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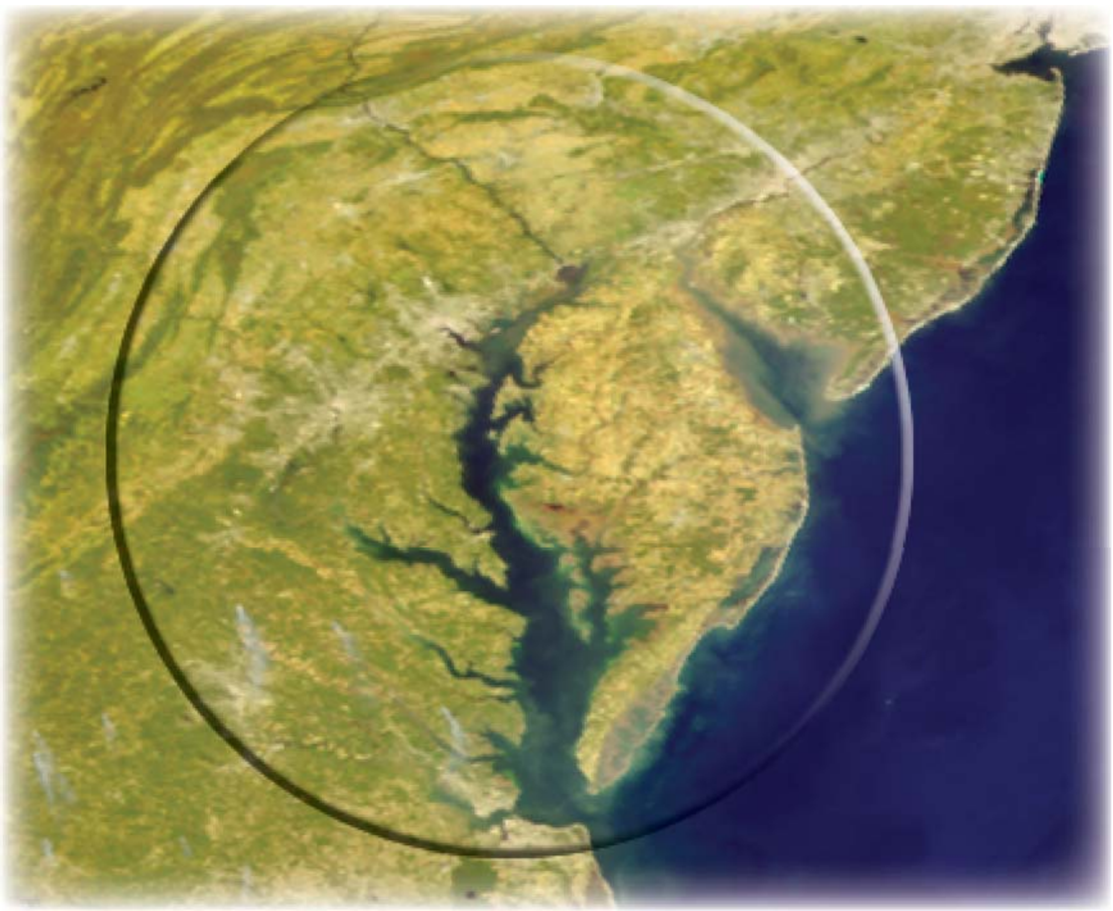
Technical Documentation of the Regional Manure Management Model for the Chesapeake Bay Watershed

Marcel Aillery, Noel Gollehon, and Vince Breneman



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Marcel Aillery, Noel Gollehon, and Vince Breneman

Abstract

The Regional Manure Management Model, developed for the ERS project on "Manure Management for Improved Water Quality," is used to evaluate the cost and feasibility of manure land application as a manure management strategy at the regional level. This model is a nonlinear mathematical programming model of animal manure-nutrient production and distribution applied to the Chesapeake Bay watershed. The model is designed to assess regional costs of manure management, transport, and land application in the Chesapeake Bay watershed, given the existing structure of the animal industry and manure-storage technologies currently in use. Manure-nutrient production is allocated within the basin to minimize costs to the animal sector, subject to land availability and policy provisions. A defining feature of the modeling system involves the integration—within an optimization framework of spatial data from a Geographic Information System and farm-level data from the 1997 Agricultural Census—aggregated to the county level. The framework captures important spatial interactions involving animal concentrations and land available for manure spreading that can significantly affect manure land application costs faced by animal producers.

Keywords: Technical documentation, regional analysis, Chesapeake Bay, animal waste, manure management, nutrient management plan, manure land application, manure transport, cost minimization, optimization model.

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Cover Photo: NASA - Goddard Space Flight Center Scientific Visualization Studio.

Contents

Summary

Regional concentrations of farms raising livestock and poultry in confinement and their potential adverse effects on water quality and public health have prompted Federal regulations and guidelines on animal waste management. The primary emphasis of recent policies is to limit the application of manure to land at rates no greater than those at which crops can extract specified nutrients from the manure. Limiting the rate of manure application will limit potential nutrient runoff to surface water. However, many confined animal operations have insufficient land on the farm to land-apply all the manure produced without exceeding nutrient requirements of the crops grown. Some of the manure, therefore, must be moved off the farm to be spread on other land in the area. In regions with many confined animals, manure-hauling distances (and the resultant costs) are determined largely by the spatial distribution of land area available for manure application relative to the location of animal operations requiring additional land.

What Is the Issue?

An accurate assessment of the costs of manure hauling and land application argues for a regional perspective that accounts for the acreage needed (in addition to land on the animal farm itself) and that considers spatial interactions across animal operations and agricultural land resources. A regional analysis—in contrast to farm-level or national sector assessments—can be more readily designed to capture the effect of competition for limited land resources under alternative policy settings. As part of a broader ERS assessment of the costs of manure management, a regional modeling framework was developed to evaluate the effect of Federal guidelines for farmland application of manure on hauling and spreading costs. Results from an initial application of the modeling system are featured in the ERS publication *Manure Management for Water Quality: Costs to Animal Feeding Operations of Applying Manure Nutrients to Land* (AER-824, June 2003).

This report, *Technical Documentation of the Regional Manure Management Model for the Chesapeake Bay Watershed Model*, presents details of the regional modeling system applied to production and disposal of animal manure in the Chesapeake Bay watershed—an environmentally sensitive area with large concentrations of confined animals. The model is used to evaluate the feasibility of land application of manure as a regional manure management strategy and the effect of key policy provisions and manure use assumptions on costs to the animal sector. The report includes an overview of the model's scope and structure, data sources, and modeling assumptions.

How Was the Study Conducted?

The model is designed to assess regional costs of managing the manure on the farm of origin and transporting and spreading it on area farmland, given the existing structure of the animal industry, manure-storage technologies, and alternative manure disposal options currently in use. The modeling system is centered on a nonlinear mathematical programming model of animal manure-nutrient production and distribution.

The regional model allocates manure nutrients produced within the Chesapeake Bay basin to agricultural land for crop use to minimize hauling and land application costs incurred by the regional animal sector, given land availability and nutrient management policies. The model was defined at a watershed spatial scale that includes portions of six States (Virginia, Maryland, Delaware, Pennsylvania, New York, and West Virginia) to account for the regional distribution of crop and pasture land as well as the animal operations competing for available land resources. A watershed scale is also appropriate for potential modeling extensions designed to assess implications of Federal manure management policies on water quality in the Chesapeake Bay.

A defining feature of the regional modeling system involves the integration within an optimization framework of (1) cropland coverage from a Geographic Information System (GIS) and(2) farm-level data from the 1997 Agricultural Census, aggregated to the county level. Counties within the watershed serve as the primary modeling unit, providing consistency with Census of Agriculture data and other county-level data. County-level specification permits subregional differentiation in animal production, nutrient uptake, waste technologies, and regulatory conditions across county and State boundaries within the watershed. Reliance on national data series for key model parameters (e.g., number of animals) is an important element of the modeling framework, ensuring consistency of data within the watershed while facilitating the potential for model updates and transferability of the model to other U.S. watersheds.

Key decision variables in the model include the quantity of manure transported by system type, the hauling distance of manure moved off the farm, and acres used for manure spreading in receiving counties. The direction and magnitude of manure transfers is determined by the nutrient and moisture content of the source manure, the nutrient uptake capacity of receiving lands, and per-unit costs of manure hauling and land application.

What Did the Study Find?

The regional modeling framework provides a unique and valuable perspective on the cost of Federal regulations and guidelines for manure land application. The integration of Census and GIS data enables the regional model to capture important spatial interactions between animal concentrations and land available for manure spreading.

With a large proportion of animal producers dependent on land off the farm for manure spreading, competition for available land resources is an important consideration in the costs of managing manure. Competition for land and the resultant hauling requirements and costs of manure management will depend, in turn, on the (policy-determined) manure application rate, quantities of manure that can be used for industrial purposes, and landowners' willingness to accept manure on farmland.

During the initial application of the model, a number of potential model improvements and extensions were identified. Several priority extensions of the model are under development for future model applications, as outlined in the conclusion of this report. For a review and analysis of findings from the initial application of the model, see *Manure Management for Water Quality: Costs to Animal Feeding Operations of Applying Manure Nutrients to Land* (AER-824, June 2003).

Technical Documentation of the Regional Manure Management Model for the Chesapeake Bay Watershed

Model version used for the ERS Project "Manure Management for Improved Water Quality"

Marcel Aillery, Noel Gollehon, and Vince Breneman

Introduction

This report presents a discussion of the Chesapeake Bay Regional Manure Management Model, developed for use in the U.S. Department of Agriculture's (USDA) Economic Research Service (ERS) project on "Manure Management for Improved Water Quality." The report is intended to document the modeling framework, addressing model purpose and scope, model structure, parameter assumptions, data sources, and output generation. The model is designed to capture the spatial relationship between manure-nutrient production and land available for manure spreading, and implications for manure-hauling costs under Federal guidelines for animal waste management. The discussion highlights the use of farm-level survey data and cropland coverages from national databases within a regional optimization framework. Discussion of the modeling framework draws on empirical findings and visual presentations from the ERS analysis of costs of manure-nutrient management (Ribaudo et al., 2003).

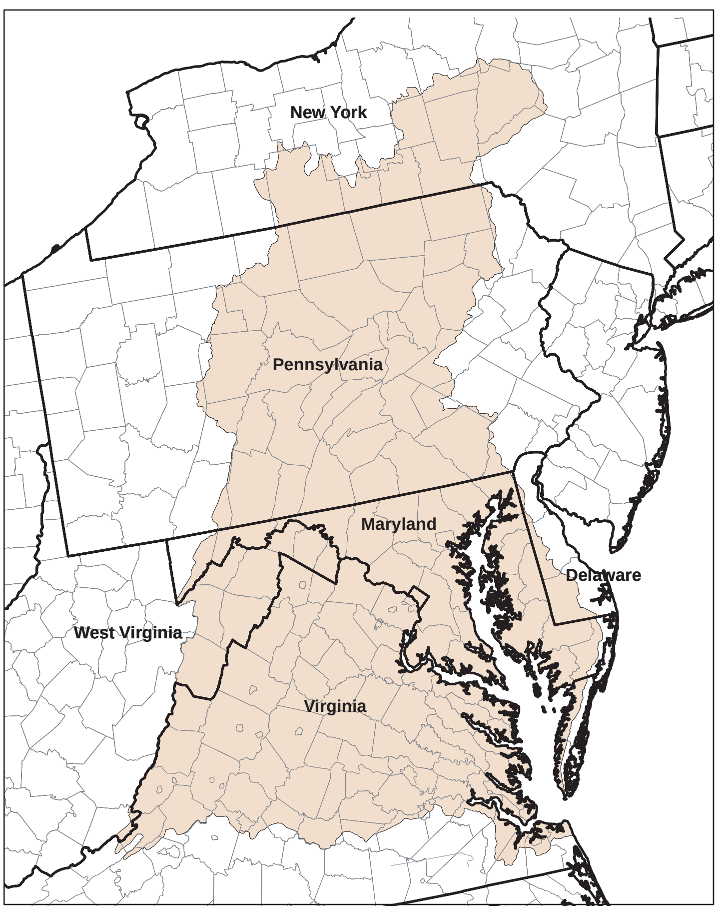
In 1999, the Environmental Protection Agency (EPA) and USDA issued joint guidelines for regulatory and voluntary measures to protect water quality and public health from animal-waste pollution. In 2003, EPA published new regulations affecting an estimated 15,500 concentrated animal-feeding operations (CAFOs) (U.S. EPA, 2003). Meanwhile, USDA has a stated goal that all animal-feeding operations (AFOs) develop and implement comprehensive nutrient management plans (CNMPs) to minimize potential pollutant loadings from confined animal facilities and manure land application (USDA, NRCS, 2000). Nutrient standards that cap total applied nutrients—including manure nutrients—based on crop need (crop-based rates) provide the basis for manure application rates under both the USDA policies and EPA regulations. Implementation of nutrient standards will likely impose additional manure-hauling requirements in regions with concentrations of confined animal production. With limits on applied manure per acre, more land is required for manure spreading than is often available on animal-feeding operations and nearby farms, resulting in increased competition for available acreage and greater hauling distances.

As part of the Manure Management for Improved Water Quality Project at ERS, a regional modeling framework was developed to evaluate the effect of crop-based nutrient application rates (reflected in Federal guidelines and regulations) on costs of manure hauling and land application. Information developed by USDA indicates that many confined animal operations have insufficient land on the farm to spread all of their manure at crop-based rates (Kellogg et al., 2000). The effect of nutrient standards for land application will require that much of the manure be moved off the confined animal farms. Where animal production is concentrated, manure-handling costs faced by producers are determined largely by the spatial distribution of land area available for manure application and the level of competition among animal farms for available land; those two factors together determine the hauling distance required to access available land. An accurate assessment of the costs of manure hauling and land application argued for a regional perspective that considers spatial interactions across animal operations and agricultural land resources, and the effect of limited land resources in areas where confined animal production is concentrated.

The modeling framework was applied to the Chesapeake Bay watershed (fig. 1). The Chesapeake Bay is among the largest and most biologically rich estuaries in the world. However, excessive nutrient loads from various

Figure 1

Chesapeake Bay watershed



Source: Ribaudo et al., 2003.

sources—including wastewater treatment plants, urban runoff, fertilizer applications, animal waste, and atmospheric deposition—have resulted in eutrophication and related ecological shifts that adversely affect wildlife and aquatic resources (Preston and Brakebill, 1999). The declining health of the Bay ecosystem in recent decades has prompted a major Federal/State initiative to reduce excessive nutrient loading to the Bay and tributary streams. Animal agriculture is potentially a major source of nitrogen and phosphorus loadings due to concentrations of large confined animal feeding operations in some areas of the watershed. The Chesapeake Bay watershed encompasses several multi-county areas where the volume of manure-nutrient production from confined animal operations exceeds the capacity of area cropland when manure nutrients are applied at crop-based rates (Gollehon et al., 2001). Federal guidelines and regulations using crop-based nutrient rates are likely to have significant cost effects in areas of the Chesapeake Bay watershed where competition exists for land on which to apply manure.

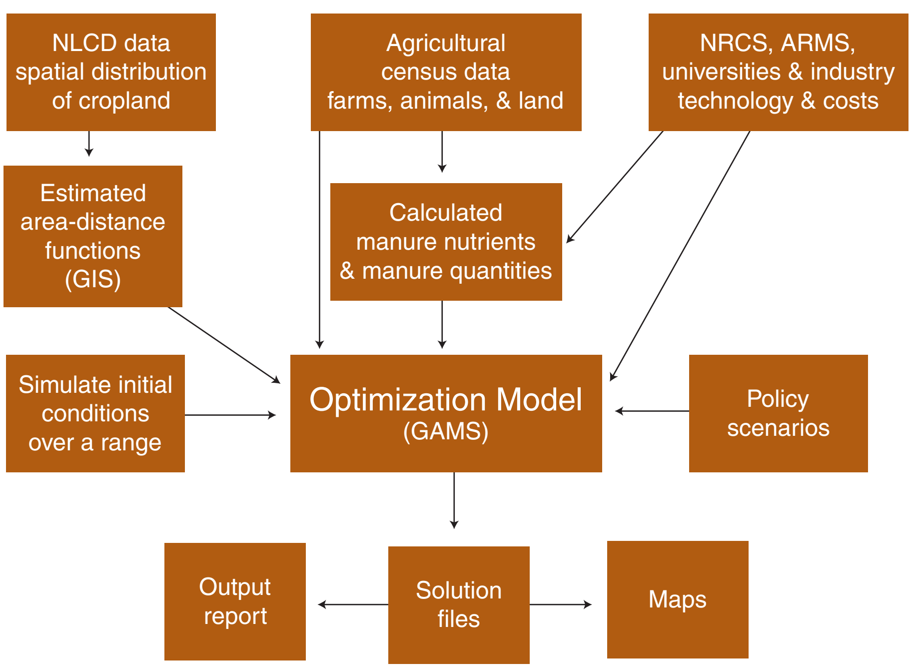
Overview of Modeling Framework

At the heart of the regional analysis conducted for the Manure Management for Improved Water Quality Project is a nonlinear mathematical programming model of animal manure-nutrient production and distribution developed for the Chesapeake Bay watershed (fig. 2). The Chesapeake Bay regional model was developed with GAMS (General Algebraic Modeling System) version 20.7, using the MINOS solver for large non-linear applications.[1] The model is designed to assess regional costs of manure management, transport, and land application in the Chesapeake Bay watershed, given the existing structure of the animal industry and manure-storage technologies currently in use. Manure production is allocated to crop and pasture land within the basin to minimize costs to the regional animal sector, subject to land availability, nutrient uptake capacity, and nutrient management policies in effect. The model is used to evaluate the cost and feasibility of land application for manure disposal, and the effect of key policy provisions and manure use assumptions on costs to the animal sector.

[1] Model applications were solved successfully on a personal computer with a Pentium 4 processor and 1 GB of RAM.

A defining feature of the modeling system involves the integration, within an optimization framework, of cropland coverages from the Geographic Information System (GIS) and farm-level data from the Agricultural Census, aggregated to the county level. The framework captures important spatial relationships involving animal concentrations and land available for manure spreading that can significantly affect manure land application costs faced by animal producers. Moreover, the reliance on national data series for key model parameters is itself an important element of the modeling framework, ensuring consistency of data across the watershed while facilitating the

Figure 2
Regional modeling system



Source: U.S. Department of Agriculture, Economic Research Service.

potential for model updates and the potential transferability of the model to other U.S. watersheds.

Model Scope

As with any model, its strengths and limitations are reflected in the study's objectives, methodology, and analytic assumptions. The following may help to clarify the reach of the modeling framework presented here:

- The regional modeling framework provides a unique and valuable perspective on the effect of Federal regulations and guidelines for manure management, both on and off the manure-producing farm. As a large portion of manure transport costs are determined by conditions off the farm, the regional model captures important spatial interactions in animal concentrations and land available for manure spreading. The effect of spatial considerations on sector costs are not as readily addressed in farm-level or national-sector analyses.
- Reliance on national data series for key model parameters ensures consistency of data across States in the watershed. County-level specification permits important subregional differentiation in such cost determinants as animal production by species, nutrient uptake, waste technologies, and regulatory conditions across county and State boundaries. However, representative costs in the model may not accurately reflect costs faced by all animal operations in a region.
- The model assesses, in particular, the cost and feasibility of manure land application in the Chesapeake Bay watershed. While manure land application is an important element of EPA regulations and USDA nutrient management policies, the model is not designed to assess the full cost effect of a specific Federal regulation or program.
- The model focuses on those costs specific to manure hauling and land application. Cost categories not considered in the model include manure-storage infrastructure and processing. Moreover, additional capital, labor, and equipment costs not captured in the model may be needed to achieve the extent of manure land application addressed in the ERS study. A recent Natural Resources Conservation Service (NRCS) assessment suggests that these costs may be substantial (USDA, 2003).
- The model provides a static, single-year assessment of sector costs given prevailing production conditions in the latter 1990s. The model does not endogenously capture adjustments in animal concentrations, crop mix, and manure-handling systems in response to manure management policies and potential attendant changes in base estimates of manure-nutrient excess and nutrient assimilative capacity of cropland.
- Measures of manure-nutrient excess are computed from farm-level survey information, based on reported manure production and agronomic rates of land application. Applied manure in the model reflects calculated rates under a nitrogen or phosphorus standard, as actual rates and patterns of manure land application are unavailable. Thus, the model can be used to assess costs under alternative nutrient standard specifications. However, since we do not have data on actual application rates in the

1997 census base year, we cannot compare costs before and after the imposition of standards.

- As a cost-minimization model, the framework provides a partial analysis of the least-cost means of manure land disposal, based on management alternatives specified under a given scenario. The model does not assess changes in the profitability of animal production, since output prices and substitution possibilities are not considered.
- While land application of manure at agronomic rates is motivated by water policy concerns, the model is not designed to assess water quality per se. The model allocates manure across the basin, consistent with land-based nutrient standards, but does not currently track potential nutrient loadings to water bodies. An assessment of water-quality implications would require integration with other modeling tools that consider nutrient fate and transport and resulting water-quality effects.

Model Spatial Scale

The modeling analysis is defined at a watershed spatial scale. The basin encompasses approximately 64,000 square miles over portions of six States—Virginia, Maryland, Delaware, Pennsylvania, New York, and West Virginia. A watershed-wide scale was important to account for regional distribution of crop and pasture land and animal operations competing for available land resources. The watershed scale is also appropriate for future modeling extensions that would address implications of Federal manure management policies on water quality in the Chesapeake Bay. While typically run at the full watershed scale, the model may be customized to run at a smaller county-aggregate scale useful for model development and/or analysis of local issues.[2]

[2] The user specifies the set of States and/or counties to be included in a given model run.

The county serves as the primary modeling unit for the regional model. The county-level specification provides consistency with Census of Agriculture data and other data available at a county level. At the same time, the county scale permits differentiation in animal production, nutrient uptake, and waste technologies across county and State boundaries within the watershed. Subregional variation in regulatory conditions may also be incorporated, where regulations are specified at a State or county level.

The full basin model includes 160 non-municipality counties with farmland in the Chesapeake Bay watershed, each potentially representing a source and a destination county. Manure is produced in a source county and land-applied (or otherwise disposed of) in a destination county. Sink counties, or destination counties with cropland wholly outside the basin area, serve as potential receiving areas for manure exported from the watershed. The full watershed model also includes 55 sink counties that are non-municipality counties within 60 kilometers (37 miles) of cropland in the Chesapeake Bay watershed, measured from the edge of the source county's cropland base. Of the 160 basin counties in the model, 52 are edge counties containing a share of cropland acreage outside the watershed. In edge counties, manure-nutrient use is apportioned by share of cropland within the basin to more accurately account for effects at a watershed scale.[3] Appendix 1 provides a list of basin and sink counties included in the model.

[3] The share of cropland within the Chesapeake Bay watershed was calculated within the Geographic Information System, using an overlay of the watershed boundary over the U.S. Geological Survey National Land Cover Dataset.

Counties are further disaggregated according to a 12-square kilometer grid system. The sub-county grids are used to spatially assign land available for manure application within a given county (hereafter termed "spreadable" land) to match observed cropland and pasture land coverages. The sub-county grids are also used to assign location of animal operations (discussed under "Model Data: Distance Functions for Manure Hauling"). While manure flows are aggregated at the county level, transport costs are calculated based on manure quantities and hauling distance from a specific county grid point. There are 1,857 sub-county grid areas with animal farms included in the Chesapeake Bay regional model.

Model Variables and Activities

Key decision variables in the model include the quantity of manure transported by system type, the hauling distance of manure moved off the farm, and acres used for manure spreading in receiving counties. The model allocates manure across the basin to minimize the regional cost of manure hauling and land application. The direction and magnitude of manure transfers are shaped by the nutrient and moisture content of the source manure, the nutrient uptake capacity of receiving lands, and per-unit costs of manure hauling and land application. In addition, policy provisions for nutrient standards, as well as assumptions on manure use for industrial purposes and landowner willingness to accept manure on cropland, have an important bearing on regional manure allocations and sector costs. (See Appendix 2 for a listing of model variables.)

Off-farm manure transfers, including within-county and out-of-county destinations, represent the primary activities in the model. Potential county-to-county transfers were developed based on an assumed maximum radial distance of 60 kilometers (km), or 37 miles, measured from the outer edge of the source county's cropland base. For the 10 percent of modeled counties with the largest manure surplus to available land base, a maximum radial distance of 150 km (93 miles) was assumed. This combination of distances provided the model with a 150-km distance in the cases where spreadable land area is most limiting and long-distance transport might be needed, while avoiding unneeded transfer possibilities in most counties where 60 km is adequate. Even with adjustments in maximum transport distance by county to reduce transfer options, there are still 4,060 county-level transfer possibilities in the full watershed model, including within-county and out-of-county transfer combinations.

County-level manure flows represent off-farm manure transfers from all confined animal farms. Manure transfers are disaggregated by sub-county source grid, manure system type, and distance interval to more accurately assess manure-hauling costs. The full model includes over 300,000 transfer alternatives.[4] The maximum set of potential county-grid transfer alternatives generated through the automated GIS procedure was filtered to exclude county combinations with little or no probability of occurrence.[5] The filtering process slightly reduced the dimensionality of the model, which helped to reduce model convergence time.

[4] There are roughly 372,000 variables and 288,000 equations in the full model specification.

[5] Filtering criteria for manure transfers excluded: (1) source counties with zero manure surplus countywide, (2) destination sink counties with zero excess land capacity (after accounting for within-county manure surplus), and (3) county-to-county combinations involving source counties with extremely low manure surplus per cropland area within-county (<0.01 ton/ac) and more than a limited hauling distance (>5 linear km) to access out-of-county lands; source counties with very low manure surplus per cropland area (>0.01 and <0.1 ton/ac) and long hauling distances (>20 km); destinations counties with extremely high manure surplus per cropland area (>0.4 ton/ac) and very long hauling distances (>60 km); destination counties with high manure surplus per cropland area (>0.25 ton/ac) and extremely long hauling distances (>120 km), and destination counties with limited cropland area (< 15,000 acres) and extremely long hauling distances (>120 km). Source-county grid transfers were limited to those grids with AFOs. Maximum hauling distances were also applied on lagoon and slurry manure with high moisture content (10 and 50 miles, respectively), limiting potential county-to-county options for these systems.

Model Data

The two primary data sources for the model include the 1997 Census of Agriculture and the 1994 National Land Cover Dataset. The 1997 Census of Agriculture was administered by the National Agricultural Statistics Service (NASS), USDA. Primary data processing for this analysis was conducted by the Economic Research Service (ERS), USDA, and Natural Resources Conservation Service (NRCS), USDA. The resulting database provided base model data on animal farms, numbers of animals (used to estimate manure production), and cropped area and production (used to estimate the land assimilative capacity of manure nutrients). The 1994 National Land Cover Dataset, developed by the U.S. Geological Survey (USGS), was used to establish the spatial pattern of land available for manure spreading. The resulting land coverage was used as a basis for developing distance functions for manure hauling and simulating the spatial distribution of animal operations. In addition to the two primary data sources, technology and cost coefficients applicable to the Chesapeake Bay watershed were obtained from various sources, including the Costs Associated with Development and Implementation of Comprehensive Nutrient Management Plans prepared by NRCS (USDA, NRCS, 2003), the Agricultural Resource Management Survey (ARMS) data developed by NASS and ERS (USDA, 2002 and 2000), and additional data obtained from published literature and subject matter specialists within the Government and universities.

Manure-Nutrient Production and Use

Farm-level data collected for the 1997 Census of Agriculture were used to estimate county-level measures of animal operations and animal-units, total manure production, surplus recoverable manure (in excess of source-farm crop need), manure-nutrient content, and potential assimilative capacity of the land for applied manure nutrients (USDA, NASS, 1999). Farm-level measures were computed from the Agricultural Census and other technical data. Results from the farm-level calculations were then aggregated to the county level and combined with data from various other sources for analytic and modeling purposes.[6] Census data coefficients are computed following procedures in Gollehon et al. (2001) and Kellogg et al. (2000).

Animal operations. The analysis focuses on confined animal species since they represent the primary source of excess manure nutrients produced on farms with confined animals. Animal species types considered in the analysis include: feedlot beef, dairy, swine, and poultry (chicken and turkey). Numbers of confined animals and numbers of farms with confined animals—or Animal Feeding Operations (AFOs)—were obtained by county from the Census of Agriculture. This subset of animal farms does not represent the total production of manure nutrients, but rather the nutrient production for those operations for which State and Federal animal-waste disposal policies are most relevant.

Manure-nutrient production. Production of primary manure nutrients—nitrogen and phosphorus—is estimated based on census-derived animal numbers and coefficients of manure production by animal type. Computation of manure nutrients followed a three-step process. First, animal

[6] Our analysis meets all respondent confidentiality requirements of the published Census of Agriculture values.

numbers were converted to an average number of annual animal-units[7] (AU) from reported end-of-year inventory and annual sales data. Second, quantities of manure were computed using coefficients of manure production by animal type and the number of AU. Data development on manure production was geared primarily to AFOs operating above a minimum scale to reflect commercial operations.[8] Third, the recoverable portion of the manure nutrients per ton of manure was computed by animal type after adjusting for losses during collection, transfer, and storage. Recoverable manure nutrients represent that portion of manure that can be collected and applied to land net of storage and handling losses at the source site. Nutrient content of recoverable manure reflects a composite nutrient composition of manure produced by county, based on county-level distributions of animal species from the Census of Agriculture. (See Kellogg et al. (2000) for details of the estimation process for manure-nutrient production and loss coefficients.)[9]

Nutrient assimilative capacity. Farmland assimilative capacity for nutrients is estimated across farm types (i.e., non-animal farms, confined animal farms, and non-confined animal farms) based on acreage and reported yields for major field crops and pasture, aggregated to the county level. Farmland acreage available for manure spreading is calculated based on acreage in 24 major field crops and permanent pasture from the Census of Agriculture.[10] Crop and pasture land acreage in out-of-basin sink counties is assumed available for manure from the watershed, after adjusting for application of locally produced manure within the sink county. See Kellogg et al. (2000) for details of the estimation process for manure-nutrient uptake coefficients.

Manure-nutrient excess. Manure-nutrient excess refers to the quantity of manure that cannot be spread at crop-based agronomic rates on the source animal farm and thus must be hauled off the farm for land application. Manure-nutrient excess is computed under both a nitrogen-based (N) standard and a phosphorus (P) standard. These standards differ by the nutrient that determines the per-acre crop application rate, with a P standard generally allowing less manure per acre. Onfarm manure-nutrient excess is estimated by applying farm-level census measures of manure-nutrient production relative to the farm's potential to use nutrients for crop production. Excess recoverable manure nutrients are calculated as those that exceed the onfarm assimilative capacity of confined feeding operations, based on the amount of land controlled by farms with confined animals.[11] County surplus manure to be hauled off-farm is calculated for each nutrient standard based on an aggregation of farm-level manure-nutrient excess across animal farms.

Land base for surplus manure. The farmland base potentially available for surplus manure is defined to include all cropland and pasture land in 24 major crops on non-animal farms and some portion of acreage in those crops on both confined and nonconfined animal operations. Acreage in nonconfined operations was adjusted for nonrecoverable manure-N available on the farm. Acreage in confined animal operations is from farms with surplus capacity to absorb off-farm manure nutrients, accounting for their own crop nutrient needs.

[7] Annual animal-units reflect a biologically based definition of an AU of 1,000 pounds of live animal weight for feedlot beef, dairy, swine, and poultry, using average animal weights.

[8] Operations were included if: (1) animals generated more than $2,000 in sales on the farm, or (2) at least three AU were reported on the farm. Confined animals and their minimum scales were: feedlot beef (15 head), dairy (20 head), swine (50 head for slaughter), and poultry (100 head of broilers or 50 head of layers or turkeys). Of particular note, these data do not include estimates of the recoverable portion of manure from cattle, other than fattened cattle and milk cows (bulls, beef cows, dairy and beef replacement heifers, calves less than 500 pounds, and calves greater than 500 pounds not in a feedlot). If cattle other than fattened cattle and milk cows were included in the analysis, farm numbers would double, the number of AU would increase by only 6 percent, and recoverable manure nitrogen would increase by about 5 percent.

[9] Adjustments in base manure-nutrient composition measures to reflect changes in animal mix, feed mix, genetic stock, and nutrient losses may be incorporated into the model through a series of factor adjustments for nitrogen and phosphorus.

[10] Adjustments in the composite uptake rate by county to reflect changes in crop mix and/or crop yield may be incorporated into the model through a series of factor adjustments applied by farm type for crop and pasture land.

[11] We recognize this calculation process has the potential to overstate excess manure nutrients since some manure is moved off many production farms. However, total excess nutrients on confined livestock farms were more likely to be understated since neither commercial fertilizer applications nor atmospheric deposition of nutrients were considered in this analysis. Most crop farms without animals, and many farms with animals, use chemical fertilizers because they are less bulky, easier to apply, and have a more predictable nutrient content than manure.

The model assumes that all acreage on confined animal operations is available for manure spreading. In the case of non-animal farms and nonconfined animal farms, a given percentage of total farmland base is assumed available for spreading, reflecting assumptions on the willingness of landowners to accept manure. Landowners may be reluctant to accept manure for various reasons. These factors include uncertainty about manure-nutrient content and availability, high transportation and handling costs relative to commercial fertilizer, soil compaction from spreading equipment, dispersion of weed seeds, concerns for added regulatory oversight, and public perception regarding odor and pathogen issues (Risse et al., 2001). While little data exist on levels of landowner willingness to accept manure on their fields, findings from this empirical study suggest that this is an important determinant of costs facing animal producers. Adjustments to reflect willingness to accept manure, specified separately for cropland and pasture land, are used to reduce the model land base effectively available for manure spreading.[12]

Manure application rates. Application rates for manure applied off-farm are computed for each within-county and out-of-county transfer based on average nutrient content of manure from the source county and average per-acre nutrient uptake on farmland in the destination county, adjusted for nutrient standard requirements and field losses. Average manure-nutrient composition by county is derived from animal mix data from the Agricultural Census and coefficients on nutrient production per AU (Kellogg et al., 2000). Average per-acre nutrient uptake rate by county is derived from cropping pattern and yield data from the Agricultural Census. Application rates and total quantity of manure that can be applied are tallied separately for confined animal farms to reflect the cropping patterns and yields specific to farms with confined animals.[13]

Manure application rates in the model vary with the nutrient standard in effect. Under an N standard, manure is applied based on crop nitrogen needs over the growing season; under a P standard, manure applications are based on crop phosphorus needs. Manure applied according to a P standard is generally applied at a lower per-acre rate than under an N standard, implying more land is needed for a given quantity of manure.[14] Reduced application rates under a P standard reflect the ratio of N and P requirements of most crops relative to the N and P ratio typical of most manure. The model user may specify the share of acres required to meet a given nutrient standard if values are known, with variable shares permitted across county subregions and crop and pasture land categories.[15]

Manure application rates are further adjusted to reflect the level of application loss. An estimated 30 percent of manure-N applied is not available to the crop due to unavoidable losses of nitrogen, primarily from volatization of ammonia. Applied manure under the N standard allows for sufficient manure-N to meet both full crop needs for nitrogen, plus the 30-percent field loss (Kellogg et al., 2000). An additional loss adjustment factor reflects the extent of manure incorporation—the base N loss factor is adjusted downward by 5 percent for fields with soil incorporation and 30 percent for fields without incorporation (Fleming et al., 1998).

[12] In order to bound potential cost estimates, the ERS study fixed levels of willingness to accept manure over a range from 10 percent to 100 percent of crop and pasture land on non-animal farms and nonconfined animal farms (Ribaudo et al., 2003).

[13] Manure application rates are automatically modified to reflect adjustments in manure nutrient content (due to changes in feed supplements or animal mix) and nutrient uptake rates (due to changes in cropping patterns or yields).

[14] Under a multi-year P standard, applied manure per acre is equivalent to that under an N standard, with treated acres rotated over a multi-year sequence to fully use excess stored manure-P, thus minimizing application costs.

[15] Since reliable data on the share of land requiring the more stringent phosphorus standard are not available at a watershed scale, separate model scenarios were specified in the ERS study as if all acres would apply manure according to either an annual N or P standard, thus bracketing the full range of possible cost effects.

Technology Use and Input Costs

Technology use and input cost data supplemented available production data from the Agricultural Census in assessing costs of production adjustments within the animal sector. Data categories involve nutrient management plans; manure storage and handling systems; commercial fertilizer offsets; industrial uses of manure; and feed supplements.

Nutrient management plans. Implementation of nutrient management plans is recommended under USDA guidelines for all confined animal operations and required under new Federal regulations for CAFOs. NRCS was the primary source of cost data for nutrient management planning (USDA, NRCS, 2003). Cost components for manure management addressed in the study include plan development, manure testing, and soil testing. Costs for plan development and manure testing are applied to the source county; soil testing costs are applied to the destination county. Plan development cost ($400/confined animal farm) was calculated as an annualized cost of developing the nutrient management elements of a CNMP based on an average of 45 hours per farm and $45/hour. Manure testing cost ($200/farm) reflects collection ($10) and analysis ($40) four times annually, applied over the number of confined animal farms in the watershed. Annual soil testing cost ($0.40/acre receiving manure) is based on $20/sample with 10 acres per soil test, or $2/acre, and one soil test every 5 years. Nutrient management plan costs not specifically related to manure land application, such as record-keeping and visual inspection, are not addressed here. Costs associated with training and certification for manure application and calibration of the manure spreader were assumed to be incorporated within reported application costs per ton of manure hauled.

Manure storage and handling systems. Manure production levels from the Agricultural Census were apportioned by manure storage and handling systems by county (table 1). Three representative manure system categories were defined in the study—lagoon systems (open, uncovered storage), slurry systems, and dry systems (primarily poultry litter in the Chesapeake Bay watershed). Allocation of manure production by storage/handling system was necessary to capture important cost differences across manure-hauling modes, hauling weight, and application.

Allocation of manure production by manure-storage system category was computed based on AUs by species as a share of total confined AUs, system shares by animal species, and manure generation per AU. Animal-units by species as a share of total confined AUs were obtained from the information developed from the Agricultural Census. Information on manure system shares for hog and dairy operations was obtained from Agricultural Resource Management Survey (ARMS) data (USDA, ERS, 2000). Manure shares for lagoon, slurry, and dry systems by animal species were based on animal operations with a single system. Hog values were based on reported values for Virginia, the sole State in the Chesapeake Bay watershed represented in the 1998 ARMS hog survey. Dairy values were reported for Virginia, New York, and Pennsylvania in the 2000 ARMS dairy survey, with estimates for Delaware and Maryland based on Pennsylvania. Beef cattle

Table 1—Manure-hauling and application costs by system type

System type	Distance interval	Hauling mode	Base charge[1]	Application cost only	Distance charge
	Miles		*$ per ton*		*$ per mile*
Lagoon	Onfarm	Pump/spray field	1.25	0.375	0.25
	0.5-2.0	Truck mounted liquid sprayer	2.00	0.600	0.30
	2.0-10.0	Truck mounted liquid sprayer	2.00	0.600	0.30
Slurry	Onfarm	Tractor/spreader (honey wagon)	2.00	0.600	0.30
	0.5-2.0	Truck mounted liquid sprayer	2.00	0.600	0.30
	2.0-10.0	Tanker truck	2.00	0.600	0.30
	>10.0	Tanker truck	2.00	0.600	0.30
Dry	Onfarm	Spreader truck	6.00	1.400	0.50
	0.5-2.0	Spreader truck	6.00	1.400	0.50
	2.0-10.0	Truck	10.00	3.700	0.11
	>10.0	Truck	10.00	3.700	0.11

[1] Includes cost of manure hauling/unloading and land application (without incorporation).

Sources: NRCS, 2003; Fleming et al., 1998; Pease et al., 2001; and Borton et al., 1995.

estimates were assumed equivalent to dairy estimates by State. Poultry production is assumed to use dry litter systems.

Manure-hauling weights are based on wet tons of manure, which contain moisture and bedding content that vary by manure system and species type (USDA, NRCS, 1999; and Barker et al., 2001). Wet manure weights are estimated from a dry manure weight (theoretic zero-moisture weight), adjusted by moisture and bedding material. Dry manure estimates per AU in dry tons per species type are: dairy, 2.156; feedlot beef, 1.143; swine, 1.2635; and poultry, 3.0 (Kellogg et al., 2000). Estimates of moisture content by system type are as follows: lagoon, 99 percent (all species); slurry, 90 percent (all species); dry, 30 percent (poultry); and dry, 50 percent (non-poultry). Manure bedding as a percentage of dry manure tonnage, by species, are: dairy, 30 percent; poultry, 10 percent; and feedlot beef and hogs, 0.[16]

Model costs for manure hauling and application are presented in table 1. Hauling and application charges were based on published literature (Pease et al., 2001; and Fleming et al., 1998), supplemented with data from NRCS (USDA, NRCS, 2003). Charges reflect a base rate per wet ton (manure loading/unloading and application) and cost per ton-mile (manure hauling). Charges are specified by storage/hauling mode and distance interval to reflect substantial differences in per-unit costs. (Application costs, expressed on a per-ton basis, are separated out for reporting purposes).

Maximum hauling distances for lagoon and slurry waste were fixed at 10 and 50 road miles, respectively; hauling distance for dry litter system waste was bounded by maximum transport distances in the model. Hauling costs were based on a round trip distance, with no backhauling. All manure-hauling costs are applied to the source county, although the model provides flexibility in assigning a share of costs across source and destination counties.

Manure incorporation costs—not reflected in application costs above—assume a cost of $6.00 per acre (Iowa State Farm Survey, 2001), with an

[16] While moisture content varies with the manure system type, manure-nutrient content per dry ton of manure is based on a composite across species by county and is not varied by manure system type.

estimated 40 percent of acres using incorporation based on information from the ARMS hog and dairy surveys.

Commercial fertilizer. The calculation of savings from fertilizer offsets assumes that organic nutrients from manure replaces chemical fertilizer on a 1:1 basis. Calculation further assumes that only the manure nutrients beneficially used in crop production are valued. Thus, excess P applied under a nitrogen standard is not considered in calculation of fertilizer savings, i.e., no benefit was given for manure nutrients in excess of crop needs. Moreover, savings do not consider the additional benefits of manure as a soil amendment (organic matter and soil tilth).

Chemical fertilizer cost savings are based on reported 1997 prices by USDA's National Agricultural Statistics Service (NASS), based on representative fertilizer products for the Northeastern U.S. (USDA, NASS, 2001). Nitrogen price reflects the U.S. average price ($160/ton) for a nitrogen solution of 30 percent N, or a price per active ingredient of $0.27/lb. N. (The 30-percent nitrogen solution is selected as a representative form of N because it was the lowest priced form of N with adequate use for NASS to record prices for both regions—Northeast and Southeast—encompassing area within the Chesapeake Bay watershed.) Phosphorus price reflects the price per ton of triple superphosphate (45 percent P), averaged across the Northeast and Southeast ($267/ton), or an active ingredient price of $0.30/lb. P. Cost-savings for reduced fertilizer application costs (under an N standard) of $5/acre were from Fleming (1998).

Industrial uses of manure. Primary industrial uses of manure include use as an input source for power generation and as a direct ingredient in composted fertilizer products, primarily for specialty uses (i.e., residential, nursery, and golf courses). Industrial uses of manure lessen the aggregate cost of manure land application in the basin through reductions in both the amount of manure requiring application on crop and pasture land and the need for long distance hauls in areas where animal production is concentrated. Information on manure use in existing applications was obtained by processing facility via personal contact with extension agents and industry representatives.

Manure used in industrial uses is represented in the model as an exogenous reduction in the total supply of poultry litter manure to be land-applied. Manure tonnage in industrial uses, expressed in wet tons (with bedding and moisture included), is converted to dry-ton equivalents for consistency with modeling units for manure nutrients. Reductions in dry manure tonnage requiring land application are then apportioned across counties in the vicinity of a given processing facility, based on the relative proximity and volume of manure surplus by county.

Two alternative industrial use scenarios were developed for the recent ERS study, representing a near-term (2002-04) and mid-term (within 5-year) time frame (table 2). An estimated 200,000 tons of poultry litter would be diverted to industrial alternatives in the near-term, increasing to 376,000 tons within 5 years. Estimates represent approximately 0.30 and 0.65 percent of the total manure produced in the region, respectively. Near-term estimates include existing composting facilities and two new large-scale

Table 2—Estimated county-level quantities of poultry litter (wet tons) used for industrial purposes—1997, 2002-04, and 2005+

State/county	Base case (1997)	Near-term (2002-04)	Mid-term (2005+)
Delaware:			
Kent	0	0	10,000
Sussex	0	72,500	118,500
Maryland:			
Caroline	0	5,000	5,000
Dorchester	0	3,500	5,500
Somerset	0	0	28,700
Wicomico	0	45,000	61,000
Worchester	0	13,000	75,000
Virginia:			
Accomack	0	0	12,300
Rockingham	0	60,000	60,000
Total		199,000	376,000

Source: U.S. Department of Agriculture, Economic Research Service.

plants. Future estimates reflect projected growth in composting operations, full use of existing plants' capacity, and the completion of industrial uses currently in the planning or construction stage. (For more information on industrial use scenarios, see Ribaudo et al., 2003.)

Feed supplements. Phytase has been used as a feed supplement for swine and poultry to increase phosphorus use in feed rations and thus reduce phosphorus content of excreted manure. The model assumes a 30-percent reduction in phosphorus content per ton of dry manure with use of phytase as a feed supplement (Council for Agricultural Science and Technology, 2002). Use of phytase is thus represented as an adjustment in the phosphorus content of the county-composite manure, based on manure-P generated by species type, the mix of AUs in the county, and the share of AUs by species receiving phytase feed supplements. The baseline model condition assumes that phytase was not used (consistent with production conditions in the 1997 Agricultural Census survey year); additional model runs were generated to reflect full phytase adoption on hog and poultry operations.

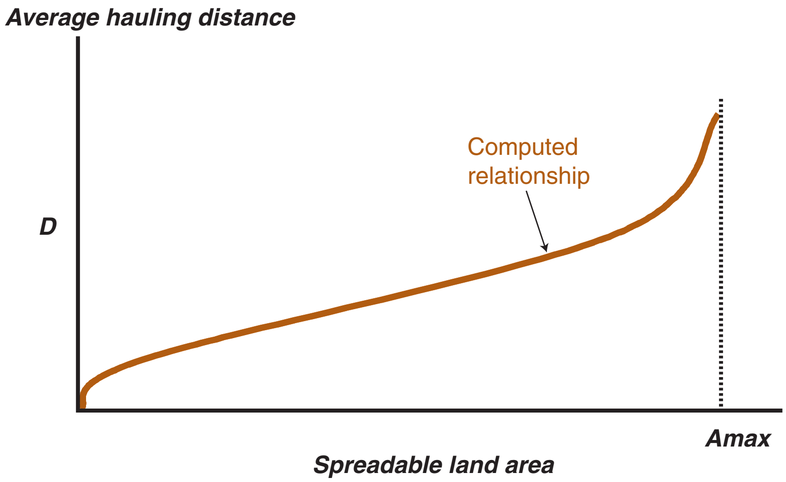
Distance Functions for Manure Hauling

Hauling distances for off-farm manure spreading are assessed based on area-to-distance functions derived from county land use patterns. These functions are a central component of the optimization model—linking the area needed for manure spreading in a destination county with average transport distance required to access the area from a given source county. By incorporating spatial relationships involving animal operations and spreadable land area, area-to-distance functions are intended to capture the inherent competition for land that exists among producers required to move surplus manure off the farm. Figure 3 shows a stylized area-to-distance relationship for manure hauling.

Competition for spreadable land is, in part, a function of the spatial pattern of spreadable area. Where farmland is scattered, a higher slope of the area-

Figure 3

Stylized area-to-distance relationship for manure hauling



Notes: *Amax* based on Census of Agriculture data. The computed relationship was based on GIS procedures applied to National Land Cover Dataset and Census of Agriculture data.

Source: U.S. Department of Agriculture, Economic Research Service.

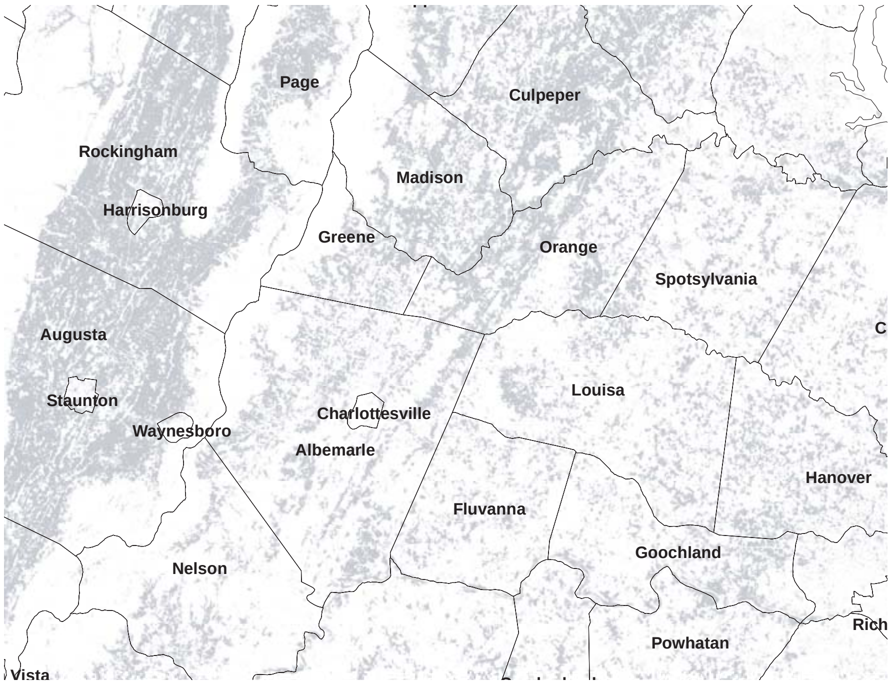
to-distance relationship reflects relatively long average hauls within the destination county to access a given acreage. Where farmland distribution is more dense, a reduced slope reflects comparatively shorter hauls to access a given acreage. The degree of competition also depends on the number, size, and proximity of confined animal operations, both within and out-of-county. Where land is limited, greater concentrations of animal production will increase competition for spreadable acreage, resulting in longer hauling distances to access available land and greater potential for out-of-county manure exports.

GIS estimation of area-to-distance functions involved a series of procedures. First, the spatial coverage for spreadable land was developed for the Chesapeake Bay watershed (CBW) study area. Second, the location of animal feeding operations was assigned within CBW basin counties. Third, area-to-distance relationships were calculated for within-county transfers. Fourth, distant intercepts and area-to-distance relationships were calculated for out-of-county transfers. Fifth, the slope of linearized area-to-distance functions were estimated for direct use in the model. Finally, area-to-distance relationships were adjusted to reflect adjustments in landowner willingness to accept manure.

Spreadable land coverage. The modeling system uses the National Land Cover Dataset (NLCD) developed by the U.S. Geological Survey (Homer et al., 2000; and USGS, 2004) to assess the spatial pattern of land available for manure application. This dataset is based on 1992 Landsat thematic mapper imagery at 30-meter resolution, classified into 21 land use categories. By combining the crop and pasture land categories, we can assemble a spatial data set of potentially spreadable land in all counties of the study region, both within the Chesapeake Bay watershed and adjacent counties within a 60-km reach of the watershed boundary. Figure 4 shows the spatial distribution of crop and pasture land in a portion of northwestern Virginia.

Figure 4

Crop and pasture land distribution in northwest Virginia



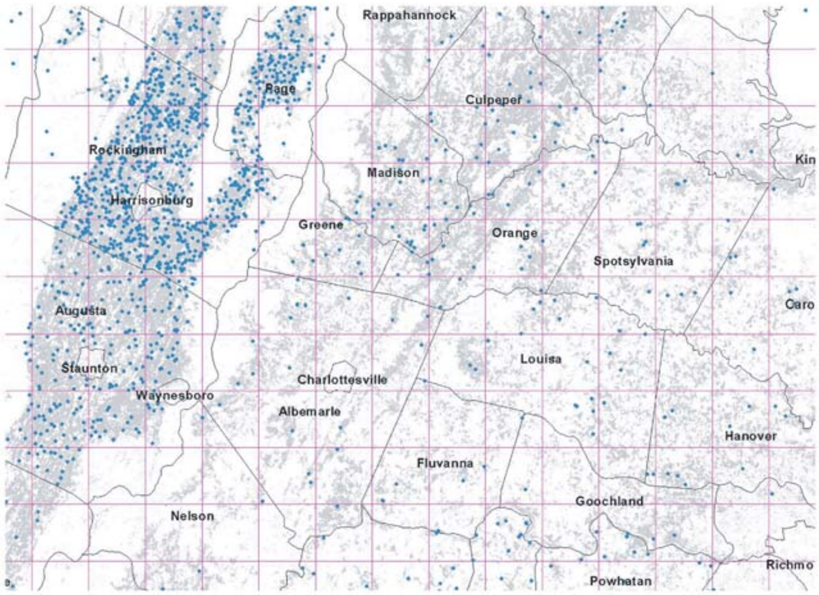
Note: Grey shading indicates crop and pasture land.

Source: U.S.Department of Agriculture, Economic Research Service, based on U.S. Geological Survey National Land Cover Dataset.

Location of animal operations. The degree of competition for spreadable land is influenced by the number, location, and size of confined animal operations. While the number and average size of animal feeding operations can be obtained from the census at a county level, the specific locations of operations within a county were unavailable. (The census does not collect precise locational information, and the data are not generally available at a regional scale from other sources.) Therefore, animal operations in the Chesapeake Bay watershed had to be locationally assigned by county within the GIS. For purposes of this analysis, animal operations were randomly assigned within crop and pasture land portions of each county, using a 30-meter grid overlay of the county. Manure production and manure by system shares are applied uniformly across animal farms by grid location in the model. Figure 5 shows the assignment of farm operations with confined animals over cropland areas in northwestern Virginia.

The random assignment of animal operations in the GIS may yield somewhat conservative estimates of actual hauling distances. While the majority of animal operations tend to be located in proximity to crop and pasture land, some operations may be separated from arable land suitable for manure spreading since production is not as sensitive to soil conditions. Moreover, the spatial concentrations of manure production within a county—reflecting the presence of larger CAFO operations and observed clustering of animal operations—will tend to increase competition for adja-

Figure 5
Assignment of animal operations



Note: 1 dot = 1 animal feeding operation. This map illustrates the spatial assignment of animal feeding operations within crop and pasture land area, by county and grid.

Source: U.S. Department of Agriculture, Economic Research Service, based on U.S. Geological Survey National Land Cover Dataset.

cent land resources. Nonetheless, the random assignment procedure was regarded as reasonable at a watershed scale, given limitations of the data.

Within-county area-to-distance relationships. We then used the GIS to compute area-to-distance relationships for within-county manure transfers for each within-basin county in the model. Area-to-distance functions for in-county manure transfers represent the average hauling distance from animal farms in a given county to spreadable land within the same county. With limited amounts of surplus manure, spreadable land is relatively accessible and hauling distances are generally short. As manure-spreading requirements increase, animal operations must compete increasingly for the same acreage—reducing accessibility and increasing the average hauling distance needed to access available acreage.[17]

Area-to-distance relationships for within-county transfers were computed for each basin county in the model by incrementally increasing, through a series of expanding 30-meter concentric bands, the search for farmland in the same source county around each of the assigned animal operations. The change in aggregate spreadable area—excluding non-farmland and farmland previously claimed by a competing operation in closer proximity—is measured for each additional distance increment. Thus, the area-to-distance relationship reflects the average distance that must be traveled across all confined animal operations to access a given level of spreadable acreage, accounting for competition among animal producers within the county. The relationship between the spreadable acreage requirement and average distance hauled is upward sloping and fairly linear along much of the observed range (computed line in figure 6).

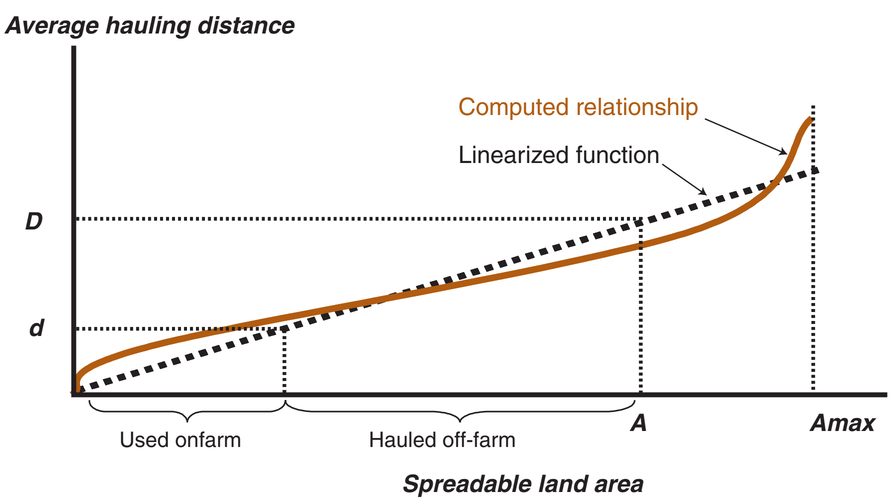
[17] The actual area of available spreadable acreage used for manure application in a given county is determined by the optimization model, reflecting manure flows within and across counties that minimize aggregate hauling and application costs in the basin.

Out-of-county area-to-distance relationships. Out-of-county relationships represent manure-hauling distances from confined animal operations within a source county to spreadable acreage in other destination counties. Unique out-of-county relationships were generated for all county-to-county combinations within an assumed 60-km linear transport radius. The transport radius for the 16 counties (10 percent of all basin counties) with the highest concentrations of surplus manure relative to spreadable land was expanded to 150 km (93 linear miles), reflecting the greater hauling distances that are likely to be required from areas where animal production is concentrated.

A three-stage process was used to generate the area-to-distance relationships for out-of-county transfers (nonlinear curve shown in figure 7). First, to reduce the number of possible source-county grid alternatives, animal farms were aggregated (binned) using a 12-km grid overlay across the entire area. Although the binning procedure reduces the precision of travel distances for out-of-county functions, the procedure was necessary to ensure tractability for model optimization. Second, for each 12 km grid with animal operations, distance was measured from the grid centroid to the closest edge of spreadable area in the destination county; this distance represents the intercept term of the functional relationship. Third, the area-to-distance relationship within the destination county was computed in a fashion similar to that for in-county transfers. Thus, the area-to-distance relationship represents average hauling distance to access a given spreadable area within the destination county but measured from the direction of the source county.

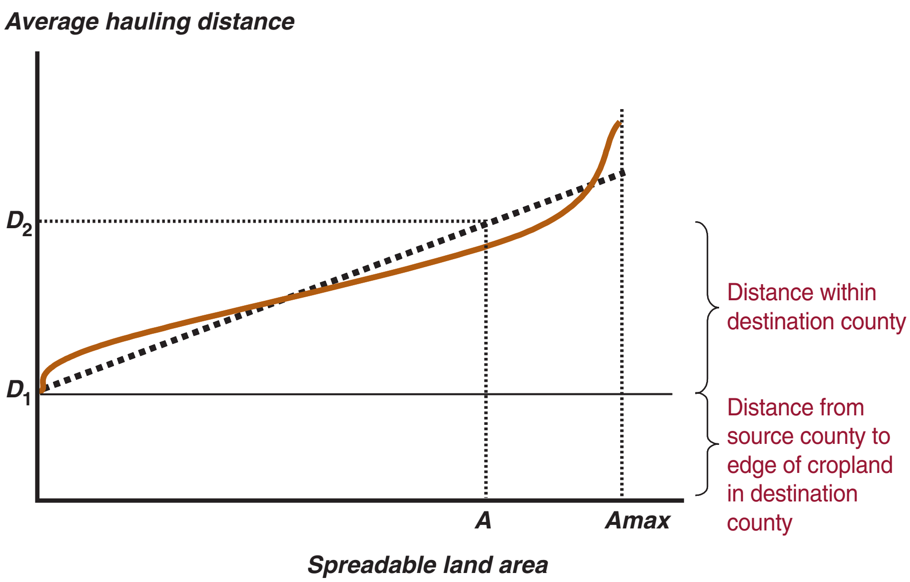
Estimating linearized area-to-distance functions. For use in the regional model, area-to-distance relationships estimated from the GIS were linearized by truncating the upper and lower tails of the distribution (10 percent of acreage, respectively) and fitting a linear function to the mid-range observations (80 percent) (linear portions of figures 6 and 7). The use of linear representations reflects the significantly reduced computer memory requirements relative to non-linear functions for the area-to-distance relationship, and the fact that observed relationships are very nearly linear over

Figure 6
Within-county area-to-distance relationship



Source: U.S. Department of Agriculture, Economic Research Service.

Figure 7
Out-of-county area-to-distance relationship



Source: U.S. Department of Agriculture, Economic Research Service.

the relevant mid range. Regression coefficients for the linearized area-to-distance functions were incorporated as parameters in the regional model. These include a unique set of slope coefficients for each within-county and out-of-county function, as well as individual distance intercept terms by source-county grid for each out-of-county function.

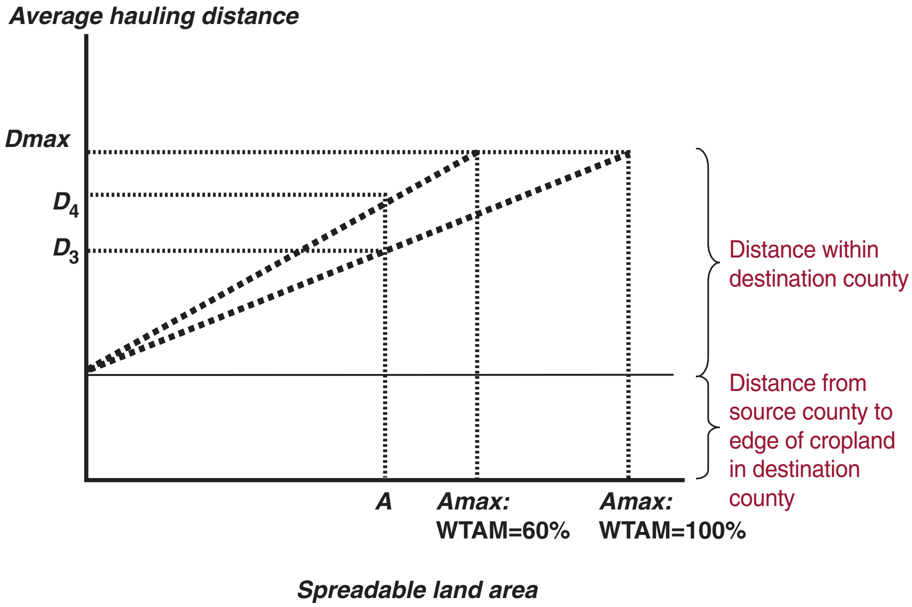
The developed slope and distance intercept terms are then applied to the spreadable acres obtained from the 1997 Census of Agriculture. The slope represents the average transport distance to use all the spreadable crop and pasture land, accounting for competition from neighboring farms that also require land to spread manure. For example, let *Amax* represent the maximum spreadable area in figure 6. If the area needed for manure land application by producers in the county for a given nutrient standard is *A*, then distance *D* would be the average distance traveled to access A acres. (In figure 6, acreage includes both on-farm acres and off-farm acres.) Figure 7 has a similar interpretation, except that a distance intercept accounts for the transport distance from the manure source to the edge of potentially spreadable land in receiving counties. Thus, the total distance to access land area A in figure 7 is represented by distance from the origin to D_2, with the origin to D_1, representing the distance to a receiving county and D_1 to D_2 the distance within the receiving county.

Adjustment for landowner willingness to accept manure. Area-to-distance functions derived from the GIS assume full acceptance of manure on all of the spreadable land base. Restrictions on availability of spreadable land due to the unwillingness of some landowners to accept manure is captured in the model through automated adjustments in both: (1) the quantity of spreadable acreage, and (2) the slope of area-to-distance functions, or hauling distance required to access a given spreadable area. Figure 8 shows the effect of a stylized reduction in available spreadable area on manure-hauling distance.

As spreadable area is reduced (to 60 percent of the maximum land base), producers must haul a greater distance on average (D_3 to D_4) to access the same amount of spreadable area *A*.

Figure 8

Shift in area-to-distance function with changes in landowner willingness to accept manure (WTAM)



Source: U.S. Department of Agriculture, Economic Research Service.

Model Equation System

The following section presents a review of the modeling equation system, with model variables defined by equation. Model equations include: (1) an objection function that minimizes sector costs relating to manure hauling and land application, (2) balance equations that track stocks and flows of manure and manure nutrients, (3) constraints on land availability, distribution of confined animal farms (manure sources), and manure-nutrient application, and (4) cost accounting equations. Appendix 3 provides a listing of equation variables used below, with the names of corresponding GAMS model variables (Appendix 2) and model report variables (Appendix 4).

The regional optimization model minimizes the net cost of applying manure in the Chesapeake Bay watershed, subject to total manure produced, crop and pasture land available for manure spreading (onfarm and off-farm), and share of manure diverted to non-land-based uses. Net costs are defined as costs associated with manure land application, plus a penalty cost for manure that cannot be land-applied within the basin, less savings on reduced commercial fertilizer. The model allocates manure production in basin counties (*ct*) to spreadable land in destination counties (*ct2*), both within and outside the source county, to minimize the objective function expression (OBJ):

$$(1)\quad OBJ = \sum_{ct}\sum_{ct2}[HAC_{ct,ct2} + INC_{ct2} + NM1_{ct} + NM2_{ct2} + ELA_{ct} - FS_{ct2}].$$

Costs include manure-hauling and application costs (HAC), manure-incorporation costs (INC), and nutrient management plan charges for source (NM1) and destination (NM2) counties (see equations 17 and 18 for cost items included). A penalty cost applied to manure levels' exceeding land application capacity in the basin (ELA) ensures that all manure is land-applied subject to available land (see equation 8 for calculation of surplus manure). However, the penalty cost is removed from the actual total cost value reported in the model solution report. Aggregate costs are further adjusted to reflect savings from reduced purchase and application costs for chemical fertilizers (FS). Net cost reported in the model solution is defined as total cost, net of savings from chemical fertilizer use.

In general, wet manure quantities are used to assess manure hauling and application costs, while manure-nutrient content and uptake determine the volume and direction of manure flows. Primary manure transfer equations are as follows:

$$(2)\quad M\_TRAN_{ct,ct2} = ((M\_AP_{ct,ct2,N*} * SH\_N_{ct2}) + (M\_AP_{ct,ct2,P*} * (1 - SH\_N_{ct2})))$$
$$* AC\_SPR_{ct,ct2}$$

$$(3)\quad \sum_{ct} AC\_SPR_{ct,ct2} \leq Amax_{ct2} * WTAM_{ct2}$$

$$(4)\quad M\_TRAN_{ct,ct2} = \sum_{gr}\sum_{sy}\sum_{ds} M\_TRN_{ct,gr,ct2,sy,ds}$$

$$(5)\quad \sum_{ds} M\_TRN_{ct,gr,ct2,sy,ds} \leq M\_PRD_{ct} * SH\_M_{ct,gr,sy}$$

(where N^* represents a nitrogen standard and P^* represents a phosphorus standard, *gr* is county grid location, *sy* is manure system (lagoon, slurry, and dry), and *ds* is hauling distance interval in miles. Onfarm hauling distance is fixed based on average onfarm distance by county computed from the Census. Off-farm hauling distance is an endogenously derived, continuous variable falling within one of three distance intervals (0.5-2 miles, 2-10 miles, and more than 10 miles), with per-unit hauling cost dependent on the distance interval.

Manure transfers (M_TRAN) refer to manure hauled off the source farm and land-applied within or outside the county. In equation 2, dry manure tons by manure transfer is defined as the product of manure application rate (M_AP) by manure transfer—weighted by acreage shares under an N standard (SH_N) and P standard (1- SH_N)—and receiving acres (AC_SPR) in the destination county. Adjustments in applied manure per acre provide the link between restrictions on manure-nutrient use and manure transfers in the model.

Equation 3 restricts applied manure from all potential source counties to total spreadable acreage (Amax) in the destination county, adjusted for assumptions on land operator willingness to accept manure (WTAM). Equation 4 sets aggregate county-level manure transfers (M_TRAN) equal to the sum of manure transfers by source-county grid location (*gr*), system type (*sy*), and distance interval (*ds*). Equation 5 restricts source-county manure transfers by grid (*gr*) and system type (*sy*), based on the share (SH_M) of total manure production (M_PRD) across system type and grid, based on assignment procedures followed in the GIS.

Equations 6 through 8 balance manure production, onfarm surplus manure, manure transferred off-farm, and quantity of manure exceeding land application capacity in the basin.

$$(6)\quad \text{M\_SRP}_{ct} = \text{M\_PROD}_{ct} - \text{M\_ONFRM}_{ct}$$

$$(7)\quad \text{M\_USE}_{ct2} = \text{M\_ONFRM}_{ct2} + \sum_{ct} \text{M\_TRAN}_{ct,ct2}$$

$$(8)\quad \text{M\_ELA}_{ct} = \text{M\_SRP}_{ct} - \sum_{sy} \text{M\_IND}_{ct,sy} - \sum_{ct2} \text{M\_TRAN}_{ct,ct2}$$

Equation 6 sets county surplus manure to be moved off the farm (M_SRP) equal to manure production (M_PROD) less that used onfarm (M_ONFRM) in the source county. Equation 7 fixes manure use (M_USE) as onfarm manure use plus that quantity obtained from all off-farm sources (M_TRAN) in the destination county. Equation 8 sets the manure that exceeds land application capacity (M_ELA) within the assumed transport radius of a source county equal to the manure surplus in the source county less the sum of industrial uses (M_IND) and the sum of manure transfers out-of-county. Quantities of M_ELA manure are minimized in the model through the use of a penalty cost parameter that assigns a high cost to manure not land-applied in the basin.

Hauling distances for off-farm transfers are computed based on equations 9–11.

$$DS_{ct,gr,ct2} = [(\alpha_{ct,gr,ct2} * \delta^{1}_{ct,ct2}) + (\beta_{ct,ct2} * (AC\_ONF_{ct} + \sum_{ct} AC\_SPR_{ct,ct2}))] * \delta^{2}_{ct2} \quad (9)$$

$$DS_{ct,gr,ct2} * M\_TRN_{ct,gr,ct2} = \sum_{sy} \sum_{ds} (DST_{ct,gr,ct2,sy,ds} * M\_TRN_{ct,gr,ct2,sy,ds}) \quad (10)$$

$$D\_MN_{ds} \leq DST_{ct,gr,ct2,sy,ds} \leq D\_MX_{ds} \quad (11)$$

In equation 9, average hauling distance (DS) from source county (*ct*) and grid (*gr*) is calculated as a function of spreadable acres in the destination county (*ct2*). Off-farm hauling distance by manure transfer is computed based on acreage using manure from the source county (AC_SPR)—above a fixed acreage for onfarm manure use on confined animal farms (AC_ONF)—in the destination county. Intercept α and slope coefficient are β estimated from the GIS-derived linear regressions for within-county and out-of-county transfers.[18] The intercept term, representing linear hauling distance from the source farm for out-of-county transfers, is adjusted (δ^1) for selected county-to-county transfers to reflect significant natural barriers (e.g., large bodies of water). In addition, a circuity parameter (δ^2) is used to convert linear distance to road miles.[19] Thus, equation 9 establishes the key linkage in the model involving: (1) acreage accessed for manure spreading and (2) average hauling distance within and between counties, with values of each derived endogenously across county-transfer combinations.

In equation 10, average hauling distance (DS) from source-county grid to a given destination county represents a weighted average of hauling distances (DST) by manure-system type (*sy*) and distance interval (*ds*). This equation effectively integrates per-unit manure-hauling costs within area-to-distance relationships from the GIS, linking: (1) average hauling distance by county transfer with (2) individual hauls from source-county grid points. Minimum (D_MN) and maximum (D_MX) distance is specified by distance interval in equation 11, used in assessing per-unit costs.

Stocks and flows of manure nutrients (*np*)—nitrogen *n* or phosphorus *p*—are tied to manure quantities as follows:

$$M\_SRP_{ct} = NP\_EXC_{ct,np} / NP\_M_{ct,np} \quad (12)$$

$$NP\_ONF_{ct2,np} = M\_ONFRM_{ct2} * NP\_M_{ct,np} \quad \text{where}_{ct} =_{ct2} \quad (13)$$

$$NP\_TRN_{ct,ct2,np} = M\_TRAN_{ct,ct2} * NP\_M_{ct,np} \quad (14)$$

Total excess manure nutrients (NP_EXC) are obtained from farm-level census data on manure production and onfarm assimilative capacity, aggregated to the county level. Equation 12 calculates manure surplus (M_SRP) based on pounds of excess N or P (*np*), depending on the nutrient standard in effect (*N** or *P**), and county-average nutrient content in lbs. per dry ton of manure (NP_M). In equation 13, onfarm manure nutrients (NP_ONF) reflect the quantity (M_ONFRM) and composition (NP_M) of manure produced and used on confined animal feeding operations. In equation 14, manure-nutrient flows (NP_TRN) are tied to manure transfers off the farm.

[18] For in-county manure transfers, the intercept term of the area-to-distance relationship is set to zero.

[19] A fixed circuity parameter of 1.2 reflects an average of State-level parameters reported for the Chesapeake Bay watershed region (U.S. Department of Commerce, 1978).

$$(15)\quad HAC_{ct,ct2} = \sum_{gr} \sum_{sy} \sum_{ds} [\, C1_{sy,ds} * (C2_{sy,ds} * DST_{ct,gr,ct2,sy,ds})\,] * (M\_TRN_{ct,gr,ct2,sy,ds} / (1-(MS_{sy} + BED_{sy})\,]$$

$$(16)\quad INC_{ct2} = (\, C3 * SH\_I_{ct2} * (\, AC\_ONF_{ct2} + \sum_{ct} AC\_SPR_{ct,ct2}\,) * SH\_C_{ct2})$$

In equation 15, manure-hauling and application costs (HAC) are computed for onfarm and off-farm transfers. Costs reflect loading, unloading, and application costs per ton hauled (C1), hauling cost per ton-mile (C2), distance hauled (DST), and dry tons of manure hauled (M_TRN), adjusted for moisture content (MS) and bedding (BED). Hauling and application costs vary across animal-waste systems due to differences in manure moisture content and equipment use. The model simulates a stepwise cost function for manure-hauling/application cost, with cost coefficients defined by system type (lagoon, slurry, and dry) and distance interval hauled. Costs of manure incorporation into the soil (INC) are computed in equation 16 based on per-acre charge (C3), total onfarm and off-farm acres using manure, share of acres in cropland (SH_C) (as manure is not generally incorporated on pasture land), and share of manured cropland using incorporation (SH_I).

$$(17)\quad NM1_{ct} = (\, M\_TST + C\_NMP\,) * AFO_{ct}$$

$$(18)\quad NM2_{ct2} = S\_TST * (\, AC\_ONF_{ct2} + \sum_{ct} AC\_SPR_{ct,ct2}\,)$$

Selected nutrient management plan costs related to land application are identified for manure source farms and receiving farms. Equation 17 computes source-county costs (NM1), based on representative costs for manure testing (M_TST) and plan development costs (C_NMP), summed across confined animal-feeding operations (AFOs) in the source county. Equation 18 computes destination county costs (NM2) for soil testing, based on representative costs (S_TST) per acre of land receiving manure.

$$(19)\quad FS\_N_{ct2} = (\, PR_{N} * (N\_ONF_{ct,ct2,N} + \sum_{ct} N\_TRN_{ct,ct2,N})) + (PR_{P} * (P\_ONF_{ct,ct2,P} + \sum_{ct} P\_TRN_{ct,ct2,P}) * P\_PCT_{ct2}) + (\, C\_AP * (AC\_ONF_{ct2} + \sum_{ct} AC\_SPR_{ct,ct2}))$$

Calculation procedures for fertilizer cost savings vary, depending on the nutrient standard in effect. In equation 19, savings calculated under an N standard (FS_N) include reduced chemical fertilizer purchases and reduced chemical application costs. Savings from reduced fertilizer purchases are computed based on the price (PR) of nitrogen (*N*) and phosphorus (*P*), and the quantity of manure nutrients used by crops. Nitrogen savings reflects the full application of manure-N, both onfarm (N_ONF) and off-farm (N_TRN), as all manure-N is assumed to be beneficially used in crop production since producers are assumed to meet nutrient management guidelines. Phosphorus savings reflects use of manure-P onfarm (P_ONF) and off-farm (P_TRN)—adjusted to capture that portion of P (P_PCT) that is beneficially used by the crop (or the ratio of applied manure at an annual P standard to applied manure under an N standard). Savings from reduced chemical application costs reflects the per acre cost of chemical application (C_AP) and total acres receiving manure under an N standard.[20]

$$(20)\quad FS\_P_{ct2} = (PR_N * (N\_ONF_{ct,ct2,N} + \sum_{ct} N\_TRN_{ct,ct2,N})) + (PR_P * (P\_ONF_{ct,ct2,P} + \sum_{ct} P\_TRN_{ct,ct2,P}))$$

In equation 20, savings calculated under an annual P standard (FS_P) reflect the value of only the manure-nutrient offset. There are no savings in chemical application costs (chemical fertilizer application is still required), as manure-N is insufficient to meet full crop needs. In contrast to the N standard where some portion of applied manure-P cannot be used by the crop, all applied manure nutrients are beneficially used under a P standard.[21]

$$(21)\quad FS_{ct2} = (FS\_N_{ct2} * SH\_N_{ct2}) + (FS\_P_{ct2} * (1 - SH\_N_{ct2}))$$

Equation 21 computes an acreage-weighted fertilizer cost savings (FS), based on the share of acres under an N standard and the more stringent (annual or multi-year) P standard.

[20] It is assumed that chemical nutrients are applied at crop-based rates, that manure nutrients directly offset nutrients obtained from chemical fertilizers, and that per acre field application costs are fixed regardless of the level of applied chemical fertilizer.

[21] The model can be easily modified to consider a multiple-year application of manure-P, in cases where soil-P levels allow for heavier manure applications. Under a multiyear P application, manure treatments are rotated over the farm acreage. Producers are permitted to apply multiple years' manure quantities at one time (up to the N standard level) on a given field where nutrients can be used in subsequent years of the multiyear rotation. Savings reflect the full value of the manure nutrients, as all applied manure nutrients are fully used by the crop. Savings also reflect a partial reduction in chemical field application costs, based on the share of acres treated annually within the multiyear rotation (equivalent to P_PCT). For the multiyear P case, equation 20 would be modified to include the additional cost savings:

$$+ (C\_AP * (AC\_ONF_{ct2} + \sum_{ct} AC\_SPR_{ct,ct2}) * P\_PCT_{ct2})$$

Output Generation

For a given model solution, the optimization model generates a series of output variables in a standard GAMS output file. Customized computer programs are used to extract and organize selected output variables and associated values for display and analysis.

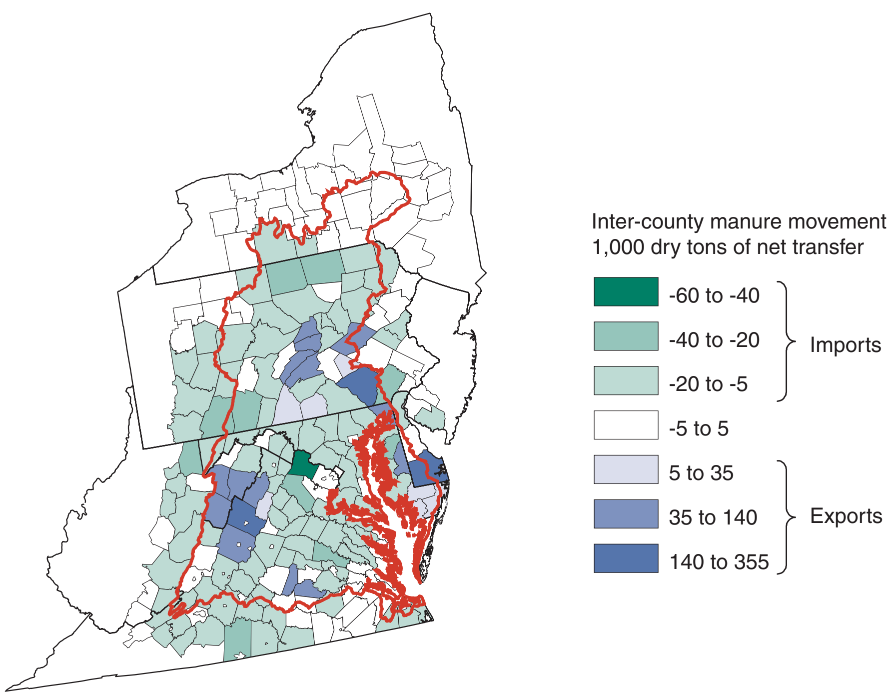
Appendix 4 includes a list of report variables from a standard output file. Report variables include those endogenously derived within the model, plus additional variables computed from the solution results. Report variables are organized under costs, acres, manure quantities, manure nutrients, and hauling distance.

Model reporting variables are reported at various spatial scales—county grid, county aggregate, and full basin levels. Model solution values for edge counties, or those that straddle the watershed boundary, are apportioned by share of farmland within the watershed to more accurately account for manure disposition at the basin level. Consequently, aggregate values may be reported only for the full modeled area and watershed area (without sinks). Aggregate costs are also reported with and without adjustments for chemical fertilizer savings.

Map presentations, developed in ARC-View, are generated from output solution variables reported at a county level. Maps are particularly useful in highlighting spatial values across the basin under various policy and resource assumptions. Figure 9 presents a sample map for the Chesapeake

Figure 9

Net manure exports in the Chesapeake Bay watershed assuming landowner willingness to accept manure of 60 percent



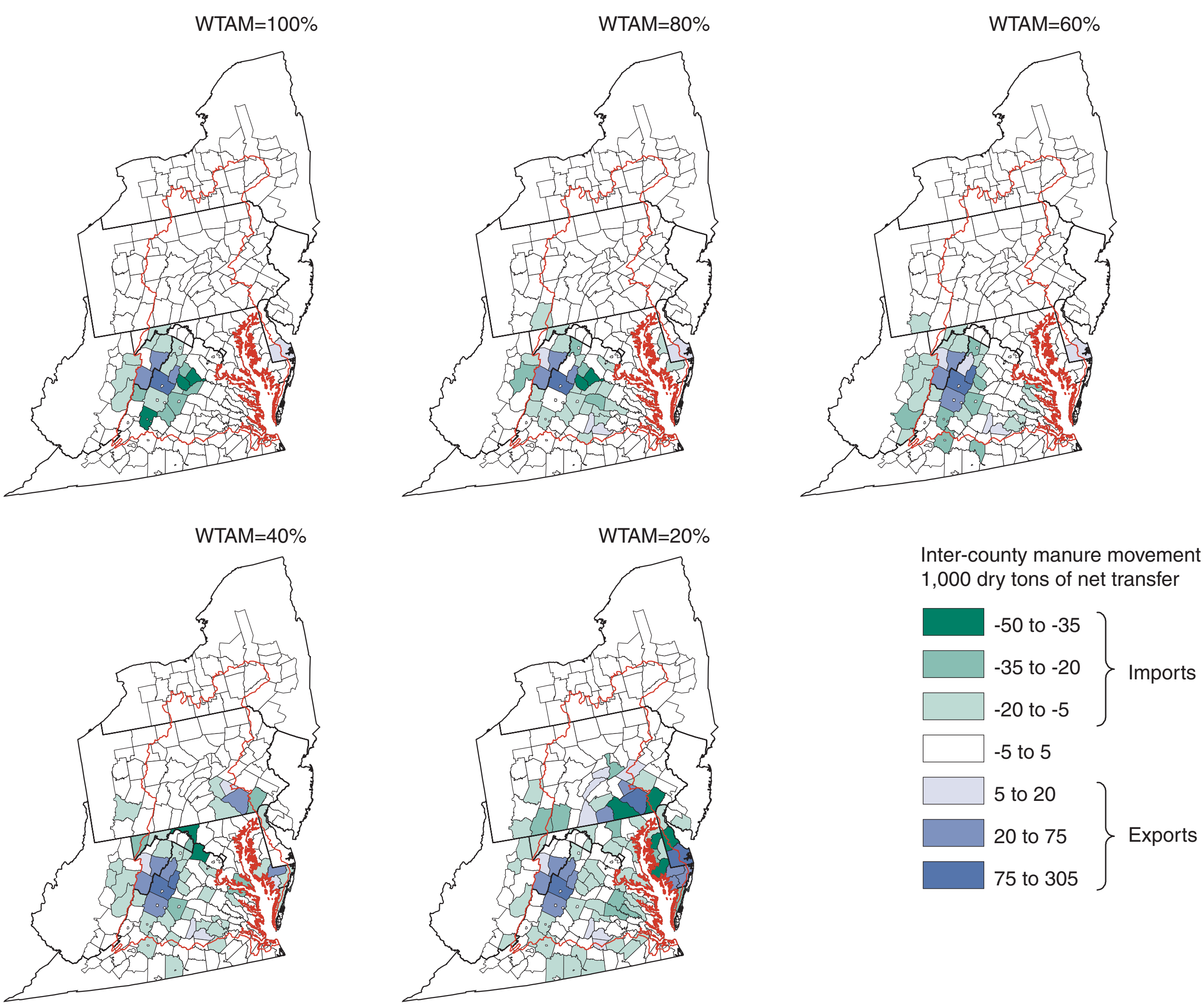
Source: U.S. Department of Agriculture, Economic Research Service.

Bay watershed, indicating net manure exports under a P standard, given a landowner-willingness-to-accept-manure level of 60 percent. Figure 10 presents a multi-sequence map set that captures the effect of alternative levels of landowner willingness to accept manure on county-level exports and imports under an N standard. Figure 10 shows that as the willingness to accept manure declines, the model transports manure increasingly longer distances and that more counties become net manure importers to access adequate land at the basin level to meet an N standard.

Maps may also be used to isolate key information for a single county. Figure 11 shows manure transfers from a single source county (Rockingham County, VA) to destination counties across the basin under a P standard. As manure transfers are estimated simultaneously across all counties, the direction and volume of manure flows that minimize aggregate costs to the basin necessarily reflect the effect of competing manure sources in neighboring counties.

Figure 10

Effect of landowner willingness to accept manure (WTAM) on the spatial distribution of manure transfers in the Chesapeake Bay watershed, based on 1997 animal production and an N standard

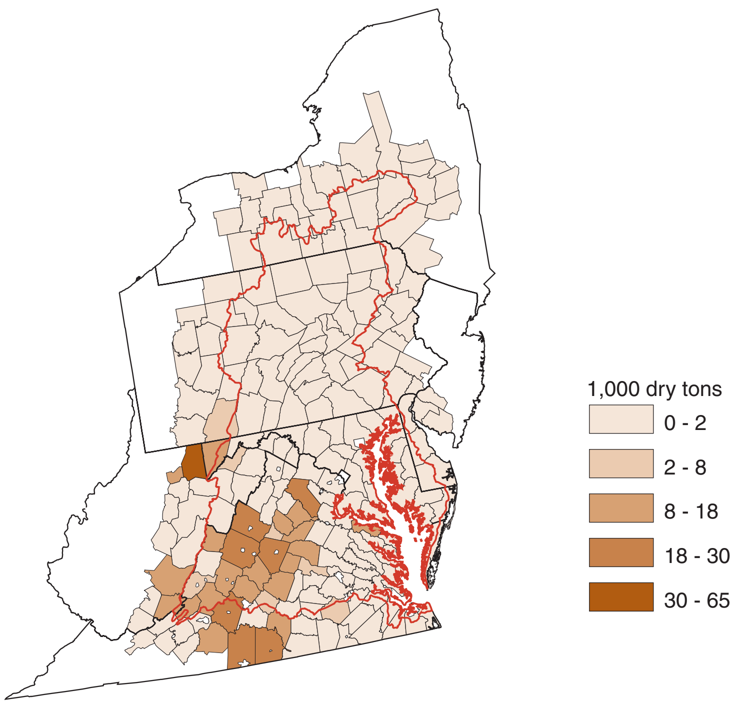


Source: U.S. Department of Agriculture, Economic Research Service.

Output data at the aggregate basin level may best be characterized in graphical form. In figure 12, a pie chart shows the share of manure produced in the Chesapeake Bay watershed, by disposition of use. In figure 13, a segmented bar graph is used to depict the disposition of manure under alternative levels of willingness to accept, given a P standard. Figure 14 presents a combination bar-line graph showing both manure management costs and manure quantities exceeding land application levels across alternative willingness to accept levels under a P standard. (For more discussion about these outputs, see Ribaudo et al., 2003.)

Figure 11

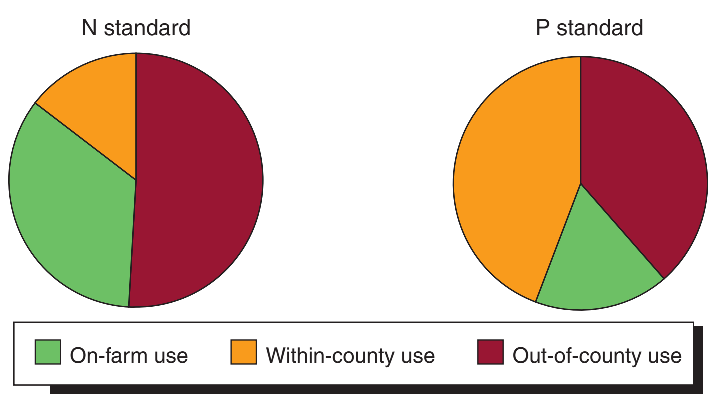
Manure transfers from Rockingham County, Virginia, with a P standard and 60-percent willingness to accept manure



Source: U.S. Department of Agriculture, Economic Research Service.

Figure 12

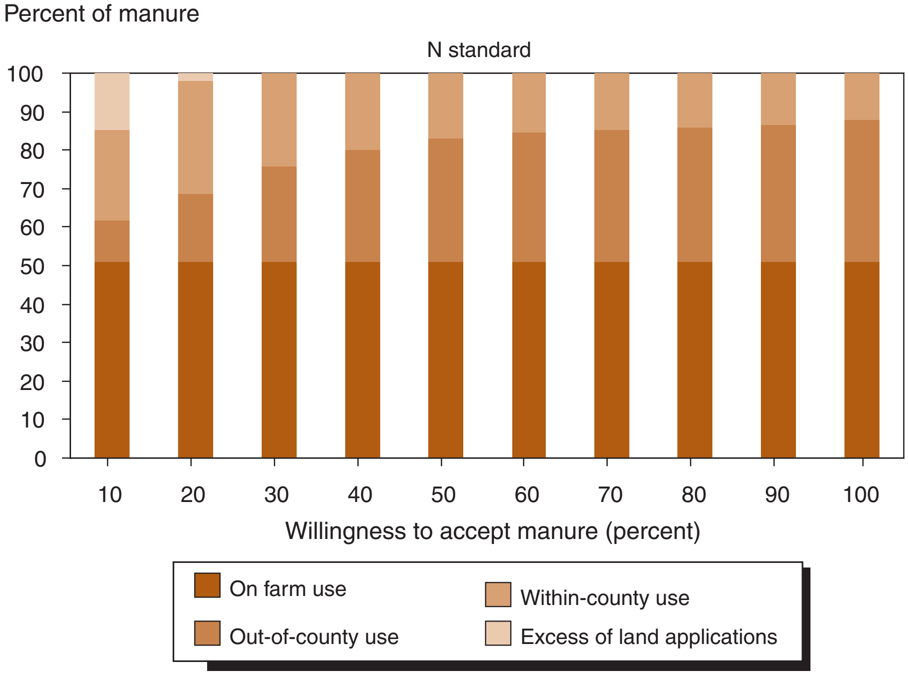
Disposition of manure in the Chesapeake Bay watershed under both N and P standards with a willingness to accept manure of 70 percent



Source: U.S. Department of Agriculture, Economic Research Service.

Figure 13

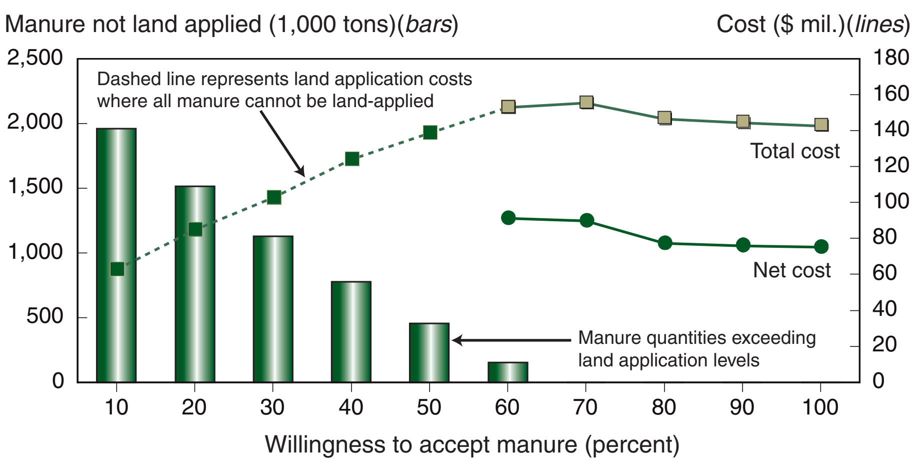
Effect of landowner willingness to accept manure on manure disposition in the Chesapeake Bay watershed



Source: Ribaudo et al., 2003.

Figure 14

Effect of landowner willingness to accept manure on land application costs and manure exceeding land application capacity in the Chesapeake Bay watershed: P standard



Source: Ribaudo et al., 2003.

Conclusion and Future Extensions

The Chesapeake Bay Regional Model, developed under the ERS Manure Management for Improved Water Quality Project, provides a useful framework to assess the importance of spatial factors—spreadable land base, animal concentrations, and manure-storage technologies—on potential manure management costs facing animal producers. Indeed, findings from application of the model suggest that spatial factors underlying competition for spreadable land in the Chesapeake Bay watershed are an important consideration in accurately assessing the feasibility and costs of new manure management guidelines to the animal sector. The modeling framework is also notable for its integration of farm-level survey data from the Agricultural Census, aggregated to the county level, with geo-specific data from the National Land Cover Dataset. The resulting database—developed from public secondary data sources—captures important intra-regional variation in key cost determinants for animal waste management. Moreover, the reliance on national data series ensures data consistency across a watershed scale, while facilitating data update and model transferability to other watersheds. Results from an initial application of the modeling system are featured in a recent ERS publication (Ribaudo et al., 2003).

While the Chesapeake Bay regional modeling system was successfully applied as a part of the ERS's water quality analysis, the developers noted potential model improvements and extensions as limitations were revealed during the initial application. Many of these improvements and extensions are being incorporated for subsequent applications of the regional modeling framework. Areas of model development (not in priority order) currently identified include:

- Inclusion of air emissions by manure-handling technology;
- Developing a procedure to respecify the spatial grid sizes used for aggregating (binning) of animal operations to achieve more efficient and rapid model convergence;
- Incorporating model differentiation in manure-nutrient production and related management requirements across CAFOs and non-CAFO animal farms;
- Developing the data and model capacity to adjust the available land base for manure spreading to reflect stream buffer guidelines, use of municipal sewage byproducts, and agricultural land conversion;
- Developing consistent regional data on public cost-sharing for manure-hauling and other manure management options, the use of backhauling, and local manure-pricing practices. These factors can adjust the effective hauling costs faced by animal producers as well as the distributional pattern of manure management costs;
- Incorporating onfarm drying technologies as a manure management alternative;
- Developing a process to estimate within the model the cost of reducing the stock of animals as a means of addressing manure that cannot be land-applied within the basin;

- Developing a process to integrate our model findings on the spatial distribution of land-applied manure with other models designed to address nutrient transport and water quality.

Implementation of improvements and extensions to the Chesapeake Bay regional model will depend on research priorities, resources allocated to the project, and availability of supporting data. Cooperation with regional subject-area experts remains an important consideration, as many of these data items are local in nature and not readily available through national data series.

References

Barker, James C., Joseph P. Zublena, and F.R. Walls. 2001. "Animal and Poultry Manure Production and Characterization," North Carolina State University, Cooperative Extension Service, Raleigh, NC. *www.bae.ncsu.edu/people/faculty/barker/a&pmp&c/table_of_content.htm*

Borton, L.R., C.A. Rotz, H.L. Person, T.M. Harrigan, and W.G. Bickert. 1995. "Simulation to Evaluate Dairy Manure Systems," *Applied Engineering in Agriculture*. Vol. 11, No. 2, pp. 301-310.

Council for Agricultural Science and Technology. July 2002. *Animal Diet Modification to decrease the Potential for Nitrogen and Phosphorus Pollution*. Issue Paper 21.

Fleming, R., B. Babcock, and E. Wang. 1998. "Resource or Waste? The Economics of Swine Manure Storage and Management." *Review of Agricultural Economics*, Vol. 20, No. 1, pp. 96-113.

Gollehon, N., M. Caswell, M. Ribaudo, R. Kellogg, C. Lander, and D. Letson. June 2001. *Confined Animal Production and Manure Nutrients*. Agriculture Information Bulletin No. 771. U.S. Department of Agriculture, Economic Research Service.

Homer, Collin, Chengquan Huang, Limin Yang, and Bruce Wylie. 2000. Development of a Circa 2000 Landcover Database for the United States. U.S. Department of the Interior, U.S. Geological Survey, EROS Data Center, Sioux Falls, SD. Available at: *http://landcover.usgs.gov/pdf/asprs_final.pdf*

Kellogg, Robert, Charles Lander, David Moffitt, and Noel Gollehon. October 2000. *Manure Nutrients Relative to the Capacity of Cropland and Pastureland to Assimilate Nutrients: Spatial and Temporal Trend for the United States.* U.S. Department of Agriculture, Natural Resources Conservation Service.

Pease, James, Beth Ann Pelletier, and David Kenyon. January 29-31, 2001. "Poultry Litter Transport Alternatives for Land Application in Virginia." Southern Agricultural Economics Association, 2001 Annual Meeting, Ft. Worth Texas.

Preston, S.D., and J.W. Brakebill. 1999. *Application of Spatially Referenced Regression Modeling for the Evaluation of Total Nitrogen Loading in the Chesapeake Bay Watershed.* USGS Water-Resources Investigations Report 99-4054, U.S. Geological Survey, Reston, VA.

Ribaudo, Marc, Noel Gollehon, Marcel Aillery, Jonathan Kaplan, Robert Johansson, Jean Agapoff, Lee Christensen, Vince Breneman, and Mark Peters. June 2003. *Manure Management for Water Quality: Costs to Animal Feeding Operations of Applying Manure Nutrients to Land.* Agricultural Economic Report No. 824. U.S. Department of Agriculture, Economic Research Service.

Risse, L.M., M.L. Cabrerea, A.J. Franzluebbers, J.W. Gaskin, J.E. Gilley, R. Killorn, D.E. Radcliffe, W.E. Tollner, and J. Zhang. 2001. "Land Application of Manure for Beneficial Reuse." National Center for Manure and Animal Waste Management white paper.

U.S. Department of Agriculture, Economic Research Service. 2002. "briefing room: farm income and costs, commodity costs and returns." Available at: *http://www.ers.usda.gov/briefing/farmincome/costsandreturns.htm*.

U.S. Department of Agriculture, Economic Research Service. 2000. Data from the 1998 Agricultural Resource Management Survey, Hogs Production Practices and Costs and Returns Report, unpublished.

U.S. Department of Agriculture, National Agricultural Statistics Service. 1999. *1997 Census of Agriculture*. AC97-A-51. Volume 1, Geographic Area Series.

U.S. Department of Agriculture, Natural Resources Conservation Service. June 2003. *Costs Associated With Development and Implementation of Comprehensive Nutrient Management Plans, Part I—Nutrient Management, Land Treatment, Manure and Wastewater Handling and Storage, and Recordkeeping.*

U.S. Department of Agriculture, Natural Resources Conservation Service. December 2000. *Comprehensive Nutrient Management Planning Technical Guidance.*

U.S. Department of Commerce, Bureau of the Census. 1978. "Description and Technical Documentation of the PICADAD File." U.S. Government Printing Office.

U.S. Environmental Protection Agency. February 12, 2003. "National Pollutant Discharge Elimination System Permit Regulation and Effluent Limitation Guidelines and Standards for Concentrated Animal Feeding Operations (CAFOs); Final Rule." 40 CFR Parts 9, 122, 123, and 412. Federal Register. Vol. 68, No. 29. pp. 7,176-7,274.

U.S. Geological Survey. 2004. 1994 National Land Cover Data. *http://landcover.usgs.gov/index.asp*.

Appendix Tables

Appendix 1—Basin and sink counties included in the Chesapeake Bay regional model

Model	FIPS	State	County	Edge County
Basin counties:				
C001	10001	DE	KENT	y
C002	10003	DE	NEW CASTLE	y
C003	10005	DE	SUSSEX	y
C004	24001	MD	ALLEGANY	
C005	24003	MD	ANNE ARUNDEL	
C006	24005	MD	BALTIMORE	
C007	24009	MD	CALVERT	
C008	24011	MD	CAROLINE	
C009	24013	MD	CARROLL	
C010	24015	MD	CECIL	y
C011	24017	MD	CHARLES	
C012	24019	MD	DORCHESTER	
C013	24021	MD	FREDERICK	
C014	24023	MD	GARRETT	y
C015	24025	MD	HARFORD	
C016	24027	MD	HOWARD	
C017	24029	MD	KENT	
C018	24031	MD	MONTGOMERY	
C019	24033	MD	PRINCE GEORGE'S	
C020	24035	MD	QUEEN ANNE'S	
C021	24037	MD	ST. MARY'S	
C022	24039	MD	SOMERSET	
C023	24041	MD	TALBOT	
C024	24043	MD	WASHINGTON	
C025	24045	MD	WICOMICO	
C026	24047	MD	WORCESTER	y
C027	36003	NY	ALLEGANY	y
C028	36007	NY	BROOME	y
C029	36015	NY	CHEMUNG	y
C030	36017	NY	CHENANGO	
C031	36023	NY	CORTLAND	y
C032	36025	NY	DELAWARE	y
C033	36043	NY	HERKIMER	y
C034	36053	NY	MADISON	y
C035	36067	NY	ONONDAGA	y
C036	36077	NY	OTSEGO	y
C037	36095	NY	SCHOHARIE	y
C038	36097	NY	SCHUYLER	y
C039	36101	NY	STEUBEN	y
C040	36107	NY	TIOGA	
C041	36109	NY	TOMPKINS	y
C042	42001	PA	ADAMS	
C043	42009	PA	BEDFORD	
C044	42011	PA	BERKS	y
C045	42013	PA	BLAIR	
C046	42015	PA	BRADFORD	
C047	42021	PA	CAMBRIA	y
C048	42023	PA	CAMERON	
C049	42027	PA	CENTRE	
C050	42029	PA	CHESTER	y

Appendix 1—Basin and sink counties included in the Chesapeake Bay regional model—Continued

Model	FIPS	State	County	Edge County
C051	42033	PA	CLEARFIELD	y
C052	42035	PA	CLINTON	
C053	42037	PA	COLUMBIA	
C054	42041	PA	CUMBERLAND	
C055	42043	PA	DAUPHIN	
C056	42047	PA	ELK	y
C057	42055	PA	FRANKLIN	
C058	42057	PA	FULTON	
C059	42061	PA	HUNTINGDON	
C060	42063	PA	INDIANA	y
C061	42067	PA	JUNIATA	
C062	42069	PA	LACKAWANNA	y
C063	42071	PA	LANCASTER	
C064	42075	PA	LEBANON	y
C065	42079	PA	LUZERNE	y
C066	42081	PA	LYCOMING	
C067	42087	PA	MIFFLIN	
C068	42093	PA	MONTOUR	
C069	42097	PA	NORTHUMBERLAND	
C070	42099	PA	PERRY	
C071	42105	PA	POTTER	y
C072	42107	PA	SCHUYLKILL	y
C073	42109	PA	SNYDER	
C074	42111	PA	SOMERSET	y
C075	42113	PA	SULLIVAN	
C076	42115	PA	SUSQUEHANNA	
C077	42117	PA	TIOGA	
C078	42119	PA	UNION	
C079	42127	PA	WAYNE	y
C080	42131	PA	WYOMING	
C081	42133	PA	YORK	
C082	51001	VA	ACCOMACK	y
C083	51003	VA	ALBEMARLE	
C084	51005	VA	ALLEGHANY	
C085	51007	VA	AMELIA	
C086	51009	VA	AMHERST	
C087	51011	VA	APPOMATTOX	y
C088	51015	VA	AUGUSTA	
C089	51017	VA	BATH	
C090	51019	VA	BEDFORD	y
C091	51023	VA	BOTETOURT	y
C092	51029	VA	BUCKINGHAM	
C093	51031	VA	CAMPBELL	y
C094	51033	VA	CAROLINE	
C095	51036	VA	CHARLES CITY	
C096	51041	VA	CHESTERFIELD	
C097	51043	VA	CLARKE	
C098	51045	VA	CRAIG	y
C099	51047	VA	CULPEPER	
C100	51049	VA	CUMBERLAND	
C101	51053	VA	DINWIDDIE	y
C102	51057	VA	ESSEX	
C103	51059	VA	FAIRFAX	
C104	51061	VA	FAUQUIER	
C105	51065	VA	FLUVANNA	

Appendix 1—Basin and sink counties included in the Chesapeake Bay regional model—Continued

Model	FIPS	State	County	Edge County
C106	51069	VA	FREDERICK	
C107	51071	VA	GILES	y
C108	51073	VA	GLOUCESTER	
C109	51075	VA	GOOCHLAND	
C110	51079	VA	GREENE	
C111	51085	VA	HANOVER	
C112	51087	VA	HENRICO	
C113	51091	VA	HIGHLAND	
C114	51093	VA	ISLE OF WIGHT	y
C115	51095	VA	JAMES CITY	
C116	51097	VA	KING AND QUEEN	
C117	51099	VA	KING GEORGE	
C118	51101	VA	KING WILLIAM	
C119	51103	VA	LANCASTER	
C120	51107	VA	LOUDOUN	
C121	51109	VA	LOUISA	
C122	51113	VA	MADISON	
C123	51115	VA	MATHEWS	
C124	51119	VA	MIDDLESEX	
C125	51121	VA	MONTGOMERY	y
C126	51125	VA	NELSON	
C127	51127	VA	NEW KENT	
C128	51131	VA	NORTHAMPTON	y
C129	51133	VA	NORTHUMBERLAND	
C130	51135	VA	NOTTOWAY	y
C131	51137	VA	ORANGE	
C132	51139	VA	PAGE	
C133	51145	VA	POWHATAN	
C134	51147	VA	PRINCE EDWARD	y
C135	51149	VA	PRINCE GEORGE	y
C136	51153	VA	PRINCE WILLIAM	
C137	51157	VA	RAPPAHANNOCK	
C138	51159	VA	RICHMOND	
C139	51161	VA	ROANOKE	y
C140	51163	VA	ROCKBRIDGE	
C141	51165	VA	ROCKINGHAM	
C142	51171	VA	SHENANDOAH	
C143	51177	VA	SPOTSYLVANIA	
C144	51179	VA	STAFFORD	
C145	51181	VA	SURRY	y
C146	51187	VA	WARREN	
C147	51193	VA	WESTMORELAND	
C148	51199	VA	YORK	
C149	51550	VA	CHESAPEAKE	y
C150	51800	VA	SUFFOLK	y
C151	51810	VA	VIRGINIA BEACH	y
C152	54003	WV	BERKELEY	
C153	54023	WV	GRANT	
C154	54027	WV	HAMPSHIRE	
C155	54031	WV	HARDY	
C156	54037	WV	JEFFERSON	
C157	54057	WV	MINERAL	
C158	54063	WV	MONROE	
C159	54065	WV	MORGAN	
C160	54071	WV	PENDLETON	

Appendix 1—Basin and sink counties included in the Chesapeake Bay regional model—Continued

Model	FIPS	State	County	Edge County
Sink counties:				
C167	34011	NJ	CUMBERLAND	
C168	34015	NJ	GLOUCESTER	
C169	34033	NJ	SALEM	
C170	36001	NY	ALBANY	
C173	36011	NY	CAYUGA	
C177	36035	NY	FULTON	
C178	36039	NY	GREENE	
C180	36051	NY	LIVINGSTON	
C182	36055	NY	MONROE	
C183	36057	NY	MONTGOMERY	
C184	36065	NY	ONEIDA	
C186	36069	NY	ONTARIO	
C188	36093	NY	SCHENECTADY	
C191	36099	NY	SENECA	
C193	36105	NY	SULLIVAN	
C195	36121	NY	WYOMING	
C196	36123	NY	YATES	
C197	42005	PA	ARMSTRONG	
C200	42025	PA	CARBON	
C202	42031	PA	CLARION	
C204	42045	PA	DELAWARE	
C206	42051	PA	FAYETTE	
C207	42053	PA	FOREST	
C209	42065	PA	JEFFERSON	
C212	42077	PA	LEHIGH	
C214	42083	PA	MCKEAN	
C215	42089	PA	MONROE	
C216	42091	PA	MONTGOMERY	
C217	42095	PA	NORTHAMPTON	
C218	42103	PA	PIKE	
C223	42129	PA	WESTMORELAND	
C227	51021	VA	BLAND	
C229	51025	VA	BRUNSWICK	
C231	51037	VA	CHARLOTTE	
C234	51063	VA	FLOYD	
C235	51067	VA	FRANKLIN	
C237	51081	VA	GREENSVILLE	
C238	51083	VA	HALIFAX	
C240	51111	VA	LUNENBURG	
C241	51117	VA	MECKLENBURG	
C245	51143	VA	PITTSYLVANIA	
C248	51155	VA	PULASKI	
C250	51175	VA	SOUTHAMPTON	
C252	51183	VA	SUSSEX	
C256	54001	WV	BARBOUR	
C257	54025	WV	GREENBRIER	
C258	54055	WV	MERCER	
C260	54075	WV	POCAHONTAS	
C261	54077	WV	PRESTON	
C262	54083	WV	RANDOLPH	
C263	54089	WV	SUMMERS	
C264	54091	WV	TAYLOR	
C265	54093	WV	TUCKER	
C266	54097	WV	UPSHUR	
C267	54101	WV	WEBSTER	

Note: y denotes counties with a portion of cropland area outside the basin.

Appendix 2—Model variables

TOTCOST	TOTAL COST - MANURE USE AND DISPOSAL	($MIL)
D_IN(CT,CT2)	AVE DIST FOR M IN-CNTY HAUL - WITHOUT INTERCEPT	(KMS)
D_EX(CT,CT2)	AVE DIST FOR M EXPT-CT HAUL - WITHOUT INTERCEPT	(KMS)
DIST_IN(CT,CT2)	AVE DIST FOR M IN-CNTY HAUL - WITH INTERCEPT	(KMS)
DIST_EX(CT,GR,CT2)	AVE DIST FOR M EXPT-CT HAUL - WITH GRID INTERCEPT	(KMS)
DST_IN(CT,CT2,SYS,DST)	AVE DIST HAULED - FROM AC CALC - IN-COUNTY	(KMS)
DST_EX(CT,GR,CT2,SYS,DST)	AVE DIST HAULED - FROM AC CALC - EXPORTS	(KMS)
HCST_ON(CT,CT2,SYS)	HAULING & APPL COST - ONFARM - NON-EXCESS	($MIL)
HCST_IN(CT,CT2,SYS,DST)	HAULING & APPL COST - IN-COUNTY	($MIL)
HCST_EX(CT,GR,CT2,SYS,DST)	HAULING & APPL COST - EXPORTS	($MIL)
HC_ON(CT,CT2)	HAULING & APPL COST - ONFARM - NON-EXCESS	($MIL)
HC_IN(CT,CT2)	HAULING & APPL COST - IN-COUNTY	($MIL)
HC_EX(CT,GR,CT2)	HAULING & APPL COST - EXPORTS	($MIL)
HC1(CT)	HAULING & APPL COST BY SOURCE CNTY - IN-COUNTY	($MIL)
HC2(CT)	HAULING & APPL COST BY SOURCE CNTY - EXPORTS	($MIL)
HCOST(CT)	TOTAL MANURE HAULING & APPL COST BY SOURCE COUNTY	($MIL)
HCST	TOTAL MANURE HAULING & APPL COST ACROSS SOURCE CNTS	($MIL)
HLC1(CT2)	HAULING & APPL COST BY DESTINATION CNTY - IN-COUNTY	($MIL)
HLC2(CT2)	HAULING & APPL COST BY DESTINATION CNTY - EXPORTS	($MIL)
HLCOST(CT2)	TOTAL MANURE HAULING & APPL COST BY DEST COUNTY	($MIL)
HLCST	TOTAL MANURE HAULING & APPL COST ACROSS DEST CNTS	($MIL)
COST_SHR(CT)	COST-SHARE PAYMENTS - MANURE HAULING	($MIL)
CST_SHR	COST-SHARE PAYMENTS - MANURE HAULING	($MIL)
HAULCST	TOTAL MANURE HAULING & APPL COST	($MIL)
M_PURCH(CT2)	MANURE PURCHASE COST - BY DESTINATION COUNTY	($MIL)
M_REVN(CT)	MANURE REVENUES - BY SOURCE COUNTY	($MIL)
M_PRCH	MANURE PURCHASE COST	($MIL)
M_REV	MANURE REVENUES	($MIL)
STORCOST(CT)	MANURE STORAGE COST BY COUNTY	($MIL)
STORCST	MANURE STORAGE COST	($MIL)
INCORP(CT2)	MANURE INCORPORATION COST	($MIL)
INCRP	MANURE INCORPORATION COST	($MIL)
NMP_SRCE(CT	NUTRIENT MNGMT PLAN CHARGE - SOURCE COUNTIES	($MIL)
NMP_SRC	NUTRIENT MNGMT PLAN CHARGE - SOURCE COUNTIES	($MIL)
NMP_DEST(CT2)	NUTRIENT MNGMT PLAN CHARGE - DESTINATION COUNTIES	($MIL)
NMP_DST	NUTRIENT MNGMT PLAN CHARGE - DESTINATION COUNTIES	($MIL)
CHMSAV_N(CT2)	SAVINGS IN CHEMICAL APPLICATIONS - N STANDARD	($MIL)
CHMSAV_P(CT2)	SAVINGS IN CHEMICAL APPLICATIONS - P STANDARD	($MIL)
CHMSAV	SAVINGS IN CHEMICAL NUTRIENT APPLICATIONS	($MIL)
AU_RED(CT)	REDUCTION IN ANIMAL-UNITS	(AU)
AU_VAL(CT)	VALUE OF A REDUCTION IN ANIMAL-UNITS	($MIL)
AU_VL	VALUE OF A REDUCTION IN ANIMAL-UNITS	($MIL)
AC_SPR1(CT,CT2)	SPREAD ACS FOR EXCESS M - INTRA-COUNTY	(1000 ACS)
AC_SPR2(CT,CT2)	SPREAD ACS FOR EXCESS M - INTER-COUNTY EXPORTS	(1000 ACS)
AC_SPR(CT2)	TOTAL SPREAD ACS FOR EXCESS M - BY DEST COUNTY	(1000 ACS)
AC_ON_SY(CT,CT2,SYS)	ONFARM SPREAD ACS - BY SYSTEM	(1000 ACS)

Appendix 2—Model variables—Continued

M_PROD(CT)	TOTAL MANURE PRODUCTION - REG AND NON-REG	(1000 TONS)
M_ONFRM_R(CT,CT2)	MANURE PRODUCED & USED ONFARM ON REGULATED AFOS	(1000 TONS)
M_TRAN(CT,CT2)	EXCESS MANURE TRANSFERS BY COUNTY	(1000 TONS)
M_TRAN1(CT)	EXCESS MANURE TRANSFERRED - BY SOURCE COUNTY	(1000 TONS)
M_TRAN2(CT2)	EXCESS MANURE TRANSFERRED - BY DESTINATION COUNTY	(1000 TONS)
M_TRANCT(CT2)	EXCESS MANURE TRANSFERRED WITHIN COUNTY	(1000 TONS)
M_EXPRT(CT)	EXCESS MANURE EXPORTED - BY SOURCE COUNTY	(1000 TONS)
M_IMPRT(CT2)	EXCESS MANURE IMPORTED - BY DESTINATION COUNTY	(1000 TONS)
M_SINK(CT2)	EXCESS MANURE EXPORTED TO SINK	(1000 TONS)
M_STOR(CT)	EXCESS MANURE STORAGE - NOT LAND APPLIED	(1000 TONS)
M_USE(CT2)	MANURE USE ON ALL FARMLAND - ONFARM AND EXCESS	(1000 TONS)
M_TRAN_G(CT,GR,CT2)	EXCESS M TRANSFERS BY COUNTY AND GRID	(1000 TONS)
M_TRN_G(CT,GR)	EXCESS M TRANSFERS BY COUNTY AND GRID	(1000 TONS)
M_PRD_SY(CT,SYS)	MANURE PRODUCTION BY WASTE SYSTEM	(1000 TONS)
M_REG_SY(CT,SYS)	REGULATED M BY WASTE SYSTEM	(1000 TONS)
M_SY(CT,SYS)	REGULATED EXCESS M HAULED & USED BY SYSTEM	(1000 TONS)
M_ONF_SY(CT,CT2,SYS)	NON-EXCESS M USED ON REGULATED FARMS - BY TECHNOLOGY	(1000 TONS)
M_SYS_IN(CT,CT2,SYS)	EXCESS M TRANSFER - INCOUNTY - BY SYSTEM	(1000 TONS)
M_SYS_G(CT,GR,CT2,SYS)	EXCESS M TRANSFER - EXPORTS - BY SYSTEM	(1000 TONS)
M_SYS_EX(CT,CT2,SYS)	EXCESS M TRANSFER - EXPORTS - BY SYSTEM	(1000 TONS)
M_SYS2(CT,CT2,SYS,DST)	M TRANSFER - BY WASTE TECH AND DST SEG	(1000 TONS)
M_SYS2_G(CT,GR,CT2,SYS,DST)	M TRANSFER - BY TECHNOLOGY AND DST SEG	(1000 TONS)
M_STR_SY(CT,SYS)	MANURE STORAGE - BY WASTE-SYSTEM TECHNOLOGY	(1000 TONS)
N_PROD(CT)	TOTAL MANURE-N PRODUCTION	(MIL LBS)
N_TRAN(CT,CT2)	EXCESS MANURE-N TRANSFERS BY COUNTY	(MIL LBS)
N_TRAN1(CT)	EXCESS MANURE-N USED - BY SOURCE COUNTY	(MIL LBS)
N_TRAN2(CT2)	EXCESS MANURE-N USED - BY DESTINATION COUNTY	(MIL LBS)
N_M_ONF(CT2)	MANURE-N USED ON ANIMAL OPERATIONS	(MIL LBS)
P_PROD(CT)	TOTAL MANURE-P PRODUCTION	(MIL LBS)
P_TRAN(CT,CT2)	EXCESS MANURE-P TRANSFERS BY COUNTY	(MIL LBS)
P_TRAN1(CT)	EXCESS MANURE-P USED - BY SOURCE COUNTY	(MIL LBS)
P_TRAN2(CT2)	EXCESS MANURE-P USED - BY DESTINATION COUNTY	(MIL LBS)
P_M_ONF(CT2)	MANURE-P USED ON ANIMAL OPERATIONS	(MIL LBS)

Appendix 3—Variables used in equation listing (text), with names of corresponding GAMS model variables (Appendix 2) and model report variables (Appendix 4)[1]

Item	Description	GAMS model linkage—data parameter or model variable (See Appendix 2)	GAMS model linkage—aggregate output variable (See Appendix 4)
Subscripts:			
ct	Counties in the watershed that produce manure	CT	CT
ct2	Counties that receive manure	CT2	CT2
sy	Manure system (lagoon, slurry, and dry)	SYS	SYS
ds	Hauling distance interval (onfarm and 0.5-2 miles, 2-10 miles, >10 miles for off-farm)	DST	DST
gr	County grid location	GR	GR
*N**	Nitrogen standard in effect	--	--
*P**	Phosphorus standard in effect	--	--
np	Nutrient under consideration	--	--
Variables:			
OBJ	Objective function value	TOTCOST	--
HAC	Manure hauling and application costs	HCOST	HAULCSTB
INC	Manure incorporation costs	INCORP	INCRPB
NM1	Source-county nutrient management plan costs	NMP_SRCE	NMP_SRCB
NM2	Destination county nutrient management plan costs	MVP_DEST	NMP_DSTB
ELA	Penalty cost applied to manure levels exceeding land application capacity	STORCOST	STORCSTB
FS	Savings from reduced purchase and application costs for chemical fertilizers	CHMSAV_N CHMSAV_P	CHMSVB_N CHMSVB_P
M_TRAN	Dry manure tons transferred from sources to destinations	M_TRAN M_TRAN_G	M_TRAN1B M_TRAN2B
M_AP	Manure application rate	M_APPL	AVEAPPL
SH_N	Share of acreage under an N standard	N_SHR_C N_SHR_P	--
AC_SPR	Acres receiving manure in the destination county	AC_SPR	AC_SPRB
Amax	Total acreage potentially available in the destination county	ACSPR_MX	--
WTAM	Land operator willingness to accept manure	ACCEPT_C ACCEPT_P	--
M_TRN	Manure transfers by source-county grid location, system type and distance interval	M_SYS2 M_SYS2_G	M_TRAN1B M_TRAN2B
M_PROD	Total manure production in each source county	M_PROD	M_PRODB
SH_M	Share of manure produced in each source-county grid location by system type	M_SYS2_G	--
M_SRP	Surplus manure to be moved off the farm	M_EXC	M_EXCB
M_ONFRM	Manure used on the farm of production	M_ONFRM	M_ONFRMB
M_USE	On-farm manure use plus manure obtained from all off-farm sources in the destination county	M_USE	M_USEB
M_ELA	Manure produced that exceeds land application capacity	M_STOR	M_STORB
M_IND	Manure used in industrial uses	M_OTHUSE	M_INDSTB

Appendix 3—Variables used in equation listing (text), with names of corresponding GAMS model variables (Appendix 2) and model report variables (Appendix 4)[1]—Continued

Item	Description	GAMS model linkage—data parameter or model variable (See Appendix 2)	GAMS model linkage—aggregate output variable (See Appendix 4)
Variables:—continued			
M_ELA	Manure produced that exceeds land application capacity	M_STOR	M_STORB
M_IND	Manure used in industrial uses	M_OTHUSE	M_INDSTB
DS	Average hauling distance	DIST_IN DIST_EX	AVDS_INM AVDS_EXM
α	Intercept of the estimated area to distance relationship	GRD_DIST	--
δ^1	Adjustment to selected county-to-county transfers to reflect significant natural barriers (e.g., large bodies of water)	BARRIER	--
β	Slope of the estimated area to distance relationship	D_COEF1 D_COEF2	--
AC_ONF	Acreage on manure source farms used to apply on-farm produced manure	AC_ONFRM	AC_ONFMB
δ^2	Circuity parameter used to convert linear distance to road miles	CRC_FCT	--
DST	Hauling distance by manure system and distance interval	DST_IN DST_EX	--
D_MN	Minimum distance for distance interval *ds*, based on system type and technology	MNHAUL_S MNHAUL_M MNHAUL_L	--
D_MX	Maximum distance for distance interval *ds*, based on system type and technology	MXHAUL_S MXHAUL_M	--
NP_EXC	Total excess manure nutrients in the county	N_EXC P_EXC	N_EXCB P_EXCB
NP_M	County-average nutrient content per dry ton of manure	N_TON_M P_TON_M	--
NP_ONF	Onfarm manure nutrients	N_M_ONF P_M_ONF	N_M_ONFB P_M_ONFB
NP_TRN	Manure nutrients transfers off the farm	N_TRAN P_TRAN	--
C1	Manure loading, unloading, and application costs per ton hauled	CST_TN	HC_WTN
C2	Manure hauling cost per ton-mile	CST_ML	--
MS	Manure moisture content	MOIST	--
BED	Manure bedding content	BED_SYS	--
C3	Per-acre charge for manure incorporation	AP_CST	--
SH_I	Share of manured cropland using incorporation	INCRP_SHR	--
SH_C	Cropland acres share	CRPL_SHR	--
FS_N	Savings in commercial fertilizer purchases and application under an N standard	CHMSAV_N	CHMSVB_N
PR	Commercial fertilizer price	N_PRICE P_PRICE	--

Appendix 3—Variables used in equation listing (text), with names of corresponding GAMS model variables (Appendix 2) and model report variables (Appendix 4)[1]—Continued

Item	Description	GAMS model linkage—data parameter or model variable (See Appendix 2)	GAMS model linkage—aggregate output variable (See Appendix 4)
Variables:—continued			
N_ONF	Manure-N applied on source farms	N_M_ONF	N_M_ONFB
N_TRN	Manure-N transferred off source farms for land application	N_TRAN	N_TRAN1B
P_ONF	Manure-P applied on source farms	P_M_ONF	P_M_ONFB
P_TRN	Manure-P transferred off source farms for land application	P_TRAN	P_TRAN1B
P_PCT	Portion of P beneficially used by the crop	PN_RATIO2	--
C_AP	Per-acre cost of applying commercial fertilizer under an N standard	CHMAP_SV	--
FS_P	Savings in commercial fertilizer purchases under a P standard	CHMSAV_P	CHMSVB_P

[1] GAMS is the General Algebraic Modeling System.

Appendix 4—Model report variables

Costs:

* TOTCOST	TOTAL COST - MANURE USE AND DISPOSAL	($ MIL)
TOTCOSTB	TOTAL COST - MANURE USE AND DISPOSAL - CH.BASIN	($ MIL)
TOTCST2	TOTAL COST - WITH STORCST NETTED OUT	($ MIL)
TOTCST2B	TOTAL COST - WITH STORCST NETTED OUT - CH.BASIN	($ MIL)
* CST_SHR	COST-SHARE PAYMENTS - MANURE HAULING	($ MIL)
* HAULCST	TOTAL MANURE HAULING COST	($ MIL)
HAULCSTB	TOTAL MANURE HAULING & APPL COST - CH.BASIN	($ MIL)
HCOST_ON	TOTAL MNR HAULING & APPL COST - ON-FARM	($ MIL)
HCST_ONB	TOTAL MNR HAULING & APPL COST - ON-FARM - CH.BASIN	($ MIL)
HCOST_IN	TOTAL MNR HAULING & APPL COST - OFF-FARM IN-CNTY	($ MIL)
HCST_INB	TOTAL MNR HAULING & APPL COST - OFF-FARM IN-CNTY - CHB	($ MIL)
HCOST_EX	TOTAL MNR HAULING & APPL COST - OFF-FARM OUT-OF-CNTY	($ MIL)
HCSTEXB1	TOTAL MNR HAULING & APPL COST - OFF-FARM OUT-OF-CNTY - SOURCE	($ MIL)
HCSTEXB2	TOTAL MNR HAULING & APPL COST - OFF-FARM OUT-OF-CNTY - DEST	($ MIL)
* STORCST	MANURE STORAGE COST	($ MIL)
STORCSTB	MANURE STORAGE COST - CH.BASIN	($ MIL)
* INCRP	MANURE INCORPORATION COST	($ MIL)
INCRPB	MANURE INCORPORATION COST - CH.BASIN	($ MIL)
* NMP_SRC	NUTRIENT MNGMT PLAN CHARGE - SOURCE COUNTIES	($ MIL)
NMP_SRCB	NUTRIENT MNGMT PLAN CHARGE - SOURCE COUNTIES	($ MIL)
* NMP_DST	NUTRIENT MNGMT PLAN CHARGE - DESTINATION COUNTIES	($ MIL)
NMP_DSTB	NUTR MNGMT PLAN CHARGE - DEST COUNTIES - CH.BASIN	($ MIL)
* CHMSAV	SAVINGS IN CHEMICAL NUTRIENT APPLICATIONS	($ MIL)
CHMSV_N	SAVINGS IN CHEMICAL APPLICATIONS - N-STANDARD	($ MIL)
CHMSV_P	SAVINGS IN CHEMICAL APPLICATIONS - P-STANDARD	($ MIL)
CHMSVB_N	SAVINGS IN CHEMICAL APPL - N-STANDARD - CH.BASIN	($ MIL)
CHMSVB_P	SAVINGS IN CHEMICAL APPL - P-STANDARD - CH.BASIN	($ MIL)
MNR_TSTB	TOTAL ANNUAL COST - MANURE TESTING	($ MIL)
REC_RPTB	TOTAL ANN COST - RECORD KEEPING AND REPORTING	($ MIL)
VIS_INSB	TOTAL ANNUAL COST - VISUAL INSPECTION	($ MIL)
CRT_APPB	TOTAL COST - TRAINING & CERTIFICATION FOR M APPL	($ MIL)
NMP_DEVB	TOTAL COST - DEVELOPMENT OF NMP	($ MIL)
SL_TSTB	TOTAL COST - ONFARM SOIL TESTING	($ MIL)
CAL_SPRB	TOTAL COST - CALIBRATION OF MANURE SPREADER	($ MIL)

Acres:

AC_SPR1_	TOTAL SPREAD ACS - EXCESS M - WITHIN COUNTY	(1000 ACS)
AC_SPR1B	TOTAL SPREAD ACS - EXCESS M - WITHIN COUNTY - CH.BASIN	(1000 ACS)
AC_SPR2_	TOTAL SPREAD ACS - EXCESS M - OUT-OF-COUNTY	(1000 ACS)
AC_SPR2B	TOTAL SPREAD ACS - EXCESS M - OUT-OF-COUNTY - CH.BASIN	(1000 ACS)
AC_SPR_	TOTAL SPREAD ACS - EXCESS M - BY DEST COUNTY	(1000 ACS)
AC_SPRB	TOTAL SPREAD ACS - EXCESS M - BY DEST COUNTY - CH.BASIN	(1000 ACS)
AC_ONFM	ONFARM ACRES - APPLIED MANURE	(1000 ACS)
AC_ONFMB	ONFARM ACRES - APPLIED MANURE - CH.BASIN	(1000 ACS)

Manure quantity (dry):

M_PROD_	TOTAL MANURE PRODUCTION	(1000 TONS)
M_PRODB	TOTAL MANURE PRODUCTION - CH.BASIN	(1000 TONS)
M_EXC_	EXCESS MANURE ON ANIMAL FARMS	(1000 TONS)
M_EXCB	EXCESS MANURE ON ANIMAL FARMS - CH.BASIN	(1000 TONS)
M_INDUST	EXCESS MANURE IN INDUSTRIAL USES	(1000 TONS)
M_INDSTB	EXCESS MANURE IN INDUSTRIAL USES - CH.BASIN	(1000 TONS)

Manure quantity (dry):—continued		
M_STOR_	TOTAL MANURE STORAGE - NONCLEARING	(1000 TONS)
M_STORB	TOTAL MANURE STORAGE - NONCLEARING - CH.BASIN	(1000 TONS)
M_ONFRM_	MANURE PRODUCED AND USED ON OWN LVSTK FARM	(1000 TONS)
M_ONFRMB	MANURE PRODUCED AND USED ON OWN LVSTK FARM - CH.BASIN	(1000 TONS)
M_TRAN1_	EXCESS MANURE TRANSFERRED - BY SOURCE CTY	(1000 TONS)
M_TRAN1B	EXCESS MANURE TRANSFERRED - BY SOURCE CTY - CH.BASIN	(1000 TONS)
M_TRAN2_	EXCESS MANURE TRANSFERRED - BY DEST CTY	(1000 TONS)
M_TRAN2B	EXCESS MANURE TRANSFERRED - BY DEST CTY - CH.BASIN	(1000 TONS)
M_TRNCT_	EXCESS MANURE TRANSFERRED WITHIN COUNTY	(1000 TONS)
M_TRNCTB	EXCESS MANURE TRANSFERRED WITHIN COUNTY - CH.BASIN	(1000 TONS)
M_EXPRT	EXCESS MANURE EXPORTED - BY SOURCE COUNTY	(1000 TONS)
M_EXPRTB	EXCESS MANURE EXPORTED - BY SOURCE COUNTY - CH.BASIN	(1000 TONS)
M_IMPRT_	EXCESS MANURE IMPORTED - BY DEST COUNTY	(1000 TONS)
M_IMPRTB	EXCESS MANURE IMPORTED - BY DEST COUNTY - CH.BASIN	(1000 TONS)
* M_SINK_	EXCESS MANURE EXPORTED TO SINK	(1000 TONS)
* M_SINKB	EXCESS MANURE EXPORTED TO SINK - CH.BASIN	(1000 TONS)
M_USE_	MANURE USE ON ALL FARMLAND - ONFARM & EXCESS	(1000 TONS)
M_USEB	MANURE USE ON ALL FARMLAND - ONFARM & EXCESS - CH.BASIN	(1000 TONS)
M_PR_SY_(SYS)	MANURE PRODUCTION BY WASTE SYSTEM	(1000 TONS)
M_PR_S_1	MANURE PRODUCTION FOR LAGOON WASTE SYSTEM	(1000 TONS)
M_PR_S_2	MANURE PRODUCTION FOR SLURRY WASTE SYSTEM	(1000 TONS)
M_PR_S_3	MANURE PRODUCTION FOR DRY WASTE SYSTEM	(1000 TONS)
M_PR_SYB(SYS)	MANURE PRODUCTION BY WASTE SYSTEM - CH.BASIN	(1000 TONS)
M_PR_S1B	MANURE PRODUCTION FOR LAGOON WASTE SYSTEM - CH.BASIN	(1000 TONS)
M_PR_S2B	MANURE PRODUCTION FOR SLURRY WASTE SYSTEM - CH.BASIN	(1000 TONS)
M_PR_S3B	MANURE PRODUCTION FOR DRY WASTE SYSTEM - CH.BASIN	(1000 TONS)
M_IND_(SYS)	EXCESS MANURE IN INDUSTRIAL USES BY SYSTEM	(1000 TONS)
M_IND_1	EXCESS LAGOON MANURE IN INDUSTRIAL USES BY SYSTEM	(1000 TONS)
M_IND_2	EXCESS SLURRY MANURE IN INDUSTRIAL USES BY SYSTEM	(1000 TONS)
M_IND_3	EXCESS DRY MANURE IN INDUSTRIAL USES BY SYSTEM	(1000 TONS)
M_INDB(SYS)	EXCESS MANURE IN INDUSTRIAL USES BY SYSTEM - CH.BASIN	(1000 TONS)
M_IND1B	EXCESS LAGOON MANURE IN INDUSTRIAL USES BY SYSTEM - CH.BASIN	(1000 TONS)
M_IND2B	EXCESS SLURRY MANURE IN INDUSTRIAL USES BY SYSTEM - CH.BASIN	(1000 TONS)
M_IND3B	EXCESS DRY MANURE IN INDUSTRIAL USES BY SYSTEM - CH.BASIN	(1000 TONS)
M_SY_(SYS)	EXCESS MANURE TRANSFERRED BY SYSTEM	(1000 TONS)
M_SY_1	EXCESS MANURE TRANSFERRED BY LAGOON SYSTEM	(1000 TONS)
M_SY_2	EXCESS MANURE TRANSFERRED BY SLURRY SYSTEM	(1000 TONS)
M_SY_3	EXCESS MANURE TRANSFERRED BY DRY SYSTEM	(1000 TONS)
M_SYB(SYS)	EXCESS MANURE TRANSFERRED BY SYSTEM - CH.BASIN	(1000 TONS)
M_SY1B	EXCESS MANURE TRANSFERRED BY LAGOON SYSTEM - CH.BASIN	(1000 TONS)
M_SY2B	EXCESS MANURE TRANSFERRED BY SLURRY SYSTEM - CH.BASIN	(1000 TONS)
M_SY3B	EXCESS MANURE TRANSFERRED BY DRY SYSTEM - CH.BASIN	(1000 TONS)
M_ON_SY_(SYS)	MANURE USED ONFARM BY SYSTEM	(1000 TONS)
M_ON_S_1	MANURE USED ONFARM FROM LAGOON SYSTEM	(1000 TONS)
M_ON_S_2	MANURE USED ONFARM FROM SLURRY SYSTEM	(1000 TONS)
M_ON_S_3	MANURE USED ONFARM FROM DRY SYSTEM	(1000 TONS)
M_ON_SYB(SYS)	MANURE USED ONFARM BY SYSTEM - CH.BASIN	(1000 TONS)
M_ON_S1B	MANURE USED ONFARM FROM LAGOON SYSTEM - CH.BASIN	(1000 TONS)
M_ON_S2B	MANURE USED ONFARM FROM SLURRY SYSTEM - CH.BASIN	(1000 TONS)
M_ON_S3B	MANURE USED ONFARM FROM DRY SYSTEM - CH.BASIN	(1000 TONS)

Manure quantity (dry):—continued

M_SY_IN_(SYS)	EXCESS M TRANSFERRED IN-COUNTY BY SYSTEM	(1000 TONS)
M_SY_I_1	EXCESS M TRANSFERRED IN-COUNTY LAGOON SYSTEM	(1000 TONS)
M_SY_I_2	EXCESS M TRANSFERRED IN-COUNTY SLURRY SYSTEM	(1000 TONS)
M_SY_I_3	EXCESS M TRANSFERRED IN-COUNTY DRY SYSTEM	(1000 TONS)
M_SY_INB(SYS)	EXCESS M TRANSFERRED IN-COUNTY BY SYSTEM - CH.BASIN	(1000 TONS)
M_SY_I1B	EXCESS M TRANSFERRED IN-COUNTY LAGOON SYSTEM - CH.BASIN	(1000 TONS)
M_SY_I2B	EXCESS M TRANSFERRED IN-COUNTY SLURRY SYSTEM - CH.BASIN	(1000 TONS)
M_SY_I3B	EXCESS M TRANSFERRED IN-COUNTY DRY SYSTEM - CH.BASIN	(1000 TONS)
M_SY_EX_(SYS)	EXCESS MANURE EXPORTED BY SYSTEM	(1000 TONS)
M_SY_E_1	EXCESS MANURE EXPORTED BY LAGOON SYSTEM	(1000 TONS)
M_SY_E_2	EXCESS MANURE EXPORTED BY SLURRY SYSTEM	(1000 TONS)
M_SY_E_3	EXCESS MANURE EXPORTED BY DRY SYSTEM	(1000 TONS)
M_SYEXB1(SYS)	EXCESS M EXPORTED BY SYSTEM - CH.BASIN - ADJ ON CT	(1000 TONS)
M_SYE1B1	EXCESS M EXPORTED BY LAGOON SYSTEM - CH.BASIN - ADJ ON CT	(1000 TONS)
M_SYE2B1	EXCESS M EXPORTED BY SLURRY SYSTEM - CH.BASIN - ADJ ON CT	(1000 TONS)
M_SYE3B1	EXCESS M EXPORTED BY DRY SYSTEM - CH.BASIN - ADJ ON CT	(1000 TONS)
M_SYEXB2(SYS)	EXCESS M EXPORTED BY SYSTEM - CH.BASIN - ADJ ON CT2	(1000 TONS)
M_SYE1B2	EXCESS M EXPORTED BY LAGOON SYSTEM - CH.BASIN - ADJ ON CT2	(1000 TONS)
M_SYE2B2	EXCESS M EXPORTED BY SLURRY SYSTEM - CH.BASIN - ADJ ON CT2	(1000 TONS)
M_SYE3B2	EXCESS M EXPORTED BY DRY SYSTEM - CH.BASIN - ADJ ON CT2	(1000 TONS)
M_STR_(SYS)	EXCESS M STORED -NOT CLEARING- BY SYSTEM	(1000 TONS)
M_STR_1	EXCESS M STORED -NOT CLEARING- LAGOON SYSTEM	(1000 TONS)
M_STR_2	EXCESS M STORED -NOT CLEARING- SLURRY SYSTEM	(1000 TONS)
M_STR_3	EXCESS M STORED -NOT CLEARING- DRY SYSTEM	(1000 TONS)
M_STRB(SYS)	EXCESS M STORED -NOT CLEARING- BY SYSTEM - CH.BASIN	(1000 TONS)
M_STR1B	EXCESS M STORED -NOT CLEARING- LAGOON SYSTEM - CH.BASIN	(1000 TONS)
M_STR2B	EXCESS M STORED -NOT CLEARING- SLURRY SYSTEM - CH.BASIN	(1000 TONS)
M_STR3B	EXCESS M STORED -NOT CLEARING- DRY SYSTEM - CH.BASIN	(1000 TONS)

Manure quantity (wet):

WMPR_SY_(SYS)	WET MANURE PRODUCTION BY WASTE SYSTEM	(1000 TONS)
WMPR_S_1	WET MANURE PRODUCTION LAGOON WASTE SYSTEM	(1000 TONS)
WMPR_S_2	WET MANURE PRODUCTION SLURRY WASTE SYSTEM	(1000 TONS)
WMPR_S_3	WET MANURE PRODUCTION DRY WASTE SYSTEM	(1000 TONS)
WMPR_SYB(SYS)	WET MANURE PRODUCTION BY WASTE SYSTEM - CH.BASIN	(1000 TONS)
WMPR_S1B	WET MANURE PRODUCTION LAGOON WASTE SYSTEM - CH.BASIN	(1000 TONS)
WMPR_S2B	WET MANURE PRODUCTION SLURRY WASTE SYSTEM - CH.BASIN	(1000 TONS)
WMPR_S3B	WET MANURE PRODUCTION DRY WASTE SYSTEM - CH.BASIN	(1000 TONS)
WMIND_(SYS)	EXCESS WET MANURE IN INDUSTRIAL USES BY SYSTEM	(1000 TONS)
WMIND_1	EXCESS WET MANURE IN INDUSTRIAL USES LAGOON SYSTEM	(1000 TONS)
WMIND_2	EXCESS WET MANURE IN INDUSTRIAL USES SLURRY SYSTEM	(1000 TONS)
WMIND_3	EXCESS WET MANURE IN INDUSTRIAL USES DRY SYSTEM	(1000 TONS)
WMINDB(SYS)	EXCESS WET MANURE IN INDUSTRIAL USES BY SYSTEM - CH.BASIN	(1000 TONS)
WMIND1B	EXCESS WET MANURE IN INDUSTRIAL USES LAGOON SYSTEM - CH.BASIN	(1000 TONS)
WMIND2B	EXCESS WET MANURE IN INDUSTRIAL USES SLURRY SYSTEM - CH.BASIN	(1000 TONS)
WMIND3B	EXCESS WET MANURE IN INDUSTRIAL USES DRY SYSTEM - CH.BASIN	(1000 TONS)
WMSY_(SYS)	EXCESS WET MANURE TRANSFERRED BY SYSTEM	(1000 TONS)
WMSY_1	EXCESS WET MANURE TRANSFERRED LAGOON SYSTEM	(1000 TONS)
WMSY_2	EXCESS WET MANURE TRANSFERRED SLURRY SYSTEM	(1000 TONS)
WMSY_3	EXCESS WET MANURE TRANSFERRED DRY SYSTEM	(1000 TONS)
WMSYB(SYS)	EXCESS WET MANURE TRANSFERRED BY SYSTEM - CH.BASIN	(1000 TONS)

Appendix 4—Model report variables—Continued

Manure quantity (wet):—continued

WMSY1B	EXCESS WET MANURE TRANSFERRED LAGOON SYSTEM - CH.BASIN	(1000 TONS)
WMSY2B	EXCESS WET MANURE TRANSFERRED SLURRY SYSTEM - CH.BASIN	(1000 TONS)
WMSY3B	EXCESS WET MANURE TRANSFERRED DRY SYSTEM - CH.BASIN	(1000 TONS)
WMON_SY_(SYS)	WET MANURE USED ONFARM BY SYSTEM	(1000 TONS)
WMON_S_1	WET MANURE USED ONFARM LAGOON SYSTEM	(1000 TONS)
WMON_S_2	WET MANURE USED ONFARM SLURRY SYSTEM	(1000 TONS)
WMON_S_3	WET MANURE USED ONFARM DRY SYSTEM	(1000 TONS)
WMON_SYB(SYS)	WET MANURE USED ONFARM BY SYSTEM - CH.BASIN	(1000 TONS)
WMON_S1B	WET MANURE USED ONFARM LAGOON SYSTEM - CH.BASIN	(1000 TONS)
WMON_S2B	WET MANURE USED ONFARM SLURRY SYSTEM - CH.BASIN	(1000 TONS)
WMON_S3B	WET MANURE USED ONFARM DRY SYSTEM - CH.BASIN	(1000 TONS)
WMSY_IN_(SYS)	EXCESS WET M TRANSFERRED IN-COUNTY BY SYSTEM	(1000 TONS)
WMSY_I_1	EXCESS WET M TRANSFERRED IN-COUNTY LAGOON SYSTEM	(1000 TONS)
WMSY_I_2	EXCESS WET M TRANSFERRED IN-COUNTY SLURRY SYSTEM	(1000 TONS)
WMSY_I_3	EXCESS WET M TRANSFERRED IN-COUNTY DRY SYSTEM	(1000 TONS)
WMSYINB1(SYS)	EXCESS WET M - INTRA-COUNTY BY SYSTEM - CH.BASIN - ADJ ON CT	(1000 TONS)
WMSYI1B1	EXCESS WET M - INTRA-COUNTY LAGOON SYSTEM - CH.BASIN - ADJ ON CT	(1000 TONS)
WMSYI2B1	EXCESS WET M - INTRA-COUNTY SLURRY SYSTEM - CH.BASIN - ADJ ON CT	(1000 TONS)
WMSYI3B1	EXCESS WET M - INTRA-COUNTY DRY SYSTEM - CH.BASIN - ADJ ON CT	(1000 TONS)
WMSYINB2(SYS)	EXCESS WET M - INTRA-COUNTY BY SYSTEM - CH.BASIN - ADJ ON CT2	(1000 TONS)
WMSYI1B2	EXCESS WET M - INTRA-COUNTY LAGOON SYSTEM - CH.BASIN - ADJ ON CT2	(1000 TONS)
WMSYI2B2	EXCESS WET M - INTRA-COUNTY SLURRY SYSTEM - CH.BASIN - ADJ ON CT2	(1000 TONS)
WMSYI3B2	EXCESS WET M - INTRA-COUNTY DRY SYSTEM - CH.BASIN - ADJ ON CT2	(1000 TONS)
WMSY_EX_(SYS)	EXCESS WET MANURE EXPORTED BY SYSTEM	(1000 TONS)
WMSY_E_1	EXCESS WET MANURE EXPORTED LAGOON SYSTEM	(1000 TONS)
WMSY_E_2	EXCESS WET MANURE EXPORTED SLURRY SYSTEM	(1000 TONS)
WMSY_E_3	EXCESS WET MANURE EXPORTED DRY SYSTEM	(1000 TONS)
WMSYEXB1(SYS)	EXCESS WET M EXPORTED BY SYSTEM - CH.BASIN - ADJ ON CT	(1000 TONS)
WMSYE1B1	EXCESS WET M EXPORTED LAGOON SYSTEM - CH.BASIN - ADJ ON CT	(1000 TONS)
WMSYE2B1	EXCESS WET M EXPORTED SLURRY SYSTEM - CH.BASIN - ADJ ON CT	(1000 TONS)
WMSYE3B1	EXCESS WET M EXPORTED DRY SYSTEM - CH.BASIN - ADJ ON CT	(1000 TONS)
WMSYEXB2(SYS)	EXCESS WET M EXPORTED BY SYSTEM - CH.BASIN - ADJ ON CT2	(1000 TONS)
WMSYE1B2	EXCESS WET M EXPORTED LAGOON SYSTEM - CH.BASIN - ADJ ON CT2	(1000 TONS)
WMSYE2B2	EXCESS WET M EXPORTED SLURRY SYSTEM - CH.BASIN - ADJ ON CT2	(1000 TONS)
WMSYE3B2	EXCESS WET M EXPORTED DRY SYSTEM - CH.BASIN - ADJ ON CT2	(1000 TONS)
WMSTR_(SYS)	EXCESS WET M STORED -NOT CLEARING- BY SYSTEM	(1000 TONS)
WMSTR_1	EXCESS WET M STORED -NOT CLEARING- LAGOON SYSTEM	(1000 TONS)
WMSTR_2	EXCESS WET M STORED -NOT CLEARING- SLURRY SYSTEM	(1000 TONS)
WMSTR_3	EXCESS WET M STORED -NOT CLEARING- DRY SYSTEM	(1000 TONS)
WMSTRB(SYS)	EXCESS WET M STORED -NOT CLEARING- BY SYSTEM - CH.BASIN	(1000 TONS)
WMSTRB_1	EXCESS WET M STORED -NOT CLEARING- LAGOON SYSTEM - CH.BASIN	(1000 TONS)
WMSTRB_2	EXCESS WET M STORED -NOT CLEARING- SLURRY SYSTEM - CH.BASIN	(1000 TONS)
WMSTRB_3	EXCESS WET M STORED -NOT CLEARING- DRY SYSTEM - CH.BASIN	(1000 TONS)
WMUS_SY_(SYS)	TOTAL WET MANURE USED - ONFARM AND OFF-FARM - ALL SYSTEMS	(1000 TONS)
WMUS_S_1	TOTAL WET MANURE USED - ONFARM AND OFF-FARM - LAGOON SYSTEM	(1000 TONS)
WMUS_S_2	TOTAL WET MANURE USED - ONFARM AND OFF-FARM - SLURRY SYSTEM	(1000 TONS)
WMUS_S_3	TOTAL WET MANURE USED - ONFARM AND OFF-FARM - DRY SYSTEM	(1000 TONS)
WMUS_SYB(SYS)	TOTAL WET MANURE USED - ONFARM AND OFF-FARM- CH.BASIN- ALL SYSTEMS	(1000 TONS)

Appendix 4—Model report variables—Continued

Manure quantity (wet):—continued

WMUS_S1B	TOTAL WET MANURE USED - ONFARM AND OFF-FARM- CH.BASIN-LAGOON SYSTEM	(1000 TONS)
WMUS_S2B	TOTAL WET MANURE USED - ONFARM AND OFF-FARM- CH.BASIN-SLURRY SYSTEM	(1000 TONS)
WMUS_S3B	TOTAL WET MANURE USED - ONFARM AND OFF-FARM- CH.BASIN-DRY SYSTEM	(1000 TONS)
WMPROD_	TOTAL WET MANURE PRODUCTION	(1000 TONS)
WMPRODB	TOTAL WET MANURE PRODUCTION - CH.BASIN	(1000 TONS)
WMINDUST	EXCESS WET MANURE IN INDUSTRIAL USES	(1000 TONS)
WMINDSTB	EXCESS WET MANURE IN INDUSTRIAL USES - CH.BASIN	(1000 TONS)
WMONFRM	WET MANURE PRODUCED AND USED ON OWN LVSTK FARM	(1000 TONS)
WMONFRMB	WET MANURE PRODUCED AND USED ON OWN LVSTK FARM - CH.BASIN	(1000 TONS)
WMTRNCT_	EXCESS WET MANURE TRANSFERRED WITHIN COUNTY	(1000 TONS)
WMTRNCTB	EXCESS WET MANURE TRANSFERRED WITHIN COUNTY - CH.BASIN	(1000 TONS)
WMEXPRT_	EXCESS WET MANURE EXPORTED - BY SOURCE COUNTY	(1000 TONS)
WMEXPRTB	EXCESS WET MANURE EXPORTED - BY SOURCE COUNTY - CH.BASIN	(1000 TONS)
WMIMPRT_	EXCESS WET MANURE IMPORTED - BY DEST COUNTY	(1000 TONS)
WMIMPRTB	EXCESS WET MANURE IMPORTED - BY DEST COUNTY - CH.BASIN	(1000 TONS)
WMTRAN1_	EXCESS WET MANURE TRANSFERRED - BY SOURCE CTY	(1000 TONS)
WMTRAN1B	EXCESS WET MANURE TRANSFERRED - BY SOURCE CTY - CH.BASIN	(1000 TONS)
WMTRAN2_	EXCESS WET MANURE TRANSFERRED - BY DEST CTY	(1000 TONS)
WMTRAN2B	EXCESS WET MANURE TRANSFERRED - BY DEST CTY - CH.BASIN	(1000 TONS)
WMEXC_	EXCESS WET MANURE ON ANIMAL FARMS	(1000 TONS)
WMEXCB	EXCESS WET MANURE ON ANIMAL FARMS - CH.BASIN	(1000 TONS)
WMUSE_	WET MANURE USE ON ALL FARMLAND - ONFARM & EXCESS	(1000 TONS)
WMUSEB	WET MANURE USE ON ALL FARMLAND - ONFARM & EXCESS - CH.BASIN	(1000 TONS)
WMSTOR_	TOTAL WET MANURE STORAGE - NONCLEARING	(1000 TONS)
WMSTORB	TOTAL WET MANURE STORAGE - NONCLEARING - CH.BASIN	(1000 TONS)

Manure nutrients:

N_PROD_	TOTAL MANURE-N PRODUCTION	(MIL LBS)
N_PRODB	TOTAL MANURE-N PRODUCTION - CH.BASIN	(MIL LBS)
N_EXC_	EXCESS MANURE-N ON ANIMAL FARMS	(MIL LBS)
N_EXCB	EXCESS MANURE-N ON ANIMAL FARMS - CH.BASIN	(MIL LBS)
N_TRAN1_	EXCESS MANURE-N TRANSFERRED - BY SOURCE CTY	(MIL LBS)
N_TRAN1B	EXCESS MANURE-N TRANSFERRED - BY SOURCE CTY - CH.BASIN	(MIL LBS)
N_TRAN2_	EXCESS MANURE-N TRANSFERRED - BY DEST COUNTY	(MIL LBS)
N_TRAN2B	EXCESS MANURE-N TRANSFERRED - BY DEST COUNTY - CH.BASIN	(MIL LBS)
N_M_ONF_	ONFARM MANURE-N USED ON ANIMAL FARMS	(MIL LBS)
N_M_ONFB	ONFARM MANURE-N USED ON ANIMAL FARMS - CH.BASIN	(MIL LBS)
P_PROD_	TOTAL MANURE-P PRODUCTION	(MIL LBS)
P_PRODB	TOTAL MANURE-P PRODUCTION - CH.BASIN	(MIL LBS)
P_EXC_	EXCESS MANURE-P ON ANIMAL FARMS	(MIL LBS)
P_EXCB	EXCESS MANURE-P ON ANIMAL FARMS - CH.BASIN	(MIL LBS)
P_TRAN1_	EXCESS MANURE-P TRANSFERRED - BY SOURCE CTY	(MIL LBS)
P_TRAN1B	EXCESS MANURE-P TRANSFERRED - BY SOURCE CTY - CH.BASIN	(MIL LBS)
P_TRAN2_	EXCESS MANURE-P TRANSFERRED - BY DEST COUNTY	(MIL LBS)
P_TRAN2B	EXCESS MANURE-P TRANSFERRED - BY DEST COUNTY - CH.BASIN	(MIL LBS)
P_M_ONF_	ONFARM MANURE-P USED ON ANIMAL FARMS	(MIL LBS)
P_M_ONFB	ONFARM MANURE-P USED ON ANIMAL FARMS - CH.BASIN	(MIL LBS)

Appendix 4—Model report variables—Continued

Hauling distance:		
AVDST_ON	AVE HAULING DISTANCE - ON-FARM	(KMS)
AVDST_IN	AVE HAULING DISTANCE - EXCESS M - WITHIN COUNTY	(KMS)
AVDST_EX	AVE HAULING DISTANCE - EXCESS M - OUT-OF-COUNTY	(KMS)
AVDS_ONM	AVE HAULING DISTANCE - ON-FARM	(MILES)
AVDS_INM	AVE HAULING DISTANCE - EXCESS M - WITHIN COUNTY	(MILES)
AVDS_EXM	AVE HAULING DISTANCE - EXCESS M - OUT-OF-COUNTY	(MILES)
Application rate:		
AVAP_OFF	AVE MANURE APPLICATION RATE - OFF-FARM	(DRY TONS-AC)
AVAP_ON	AVE MANURE APPLICATION RATE - ON-FARM	(DRY TONS-AC)
AVEAPPL	AVE MANURE APPLICATION RATE - ALL	(DRY TONS-AC)
Hauling cost per ton:		
HC_ON_TN	HAULING & APPL COST PER TON HAULED - ONFARM	($-DRY TON)
HC_IN_TN	HAULING & APPL COST PER TON HAULED - INCOUNTY	($-DRY TON)
HC_EX_TN	HAULING & APPL COST PER TON HAULED - OUT-OF-COUNTY	($-DRY TON)
HC_TN	HAULING & APPL COST PER TON HAULED - TOTAL	($-DRY TON)
TC_TN	TOTAL COST PER TON HAULED	($-DRY TON)
HCON_WTN	HAULING & APPL COST PER TON HAULED - ONFARM	($-WET TON)
HCIN_WTN	HAULING & APPL COST PER TON HAULED - INCOUNTY	($-WET TON)
HCEX_WTN	HAULING & APPL COST PER TON HAULED - OUT-OF-COUNTY	($-WET TON)
HC_WTN	HAULING & APPL COST PER TON HAULED - TOTAL	($-WET TON)
TC_WTN	TOTAL COST PER TON HAULED	($-WET TON)
Application costs:		
APPL_ON(CT,CT2,SYS)	MANURE APPLICATION COST - ONFARM	($ MIL)
APPL_IN(CT,CT2,SYS,DST)	MANURE APPLICATION COST - INCOUNTY	($ MIL)
APPL_EX(CT,GR,CT2,SYS,DST)	MANURE APPLICATION COST - OUT-OF-CNTY	($ MIL)
AP_ON(CT,CT2)	TOTAL M APPL COST - ONFARM	($ MIL)
AP_IN(CT,CT2)	TOTAL M APPL COST - INCOUNTY	($ MIL)
AP_EX(CT,GR,CT2)	M APPL COST - OUT-OF-COUNTY GRID	($ MIL)
AP1(CT)	APPL COST BY SOURCE CNTY - INCOUNTY	($ MIL)
AP2(CT)	APPL COST BY SOURCE CNTY - EXPORTS	($ MIL)
APCOST(CT)	TOTAL APPL COST BY SOURCE COUNTY	($ MIL)
APCST_	APPL COST ACROSS SOURCE COUNTIES	($ MIL)
APCSTB	APPL COST ACROSS SOURCE CNTIES - CH.BASIN	($ MIL)
APL1(CT2)	APPL COST BY DEST CNTY - INCOUNTY	($ MIL)
APL2(CT2)	APPL COST BY DEST CNTY - EXPORTS	($ MIL)
APLCOST(CT2)	TOTAL APPL COST BY DEST COUNTY	($ MIL)
APLCST_	APPL COST ACROSS DEST COUNTIES	($ MIL)
APLCSTB	APPL COST ACROSS DEST COUNTIES - CH.BASIN	($ MIL)
AC_SHARE(CT2)	ACREAGE MANURED AS A SHARE OF TOTAL AVAILABLE	(.XX)

* Asterisks denote endogenously specified variables in the model; all others are derived from the model solution based on levels of endogenous variables.