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Forest Buffer Strips
Mapping the Water Quality Benefits

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ABSTRACT

Forest buffer strips are widely recommended for trapping nonpoint-source pollutants and protecting surface water quality, yet few models are designed to identify key areas for buffer installation and management. This article presents a conceptual model of polluted runoff dynamics to provide traction in estimating watershed-wide forest buffer needs. Inputs required for these estimates include elevation and land-cover maps, along with derived products that represent basic nutrient runoff principles.

Keywords: hydrology; nonpoint-source pollution

Section 303(d) of the Clean Water Act (33 USC 1313; 40 CFR 130.7) pursues the goal of fishable and swimmable waters by distributing management to individual states and requiring water body–specific plans to keep pollutants below the total maximum daily load (TMDL), beyond which waters are impaired. A review of 55 state-prepared TMDLs in nine of the 10 regions of the US Environmental Protection Agency (EPA) revealed that nonpoint-source controls such as forest buffers remain mostly unidentified and unenforceable (Houck 1999), which supports observations by (Ellefson et al. 2001) that compliance with spatially distributed management is posing a costly new challenge. Tools that direct managers toward the most critical watershed areas for buffering may prove helpful.

This research developed the Contributing Area–Dispersal Area (CADA) Export Coefficient (EC) model to direct watershed field visits to those sites where a significant pollutant load goes unfiltered into surface waters. Unlike a traditional export coefficient model, as described by Mattikalli and Richards (1996), the CADA model does not assume that every watershed area of similar land cover exports the same pollutant load to surface waters. Instead, the CADA-EC model adjusts pollutant export values using an assessment of surrounding watershed runoff and buffering capacity. Although forest management activities currently are not subject to TMDL regulations (Malmsheimer and Goergen 2000), the CADA-EC model can enhance foresters' efforts to improve our nation's waters.

Water Quality and Forests

Among the numerous management practices available to mitigate the water

Above: **A pastoral scene along the riparian edge of a tributary to the West Branch Delaware River. This watershed is the source for 25 percent of New York City's drinking water.**

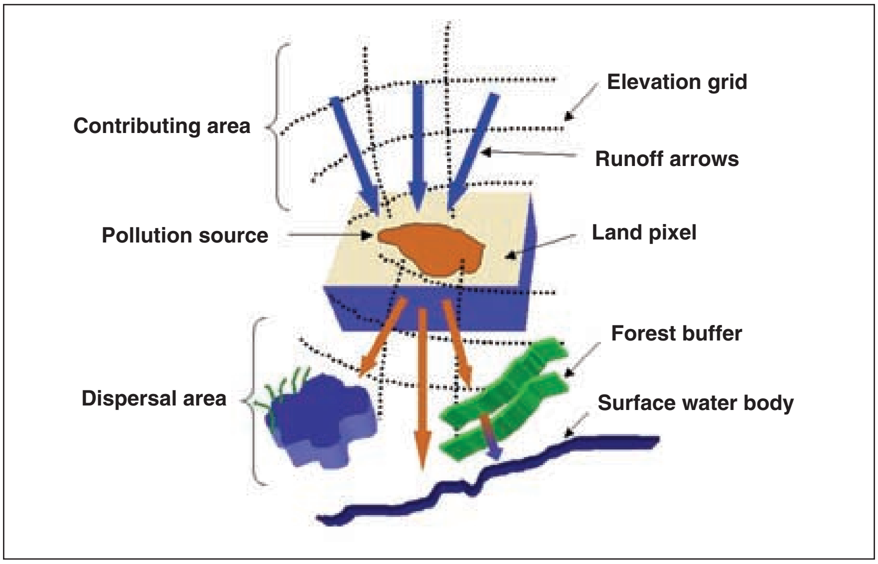

Figure 1. **Schematic of how the contributing area and dispersal area (CADA) interact to determine the fate of a land surface pollutant. The upslope area determines runoff likelihood, and the downslope area determines likely filtering.**

quality impact of agricultural nonpoint-source runoff, forest buffers remain one of the more widely adopted methods (Correll 1997). Despite the popularity of buffers, no efficient or automated methods exist for determining where buffers are likely to have the greatest impact within large watersheds where a river winds through a variety of land-use types.

Such a place is the topographically rugged Catskill and Delaware watershed. These 1,581 square miles are home to forests, crops, and cows and also to small towns, resorts, and numerous waterways supplying nearly 90 percent of New York City's drinking water. The city must ensure that this supply remains compliant with EPA drinking water standards and is thereby faced with either building a water filtration plant (at $6 to $8 billion for construction and $300 million for annual operation) or maximizing natural watershed filtration using methods such as forest buffers (Chichilnisky and Heal 1998). Although the city still enjoys a filtration avoidance determination, it has decided to begin construction of an ultraviolet disinfection facility to remove *Giardia* and *Cryptosporidia* pathogens.

Management and Modeling Dilemma

Estimating the capacity of forest buffers to filter nonpoint-source pollutants is a complex task. Tabacchi et al. (2000) and Correll (1997) present research documenting the forest buffer's influence as source and sink on hydrologic, chemical, and sediment balances, which depends on details of its canopy, woody stems, roots, and symbionts and the surrounding soils and environment. Although focusing on phosphorous pollutants—a primary concern for inland waters—simplifies the problem, dissolved phosphorous remains particularly tricky. Research has shown that a forest buffer can alternate between uptake and release of dissolved phosphorous depending on the details of local soil chemistry and vegetation management, such as harvesting nutrient-saturated material (Uusi-Kamppa et al. 1997).

Particulate phosphorous, which is the primary form of phosphorous in agricultural runoff, fortunately has been more reliably predicted (Uusi-Kamppa et al. 1997; Reed-Anderson et al. 2000), particularly when overland flow is mechanically or naturally spread across the landscape (Franklin et al. 1992; Dillaha and Inamdar 1997). Particulate phosphorous is therefore the focus of this work.

The traditional approach to simulating nutrient-buffer dynamics is ill suited for scoping future buffer needs for three reasons. Two of these issues stem from the complexity of data inputs for simulation, which include detailed spatial knowledge of precipitation, evaporation, erosion, sedimentation, infiltration, adsorption, and plant assimilation rates as well as natural and anthropogenic disturbances (Uusi-Kamppa et al. 1997).

First, the *cost* of gathering the needed data inputs to drive highly parameterized nutrient-buffer simulation models such as VFSMOD (vegetative filter strip model) and REMM (riparian ecosystems management model) would become prohibitive for areas larger than a hillslope. Second, the *process* of gathering the exhaustive data inputs for existing models would itself reveal basic buffer needs to knowledgeable field staff, precluding any benefits from using an automated tool. Third, the *output* of existing models does not explicitly track the pollutant pathway in nonbuffered areas and is thereby incapable of identifying buffer needs and potential buffer benefits.

Given these model limitations, this article recommends an alternative approach that uses readily available land-cover and terrain data to parameterize conceptual models that describe the runoff and trapping of surface pollutants such as particulate phosphorous. It should be noted that the arrogance of these watershed-wide buffering estimates is tempered by presenting results bounded in uncertainty, not as a single value.

Conceptual Model of Runoff

The science of watershed hydrology recognizes that heterogeneities in precipitation, land cover, soil types, topography, and human behavior all interact to make the spatial patterns of NPS runoff and the precise benefits of forest buffers difficult to predict. Predictions are needed, however, and hydrologists have done a remarkable job constructing simplified conceptual models that individually explain three basic components of nonpoint-source runoff.

The three component watershed models integrated in this research individually explain that

- The likelihood for excess pollutant on a watershed site is a function of the land-cover type or use, as defined by its export coefficient value.
- The likelihood for runoff to leave a

watershed site is a function of the size of the upslope contributing area and slope.

• The likelihood for polluted runoff to enter a surface water body is a function of the opportunities for pollution filtering within the runoff dispersal area. *Figure 1* illustrates how the fate of excess land surface phosphorous is controlled by the site's contributing and dispersal area.

Development of the CADA-EC model for estimating the impact of multiple forest buffers on phosphorous nonpoint-source runoff is based on a large volume of research documenting the reliability of each of the three separate conceptual models.

First, in agricultural catchments practicing traditional fertilization procedures, land-cover maps have explained a significant amount of the annual nutrient load observed at the basin outlet. This export coefficient model uses maps of watershed land cover to generate estimates of range in nitrogen or phosphorous pollution leaving the watershed (Reckhow and Simpson 1980; Beaulac and Reckhow 1982; Mattikalli and Richards 1996).

Second, in humid watersheds with moderate to steep relief and shallow depth to bedrock, watershed elevation maps have explained a significant amount of the pattern observed in runoff networks. This topographic index uses maps of watershed elevation to generate maps indicating the likelihood for saturation or runoff (Dunne and Black 1970; Beven and Kirkby 1979; Beven 1997).

Third, in cases where runoff carries sediment or particulate phosphorous, the presence of a forest or grass vegetative buffer has predictably filtered between 40 and 95 percent of the runoff load (Haycock et al. 1997; Reed-Anderson et al. 2000). This article extends this conceptual model to the watershed scale, and I will call it the buffer index (BI). The BI uses maps of buffer presence together with maps of elevation to estimate the potential for phosphorous filtering in buffers downslope of a watershed site.

The decision to combine these three models is based on their demonstrated robustness across many watersheds; their adherence to remaining as simple as possible, but no simpler, as recommended by authors of widely adopted models (Beven 1993; Einstein and Calaprice 1996) and contrasted with models that only function in data-rich research watersheds (Endreny and Wood 1999); and their ease of use and ability to serve environmental managers, not just academicians (Singh 1995).

Table 1. Range of unadjusted export coefficient (EC) values for land-cover classes, West Branch Delaware River watershed.

Land-cover class	Range of EC values		
	kilograms per hectare per year		
Deciduous forest	0.0350	0.1400	0.2325
Coniferous forest	0.0600	0.2000	0.2750
Grass, shrub	0.0305	0.2075	0.2538
Pasture	0.1900	0.2500	0.3775
Cornfield	0.6700	0.9500	2.6750
Winter spread manure, cornfield	3.0500	8.7000	15.1500
Alfalfa	0.6400	0.7600	1.2400
Bare soil	0.1000	0.1500	0.2000
Urban area	0.4875	0.9250	2.4500

Source: Reckhow et al. (1980).

Case Study of Water Quality Problems

The West Branch Delaware River, which flows into the Cannonsville Reservoir and provides up to 25 percent of New York City's drinking water, drains a 350-square-mile mixed agriculture-forested watershed that suffers from excessive phosphorous nonpoint-source runoff. While the particulate phosphorous loads originate predominantly from cornfields and the nearly 12,000 head of cattle, septic systems and wastewater treatment plants contribute the disproportionate share of dissolved phosphorous (Brown et al. 1989). The total phosphorous load into the West Branch Delaware River stimulates excessive and unwanted algal growth in the reservoir, and strategies have long been sought to use forest buffers to filter the nonpoint-source phosphorous. The annual pollutant load for this watershed was simulated using the Arc macro language scripts within the ArcInfo GIS package and 30-meter pixel (picture element) datasets.

Export coefficients. The first step in the CADA-EC model is to assign EC values to each land-cover pixel on the watershed land-cover map. As shown in *table 1,* these values represent the likely range of phosphorous discharged per hectare per year from each land-cover type. When applying the CADA-EC model to the West Branch Delaware River watershed, the range of unadjusted EC values were used to represent the uncertainty and variability in using empirical data from other watersheds. Although the traditional EC model simply sums the exported load for all pixels in the watershed to obtain a total basin phosphorous load, this article emphasizes another approach.

Critical to the CADA-EC model is the use of dynamic EC values that are weighted before they are summed. The CADA-EC model replaces the use of identical EC values for all identical land-cover types and instead weights each EC value according to the magnitude of upslope runoff and the downslope buffering. Incorporating this flexible behavior is in keeping with field observations that certain watershed areas generate more runoff than others and that runoff entering a buffer has a better chance to trap pollutants than one passing directly to a stream *(fig. 1).* In short, while this alternate approach predicts the same total basin phosphorous load as the traditional EC model, it maps areas of low and high pollution loading after thoroughly scouring the surrounding watershed terrain and land cover.

Topographic index. The second step in the CADA-EC model is to use the digital terrain map to examine the contributing area and estimate the runoff likelihood, represented by topographic index (TI) values. The TI is computed by dividing the upslope contributing area draining into each pixel by the local pixel slope. TI values have their

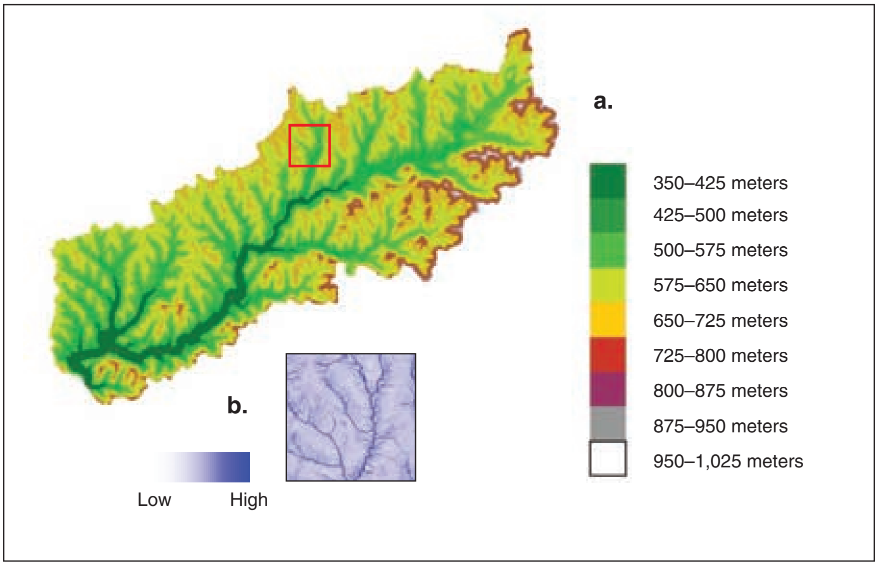

Figure 2. **(a) Elevation map of the West Branch Delaware River, ranging from 350 to 1,000 meters, with the red square highlighting the area of detail in (b), the computed topographic index map, where dark blue indicates areas likely to generate more runoff.**

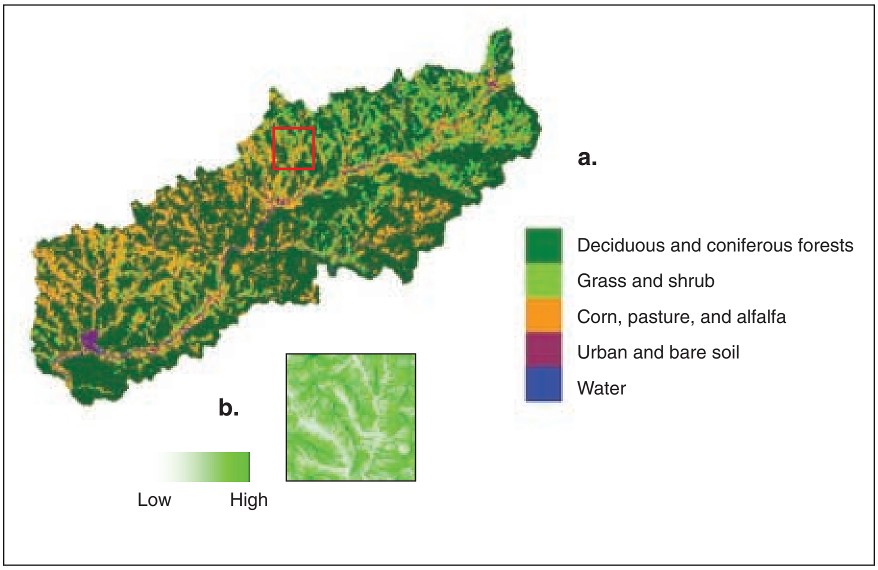

Figure 3. **(a) Land-cover map of the West Branch Delaware River, consolidating agricultural and forestland cover types for image clarity. The red square highlights the area of detail in (b), the computed buffer index map, where light green indicates areas with little buffering downslope.**

greatest meaning when they are normalized by the watershed's average topographic index (TI_{avg}) value. When this normalized TI value is greater than 1, the local TI value has above-average upslope areas, or a flatter pixel slope, and therefore has a greater likelihood of being saturated and generating runoff toward downslope waterways. *Figure 2* shows both the West Branch Delaware River watershed pixel map of elevation data and its associated TI, which represents a soil saturation and runoff likelihood map for the watershed.

Buffer index. The third step in the CADA-EC model is to use both the digital terrain map and the land-cover map to compute the BI. The BI is the product of the runoff dispersal area for each watershed pixel (derived from the terrain map) and the number of forest or grass buffer pixels in that dispersal area (derived from the land-cover map). Whereas the BI can focus on a single buffer category (e.g., grass, wetland, or forest), combining all field-observed buffers captures the total downslope likelihood for phosphorous filtering. Normalizing the BI by the average buffer index (BI_{avg}) provides an index that reveals below-average buffering when values are below 1, which indicates a greater chance for pollutant discharge into waterways. *Figure 3* shows both the West Branch Delaware River watershed land-cover map and the derived BI map, where higher values are associated with an increased likelihood for filtering.

The CADA-EC model performs a search of the entire watershed to identify areas receiving a large volume of upslope runoff, having available nutrients for export, and draining into few or no buffers downslope. Inadequate downslope filtering is the focus for new forest buffers. Research summarized by Uusi-Kamppa et al. (1997) reports a range in total phosphorous trapping efficiency of both forest and grass buffers, where the two systems are considered to trap with equal efficiency (Dillaha and Inamdar 1997). *Figure 4* depicts phosphorous retention leveling out prior to the 30-meter buffer width, yet the scatter in these data justified use of a conservative buffer 50 percent retention value in CADA-EC model simulations.

Model Predictions

The CADA-EC model uses GIS map algebra tools to multiply the export coefficient map by a normalized map of the TI and the inverse of the BI to generate a watershed map illustrating the likelihood for each pixel to discharge phosphorous into the Cannonsville Reservoir:

$$EC_{Wi} = EC_i \cdot \frac{TI_i}{TI_{avg}} \cdot \frac{BI_{avg}}{BI_i}$$

where EC_{Wi} is the weighted export coefficient value for pixel *i*. Predicted annual total phosphorous loads into the West Branch Delaware River, along with their error value, are shown in *Figure 5*. The observed data are based on storm event sampling performed by the New York State Department of Environmental Protection. It is important to note that these predicted and observed phosphorous values represent agricultural sources in addition to wastewater and septic sources (Longabucco and Rafferty 1998). More important than basin loads, however, are the maps isolating where loading is most pronounced and buffers needed.

Field observations, while historical, reported nonpoint-source phosphorous loads entering the West Branch Delaware River system in the same principal areas predicted by the CADA-EC model (Brown et al. 1989). Hence, maps of model outputs can reasonably isolate areas where additional buffers are needed and where existing buffers should be actively managed to maximize particulate phosphorous trapping and minimize dissolved phosphorous leaching. *Figure 6* shows an agricultural section of the West Branch Delaware River watershed where phosphorous runoff contributed a disproportionate share of the entire basin load, thereby indicating downslope areas where forest buffers are needed to improve water quality.

Gathering Inputs

Inputs for the CADA-EC model are publicly available from many federal and state environmental management agencies, and more detailed or updated images can be purchased from satellite and airborne remote sensing operations. Digital elevation model data are downloadable from the US Geological Survey Eros Data Center (http://edc.usgs.gov/dsprod/prod.html) with pixel resolutions ranging from 30 meters to 1 kilometer. The resolution needed depends on the variation in the terrain, but most watershed studies would benefit from 90-meter resolution or finer. Key land-cover types within the watershed include the water resources, agricultural fields, and forests and forest buffers. Landsat satellite 30-meter pixel multiresolution land-cover (MRLC) imagery, available from EPA (www.epa.gov/mrlc), works well in distinguishing agricultural and forested land, but these images may benefit from reclassification of narrow water bodies and forest buffers.

The national hydrography dataset (NHD), available from USGS (http://nhd.usgs.gov), is a good source for

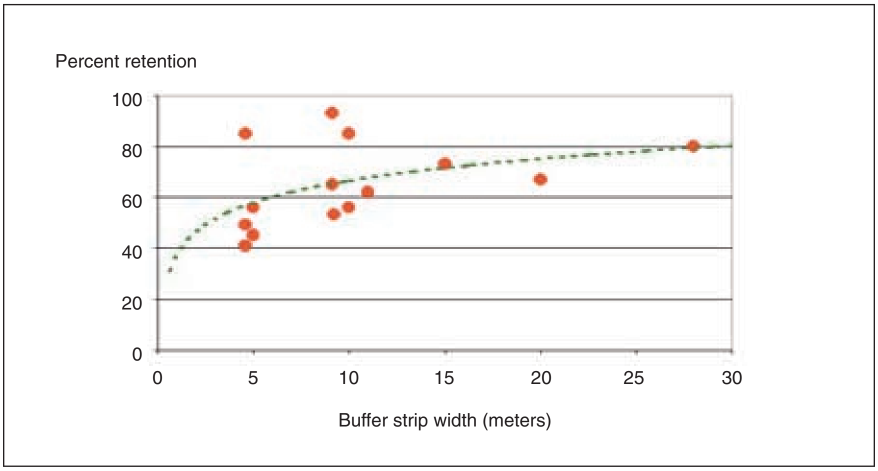

Figure 4. **Percent retention of phosphorous runoff by grass and forest buffers, indicating that trapping variability begins to level off at the 15-meter pixel width. *Source:* Uusi-Kamppa et al. (1997).**

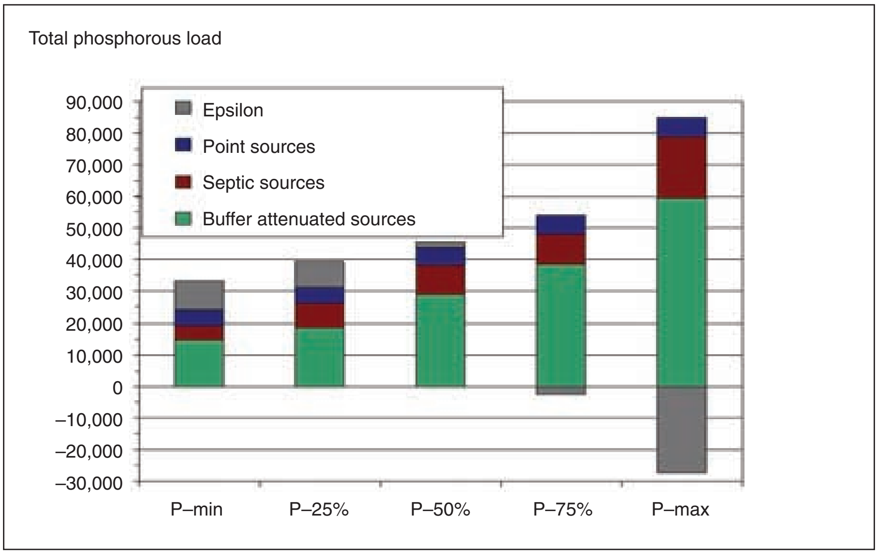

Figure 5. **Average predicted loading of total phosphorous into the West Branch Delaware River for 1993 and 1994, along with the error (predicted – observed = epsilon) of this prediction based on observed data collected by Longabucco and Rafferty (1998).**

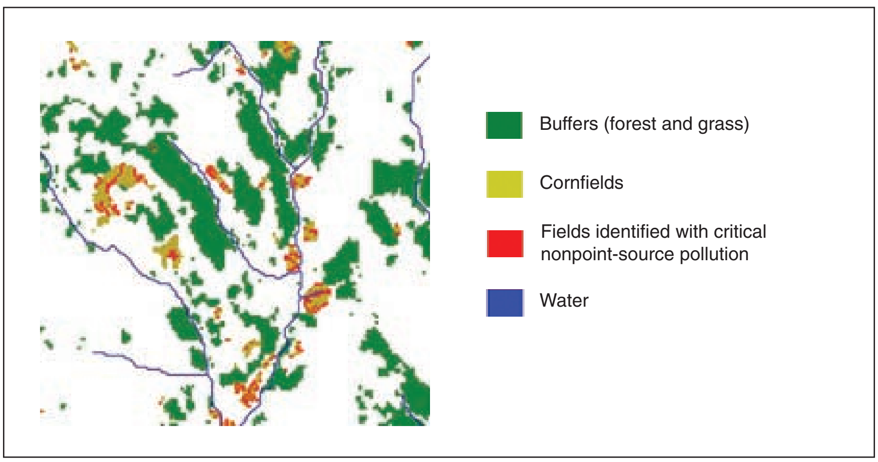

Figure 6. **A section of the West Branch Delaware River watershed. Red indicates the agricultural areas contributing the disproportionate share of the polluted runoff, thereby targeting multiple downslope watershed areas for possible forest buffer strips.**

identifying narrow streams and other water resources. Forest buffers narrower than 30 meters can often be identified with the 1-meter resolution digital orthophotography quarter quadrangles, available from most states (e.g., New York's DOQQ product is available at www.nysgis.state.ny.us/gateway/mg/interactive_main.html). For a discussion of other products available from airborne remote sensing, see King (2000), who points out that the 1-meter data should be limited to smaller watershed studies (less than 4 square miles) because of image file size constraints in larger watersheds.

The CADA-EC model is designed as both a learning tool and a management tool. Because of its simplicity, its predictions are bounded in uncertainty and for that reason stand to capture the average behavior of the watershed. Managers should field-check all proposed sites, but model-generated maps of target areas can certainly aid in the effort.

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