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Estimating sediment, nitrogen, and phosphorous loads from the Pipestem Creek watershed, North Dakota, using AnnAGNPS

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ABSTRACT

Agricultural pollution is a significant problem in North Dakota. Water quality in the Pipestem Creek watershed upstream of Pingree, North Dakota, USA, has been a major environmental concern amongst other adjacent watersheds within the region. The annualized agricultural non-point source (AnnAGNPS) model, a large-scale watershed model designed to predict sediment and nutrient loads, was used to evaluate non-point source pollution in a typical agricultural watershed. The best available data were assembled and used in the analysis. The model predicted runoff of 0.31 m^3/s, compared to a measured value of 0.46 m^3/s. A poor correlation was observed when comparing the model's predicted nitrogen, phosphorus, and sediment with the observed counterparts. The model's poor performance was most likely a result of the large size of the study area and the high variability in land use and management practices.

1. Introduction

The 1972 Clean Water Act (CWA) mandated by the Environmental Protection Agency (EPA) set the groundwork for the regulation, enforcement, and monitoring of surface water quality across the USA. The focus in the early decades following the CWA was on controlling point sources, such as wastewater plant discharges and construction sites (EPA, 2008). In the past decade, more attention has revolved around non-point source pollution, with the EPA stating that non-point source pollution is the most significant source of pollution in the United States. As a result, the CWA contains Section 303(d), which requires each state to list the quality-limited waters needing total maximum daily load (TMDL) studies to improve the situation. According to the North Dakota Department of Health (NDDH), 18% ($\approx$6000 km) of the assessed rivers and streams fully support the beneficial use designated as aquatic life, while the remaining 82% do not support aquatic life (NDDH, 2006). Of the 82%, a little more than 62% ($\approx$3750 km) are considered threatened. According to the NDDH report, of the 95.5% of the lakes and reservoirs assessed, 56% are considered threatened (NDDH, 2006). The primary cause of these impairments can be attributed to non-point source pollution. A threatened assessment means that the continuation of current water quality and/or watershed trends would make it unlikely that these water bodies will continue to support aquatic life and human consumption (NDDH, 2006).

Nutrients in a water body such as nitrogen and phosphorus are considered to be pollutants when these nutrient concentrations become excessive, causing some organisms to proliferate at the expense of others (Davis and Masten, 2004). This point is exemplified by eutrophication, which is caused by excessive algae growth in a water body from surrounding agricultural watersheds due to the excessive presence of the necessary growth nutrients and ambient conditions that promote algal blooms. This enhanced plant growth reduces the dissolved oxygen levels when the plants decompose, potentially hindering the survival of fish and other aquatic life that depend on pristine conditions. These physical and chemical changes may interfere with the recreational and aesthetic uses of the water body, while both taste and odor problems may make the water less desirable for water supply and human consumption (Ritter and Shirmohammadi, 2001). In the Great Plains of North Dakota, low fertilizer nitrogen use efficiency (NUE) and nitrate–N (NO_3–N) leaching in irrigated and dryland crop production systems also contribute to the degradation of groundwater. AnnAGNPS can be used to evaluate the impact of management decisions like low fertilizer NUE and NO_3–N leaching on a watershed system. AnnAGNPS is an expansion of the AGNPS (Young et al., 1989) model. It is a batch process, continuous simulation, surface-runoff, pollutant-loading model written in standard ANSI FORTRAN 95. The modeling environment of AnnAGNPS is comprised of several modules that

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require intensive input preparation. The basic modeling components are hydrology, sediment, nutrient, and pesticide transport. Homogenous land areas are created with respect to soil type, land use, and land management, which can be either cell or hydrologically-based. The physical or chemical constituents are routed from the upstream land area and are either deposited within the stream channel or transported out of the watershed.

Surface runoff is estimated using the Natural Resources Conservation Service (NRCS, 2008) Curve Number (CN) method, along with the simulator for water resources in rural basins (SWRRB) and erosion-productivity impact calculator (EPIC) models (Williams et al., 1983; Williams et al., 1985). The CNs represent the runoff-producing potential of soils and have a range 0–100. The CN depends on land cover, land use, and antecedent moisture conditions (AMC). The AMC conditions are based on soil moisture; AMC I for dry conditions, AMC II for average soil moisture, and AMC III for wet conditions. The actual curve number used for calculating runoff is allowed to vary depending on the soil water content, using each soil's wilting point and field capacity values. The time of concentration for in-cell and in-channel concentrated flow is estimated for each cell within AnnAGNPS using the TR55 method (USDA, 1986). Peak discharge is estimated using an extended TR55 procedure, which utilizes unit peak discharge regression coefficients.

Overland sediment losses are calculated by a sheet and rill erosion model, which uses the Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1997). RUSLE estimates the sediment loss resulting from raindrop splash and runoff from specific field slopes in the cropland, disturbed forestland, and grassland, among other land types. The amount of sediment delivered to the channel is determined by a delivery ratio, using the hydro-geomorphic universal soil loss equation (HUSLE) (Theurer and Clarke, 1991). Field deposition is determined using a deposition ratio mass rate method, allowing for the elucidation of the particle size distribution of the sediment yield of the sheet and the rill erosion in the receiving reach of the stream system (Binger et al., 2007). Channel sediment is then routed downstream by a modified Einstein deposition equation using the Bagnold equation for the transport capacity according to the particle size class (Binger et al., 2007).

Chemical reach routing exists in two phases: those that are dissolved and hence mobile and those that are immobilized on fine sediments. The chemical reach routing includes (1) the fate and transport of nitrogen, phosphorus, and any number of pesticides, and (2) a separate reach routing routine for organic carbon. Nitrogen and phosphorous are recognized to exist in both soluble and adsorbed states. Only inorganic phosphorus is subjected to equilibrium, whereas organic phosphorus is assumed to be insoluble (Binger et al., 2007). Organic carbon is assumed to be part of the clay-size particles with a known organic carbon-to-clay ratio. Independent equilibrium is assumed for each pesticide, and each pesticide is treated separately (Binger et al., 2007).

The use of the AnnAGNPS model to evaluate an agricultural watershed and model runoff, nitrogen, phosphorus, and sediment transport were the primary focus of this study. Intensive agricultural activity has contributed to eutrophication of the Pipestem Reservoir, which has been reported to be impaired and to require a TMDL for nutrient/eutrophication, as stipulated by NDDH (NDDH, 2006). The Pipestem Creek watershed above Pingree, North Dakota was therefore selected as the study area. The impaired Pipestem Reservoir is located approximately 30 km (19 mi.) downstream of the Pipestem Creek watershed outlet, just west of Jamestown, ND. The main objectives were (1) to calibrate and validate an AnnAGNPS model for Pipestem Creek, ND, and (2) to predict the areas most susceptible to NPS pollution.

2. Model implementation

2.1. Study area

The study area covers four counties in east central North Dakota: Foster, Kidder, Stutsman, and Wells. The watershed area determined from this study is 419,389 acres (1697 km^2), with a south-eastern direction of flow of the three main contributing streams: Little Pipestem Creek, Pipestem Creek, and an Unnamed Tributary (Fig. 1). The outlet location chosen is along Pipestem Creek, 5 km (3 mi.), west of Pingree, ND. The outlet coincides with the United States Geological Survey (USGS) Gauging Station 06469400, at approximately 47.175°N and 98.986°W. The Pipestem Creek watershed is predominately agricultural in landuse, as shown in Table 1.

2.2. Input parameters

2.2.1. Topography data

This study utilized National Elevation Dataset (NED) 1-arcsecond grids (USGS, 2007), which were resampled to a resolution of 30 m. A 30 m cell size was adequate for the large area of the watershed under study, which reduces the number of grid cells for processing compared to 1/3-arcsecond grids. The TopAGNPS program, which is included with the AnnAGNPS distribution, has a maximum number of rows and columns that can be processed. A 4000 by 4000 grid cell matrix is the recommended maximum (Binger et al., 2007). The TopAGNPS program is an automated analysis tool for topographic evaluation, drainage identification, watershed segmentation, and subcatchment parameterization. It utilizes widely available digital elevation models (DEMs) for its analysis. The TopAGNPS program consists of three programs: (i) Digital Elevation Drainage Network Model (DEDNM), (ii) RASter PROperties (RASPRO), and (iii) RASter FORmatting (RASFOR) (Garbrecht and Martz, 1999).

The DEDNM program pre-processes the elevation data so that downslope drainage is obtained. Prior removal of any sinks and depressions eliminates inherent raster errors. The watershed boundary and the drainage network, channel link, and subcatchment properties and parameters can thereafter be developed. DEDNM requires an outlet location, a minimum drainage area known as the critical source area (CSA), and a minimum source channel length (MSCL). The outlet location can be determined using the AGNPS/ArcView 3 × with the Spatial Analyst interface. The CSA and MSCL values change the density of the sub-watersheds, i.e., higher CSA and MSCL values increase the size of the sub-watersheds. The Pipestem Creek watershed study utilized CSA and MSCL values of 65 ha and 400 m, respectively. These values reflect an average quarter section of land (65 ha) for each sub-watershed, which is a common cropland areal extent. The CSA and MSCL values provided the study area with 2723 sub-watersheds, or 2723 AnnAGNPS cells. The RASPRO program derives additional spatial landscape information and parameters from the DEDNM program. Examples of the raster information include: the location and extent of depressions and flat surfaces in the DEM; the distances and elevation drop to the next channel and to the watershed outlet; and the aggregation of all subcatchments draining directly into one channel link and into a single direct contributing area for that channel link. The third program in the TopAGNPS program is RASFOR, which reformats the unformatted raster data from the DEDNM and RASPRO programs. This raster data are reformatted into readable ASCII and GIS (ARC/INFO) files.

The AGFLOW program, which is included with the AnnAGNPS distribution, then uses the TopAGNPS program datasets to