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Methods for Modeling Livestock and Human Sources of Nutrients at Watershed Scale

Prem B. Parajuli

Introduction

The top five leading pollutants in U.S. rivers and streams are pathogens, sediment, nutrients, organic enrichment, and habitat alterations (USEPA, 2008). In Mississippi, sedimentation, biological impairments, fecal coliform, organic enrichment, and nutrients are ranked as the top five causes of river and stream pollution (USEPA, 2008). In Mississippi, 56.38% of the 9.67% assessed river and stream miles and 24.73% of the 29.8% assessed lake, pond, and reservoir acreage are impaired (USEPA, 2008). These percentages might increase when more water bodies are assessed and pollutant criteria are improved. The Mississippi Department of Environmental Quality developed the total maximum daily loads (TMDLs) for the various rivers and streams in Mississippi (MDEQ, 2009).

Nonpoint-source (NPS) pollution from agricultural land, forestland, and urban land can contribute to water quality degradation. Developing a TMDL requires identifying and quantifying pollutant contributions from each source and then determining the pollutant reduction needed from each source to meet applicable water quality standards. Water quality assessment at the watershed scale can be done using two techniques: (1) watershed monitoring and (2) watershed modeling. Watershed models serve as a tool for linking pollutants to the receiving streams. Models help to organize and interpret research data, and they also provide water quality predictions quickly and economically. Water quality models are used to assess water quality goal attainment and are important tools because they can be used to understand hydrologic processes, develop management practices, evaluate the risks and benefits of land use change over time, and assess the effectiveness of best management practices (BMPs).

However, methods used to model watersheds can significantly impact the modeling results, as well as the recommendations for implementing water quality improvement strategies and BMPs. To address this issue, this research report describes digital data sources to help in setting up models and methods for modeling livestock and human nutrient sources (including point loading) to surface waters at the watershed scale.

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Digital Data Sources

The watershed model utilizes geospatially referenced data to satisfy the necessary input parameters. The digital elevation model (DEM), soils, and land use data layers should be all projected in one projection system, such as Universal Transverse Mercator (UTM) 1983, zone 16. The U.S. Geological Survey (USGS) developed a national elevation dataset (NED). The 30x30-meter grid USGS model includes commonly used DEM data for watershed scale modeling. For field-scale or small-watershed-scale modeling, a 10x10-meter resolution DEM might be more appropriate. The DEM data are used to delineate the watershed boundaries and topography and can be merged if necessary to cover the watershed boundary.

Currently, two types of soil databases are available to use in watershed modeling studies. State soil geographic database (STATSGO) and soil survey geographic database (SSURGO) are commonly used digital soil databases (USDA, 2005). The SSURGO soil data provides more information about the soils than STATSGO because of the availability of more soil polygons per unit area.

The National Land Cover Database (NLCD) provides land-cover data for 1992, 2001, and 2006 for the United States and Puerto Rico (USEPA, 2006). These land-use data provide information about land classifications in the watershed to input into the model. In addition, cropland data layers that contains crop-specific digital data layers are suitable for use in geographic information systems (GIS) (USDA/NASS, 2008). These data layers have been developed annually and focus on the corn, soybean, rice, and cotton agricultural regions in the Midwestern and Mississippi Delta states.

Watershed-scale models have their own weather stations and climate generators but more site-specific climate data (precipitation, temperatures, relative humidity, wind speed, and solar radiation) can be supplied to the model. Daily climate data, which includes precipitation and daily ambient temperature data for the model simulation period, can be extracted from the National Climatic Data Center (NCDC, 2009). The watershed models generally generate missing data during model simulation.

Watershed models also use crop management inputs such as percentage of cropland areas, crop types grown in the watershed, planting and harvesting dates, and crop residues left on the ground between the crop periods. In addition, models can include crop tillage systems (conventional, reduced, no-till), as well as herbicides and fertilizers and their application rates.

Livestock Nutrient Sources

Manure and associated nonpoint-pollutant loads to land and water can be estimated for two types of livestock systems: (1) confined livestock in permitted operations and (2) livestock in pasture.

Livestock in Confined Operations

Confined livestock mainly consist of beef, dairy, poultry, and swine animals in containment areas of different animal unit (AU) sizes (ASAE, 2003). The following sections describe several related methods: (1) for estimating livestock population in permitted animal feeding operations, (2) for developing model inputs such as manure production and manure land-application rates, (3) for simulating nonpoint nutrient losses from feedlots without best management practices (BMPs), and (4) for simulating nonpoint nutrient losses from feedlots with agricultural waste BMPs (use of waste-containment structures).

The number of AUs in each permitted livestock operation within the watershed can be estimated using active livestock operation data for NPDES-permitted livestock operations from the Mississippi Department of Environmental Quality (MDEQ). The MDEQ-permitted livestock operation data can be compared with field survey data for the specific watershed. Livestock operation data should be used with their latitude and longitude coordinates to distribute feedlot locations spatially in the watershed. The watershed may consist of both year-round and seasonal livestock feeding operations.

In order to develop model inputs from the livestock sources, the livestock manure loads (dairy, beef, poultry, and swine) should first be estimated based on 1,000-kg units of animal live weight in the watershed. Total phosphorus (P) content in the model manure database may be compared with the estimated value using the American Society of Agricultural Engineers standard (ASAE, 2003). The ASAE standard assumes that dairy animals produce 86 kg per AU per day of fresh manure, which has 86% moisture content and 0.094 kg of P per kilogram of manure. Thus, dry weight of dairy manure can be estimated as 12.04 kg per AU per day, which has P content of 0.0078 kg per kilogram of dry manure. The model manure database should use very close numbers estimated by ASAE standards. Data on the type of animal, animal units, and days in the lot help to estimate dry manure loads and nutrient mass in the watershed. The total confined manure loads produced in the watershed are generally assumed to be applied in the specific land-use area in the watershed unless explained.

Both daily deposition of manure in the feedlot and land application of manure collected in the feedlot can be considered daily deposited and applied in the land areas. Manure in the feedlots is generally simulated by assuming that confined livestock populations from the watershed contributed daily applications of manure in small land areas or spatial units, such as hydrologic response units, cells, or sub-basins. The selected spatial units can be characterized with curve number (CN) of 92 to represent average feedlot condition (Young et al., 1982; and Kizil et al., 2006). The selection of land-use areas, such as cropland areas for land application of manure, is dependent on land use, target manure application rate, and the size of the spatial unit located closest to the feedlots. The percentage of manure from the feedlots that can be recovered and managed as a resource could be varied depending on type of animal. The recovery factors of 0.2 for beef cattle, 0.77 for dairy cattle, and 0.71 for hogs are recommended to estimate recovered manure that could be land-applied (Moffit and Lander, 2008).

Feedlots in the watershed could have implemented agricultural waste BMPs, which commonly call for a combination of a containment structure to collect and contain feedlot solids and a wastewater storage pit to collect feedlot runoff. These structures are generally built according to NRCS 313 conservation practice standards to meet all federal, state, and local laws and regulations (NRCS, 2008). Common application intervals/rates of manure and wastewater could be different from place to place. Reported values of P concentration from feedlot runoff ranged from 5.9–50 mg/L (Clark et al., 1975; Mankin et al., 2006) when lots were stocked with animals; the values averaged 5.9 mg/L when lots were unstocked (Mankin et al., 2006). Volume of runoff waste that could be collected in the storage pit is a function of seepage, feedlot area, evaporation loss, and average annual precipitation. The NRCS curve number method may be used to estimate runoff using equation 1 (USDA-SCS, 1972). To estimate nitrogen (N) addition from wastewater storage application, use the same procedure used for P. Calculate the N using an average N concentration of 119 mg/L when the lot is stocked with cattle and 19.8 mg/L when it is unstocked (Mankin et al., 2006).

$$Q = \frac{(I - 0.2S)^2}{I + 0.8S} \qquad (1)$$

where, Q = direct surface runoff depth in millimeters, I = rainfall in millimeters, and S = maximum potential difference between rainfall and runoff in millimeters starting at the time the storm begins (estimated as S = 25,400/N - 254, where N is a curve number).

Livestock in Pasture

Livestock in the pasture mainly consists of beef and dairy cattle during grazing season. This section describes three methods: (1) for estimating livestock population in a pasture, (2) for developing model inputs to simulate nonpoint-source nutrient losses (pasture, near-stream, and instream), and (3) for simulating nonpoint nutrient losses with off-stream watering site BMP.

Estimate the grazing livestock population of a watershed by determining the amount of grazing acreage in the area and multiplying that by the average stocking rate. Average stocking rates are determined based on county livestock data for beef cows and grazing land. The number of cow-calf pairs on grazing land can be estimated based on the annual “beef cow” population data. The beef cow population data would be a slight overprediction of the actual number of cow-calf pairs because calving rates are generally less than 100%. The average annual livestock stocking rates for counties in the watershed are spatially varied.

To estimate manure production and application on watershed grazing land, this research report recommends estimating average annual livestock stocking rates and average daily manure production by grazing cattle (ASAE, 2003). Stocking rates in the watershed could be based on rates reported in the county where most of the watershed is located.

Grazing areas in the watershed may provide cattle free access to streams or stream banks (i.e., no fencing along near-stream areas). Therefore, cattle manure deposition in the watershed is unequally distributed among pasture, riparian, and surface water areas, which may cause water quality impacts. Various studies have found that cows spend 5–26 minutes per day in streams that flow through the grazing area (Table 1). However, livestock behavior in different areas could vary because of differences in average diurnal temperature, availability of riparian areas, pasture size, stocking rates, and pasture conditions. Although Byers et al. (2005) did not measure the total time cows spent in the stream, their study found that cows spent 40–96% less time in the stream from June to December in Eatonton, Georgia, when off-stream watering sites were installed (Table 2)

The definition of “stream bank” or “near the stream” includes a buffer width of riparian area next to the stream. A larger stream would have a wider near-stream buffer

Study	In stream	Location	Months of study	References
1	13	Independence, VA	Nov.-Jan., Aug.-Sept.	Sheffield et al., 1997
2	26	Crook County, OR	Jan.-Feb.	Miner et al., 1992
3	5	Union County, OR	June-July	Clawson J.E., 1993
4	10[1]	Hemilton, New Zealand	Jan.-Aug., Dec.	Bagshawa et al., 2008

Table 1. The length of time (minutes/day) grazing cows spend in the stream.

[1]Assumed the time spent in stream is same as near-stream.

Study	Location of study	Reduction (%)	Months of study	References
1	Independence, VA	51	Aug.-Sept., Nov.-Jan.	Sheffield et al., 1997
2	Crook County, OR	94	Jan.-Feb.	Miner et al., 1992
3	Eatonton, GA	40-96	June-Dec.	Byers et al., 2005
4	Union County, OR	85	June-July	Clawson, 1993
5	Hemilton, New Zealand	0	Jan.-Aug., Dec.	Bagshaw et al., 2008
6	Long Creek, NC	0[1]	3 years	Line, 2003

Table 2. Reduction of pollutants or length of time cows spent in streams when off-stream watering sites were available.

[1]Reduction (%) measured for water quality.

zone. This report recommends using stream data either from model generation or from the national hydrography dataset (USGS, 2009) for the watershed. The streams in the watershed can be provided with 20-meter buffers on each side of the stream using GIS.

Watershed spatial units can be modeled to examine near-stream manure loading. Spatial unit area including 20-meter stream buffers can be estimated using model-generated watershed boundary and stream network data. The manure load in the stream, near-stream, and in the grazing land area can be estimated based on the time cows spend in the stream.

Off-stream watering sites reduce the time livestock spend in the stream or near-stream. Some studies have addressed the ability of an off-stream water source to improve stream water quality. Results were inconsistent on the effectiveness of off-stream watering sites at improving water quality (Table 2; Sheffield et al., 1997; Line, 2003). However, most of the studies concluded that after watering sites were implemented, cattle behavior changed and water quality improved. Researchers noted that after water trough installation, each cow spent an average of 60% less time in the stream and near the stream area (studies 1–5, Table 2). Therefore, it is evident that availability of off-stream watering sites may reduce cattle manure inputs near streams and in streams by 60%.

Human Nutrient Sources

Due to the rural and suburban characteristics of agricultural watersheds, most households in the watersheds use septic systems. Failing septic systems in rural areas of the watershed can be considered one of the human sources of water pollution, such as nutrient and bacteria losses. Septic effluent and associated nutrient loads to land and water are estimated based on the following methods.

Detailed data on failing septic systems are not available for most watersheds. As a result, the number of failing septic systems needs to be estimated indirectly. Municipal areas in the watershed could be assumed to have centralized waste management systems. The number of rural households outside municipalities in the watershed can be estimated from topographically integrated geographic encoding and referencing (TIGER) data (USCB, 2002). Each rural household may be assumed to have one septic system.

Septic systems typically fail by one of two mechanisms: (1) excessive soil conductivity in the soil absorption lateral field, which can lead to groundwater contamination; or (2) insufficient soil conductivity in the soil absorption field, which can lead to effluent surfacing. Soil types in the watershed commonly lead to failure by the second mode. Surfacing of effluent is observed in the field by greener vegetation (often in grass lawns) occurring in the lateral field area. Generally, transport of contaminants from septic system failure is by runoff-related processes. Although there is no direct method to input septic-system-derived pollutants in any watershed model, estimated septic system effluents have been applied as a fertilizer input in the soil and water assessment tool (SWAT) model (Parajuli et al., 2009; Pradhan et al., 2005).

Information about the condition and management of each septic system in the watershed is not available. This research report considered that each septic system served three people and contributed 0.32 cubic meters of sewage effluent load per household per day (U.S. EPA, 2001). Summerfelt and Penne (2007) established that septic tank sludge contained 2.6% (dry weight) of P and 3.6% (dry weight) of N. Generally, septic effluent has a lower percentage of solids than septic sludge as the effluent floats on the surface in the septic tank.

The daily dry weight of septic load can be estimated for the watershed. Failing septic systems in the watershed can be modeled using a combination of two methods: (1) land application of the septic effluents load; and (2) direct, daily point load to the outlet of each sub-basin (Parajuli et al., 2009). Land application of septic effluent can be a more likely scenario in most of the agricultural watersheds.

Develop Point Load Inputs

Methods were developed to estimate spatially variable daily point loads for (1) livestock sources and (2) human sources of nutrients to surface waters in the watershed.

Livestock in Pasture

Assuming fences are not installed between streams and pastures in subwatersheds or watersheds, grazing livestock (beef or dairy) have access to and directly deposit manure loads into the waterways. The daily dry manure — estimated to be applied as in-stream load — was considered as a direct deposit at the outlet of each subwatershed (Parajuli et al., 2008). Watershed scale models such as SWAT allow daily direct input of organic and mineral phosphorus loads to the outlet of the subwatersheds. The estimated dry manure load for each sub-basin can be converted to organic and mineral phosphorus loads (kilograms per day) using the model's fertilizer databases. The SWAT fertilizer database (beef manure) considered organic P concentration as 0.007 kg per kilogram of dry manure and mineral P concentration as 0.004 kg per kilogram of dry manure from total P (0.011 kg per kilogram of dry manure). The organic and mineral P loads (kilograms per day) for each subwatershed outlet can be estimated with the following equations:

$$OPpoint = LSR * PA * MPbeef * fMP * OPc \quad (2)$$

$$MPpoint = LSR * PA * MPbeef * fMP * MPc \quad (3)$$

where, OPpoint is the organic P point load from manure deposition (kilograms of P per day), LSR is the average livestock stocking rate for the county (AU per hectare), PA is the pasture area with stream access for the given subwatershed (in hectares), MPbeef is the daily manure production by beef cows (kilograms per AU per day), fMP is the fraction of the manure production that is directly deposited into the stream (unitless), OPc is the concentration of organic P in beef manure (kilograms of P per kilogram of manure), MPpoint is the mineral P point load from manure deposition (kilograms of P per kilogram of manure), and MPc is the concentration of mineral P in beef manure (kilograms of P per kilogram of manure).

The estimated dry manure loads based on per-unit pastureland area located in the subwatersheds using equations (2) and (3) can be directly deposited at the outlet of the subwatershed. The dry manure loads based on per-unit pastureland area are constant across county watershed pasture areas as livestock stocking rates for each county are assumed to be the same throughout. Similar methods can be applied for nitrogen point source in the model.

Human Sources

Spatially variable nutrient loads from human sources from failing septic systems in each subwatershed/watershed can be estimated as a daily direct point load input in the model. The estimated daily direct N and P loads can be fractioned into organic and mineral P to consider as a direct point load in the model similar to nutrient loads from livestock sources (Neitsch et al., 2005).

SUMMARY

Methods were described for modeling livestock and human sources of nutrient losses to surface waters for watershed-scale studies. Modeling methods that better describe the physical conditions of the watershed and nutrient sources would help to improve the prediction of pollutant loads. Accurate prediction of spatially distributed pollutant loads helps us to recommend BMPs for watershed management and water quality improvement. To improve results, watershed-modeling studies should also consider model parameterization processes such as selecting appropriate rainfall distribution parameters, evapotranspiration methods, rainfall-runoff routing methods, channel routing methods, and in-stream water-quality processes. This research report was successful in describing modeling methods for NPS and point nutrients from livestock and humans, which are applicable to other watershed-modeling studies throughout the nation.

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