 4:1057-1059.

Reinert, H. K., and R. T. Zappalorti. 1988b. Timber rattlesnakes (*Crotalus horridus*) of the Pine Barrens: their movement and habitat preference. Copeia 4:964-978.

Rhoads, S. N. 1893. A new *Synaptomys* from New Jersey. The American Naturalist 27:53-54.

Rhoads, S. N. 1903. Mammals of Pennsylvania and New Jersey. Wickersham Printing Co., Lancaster, Pennsylvania.

Rhodehamel, E. C. 1979a. Geology of the New Jersey Pine Barrens. Pages 39-60 *in* R. T. T. Forman, editor. Pine Barrens: ecosystem and landscape. Academic Press, New York.

Rhodehamel, E. C. 1979b. Hydrology of the New Jersey Pine Barrens. Pages 147-167 *in* R. T. T. Forman, editor. Pine Barrens: ecosystem and landscape. Academic Press, New York.

Rimer, A. E., J. A. Nisson, and D. E. Reynolds. 1978. Characterization and impact of stormwater runoff from various land cover types. Journal of the Water Pollution Control Federation 50:252-264.

Risser, P. G., R. L. Burgess, R. T. T. Forman, J. Terborgh, J. A. Wiens, and R. Zampella. 1982. Ecosystem fragmentation in the Pinelands of New Jersey. Pages 5-10 *in* R. E. Good, editor. Ecological solutions to environmental management concerns in the Pinelands National Reserve: proceedings of a conference. Center for Coastal and Environmental Studies, Rutgers University, New Brunswick, New Jersey.

Robbins, C. S. 1979. Effects of forest fragmentation on breeding populations in the Piedmont of the mid-Atlantic region. Atlantic Naturalist 33:31-36.

Robbins, C. S., D. K. Dawson, and B. A. Dowell. 1989. Habitat requirements of breeding forest birds of the middle Atlantic states. Wildlife Monographs 103:1-34.

Robertson, W. D., J. A. Cherry, and E. A. Sudicky. 1991. Ground-water contamination from two small septic systems on sand aquifers. Ground Water 29:82-92.

Roman, C. T., and R. E. Good. 1983. Wetlands of the New Jersey Pinelands: values, functions, and impacts. Division of Pinelands Research, Center for Coastal and Environmental Studies, Rutgers University, New Brunswick, New Jersey.

Roman, C. T., and R. E. Good. 1985. Buffer delineation model for New Jersey Pinelands wetlands. Division of Pinelands Research, Center for Coastal and Environmental Studies, Rutgers University, New Brunswick, NJ.

Roman, C. T., and R. E. Good. 1986. Delineating wetland buffer protection areas: the New Jersey Pinelands Model. Pages 224-230 *in* J. A. Kusler, editor. Proceedings of the national wetland assessment symposium. Association of State Wetlands Managers, Chester, Vermont.

Roman, C. T., R. A. Zampella, and A. Z. Jaworski. 1985. Wetland boundaries in the New Jersey Pinelands: ecological relationships and delineation. Water Resources Bulletin 21:1005-1012.

Roman, C. T., R. E. Good, and S. Little. 1987. Atlantic white cedar swamps of the New Jersey Pinelands. Pages 35-39 *in* A. D. Laderman, editor. Atlantic white cedar wetlands. Westview Press, Boulder, Colorado.

Roman, C. T., R. E. Good, and S. Little. 1990. Ecology of Atlantic white cedar swamps in the New Jersey Pinelands. Pages 163-173 *in* D. F. Whigham, R. E. Good and J. Kvet, editors. Wetland ecology and management: case studies. Kluwer Academic Publishers, Dordrecht, Netherlands.

Schneider, J. P., and J. G. Ehrenfeld. 1987. Suburban development and cedar swamps: effects on water quality, water quantity and plant community composition. Pages 271-288 *in* A. D. Laderman, editor. Atlantic white cedar wetlands. Westview Press, Boulder, Colorado.

Schonewald-Cox, C., and M. Buechner. 1992. Park protection and public roads. Pages 373-395 *in* S. K. Fiedler and S. K. Jain, editors. Conservation biology: the theory and practice of nature conservation, preservation, and management. Routledge, Chapman & Hall, Inc., New York.

Schornick, J. C., Jr., and N. M. Ram. 1978. Nitrification in four acidic streams in southern New Jersey. U.S. Geological Survey Water-Resources Investigation 77-121. U.S. Geological Survey, Trenton, New Jersey.

Shaffer, M. L. 1981. Minimum population sizes for species conservation. BioScience 31:131-134.

Shaffer, M. L. 1985. Population size and extinction: a note on determining critical population size. The American Naturalist 125:144-151.

Simberloff, D. S., and L. G. Abele. 1982. Refuge design and island biogeography theory: effects of fragmentation. The American Naturalist 120:41-50.

Snyder, D. B., and V. E. Vivian. 1981. Rare and endangered vascular plant species in New Jersey. The Conservation and Environmental Studies Center, Pemberton, New Jersey.

Soule, M. E., and D. Simberloff. 1986. What do genetics and ecology tell us about the design of nature reserves? Biological Conservation 35:19-40.

Stoltzfus, D. L. 1990. Development of community structure in relation to disturbance and ecosystem fragmentation in Atlantic white cedar swamps in the Pinelands National Reserve, New Jersey. Ph.D. Dissertation. Rutgers, The State University of New Jersey, New Brunswick, New Jersey.

Stone, W. 1893. A new *Euotomys* from southern New Jersey. The American Naturalist 27:55-56.

Sutton, C. 1988. Barred owl survey of South Jersey, 1987. Records of New Jersey Birds 14:2-5.

Szabo, Z., D. E. Rice, T. Ivahnenko, and E. F. Vowinkel. 1994. Delineation of the distribution of pesticides and nitrate in an unconfined aquifer in the New Jersey Coastal Plain by flow-path analysis. Pages 100-119 *in* D. L. Weigmann, editor. New directions in pesticide research, development, management, and policy. Virginia Polytechnic Institute and State University, Blacksburg, Virginia.

Tedrow, J. C. F. 1979. Development of Pine Barrens soils. Pages 61-79 *in* R. T. T. Forman, editor. Pine Barrens: ecosystem and landscape. Academic Press, New York.

Tiner, R. W., Jr. 1985. Wetlands of New Jersey. U.S. Fish and Wildlife Service, National Wetlands Inventory, Newton Corner, MA.

Tracy, C. R. and P. F. Brussard. 1994. Preserving biodiversity: species in landscapes. Ecological Applications 4:205-207.

Velnich, A. J. 1984. Drainage areas in New Jersey: Atlantic Coastal Basins, South Amboy to Cape May, U.S. Geological Survey Open-File Report 84-150. U.S. Geological Survey, Trenton, New Jersey.

Velnich, A. J. 1982. Drainage areas in New Jersey: Delaware River Basin and streams tributary to Delaware Bay, U.S. Geological Survey Open-File Report 82-572. U.S. Geological Survey, Trenton, New Jersey.

Vowinkel, E. F. 1991. Comparison of relations between shallow ground-water quality and land use in two New Jersey Coastal Plain aquifer systems. Pages 307-313 *in* G. E. Mallard and D. E., editors. U.S. Geological Survey toxic substances hydrology program: proceedings of the technical meeting, Monterey, California, 1991. U.S. Geological Survey Water-Resources Investigations Report 91-4034.

Vowinkel, E. F., and S. F. Siwiec. 1991. Plan to evaluate the effects of hydrogeologic conditions and human activities on water quality in the coastal plain of New York and New Jersey. U.S. Geological Survey, Water-Resources Investigations Report 91-4091. U.S. Geological Survey, West Trenton, New Jersey.

Wacker, P. O. 1979. Human exploitation of the New Jersey Pine Barrens before 1900. Pages 3-23 *in* R. T. T. Forman, editor. Pine Barrens: ecosystem and landscape. Academic Press, New York.

Walbridge, M. R., and J. P. Struthers. 1993. Phosphorus retention in non-tidal palustrine forested wetlands of the Mid-Atlantic region. Wetlands 13:84-94.

Walker, W. G., J. Bouma, D. R. Keeney, and P. G. Olcott. 1973. Nitrogen transformations during subsurface disposal of septic tank effluent in sands: II. Ground water quality. Journal of Environmental Quality 2:521-525.

Wander, W. 1981. Breeding birds of southern New Jersey cedar swamps. Records of New Jersey Birds 6:51-65.

Watt, M. K., and M. L. Johnson. 1992. Water resources of the unconfined aquifer system of the Great Egg Harbor River basin, New Jersey, 1989-90. U.S. Geological Survey, Water-Resources Investigations Report 91-4126. West Trenton, New Jersey.

Whitcomb, R. F. 1977. Island biogeography and habitat islands of eastern forests. American Birds 31:3-5.

Whitcomb, R. F., C. S. Robbins, J. F. Lynch, B. L. Whitcomb, M. K. Klimkiewicz, and D. Bystrak. 1981. Effects of forest fragmentation on avifauna of the eastern deciduous forest. Pages 123-205 *in* R. L. Burgess and D. M. Sharpe, editors. Forest island dynamics in man-dominated landscapes. Springer-Verlag, New York, New York.

White, J. E. 1961. The effects of control burning on small mammal populations of the New Jersey Pine Barrens. Ph.D. Dissertation. Rutgers University, New Brunswick, New Jersey.

Whittaker, R. H. 1979. Vegetational relationships of the Pine Barrens. Pages 315-331 *in* R. T. T. Forman, editor. Pine Barrens: ecosystem and landscape. Academic Press, New York.

Wilcove, D. S. 1985. Nest predation in forest tracts and the decline of migratory song birds. Ecology 66:1211-1214.

Winter, T. C. 1988. A conceptual framework for assessing cumulative impacts on the hydrology of nontidal wetlands. Environmental Management 12:605-620.

Xiang, W. 1993. Application of a GIS-based stream buffer generation model to environmental policy evaluation. Environmental Management 17:817-827.

Yahner, R. H. 1988. Changes in wildlife communities near edges. Conservation Biology 2:333-339.

Yuretich, R. F., D. A. Crerar, D. J. Kinsman, J. L. Means, and M. P. Borcsik. 1981. Hydrogeochemistry of the New Jersey Coastal Plain: 1. Major-element cycles in precipitation and river water. Chemical Geology 33:1-21.

Zampella, R. A. 1986. Crossley and the ecopolitics of endangered species protection: a New Jersey case study. Pages 278-293 *in* S. K. Majumdar, F. J. Brenner and A. F. Rhoads, editors. Endangered and threatened species programs in Pennsylvania and other states: causes, issues, and management. The Pennsylvania Academy of Science, Lafayette College, Easton, Pennsylvania.

Zampella, R. A. 1988. Acquisition, management, and use of public lands. Pages 214-231 *in* B. R. Collins and E. W. B. Russell, editors. Protecting the New Jersey Pinelands, a new direction in land use management. Rutgers University Press, New Brunswick, New Jersey.

Zampella, R. A. 1991. New Jersey Pinelands Commission manual for identifying and delineating Pinelands area wetlands. New Jersey Pinelands Commission, New Lisbon, NJ.

Zampella, R. A. 1994a. Characterization of surface water quality along a watershed disturbance gradient. Water Resorces Bulletin 30:1-7.

Zampella, R. A. 1994b. Morphologic and color pattern indicators of water table level in sandy Pinelands soils. Soil Science: 157:312-317.

Zampella, R. A., G. Moore, and R. E. Good. 1992. Gradient analysis of pitch pine (*Pinus rigida* Mill.) lowland communities in the New Jersey Pinelands. Bulletin of the Torrey Botanical Club 119:253-261.

Zampella, R. A., L. Craig, and M. Windisch. 1994. Water quality characteristics of Ocean County Pinelands Streams. Pinelands Commission, New Lisbon, New Jersey.

Zappalorti, R. T. 1980. A preliminary ecological study of the eastern tiger salamander, *Ambystoma tigrinum tigrinum*, Green (Amphibia, Urodel, Ambystomatidae) in southern New Jersey. Part I. Unpublished report, Endangered and Nongame Species Program, NJ Division of Fish, Game and Wildlife, Trenton, New Jersey.

Zappalorti, R. T., and J. Dowdell. 1991. An updated distributional survey and habitat evaluation of the southern gray treefrog (*Hyla chrysoscelis*, Cope) in southern New Jersey-both of historic sites and newly discovered locations, part one. Unpublished report, Endangered and Nongame Species Program, NJ Division of Fish, Game and Wildpgrlife, Trenton, New Jersey.

Zappalorti, R. T., and P. A. Vargas. 1991. Mapping and localities of a distributional survey and habitat evaluation of the southern gray treefrog (*Hyla chrysoscelis*, Cope) in southern New Jersey-of both historic sites and newly discovered locations, part two. Unpublished report, Endangered and Nongame Species Program, NJ Division of Fish, Game and Wildlife, Trenton, New Jersey.

Zripko, N. P. and A. Hasan. 1994. Depletive water use project for regional water resource planning areas of New Jersey. New Jersey Department of Environmental Protection, Office of Land and Water Planning, Trenton, New Jersey.

Appendix 1. Threatened and endangered wetland species in the Pinelands listed by the Pinelands Commission (PC), NJDEP (NJ), and the U.S. Fish and Wildlife Service (FED).

Scientific Name	Common Name	PC	NJ	FED
Plants				
Aeschynomene virginica	sensitive joint-vetch	T/E	E	T
Asclepias rubra	red milkweed	T/E	-	-
Calamagrostis pickeringii	Pickering's reedgrass	-	E	-
Calamovilfa brevipilis	pine barren reedgrass	T/E	-	-
Cardamine longii	Long's bitter cress	-	E	-
Carex barrattii	Barratt's sedge	T/E	-	-
Ceratophyllum echinatum	spiny coontail	-	E	-
Cirsium virginianum	Virginia thistle	-	E	-
Cleistes divaricata	spreading pogonia	T/E	E	-
Coreopsis rosea	pink tickseed	T/E	-	-
Cuscuta cephalanthii	button-bush dodder	-	E	-
Cyperus polystachyos	coast flatsedge	-	E	-
var. texensis	-------			
Cyperus pseudovegetus	marsh flatsedge	-	E	-
Eleocharis equisetoides	knotted spikerush	T/E	E	-
Eleocharis melanocarpa	black-fruited spikerush	-	E	-
Eleocharis brittonii	Britton's spikerush	-	E	-
Eleocharis tortilis	twisted spikerush	-	E	-
Eriophorum gracile	slender cottongrass	-	E	-
Eriophorum tenellum	rough cottongrass	-	E	-
Eupatorium resinosum	pine barren boneset	T/E	E	-
Gentiana autumnalis	pine barren gentian	T/E	-	-
Helonias bullata	swamp-pink	T/E	E	T
Hottonia inflata	featherfoil	-	E	-
Juncus brachycarpus	short-fruited rush	-	E	-
Juncus caesariensis	New Jersey rush	T/E	E	-
Juncus coriaceus	awl-leaved rush	-	E	-
Juncus elliottii	Elliott's rush	-	E	-
Kalmia polifolia	pale laurel	-	E	-
Limosella subulata	mudweed	-	E	-
Linum intercursum	Florida yellow flax	-	E	-
Liparis lilifolia	lily-leaved twayblade	T/E	-	-
Liparis loeselii	Loesel's twayblade	T/E	-	-
Listera australis	southern twayblade	T/E	-	-
Lobelia boykinii	Boykin's lobelia	T/E	E	-
Lobelia canbyi	Canby's lobelia	T/E	-	-
Ludwigia hirtella	hairy ludwigia	T/E	-	-
Ludwigia linearis	linear-leaved ludwigia	T/E	-	-
Lygodium palmatum	climbing fern	T/E	-	-
Melanthium virginicum	Virginia bunchflower	-	E	-
Muhlenbergia torreyana	pine barren smoke grass	T/E	-	-
Myriophyllum tenellum	slender water-milfoil	-	E	-
Myriophyllum verticillatum	whorled water-milfoil	-	E	-
Narthecium americanum	bog asphodel	T/E	E	-
Nuphar microphyllum	small yellow pond lily	-	E	-
Nymphoides cordata	floating heart	T/E	-	-
Panicum hemitomon	maiden cane	T/E	-	-
Panicum hirstii	Hirst's panic grass	T/E	E	-

Appendix 1 (cont'd). Threatened and endangered wetland species in the Pinelands listed by the Pinelands Commission (PC), NJDEP (NJ), and the U.S. Fish and Wildlife Service (FED).

Scientific Name	Common Name	PC	NJ	FED
Phoradendron serotinum	mistletoe	T/E	-	-
(P. flavescens)	———			
Platanthera ciliaris	yellow-fringed orchid	T/E	-	-
(Habenaria ciliaris)	———			
Platanthera cristata	crested yellow orchid	T/E	-	-
(Habenaria cristata)	———			
Platanthera integra	yellow fringeless orchid	T/E	E	-
(Habenaria integra)	———			
Platanthera peramoena	purple fringeless orchid	-	E	-
Polygala mariana	Maryland milkwort	T/E	-	-
Polygonum glaucum	sea-beach knotweed	-	E	-
Potamogeton confervoides	algae-like pondweed	-	E	-
Prenanthes autumnalis	pine barren rattlesnake root	T/E	-	-
Pycnanthemum torrei	Torrey's mountain mint	-	E	-
Ranunculus cymbalaria	sea-side crowfoot	-	E	-
Rhexia aristosa	awned meadowbeauty	T/E	E	-
Rhynchospora cephalantha	large-headed beaked rush	T/E	-	-
Rhynchospora filifolia	thread-leaved beaked rush	-	E	-
Rhynchospora globularis	grass-like beaked rush	-	E	-
Rhynchospora glomerata	clustered beaked rush	-	E	-
Rhynchospora inundata	horned beaked rush	T/E	-	-
Rhynchospora knieskernii	Knieskern's beaked rush	T/E	E	T
Rhynchospora microcephala	small-headed beaked rush	-	E	-
Ruellia caroliniensis	Carolina petunia	-	E	-
Sagittaria australis	southern arrow head	-	E	-
Sagittaria teres	slender arrow head	-	E	-
Schizaea pusilla	curly grass fern	T/E	-	-
Schwalbea americana	chaffseed	T/E	E	E
Scirpus longii	Long's bulrush	T/E	E	-
Scleria minor	slender nut rush	T/E	-	-
Scleria reticularis	reticulated nut rush	T/E	-	-
Scleria verticillata	whorled nut rush	-	E	-
Sclerolepis uniflora	bog buttons	T/E	-	-
Solidago stricta	wand-like goldenrod	T/E	-	-
Spiranthes laciniata	lace-lip ladies' tresses	-	E	-
Spiranthes tuberosa	little ladies'-tresses	T/E	-	-
Tofieldia racemosa	false asphodel	T/E	E	-
Utricularia biflora	two-flowered bladderwort	-	E	-
Utricularia gibba	humped bladderwort	T/E	-	-
Utricularia minor	lesser bladderwort	-	E	-
Utricularia olivacea	dwarf white bladderwort	T/E	E	-
Utricularia purpurea	purple bladderwort	T/E	-	-
Utricularia resupinata	reversed bladderwort	T/E	E	-
Uvularia pudica var nitida	pine barren bellwort	-	E	-
Valerianella radiata	beaked corn-salad	-	E	-
Xyris caroliniana	sand yellow-eyed grass	T/E	E	-
(X. flexuosa)	———			
Xyris fimbriata	fringed yellow-eyed grass	-	E	-
Zygadenus leimanthoides	oceanorus	-	E	-

Appendix 1 (cont'd). Threatened and endangered wetland species in the Pinelands listed by the Pinelands Commission (PC), NJDEP (NJ), and the U.S. Fish and Wildlife Service (FED).

Scientific Name	Common Name	PC	NJ	FED
Reptiles and Amphibians				
Ambystoma tigrinum	eastern tiger salamander	E	E	-
Clemmys insculpta	wood turtle	T	T	-
Clemmys muhlenbergii	bog turtle	E	E	-
Crotalus horridus	timber rattlesnake	E	E	-
Hyla andersonii	Pine Barrens treefrog	E	E	-
Hyla chrysoscelis	Cope's gray treefrog	E	E	-
Birds				
Accipiter cooperii	Cooper's hawk	E	E	-
Ardea herodias	great blue heron	T	T	-
Asio flammeus	short-eared owl	E	E	-
Asio otus	long-eared owl	T	T	-
Botaurus lentiginosus	American bittern	T	T	-
Buteo lineatus	red-shouldered hawk	E	E	-
Circus cyaneus	northern harrier	E	E	-
Cistothorus platensis	sedge wren	E	E	-
Egretta caerulea	little blue heron	T	T	-
Falco peregrinus anatum	American peregrine falcon	E	E	E
Haliaeetus leucocephalus	bald eagle	E	E	E
Nyctanassa violaceus	yellow-crowned night-heron	T	T	-
Pandion haliaetus	osprey	T	T	-
Podilymbus podiceps	pied-billed grebe	E	E	-
Strix varia	barred owl	T	T	-

Appendix 2. Land use rating schedule.

Altered Land (%)	(%) Altered Land on Soils with HPGWC[1]	Rating
<5	<25	10.00
	25-50	9.75
	50-75	9.50
	>75	9.25
5-9.9	<25	9.00
	25-50	8.75
	50-75	8.50
	>75	8.25
10-14.9	<25	8.00
	25-50	7.75
	50-75	7.50
	>75	7.25
15-19.9	<25	7.00
	25-50	6.75
	50-75	6.50
	>75	6.25
20-24.9	<25	6.00
	25-50	5.75
	50-75	5.50
	>75	5.25
25-34.9	<25	5.00
	25-50	4.75
	50-75	4.50
	>75	4.25
35-44.9	<25	4.00
	25-50	3.75
	50-75	3.50
	>75	3.25
45-54.9	<25	3.00
	25-50	2.75
	50-75	2.50
	>75	2.25
55-74.9	<25	2.00
	25-50	1.75
	50-75	1.50
	>75	1.25
>=75	<25	1.00
	25-50	0.75
	50-75	0.50
	>75	0.25

[1] High potential for ground water contamination.

Appendix 3. Ground water withdrawal rating schedule. **W** represents the withdrawal as a percentage of a basin's water budget. **R** represents the rating assigned to each percent withdrawal (water budget depletion).

W	**R**	**W**	**R**	**W**	**R**	**W**	**R**	**W**	**R**
0	10.0	20	6.0	40	4.0	60	2.7	80	1.3
1	9.8	21	5.8	41	3.9	61	2.6	81	1.3
2	9.6	22	5.6	42	3.9	62	2.5	82	1.2
3	9.4	23	5.4	43	3.8	63	2.5	83	1.1
4	9.2	24	5.2	44	3.7	64	2.4	84	1.1
5	9.0	25	5.0	45	3.7	65	2.3	85	1.0
6	8.8	26	4.9	46	3.6	66	2.3	86	0.9
7	8.6	27	4.9	47	3.5	67	2.2	87	0.9
8	8.4	28	4.8	48	3.5	68	2.1	88	0.8
9	8.2	29	4.7	49	3.4	69	2.1	89	0.7
10	8.0	30	4.7	50	3.3	70	2.0	90	0.7
11	7.8	31	4.6	51	3.3	71	1.9	91	0.6
12	7.6	32	4.5	52	3.2	72	1.9	92	0.5
13	7.4	33	4.5	53	3.1	73	1.8	93	0.5
14	7.2	34	4.4	54	3.1	74	1.7	94	0.4
15	7.0	35	4.3	55	3.0	75	1.7	95	0.3
16	6.8	36	4.3	56	2.9	76	1.6	96	0.3
17	6.6	37	4.2	57	2.9	77	1.5	97	0.2
18	6.4	38	4.1	58	2.8	78	1.5	98	0.1
19	6.2	39	4.1	59	2.7	79	1.4	99	0.1
								100	0.0