GIS Applications to Agricultural Non-Point-Source Pollution Modeling: A Status Review

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Abstract. The current applications of geographic information systems (GIS) applications to non-point-source pollution modeling for agricultural area are reviewed with respect to the requirements for GIS, the hydrological/water quality modeling processes, and integration between GIS and Non-Point-Source Pollution (NPSP) models. Some necessary considerations for future studies are also discussed by summarizing the viewpoints of various researchers.

Keywords: Agriculture, geographic information system, hydrologic/water quality modeling, non-point-source pollution

1. Introduction

Agricultural pollution is difficult to monitor since all pollution sources are non-point in nature. The non-point source pollution (NPSP) has long been a major concern all over the world. The USEPA noted in 1990 that routine agricultural activities were responsible for more than 60% of the surface water pollution problems in the US. The importance of agricultural NPSP control has frequently been emphasized in the reports of Environment Canada and Canadian Environmental Assessment Agency even related figures are not available.

Successful management of agricultural NPSP requires an understanding of the pollutant transport mechanisms from runoff to surface water. These mechanisms are very complex, and quite a few factors such as hydrological, topographical, chemical transport, soil-type and land use conditions are involved in determining NPSP process. Computer modeling has gained widespread acceptance in helping us understand and manage the complexity. Numerous lumped and distributed parameter hydrologic/water quality (H/WQ) models have been developed to predict the impacts of agriculture on the quality of surface water, including EPIC (Erosion Productivity Impact Calculator), CREAMS (Chemicals, Runoff, Erosion from Agricultural management Systems), WEPP (Water Erosion Prediction Project), ANSWERS (Aerial Nonpoint Source Watershed Environment Response Simulation), and AGNPS (AGricultural NonPoint Source). However, the models generally have limitations restricting their application. The major limitations are due to the high requirements for handling large amount of input data, and analyzing model results. In these regards, geographic information system (GIS) provides an effective tool to generate, manipulate, and organize the spatially disparate data for modeling. There have been a number of successful applications of models linked to GIS for management of agricultural NPSP (Table 1). To stress the important role of GIS in NPSP management, this paper, as the first attempt in the study area, examines the current status by a comprehensive review on literature for recent half decade from the perspective of both GISs and its integration with NPSP models.

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2. Applied Geographic Information Systems

The primary requirements for GIS in H/WQ modeling can be identified with respect to the features of the modeling work (Engel et al., 1993; Tim and Jolly, 1994). As suggested by previous studies on agricultural NPSP with GIS application, a GIS for this area should be capable of performing complex manipulation and analysis of spatial and non-spatial data for the development and preparation of data inputs to models, providing the linkage mechanisms between models having different spatial representation, facilitating the conversion and standardization of data in digital form of different scales and coordinate systems, and enabling post-simulation analysis through graphical display and spatial statistical summaries that facilitate explanation of modeling results.

Numerous GIS packages are currently available, ranging from expensive packages for workstation to PC-based and public domain software. However, it is somewhat surprising that most applications to agricultural NPSP mentioned on previous literature were limited to only a couple of systems, ArcGIS and GRASS (Table 1). The both systems have strong raster GIS capabilities. The integration and customization are greatly facilitated by the systems design. They are capable of operating on a wide variety of computers.

ArcGIS is one of most popular commercial GISs. In the system, information is stored either as polygons, arcs, or points by using relational database tables that link attributes to features. The system has many analytical and data management functions, including a sophisticated input sub-system for digitizing, editing, and reformatting data; powerful output subsystems for constructing impressive maps and reports; and useful arrays of spatial operations for topological overlay, buffer creation, and spatial query. The GRASS (Geographical Resources Analysis Support System), is a public domain software package developed by the US Army. It is highly interactive and graphically oriented (both 2-D and 3-D), providing tools for developing, analyzing, and displaying spatial information. The system is being used by numerous US organizations, including USDA Soil Conservation Service (SCS).

Nevertheless, the current generation of GIS is generally believed difficult to use, in part because of the wide range and cumbersome nature of user interface (Drungil et al., 1995; Geter et al., 1995; Srinivasan & Engel, 1994). They are lack of sophisticated spatial analysis functions for H/WQ simulation such as geostatistics interpolation. In particular for NPSP applications, the studies are limited by the GIS’s inability to analyze temporal processes of hydrology (Engel et al., 1993; Tim & Jolly, 1994). More effort on the analysis and display functions of GIS will substantially extend their capabilities for H/WQ modeling. More dynamic analytical tools within existing GISs being developed would be greatly beneficial to sophisticated NPSP modeling studies.

3. NPS Pollution Applications

A variety of specific problems were targeted, and diverse tasks were accomplished by integrating GISs with H/WQ models in previous studies on agricultural NPSP management (Table 1). The previous works ranged from primarily environmental auditing, pollution potential ranking to more sophisticate integrated spatial decision support system. Hamlett et al. (1992) used a cell based ranking model to evaluate NPSP surface pollution potential for 104 watersheds in Pennsylvania. The GIS was used to derive necessary parameters to calculate four pollution indices for each cell, including simple indicators and empirical calculations, such as USLE. Srinivasan and Engel (1994) interfaced the distributed-parameter AGNPS pollutant runoff model with GRASS to provide an event-based decision support options for a wide range of nutrient and sediment variables. With minimal user interaction, the system assists with extracting input parameters for the AGNPS from user-supplied GIS base layers, and in turn, assists with visualizing and analyzing the output of NPSP simulations. Further, the management practice alternatives can be evaluated and identified. Luzio et al. (2004) introduced AVSWAT, a GIS based hydrological system linking the Soil and Water Assessment Tool (SWAT) water quality model and ArcView Geographic Information System software. The main purpose of AVSWAT is the combined assessment of non-point and point pollution loading at the watershed scale.

As evidenced in Table 1, there has been a significant progress in GIS applied agricultural NPSP modeling area in terms of the complexity of models used. Most of recent studies aimed to solving large scale NPSP problems with multiple pollutants using distributed-parameter H/WQ models. Traditional weighted composing index approach with lumped model is being complemented by the distributed parameter modeling. In lumped-system modeling (USLE, EPIC, GLEAMS, SWAT), the spatial properties of the study area are averaged without consideration of the effects of location of land characteristics or topological relationships. In contrast, the distributed-parameter modeling
approaches (AGNPS, ANSWERS, CREAMS, HSPF, SWRRBWQ) use detailed digital terrain data and, in some cases, soils, land cover and other spatial data in the modeling of hydrological processes, and explicitly considers spatial location of each spatial unit within the watershed or catchment.

NPSP modeling is concerned with the movement of pesticides and nutrients, as well as soil erosion. As described by Engel et al. (1993) for agricultural watershed modeling, distributed-parameter models incorporate the variability in landscape features that control hydrologic flow and transport process, and thus, are potentially more realistic. Distributed-parameter modeling accounts for all parts of watershed simultaneously and incorporates spatial and temporal variability due to landscape attributes. As well, the results of “plot size” study can be extrapolated to watershed scale.

4. Integration of GIS With NPSP Model

The integration of H/WQ models with GIS for agricultural NPSP problems can take many forms, depending on specific problem to be targeted. The existing approaches can generally be classified to two categories (levels), “loose” linkage (or “Ad hoc” linkage) where the GIS and model are essentially separate, and “partial” integration in which the GIS and simulation model are linked by special purpose computer programs, mostly with convenient user-interface (Tim and Jolly, 1994). The previous studies on agricultural NPSP are summarized with the classification in Table 1.

In the first level of linkage, the input data required by the model are extracted from the GIS, and the model is run independently of the GIS. Output can be analyzed as desired by the user. This type of linkage, as demonstrated in the study of Hamlett et al. (1992), place very little demand on either the modeling system or the GIS. Its main advantage is that this approach provides a relatively quick and easy summary of NPSP potential, particularly for regional assessments. However, the results are likely to be inaccurate. A potential error is the use of GIS to aggregate spatial variable input data from several coverages for inclusion in the modeling database.

The second level of integration (partial integration) were mostly performed for more complicated modeling work with distributed-parameter H/WQ models. It involves two specific methods. First, a GIS database that can assist in the modeling is developed around an existing H/WQ model. And second, a model is developed on top of an existing GIS database. In both methods, the GIS supplies input data for modeling and then accepts modeling results for further processing and presentation. This type of linkage has the ability to estimate quantitative pollution loadings since a more complex simulation model (e.g. distributed-parameter) can be used. The approach allows the user to select the NPS model that is most appropriate for specific purpose and characteristics of study area. There are quite a few typical examples for this level of integration such as the works described by Evans et al. (1992) and He et al. (1993).

A GIS-based methodology for conducting rapid assessments of pesticide and nutrient transport within agricultural watersheds was developed by Evans et al. In the project, some new programs were developed to provide the linkage between GIS softwares (ArcInfo and ERDAS) and surface water models (SWRRBWQ and EXAMS). The programs can facilitate the compilation of digital map data and parameter estimation using GISs, and then pass resulting information to water models. The ArcInfo macro generated an derived data used as input in SWRRBWQ and EXAMS models. A program was built and used to read data from ArcInfo and ERDAS, and write to SWRRBWQ, and to compile input information for the EXAMS. The results indicated the GIS interfaces can efficiently process and transfer information between application models, rendering significant time saving. He et al. (1993) integrated AGNPS and GRASS to evaluate impacts of agricultural runoff on water quality. They developed a hydrologic modeling tool box GRASS WATERWORKS as interface of the integrated system. It derives AGNPS input files by using GRASS and basic spatial data sets. The integrated system allows the user to browse the database, examine model input parameters, and analyze simulation results using tables and maps. The time for processing input data was significantly reduced by the integration and the user-friendly interface. Srivastava (2001) illustrated the development of an integrated GIS system for a continuous simulation, pollutant-loading model, AnnAGNPS (Annualized AGricultural Non-Point Source Pollution). The integrated system, called AnnGIS, was developed using the ArcView GIS and related program extensions. Using AnnGIS, modeling studies and management plans can be efficiently and easily developed. AnnGIS helps store, organize, and manipulate spatial and tabular data, extract spatial input parameters, develop analysis scenarios, and visualize input and output data in spatial, tabular, and graphical forms.
5. Considerations for Future Studies

With the increasing requirement for NPS pollution control, the applications of GIS integrated with H/WQ model would be more prevalent. Researchers have been and will be trying to make their systems capable of simulating more complex problems with higher accuracy. However, attentions should be drawn to some particular issues that might be encountered due to the limitation of existing software conditions, to facilitate the integration of NPSP models with GIS.

Engel et al. (1993) believed that increasing the availability of data sets is worth of an effort since the digital spatial databases that support H/WQ analysis are often limited in their geographic coverage and content. As well, availability of source code for both GIS tools and models is essential for a highly-qualified integration.

Higher resolution GIS data may improve the accuracy of simulation in a targeted watershed; however, trade-offs exist between the size of the watershed and the resolution of the data due to hardware and software limitations. Thus, the study by He et al. (1993) suggested that resource planners should realize this tradeoff when using models for comprehensive watershed planning and management.

A major concern when planning a GIS integrated modeling effort is the time and effort involved. One must be willing to expend considerable effort in developing the database for a integrated model. The considerations in two studies (Mitchell et al., 1993; Tim and Jolly, 1994) indicated that the time savings for data entry into the model may offset the database time commitment since data layers with different attributes can be easily created from base data layer.

Morse et al. (1994) pointed out that care must taken in using GIS to prevent the GIS presentation capability giving a false accuracy to the underlying data and model limitations. GIS can not solve the fundamental problems of data availability, accuracy and translation, and model inaccurancy and inapplicability.

Higher level linkage between GIS and NPSP model, referring to complete integration of the two processes, can be very attractive since it can easily be adapted to the requirements of the modelers as well as the limitations in the model. The GIS and H/WQ model are developed in close interaction and within a single operating environment. The data stored in the GIS is structured to meet the demands of the model, and vice versa. However, it requires a modular modeling structure that is both functional and versatile enough to provide the framework for linkage with the unique data structures of the GIS. Furthermore, the data structure of the GIS should be compatible with the spatial discretization of the modeled system. Considerable effort would be made in the attempt for the integration.

6. Concluding Remarks

The current status of GIS applications to non-point-source pollution management for agricultural area is reviewed in this paper. The successful management of agricultural NPS pollution necessities the widespread application of GIS, mainly in the form of integration with hydrological/water quality models. Due to the complex features of NPSP problem, highly efficient capabilities are required for integrated H/WQ modeling tool. As a result, limited GIS packages are being used in the application. The existing integrated systems have been successfully applied to target various NPSP problems. The applications tend to be more sophisticated to satisfy the demand of more effective NPSP management. In ongoing efforts, some considerations should be attended concerning technical difficulties.

References


