USE OF A GEOGRAPHIC INFORMATION SYSTEM TO ADD A SPATIAL COMPONENT IN WATER-QUALITY MODEL VARIABLES TO ESTIMATE ATRAZINE LOADING IN MORGAN CREEK, MARYLAND

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Abstract

As part of an intensive study of agricultural watersheds being done by the U.S. Geological Survey (USGS) National Water-Quality Assessment (NAWQA) Program, a spatial analysis of landscape data was conducted at the Morgan Creek, Maryland (33 km^2) Watershed. A geographic information system (GIS) was used to identify areas within this watershed that would most likely produce saturation-excess and infiltration-excess overland flow. These areas were further analyzed according to their flow-path distance to streams and used to estimate the potential delivery of atrazine to surface-water bodies. In the watershed, the corn fields, on which atrazine is applied, are likely to produce more infiltration-excess overland flow than saturation-excess overland flow. The highest TWI values are located in high clay soils near the stream. This approach will be applied to multiple NAWQA agricultural watersheds throughout the country to estimate in-stream atrazine concentrations.

INTRODUCTION

Limited research has been done on understanding the spatial patterns of saturated areas and their relation to the landscape. Moreover, the capacity of hydrologic models to represent these spatial patterns and relations is insufficient (Gunter, 2004).

The likelihood of a point on the landscape being a contributing source of chemicals to a stream is determined, in part, by its distance to the stream, soil permeability, land use, and topography (Juracek, 2002; Larson and others, 2004; Gunter, 2004). These landscape factors, which are variable over space, affect two runoff-generating processes that can transport agricultural chemicals from the land surface to a stream: infiltration-excess overland flow and saturation-excess overland flow. Individually, and in combination with one another, these landscape factors have different effects on how water and chemicals are delivered to the stream. Knowing the permeability of soils where atrazine is applied may be important in understanding how chemicals and water behave at that point within a watershed. In addition, it may also be important to know the physical and chemical characteristics of the pathway upstream from that same point. If upstream conditions are conducive to high runoff, this result may affect the fate of chemicals applied at that downstream point. Likewise, knowing that the flow-path distance to the stream from that point is short and the likelihood of overland flow high may also affect the fate of chemicals from that point.

Juracek (2002) used a geographic information system (GIS) to estimate the spatial distribution of potential runoff-contributing areas in Kansas by analyzing soil properties and topographic characteristics, both of which affect saturation and infiltration-excess overland flows. Juracek (2002) quantified the topographic effect on saturation-excess overland flow by calculating Topographic Wetness Index (TWI) values following an approach described by Wolock and McCabe (1995). TWI values are defined for a point in a watershed as the natural logarithm of the upslope area per unit contour length divided by the slope at that point. Higher TWI values have comparatively larger upslope areas with relatively flat slopes and are most likely to contribute saturation-excess overland flow. In the same study, Juracek (2002) quantified the effects of spatially variable permeability on infiltration-excess overland flow. These predicted areas of potential saturation-excess and infiltration-excess overland flow were combined within the GIS to estimate potential runoff contributing areas within watersheds in Kansas. Areas with the highest potential for runoff had low soil permeability and high TWI values.

As part of the U.S. Geological Survey (USGS) National Water-Quality Assessment (NAWQA) Program, Larson and others (2004) developed an empirical model called the Watershed Regressions for Pesticides (WARP) to statistically relate atrazine concentrations in streams to watershed characteristics for 112 watersheds across the country. Using national data, they examined 34 variables in developing their model and found that atrazine-use intensity (the amount of atrazine applied in a watershed divided by the watershed area) was the most significant variable in predicting atrazine concentrations in streams. They also found that soil- and terrain-based watershed characteristics improved the predictive power of the regression models. Larson and others' (2004) approach, however, was based on average watershed characteristics of a watershed and lacked a detailed spatial component. For example, their approach did not consider whether atrazine was applied to fields prone to overland flow or in close proximity to the stream. The purpose of the analysis described in this paper is to demonstrate how a more complex spatial analysis of watershed characteristics can be incorporated into estimates of pesticide-use intensity. An extension of the study will be to apply and test this method in the set of watersheds used by Larson and others (2004).

Study Area

The enhanced spatial analysis was developed for the Morgan Creek Watershed (Figure 1). This watershed was selected because it is a part of an intensive study of agricultural watersheds currently being conducted by the NAWQA Program. The Morgan Creek Watershed (31 km^2) is located in Kent County, Maryland on the Delmarva Peninsula and drains into the tidal Chester River. The watershed lies within the Coastal Plain, which is a generally flat lowland area of moderate topographic relief (0 to 75 feet) with permeable and porous soils and sediments that are suitable for farming. Row-crop agriculture is the principal land use within the watershed and is dominated by row crops such as corn to which the herbicide atrazine is applied. The watershed receives abundant precipitation throughout the year, although irrigation systems are used during occasional droughts. Ground-water and overland runoff are important components of streamflow with base flow contributing about 60 percent of total streamflow (T. Hancock, U.S. Geological Survey, written commun., 2005).

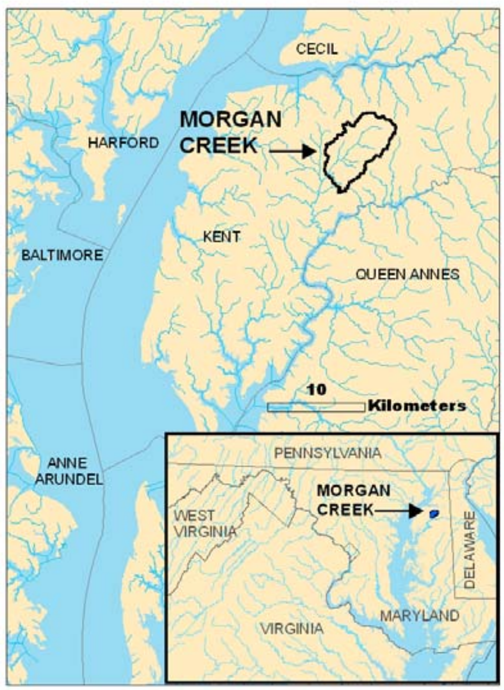


Figure 1. Location of Morgan Creek Basin, Maryland.

In the Morgan Creek Watershed, atrazine is only used on corn; therefore, subsequent analysis was done only for corn-cropped areas (Figure 2). An annual watershed-wide atrazine use of 2,428 kilograms was reported in 2004 (T. Hancock, U.S. Geological Survey, written commun., 2005). On the basis of detailed, ground-truthed land-use data, corn use areas were delineated and mapped (T. Hancock, U.S. Geological Survey, written commun., 2005). Although there are no annual estimates for atrazine fluxes in the stream for the entire watershed, there have been some atrazine measurements made at USGS streamgage 01493500 during storms. These measurements have been used to estimate an annual atrazine in-stream loading for the entire watershed of about 24 kilograms, or 1 percent of the total amount of atrazine applied to fields in the Morgan Creek Watershed (M.J. Brayton, U.S. Geological Survey, written commun., 2005).

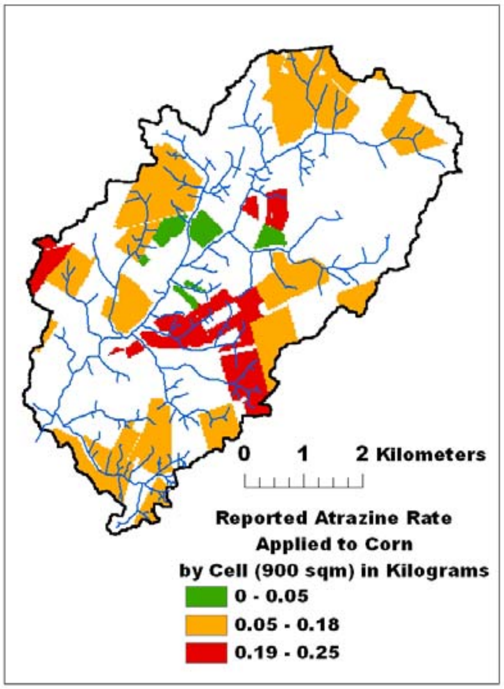


Figure 2. Location of corn fields and their reported atrazine rates by 30-meter cell in Morgan Creek Basin, Maryland.

ANALYSIS METHODS

The spatial analysis consisted of five steps described in more detail below.

1. The rate of atrazine application, TWI values (a proxy for saturation-excess overland flow), percent clay (a proxy for infiltration-excess overland flow) and the flow-path distance to the stream were all mapped in a raster format at a 30-meter resolution for the Morgan Creek Watershed.
2. The grid-cell values of TWI, percent clay, and flow-path distance each were normalized into a range varying between 0 and 1 to reflect their effects on retarding (a value of 0) or facilitating (a value of 1) the transport of atrazine to the stream.
3. The grid-cell values were combined in a simple weighting calculation to estimate the atrazine loading rate to streams contributed from each cell on the land surface.
4. All cells were summed to predict an annual watershed-wide atrazine loading to streams.
5. A transport-efficiency value was calculated. This value is defined as the estimated loading to streams divided by the total atrazine applied to the watershed.

A digital elevation model (DEM), derived from Light Detection and Ranging (LIDAR) radar, was used to calculate the TWI values at a 30-meter resolution (M.R. Nardi, U.S. Geological Survey, written commun., 2005). The TWI is computed as *ln(a/S)* for all 30-meter cells in the watershed, where *ln* is the natural logarithm, *a* is the upslope area per unit contour length, and S is the slope at that point (Wolock, 1993). The TWI is directly related to the likelihood that a grid cell in the watershed will produce saturation-excess overland flow. The percentage of clay in the soil, as given in the Soil Survey Geographical Database (SSURGO; Natural Resources Conservation Service, 2005), was used to quantify the likelihood that each cell would produce infiltration-excess overland flow. Cells most likely to produce infiltration-excess overland flow have low soil permeability, indicated in this study by high percent clay. Finally, by using a flow-direction map derived from the DEM, the flow-path distance to the nearest stream was calculated for each grid cell.

The distance to stream value for each cell was normalized into a range of 0 to 1 by the use of the following equation:

$$DIST_{norm} = (DIST_{max} - DIST) / (DIST_{max} - DIST_{min}), \quad (1)$$

where:

$DIST_{norm}$ is the normalized distance value, ranging from 0 to 1;
$DIST$ is the distance to the nearest stream from a point;
$DIST_{max}$ is the maximum distance to a stream from any point in the watershed; and
$DIST_{min}$ is the minimum distance to a stream from any point in the watershed.

The TWI value for each cell was normalized into a range of 0 to 1 as:

$$TWI_{norm} = (TWI - TWI_{min}) / (TWI_{max} - TWI_{min}) \quad (2)$$

where:

TWI_{norm} is the normalized topographic wetness index value, ranging from 0 to 1;
TWI is the topographic wetness index value at a point;
TWI_{min} is the minimum topographic wetness index value in the watershed; and
TWI_{max} is the maximum topographic wetness index value in the watershed.

The CLAY value for each cell was normalized into a range of 0 to 1 as:

$$CLAY_{norm} = (CLAY - CLAY_{min}) / (CLAY_{max} - CLAY_{min}) \quad (3)$$

where:

$CLAY_{norm}$ is the normalized percent clay value, ranging from 0 to 1;
$CLAY$ is the percent clay value at a point;
$CLAY_{min}$ is the minimum percent clay value in the watershed; and
$CLAY_{max}$ is the maximum percent clay value in the watershed.

A normalized TWI value of 1 (Figure 3) indicates optimal conditions for a cell to produce saturation-excess overland flow and deliver atrazine to the stream. A normalized CLAY value of 1 shows the locations most likely to generate infiltration-excess overland flow and deliver atrazine to the streams. A normalized DIST value of 1 indicates that the area is adjacent to a stream channel and, hence, would quickly deliver overland flow to the stream network. A normalized value of 1 for all three variables would indicate maximum efficiency for transport of atrazine from the land surface to the stream.

Quantification of the effects of the normalized landscape variables on atrazine transport from the land surface to the stream was treated in a simple multiplicative manner. For each grid cell, the amount of atrazine applied to the land surface was multiplied by two normalized transport factors as:

$$Atrazine_{contributed} = Atrazine \times DIST_{norm} \times Overland\ flow \quad (4)$$

where:

$Atrazine_{contributed}$ is the mass of atrazine delivered to the stream,
$Atrazine$ is the mass of atrazine applied to the land surface,
$DIST_{norm}$ is the normalized distance to the stream, and
Overland flow is the higher of the TWI_{norm} or $CLAY_{norm}$ values.

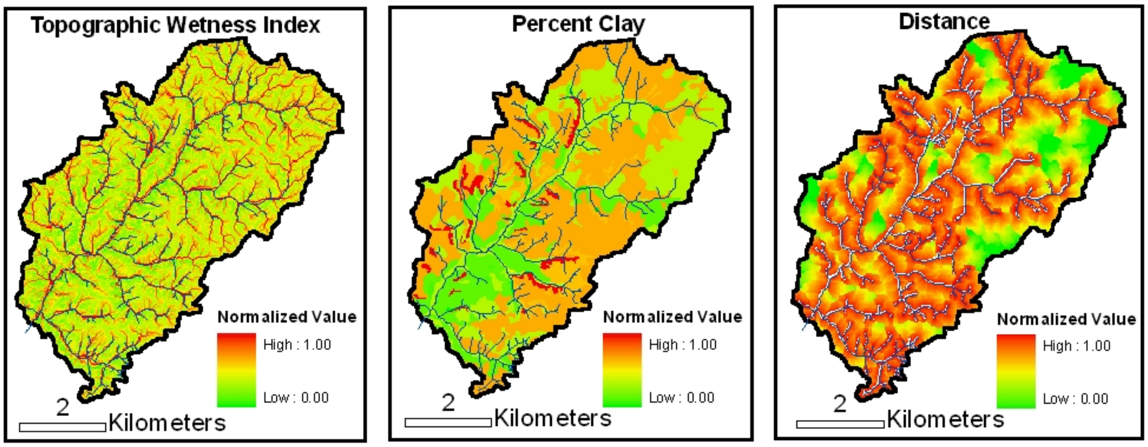


Figure 3. Normalized data for Morgan Creek Basin, Maryland

(The higher of the normalized TWI or CLAY values represents the overall likelihood that overland flow will be generated on a grid cell.) Note that equation 4 represents the combined effects of topography, soils, and stream proximity on atrazine delivery to the stream. The isolated effect of any single factor could be considered by removing the other factors from the equation. For example, the effect of distance to the stream alone can be estimated as:

$$Atrazine_{contributed} = Atrazine \times DIST_{norm} \quad (5)$$

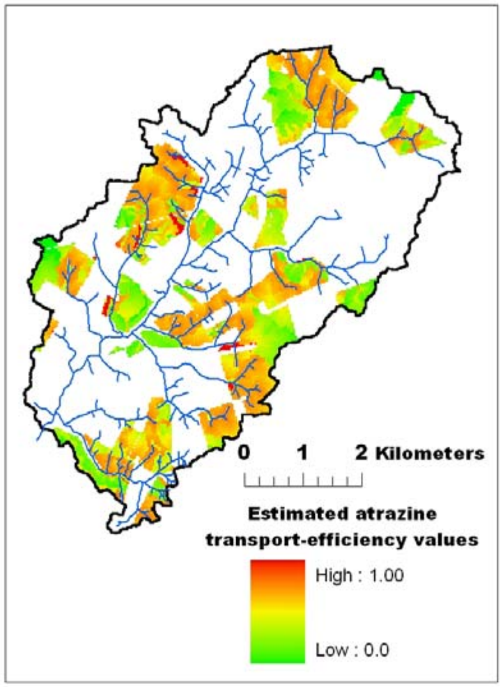
The total amount of atrazine contributed to the stream from the entire watershed was computed by summing the $Atrazine_{contributed}$ values for all grid cells in the watershed. The transport efficiency then was calculated by dividing the total atrazine contributed to the stream by the total atrazine applied to the watershed.

RESULTS AND DISCUSSION

The separate and combined effects of the landscape terrain and soil variables are shown in table 1. These effects are expressed as efficiency values, where values of 0 and 100 percent would indicate, respectively, that none or all of the atrazine applied to the land surface was transported to the stream. An efficiency value of 0 percent would represent a watershed in which all atrazine was applied to extremely permeable land surfaces (no overland flow) located far from any stream. An efficiency of 100 percent would represent a watershed where all the atrazine was applied to impermeable surfaces (high rates of overland flow) located adjacent to a stream (Figure 4).

Table 1. Estimated atrazine transport-efficiency values as a function of landscape variables.

Landscape variable	Hydrologic factor	Efficiency (%)
CLAY	Infiltration-excess overland flow	59
TWI	Saturation-excess overland flow	28
DISTANCE	Proximity to stream	82
CLAY + DISTANCE	Infiltration-excess overland flow Proximity to stream	48
TWI + CLAY	Saturation-excess overland flow Infiltration-excess overland flow	59
TWI + DISTANCE	Saturation-excess overland flow Proximity to stream	22



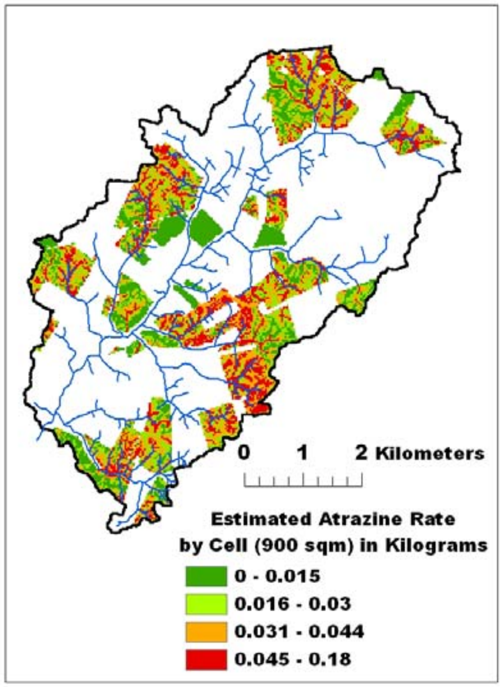
TWI	Saturation-excess overland flow	48
+ CLAY	Infiltration-excess overland flow	
+ DISTANCE	Proximity to stream	

All the landscape variables affected the theoretical efficiency of atrazine transport from the land surface to the stream. The higher efficiency for CLAY (59%) compared to TWI (28%) indicates that in Morgan Creek, the corn fields on which atrazine is applied are more likely to produce infiltration-excess overland flow (high CLAY) than saturation-excess overland flow (high TWI). The high efficiency value (82%) for proximity to the stream indicates that most corn fields in the watershed are not far from the stream. This result is a function of the specific location of corn fields in Morgan Creek and, more importantly, the assumed mathematical relation between distance to the stream and transport efficiency. For example, if equation 5 was modified such that the value of $DIST_{norm}$ was raised to some power greater than 1, then the effect of $DIST_{norm}$ would be amplified. This effect is true for all the landscape variables considered in the analysis; the specific result is sensitive to the mathematical form of the equations.

There is no increase in transport efficiency when infiltration-excess and saturation-excess overland flows are combined (Table 1) compared to infiltration-excess overland flow alone. This result implies that, in general, grid cells expected to produce saturation-excess overland flow (high TWI values) also are expected to generate infiltration-excess overland flow (high CLAY values). When stream proximity is combined with the overland-flow variables, however, the efficiency decreases compared to when stream proximity is not included. The estimated annual atrazine contributed to the stream from each grid cell (Figure 5) confirms that the highest values are located in high clay soils located near streams. (Compare Figure 3 to Figure 5.)

Figure 4. Estimated atrazine transport-efficiency values in Morgan Creek Basin, Maryland.

The results shown for Morgan Creek (Table 1) depend on the weighting factors assumed to control atrazine transport from the land surface to the stream; including other variables would change the results. Dates of atrazine application and meteorological data, including timing of the first storm event after application, are important and would add a temporal component to the analysis. Other data, such as known absorption rates of atrazine by plants and the amount of water that flows through the system in a given growing season, also would refine the method. It is worth noting



that the lowest transport efficiency in Table 1 is 22%. This value is much higher than the 1% value reported for Morgan Creek in 2004. The discrepancy may be due, in part, to lack of consideration of these additional factors.

The spatial analysis methods, including the proposed refinements, will be tested when the approach is applied to the 112 WARP study watersheds. The transport-efficiency-adjusted atrazine loading values will be related to measured atrazine concentrations in streams. Refinements to the spatial analysis will be evaluated in terms of improvements in the observed relations between atrazine-use intensity and measured stream concentrations.

Figure 5. Estimated annual atrazine mass contributed to the stream for each 30-meter cell for Morgan Creek Basin, Maryland.

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