HUDSONIA LTD
P.O. Box 5000, Annandale NY 12504 USA
845-758-0600, www.hudsonia.org

The Functions of Forests and Effect of Impervious Surfaces on Stream Health and Water Quality, with Applications to the Croton Watershed

by Aryn Wilder MS and Erik Kiviat PhD

Hudsonia Ltd

Report to the Croton Watershed Clean Water Coalition

16 January 2009

The quality of drinking water in rivers, lakes and reservoirs depends substantially on protecting the healthy function of the fine branches of headwater streams. Forests significantly help protect these streams and preserve drinking water quality in watersheds by performing a number of ecosystem services: moderating stream flow and flooding, controlling surface runoff and erosion, buffering against pollutants, and preventing sedimentation and eutrophication of waterways. Forests provide two-thirds of the drinking water in the United States, though they cover only a third of the land (Dombeck 2002). The critical role that forests play in water quality protection has been widely recognized; however, legal protection for upland forests surrounding headwater streams in the northeastern United States is still largely lacking. The rate of urban development within nonfederal forest land has increased (Alig et al. 2003), along with the replacement of trees with impervious surfaces (e.g. roofs, roads) that alter watershed hydrology and degrade waterways. The increase of impervious surfaces on forest land will continue as long as society places a higher value on suburban and urban development than on the ecosystem services of intact forests. In this summary report we briefly review the functions of forests in preserving and improving water quality. We provide further detail and discussion of the influence of forests on surface runoff, erosion, floods, droughts, pollutants, sedimentation and eutrophication in Wilder and Kiviat (2008). Here we discuss the potential impacts of urbanization on the water supply of the Croton watershed, focusing primarily on the effects of impervious surfaces on phosphorus loading and stream degradation. The goal of this synthesis is to highlight the benefits of intact forests and the effects of impervious surfaces in watersheds, so that these issues may be considered in light of increasing urbanization pressure.

Healthy forests preserve water quality by 1) slowing runoff, thus reducing floods, erosion, and sedimentation of rivers and reservoirs, and by 2) promoting infiltration of water into the soil, where it recharges groundwater and is purified by a number of biotic and abiotic processes. Excess surface runoff moves unchecked quantities of pollutants into streams and increases the volume and velocity of waterways, causing bank erosion and sedimentation of water bodies (Bormann et al. 1974, Arnold and Gibbons 1996, Trimble 1997, Gaister et al. 2006, McHale et al. 2008). Trees, shrubs and litter provide mechanical obstruction that slows surface runoff and its accumulation in stream channels; the canopy, litter and roots shield and stabilize upland soil from erosion caused by runoff, wind and the erosive energy of raindrops (Kittredge 1948).

Forests have highly modified soils that promote infiltration of water, thereby reducing surface runoff. Organic matter, roots and soil fauna maintain the porosity and permeability of the forest floor, and evapotranspiration keeps soil unsaturated (Kittredge 1948, de la Cretaz and Barten 2007). The high infiltration capacity of forest soil enables the movement of water to depths where microbial, macrophytic and soil chemical processes filter pollutants (Magill et al. 1997, Casey and Klaine 2001, McHale et al. 2008, Tervahauta et al. in press). Infiltration and subsurface flow are mechanisms by which groundwater is recharged and streamflow is sustained through the dry season (Heisig 2000, de la Cretaz and Barten 2007).

The rates of infiltration, water retention and surface runoff generation of forest soils depend on forest maturity and type, and on the physical characteristics of the watershed. Not surprisingly, water yields tend to be higher from newly harvested and clearcut forests. As Dr. Mike Dombeck, former Forest Service chief, describes, "it is a bit like the difference between a woodlot and a parking lot" (Dombeck 2002). Harvest experiments at Hubbard Brook Experimental Forest in New Hampshire initially resulted in higher water yield in streams, in conjunction with increased flow variability, erosion, sedimentation, eutrophication and algal blooms (Likens et al. 1970, Bormann et al. 1974). Within 10 years, however, water yield dropped to below pretreatment yields as young vegetation established, consistent with the findings of other studies in northeastern forests (Hornbeck et al. 1995). Harvesting can be followed by changes in tree species composition that further decrease overall water yield. Transpiration from forests composed of pioneer species, such as birch and cherry, may be greater than from mature, undisturbed forests, thereby decreasing water available for export by streams. Harvesting can also change nutrient cycling dynamics, as young forests may consume more nutrients and prevent their deposition into streams. Research has generally confirmed the idea that intact, mature forests (dominated by mature trees 30 cm or larger in diameter at breast height) are best at producing the purest water most consistently. In addition, intact forests are better able to resist potential biological disturbances, for example, invasion by exotic plants and earthworms, and excessive grazing by overabundant deer (Luken and Goessling 1995, Cadenasso and Pickett 2001, Hunter and Mattice 2002). Exotic plants may outcompete native species, deer denude and kill trees and shrubs, and earthworms may potentially modify the litter layer that protects the forest floor from erosion (Pelletier 2001, Lawrence et al. 2003). These biological disturbances, in turn, can have repercussions on water quality by changing the influences the forest features have on watershed hydrology.

Models have been developed to predict hydrological dynamics based on physical characteristics like precipitation, slope, depth to bedrock, and soil permeability (Dvorak 1960, Beven and Kirby 1979, Frankenberger et al. 1999, Moffett et al. 2003, Gorsevski et al. 2008). For example, surface runoff can be estimated by precipitation, soil permeability, slope, and specific soil condition variables (Dvorak 1960). Areas of less permeable, shallow soils on steep slopes tend to contribute more runoff to surface water bodies than regions with deeper, more permeable soil and gentler slopes. Soils throughout the Croton watershed are generally well-drained; however, they are very shallow in the northern part of the watershed which lies on the Hudson Highlands (Cline 1963, Cadwell et al. 1989). Moffett et al. (2003) used Geographic Information System (GIS) and spatial data to model the risk of pollutant transmission to surface water bodies in the Croton watershed based on land use, soil and slope data, identifying a number of sub-basins with likely impaired water quality. Gorsevski et al. (2008) incorporated vegetation parameters into a hydrological model along with precipitation, slope, depth to bedrock, and soil permeability, and found that regenerated and clearcut areas produced more surface runoff than mature forested areas.

Examining the physical characteristics of watersheds may help determine hydrologically sensitive locations, i.e., areas that have the potential to generate large amounts of surface runoff; however, stream and water quality degradation are most often a result of land use changes. When forests are removed and replaced by impervious surfaces, for example, roads, parking areas and roofs in addition to compacted residential and recreational turf, water quality degradation occurs as a result of hydrological changes and increased pollution. Impervious surface coverage has been recognized as an accurate predictor of stream health, with many studies showing strong correlations between the degree of impervious coverage in a watershed and the health of its receiving stream (Klein 1979, Griffin 1980, Schueler 1987, Todd 1989, Schueler 1992, Booth and Reinfelt 1993, Schueler 1994, Arnold and Gibbons 1996). A study in the Croton watershed reported that a small (0.38 km^2), undeveloped catchment received 33060 liters (L) of water in the form of precipitation from August 2001 to August 2002 (Burns et al. 2005). On average, in an undeveloped watershed, 50% of rainfall enters the soil as infiltration, 40% is released to the air by evapotranspiration, and 10% travels as surface runoff (NYSDEC 1992). Assuming this hydrological scenario, approximately 16530 L of precipitation infiltrated into the soil and 3306 L were converted to surface runoff. If 10 - 20% of the same watershed were covered with impervious surface, infiltration would be reduced to nearly 40% (13224 L) and surface runoff increased to 20% (6612 L; (NYSDEC 1992). In the Croton watershed, Burns et al. (2005) studied the effects of suburban development on runoff by comparing headwater catchments with variable amounts of impervious surface. They found that waterway peak discharge increased with increasing urbanization, and was three times higher in a catchment with 11% impervious surface compared to an undeveloped catchment (Burns et al. 2005).

Impervious surfaces prevent infiltration of precipitation and attenuation of pollutants by forest soil, and provide rapid transport of contaminated water to waterways. Inputs of pollutants from the intensive land use associated with imperviousness, exacerbated by the loss of the buffering capacity of forests, lead to an increase in contamination of receiving waters with suspended solids, excess nutrients, organic matter, heavy metals, pathogens and other pollutants. Heavy runoff is largely responsible for streambank erosion and the input of suspended solids in urban watersheds which harm aquatic organisms (Trimble 1997). Excess organic matter in surface runoff depletes dissolved oxygen in water bodies as it decomposes, and the addition of chlorine disinfectant to water high in organic matter can form carcinogenic trihalomethanes and haloacetic acids (Weisel et al. 1999). Deicing salts from roads and parking lots harm many aquatic organisms and affect the mixing cycle of lakes. Trash and debris, heavy metals, bacteria, petroleum hydrocarbons (including polycyclic aromatic hydrocarbons), and pesticides are also common contaminants of urban stormwater runoff. Excess nutrients, especially phosphorus and nitrogen, lead to eutrophication of streams, lakes, rivers and estuaries (CWP 2003). In a Connecticut watershed, researchers found that surface runoff and the pollutants phosphorus and nitrogen increased exponentially with impervious surface in traditional urban developments (Dietz and Clausen 2008). Streams from catchments with residential development in the Croton watershed had elevated levels of sodium, chloride, boron, sulfate, nitrate, ammonium and total phosphorus (Heisig 2000).

Phosphorus is considered particularly harmful to drinking water quality, as it is the limiting nutrient for algal growth in most New York State lakes, and is of particular concern in the New York City reservoir system (NYSDEC 1992). Algal blooms bring about water quality problems such as decreased water clarity, large daily swings in dissolved oxygen, offensive odors and fish kills. In urban and suburban settings phosphorus may come from detergents, fertilizers, flame retardants, corrosion inhibitors, plasticizers, sediment and soil-disturbance (CWP 2003). The New York State Department of Environmental Conservation (NYSDEC) set stringent limits for phosphorus in reservoirs used as direct sources of drinking water for New York City in the Croton watershed, with a total maximum daily load (TMDL) based on a 15 micrograms per liter ($\mu g\ L^{-1}$) phosphorus objective. This objective amounts to a phosphorus loading rate (including the regulated margin of safety) of 0.58 kilograms per hectare per year ($kg\ ha^{-1}\ yr^{-1}$), 0.11 $kg\ ha^{-1}\ yr^{-1}$ and 0.74 $kg\ ha^{-1}\ yr^{-1}$ for the drainage basin areas of New Croton, Cross River and Croton Falls reservoirs, respectively (NYSDEC 2000). The phosphorus loading rate for undeveloped forest land near the Croton watershed ranges from 0.05 $kg\ ha^{-1}\ yr^{-1}$ (Dillon and Kirchner 1975, Schaffner and Oglesby 1978, Moffett et al. 2003, Withers and Jarvie 2008); however, for residential development with 12% impervious surface, the rate is 0.9 $kg\ ha^{-1}\ yr^{-1}$ (NYSDEC 1992). Thus approximately 18 times more phosphorus is released from residential developments than from forested land of equal area. Enhanced stormwater treatment regulations have been promulgated, designed to remove 60% of phosphorus from at least 85% of stormwater runoff volume (NYSDEC 2008). These practices would reduce the phosphorus loading rate from residential developments with 12% imperviousness to approximately 0.44 $kg\ ha^{-1}\ yr^{-1}$ if treatments are properly implemented, maintained and strictly enforced. Nonetheless, if residential development were to reach 12% impervious surface coverage at the watershed level, loading rates would theoretically exceed TMDL standards in the Cross River reservoir, and approach the New Croton reservoir TMDL. The achievement of TMDL standards within New Croton reservoir relies heavily on local enforcement and proper function of recently-promulgated regulations which are based on simulation modeling and have had little time for testing on the ground.

Schueler (1992) studied the relationship of imperviousness and declining stream health, and identified thresholds at which waterway degradation occurs. Although thresholds are often controversial, studies of a number of stream health indicators (such as pollutant loads, streambank erosion and aquatic species diversity) in geographically and geologically diverse watersheds have shown the thresholds to be robust. In particular, Schueler's (1994) review of a number of watershed studies confirmed that stream degradation consistently occurs when catchments reach between 10 and 20% imperviousness (Schueler 1994, Arnold and Gibbons 1996, NRC 2008). The low level of impervious coverage associated with stream degradation poses a difficult challenge in managing for water quality. A number of steps has been proposed to minimize stream degradation and pollutant loading, for example, detention ponds, large-lot zoning, and low-impact development techniques (NYSDEC 1992, CSN 2008, Dietz and Clausen 2008). However, planning responses are hindered by the fact that most developments produce more than 10% impervious coverage (Cappiella and Brown 2001), and the associated hydrological changes and pollutant loading rates may be dramatic. In addition, at higher levels of imperviousness, the size and complexity of the treatment methods increase, entailing higher costs, more maintenance and more space. Forests provide similar services but at no cost, with no maintenance or impact on the land. The construction phase of development in particular causes large-scale soil disturbance and erosion (Krenitsky et al. 1998), and most zoning codes curtail the opportunities for better site design and low impact development practices by requiring excessive impervious cover for such amenities as roads and raised curbs, leading to the needs for pipe and pond treatment scenarios. A water quality risk assessment model predicted that the relatively undeveloped northeastern portion of the Croton watershed would experience the greatest increase in water quality impairment if it is built-out to its current zoning allowance

(Moffett et al. 2003). We believe the quality of the New York City watersheds warrants consideration of impervious coverage caps, and a return to land management policies that promote the long-term health of forests and the water they produce. Conserving the quantity and quality of forests in the watershed will also protect many other ecosystem services including habitat functions for rare and common species, carbon sequestration, microclimatic buffering, reduction of anthropogenic noise, and maintenance of air quality.

Summary:

Forests are critical for producing and purifying the nation's water supply, yet few laws protect them from urban development. Forests protect waterways and produce clean water by controlling surface runoff, flooding and erosion, and promoting infiltration of water into forest soils, where it is purified by biotic and abiotic processes. Mature forests have the most consistent water yields and are best at moderating flow and controlling surface runoff. A number of physical factors affects the rates of infiltration and surface runoff such as soil permeability, soil depth, and slope. The replacement of forested areas with impervious surfaces increases runoff, prevents infiltration, and leads to elevated levels of phosphorus loading and eutrophication of waterways. Studies have shown impervious surface coverage to be strongly negatively correlated with water quality, with stream degradation occurring at low levels (10 – 20%) of watershed imperviousness. Phosphorus pollution, the primary cause of algal blooms in New York lakes, may exceed total maximum daily load limits set by New York State in some reservoirs if residential impervious surfaces exceed 10 percent.

References Cited:

Alig, R. J., A. J. Plantinga, S. Ahn, and J. D. Kline. 2003. Land use changes involving forestry in the United States: 1952 to 1997, with projections to 2050- a technical document supporting the 2000 USDA Forest Service RPA assessment. U.S. Department of Agriculture, Forest Service, Pacific Northwest Station, General Technical Report, 92 pp.

Arnold, C. L., and C. J. Gibbons. 1996. Impervious surface coverage: the emergence of a key environmental indicator. *Journal of the American Planning Association* 62: 243-258.

Beven, K., and M. J. Kirby. 1979. A physically based, variable contributing area model of basin hydrology. *Hydrological Science Bulletin* 24: 43-69.

Booth, D. B., and L. E. Reinfelt. 1993. Consequences of urbanization on aquatic systems- measured effects, degradation thresholds, and corrective strategies, pp. 545-550, *Proceedings of the Watershed '93 Conference*, Alexandra, VA.

Bormann, F. H., G. E. Likens, T. G. Siccama, R. S. Pierce, and J. S. Eaton. 1974. The export of nutrients and recovery of stable conditions following deforestation at Hubbard Brook. *Ecological Monographs* 44: 255-277.

Burns, D., T. Vitvar, J. McDonnell, J. Hassett, J. Duncan, and C. Kendall. 2005. Effects of suburban development on runoff generation in the Croton River basin, New York, USA. *Journal of Hydrology* 311: 266-281.

Cadenasso, M. L., and S. T. A. Pickett. 2001. Effect of edge structure on the flux of species into forest interiors. *Conservation Biology* 15: 91-97.

Cadwell, D. H., G. G. Connally, R. J. Dineen, P. J. Fleisher, M. L. Fuller, L. Sirkin, and G. C. Wiles. 1989. Surficial Geologic Map of New York: Lower Hudson Sheet. New York State Museum and Science Service Map and Chart Series No. 40, Albany, NY.

Cappiella, K., and K. Brown. 2001. Impervious cover and land use in the Chesapeake Bay region. *Watershed Protection Techniques* 3: 835-840.

Casey, R. E., and S. J. Klaine. 2001. Nutrient attenuation by a riparian wetland during natural and artificial runoff events. *Journal of Environmental Quality* 30: 1720-1731.

Cline, M. G. 1963. *Soils and Soil Associations*. Cooperative Extension Service, New York State College of Agriculture at Cornell University, Ithaca, NY, 63 pp.

CSN. 2008. Implications of the impervious cover model: stream classification, urban subwatershed management and permitting. Chesapeake Stormwater Network, CSN Technical Bulletin No. 3, 24 pp.

CWP. 2003. New York State Stormwater Management Design Manual. Center for Watershed Protection, Report to the NYSDEC, 544 pp.

de la Cretaz, A. L., and P. K. Barten. 2007. *Land Use Effects on Streamflow and Water Quality in the Northeastern United States*. CRC Press, Boca Raton, FL, 319 pp.

Dietz, M. E., and J. C. Clausen. 2008. Stormwater runoff and export changes with development in a traditional and low impact subdivision. *Journal of Environmental Management* 87: 560-566.

Dillon, P. J., and W. B. Kirchner. 1975. The effects of geology and land use on the export of phosphorus from watersheds. *Water Research* 9: 135-148.

Dombeck, M. 2002. Strategies to boost water yield must focus of the long term. December 29, *Denver Post*.
Dvorak, J. 1960. Surface runoff as a factor of water erosion, pp. 98-111. *In* L. J. Tison [ed.], *General Assembly of Helsinki*. International Association of Scientific Hydrology, Gentbrugge, Belgium.
Frankenberger, J. R., E. S. Brooks, M. T. Walter, M. F. Walter, and T. S. Steenhuis. 1999. A GIS-based variable source area hydrology model. *Hydrological Processes* 13: 804-822.
Gaister, J. C., F. J. Pazzaglia, B. R. Hargreaves, D. P. Morris, S. C. Peters, and R. N. Weisman. 2006. Effects of urbanization on watershed hydrology: The scaling of discharge with drainage area. *Geology* 34: 713-716.
Gorsevski, P. V., J. Boll, E. Gomezdelcampo, and E. S. Brooks. 2008. Dynamic riparian buffer widths from potential non-point source pollution areas in forested watersheds. *Forest Ecology and Management* 256: 664-673.
Griffin, D. M. 1980. Analysis of a non-point pollution export from small catchments. *Journal of the Water Pollution Control Federation* 52: 780-790.
Heisig, P. 2000. Effects of residential and agricultural land uses on the chemical quality of small streams in the Croton Watershed, southeastern New York. U.S. Geological Survey, Water Resources Investigation Report, 15 pp.
Hornbeck, J. W., M. B. Adams, E. S. Corbett, E. S. Verry, and J. A. Lynch. 1995. A summary of water yield on hardwood forested watersheds in northeastern United States, pp. 282-295. *In* S. L. C. Fosbroke [ed.], *10th Central Hardwood Forest Conference*, Morgantown, WV.
Hunter, J. C., and J. A. Mattice. 2002. The spread of woody exotics into the forests of a northern landscape. *Journal of the Torrey Botanical Society* 129: 220-227.
Kittredge, J. 1948. *Forest Influences: The Effects of Woody Vegetation on Climate, Water, and Soil*. Dover Publications, New York, NY, 394 pp.
Klein, R. D. 1979. Urbanization and stream quality impairment. *Water Resources Bulletin* 15: 948-963.
Lawrence, B., M. C. Fisk, T. J. Fahey, and E. R. Suarez. 2003. Influence of nonnative earthworms on mycorrhizal colonization of sugar maple (*Acer saccharum*). *New Phytologist* 157: 145-153.
Likens, G. E., F. H. Bormann, N. M. Johnson, D. W. Fisher, and R. S. Pierce. 1970. Effects of forest cutting and herbicide treatment on nutrient budgets in the Hubbard Brook watershed-ecosystem. *Ecological Monographs* 40: 23-47.
Luken, J. O., and N. Goessling. 1995. Seedling distribution and potential persistence of the exotic shrub *Lonicera maackii* in fragmented forests. *American Midland Naturalist* 133: 124-130.
Magill, A. H., J. D. Aber, J. J. Hendricks, R. D. Bowden, J. M. Melillo, and P. A. Steudler. 1997. Biogeochemical response of forest ecosystems to simulated chronic nitrogen deposition. *Ecological Applications* 7: 402-415.
McHale, M. R., P. S. Murdoch, D. A. Burns, and B. P. Baldigo. 2008. Effects of forest harvesting on ecosystem health in the headwaters of the New York City water supply, Catskill Mountains, New York. U.S. Geological Survey, Scientific Investigations Report, 22 pp.

Moffett, K., A. Atamian, C. How, L. Wordsman, and K. Kane. 2003. Evaluating management scenarios in the Croton Watershed. Available at http://gis.esri.com/library/userconf/proc03/p0925.pdf, pp. 18, *Proceedings of the 23rd Annual ESRI International User Conference*, San Diego, CA.

NRC. 2008. *Urban Stormwater Management in the United States*. National Academies Press, Washington DC.

NYSDEC. 1992. Reducing the impacts of stormwater runoff from new development. New York State Department of Environmental Conservation, Division of Water, Bureau of Water Quality Management, 156 pp.

NYSDEC. 2000. Phase II phosphorus total maximum daily loads for reservoirs in the New York City water supply watershed. New York State Department of Environmental Conservation, 54 pp.

NYSDEC. 2008. Enhanced Phosphorus Removal Standards, pp. 1-64, *New York State Stormwater Management Design Manual (April, 2008)*. New York State Department of Environmental Conservation.

Pelletier, D. M. 2001. The effect of earthworm invasion on nutrient cycling and hydrologic losses in two northern hardwood forests, *Department of Biology*. Cornell University, Ithaca.

Schaffner, W. R., and R. T. Oglesby. 1978. Phosphorus loadings to lakes and some of their responses. Part 1. A new calculation of phosphorus loading and its application to 13 New York Lakes. *Limnology and Oceanography* 23: 120-134.

Schueler, T. R. 1987. Controlling urban runoff: a practical manual for planning and designing urban BMPs, Publication #97703 of the Washington Metropolitan Council of Governments.

Schueler, T. R. 1992. Mitigating the adverse impacts of urbanization on streams: a comprehensive strategy for local government. *In* P. Kumble and T. R. Schueler [eds.], *Watershed Restoration Sourcebook*, Publication #92701 of the Metropolitan Washington Council of Governments.

Schueler, T. R. 1994. The importance of imperviousness. *Watershed Protection Techniques* 1: 100-111.

Tervahauta, A. I., C. Fortelius, M. Tuomainen, M. Akerman, K. Rantalainen, S. Timo, T., S. J. Lehesranta, K. M. Koistinen, S. Karenlampi, and K. Yrjala. in press. Effect of birch (*Betula* spp.) and associated rhizoidal bacteria on the degradation of soil polyaromatic hydrocarbons, PAH-induced changes in birch proteome and bacterial community. *Environmental Pollution*.

Todd, D. A. 1989. Impact of land use and nonpoint source loads on lake quality. *Journal of Environmental Engineering* 115: 633-649.

Trimble, S. W. 1997. Contribution of stream channel erosion to sediment yield from an urbanizing watershed. *Science* 278: 1442-1444.

Weisel, C. P., H. Kim, P. Haltmeier, and J. B. Klotz. 1999. Exposure estimates to disinfection by-products of chlorinated drinking water. *Environmental Health Prospectives* 107: 103-110.

Wilder, A. P., and E. Kiviat. 2008. The functions and importance of forests, with applications to the Croton and Catskill/Delaware watersheds of New York. Hudsonia, Ltd., Report to Croton Watershed Clean Water Coalition, 19 pp.

Withers, P. J. A., and H. P. Jarvie. 2008. Delivery and cycling of phosphorus in rivers: A review. *Science of the Total Environment* 400: 379-395.

Appendix I- Glossary of terms

Abiotic: having to do with the non-living factors of the environment, such as light, temperature, precipitation and soil chemistry

Biotic: having to do with the living organisms of an ecosystem

Catchment: a natural drainage area

Eutrophication: the effects of the abundant accumulation of nutrients that support a dense growth of algae and other undesirable organisms

Evapotranspiration: the combined processes of evaporation and transpiration (water vapor loss from plants) to the atmosphere

Hydrology: study of the properties, distribution, and circulation of water on and below the earth's surface and in the atmosphere

Impervious Surface: roofs, roads, parking lots, pavement, and other structures formed by water-resistant material, or compacted soil

Infiltration: the seepage of water into soil

Limiting Nutrient: a particular nutrient whose supplies are exhausted in the environment before other required nutrients

Macrophytic: having to do with macroscopic plants

Phosphorus Loading Rate: quantity of phosphorus entering a waterway in a given period of time

Pollutant Attenuation: the reduction of particular pollutants by uptake, degradation, trapping, and physical and chemical adsorption

Sedimentation: the deposition of suspended solids in waterways and waterbodies

Total Maximum Daily Load (TMDL): the maximum amount of pollution that a waterbody can assimilate without violating state water quality standards