Sources of Nutrients in the Nation's Watersheds

By

Richard A. Smith and Richard B. Alexander

Hydrologists
U. S. Geological Survey
Reston, Virginia

Introduction

Animal agriculture is a common source of nutrients in watersheds, but it is never the only source. Indeed, the diverse and ubiquitous nature of nitrogen and phosphorus forms in the environment introduces significant complexity to the increasingly important task of managing nutrients in watersheds. Thus, it is appropriate near the outset of this conference to attempt a systematic quantification of nutrient sources in surface waters as a means of exploring the relative importance of animal agriculture's influence on the nutrient balance in aquatic ecosystems under different conditions.

In this paper, we present estimates of the percentage contribution of five categories of nutrient sources to the total nitrogen and total phosphorus flux from watersheds in the major water-resources regions of the conterminous United States. It is noteworthy that our estimates pertain to "in-stream" conditions rather than "input-level" contributions from each of the source categories. The latter, which represent nutrients applied to a watershed, offer a simpler way to quantify nutrient source contributions (see for example Puckett, 1995; Jaworski *et al.* 1992) but do not account for the effects of landscape and stream processing of nutrient material, and thus may give a very different picture of the importance of a particular source on water quality conditions. For example, agricultural fertilizer inputs to watersheds may be estimated from state- or county-level sales data or from estimated usage rates and cropland acreage. But fertilizer inputs generally exceed stream nutrient yields (mass per area per time) by a factor of two or more (Howarth *et al.* 1996; Carpenter *et al.* 1998) due to crop uptake and removal. When expressed in input terms, therefore, agricultural fertilizers appear to be a larger contributor to watershed nutrients than when they are expressed in in-stream terms.

Our estimates of in-stream source contributions are obtained through application of SPARROW (SPAtially Referenced Regressions On Watersheds; Smith, *et al*, 1997), a recently developed technique for interpreting water-quality monitoring data in relation to watershed sources and characteristics. We begin with a brief discussion of methods for relating in-stream nutrient flux to source inputs and develop the rationale for spatial referencing of model terms. Next, we provide a brief overview of the SPARROW model followed by a description of the data sources used here. The results pertaining to nutrient sources in general are presented in Tables 1 and 2. The results for animal agriculture are presented in map form in Figure 1. A brief discussion of the results and conclusions completes the report.

Quantifying watershed nutrient contributions by source category

A variety of deterministic and statistical methods have been used to develop estimates of nutrient contributions to watersheds from human and natural sources. The simplest deterministic approaches consist of a simple accounting of the inputs and outputs of nutrients. A mass balance is achieved by comparing major source inputs (*e.g.*, fertilizer application, livestock waste, atmospheric deposition, and point sources) with outputs (*e.g.*, river export, crop removal) and by assuming that total losses to volatilization, soil adsorption, sedimentation, groundwater storage and denitrification equal the difference between the total inputs and outputs. Such simple models must assume that loss processes operate equally on all sources and that the relative contributions of sources to watershed export are proportional to the inputs. More complex deterministic models of nutrients in watersheds describe transport and loss processes in more detail and incorporate terms for spatial and temporal variations in sources and sinks. A major limitation on the applicability of such models at the regional or national scale is the problem of obtaining the necessary data for process description, especially if processes are treated dynamically.

Statistical approaches to modeling nutrients in watersheds have their origins in simple correlations of stream nutrient measurements with watershed sources and landscape properties. Recent examples include regressions of coastal total nitrogen flux on population density, net anthropogenic sources, and atmospheric deposition (Caraco and Cole, 1999; Howarth *et al*, 1996). A noteworthy advantage of the statistical approach is the ability to quantify errors in model parameters and predictions. Simple correlative models consider sources and sinks to be homogeneously distributed in space, do not separate terrestrial from in-stream loss processes, and rarely account for the interactions between sources and watershed processes. By contrast, more complex empirical approaches (Smith *et al.* 1997; Preston and Brakebill, 1999; Alexander *et al.* 2000; Alexander *et al. in press*; Johnes, 1996; Johnes and Heathwaite, 1997) indicate that knowledge of spatial variations in watershed properties that influence nutrient attenuation can significantly improve the accuracy of estimates of export and source contributions at larger watershed and regional scales.

SPARROW (Smith *et al.* 1997), a hybrid statistical/deterministic approach, expands on previous methods by using a mechanistic regression equation to correlate measured stream nutrient flux with spatial data on sources, landscape characteristics (*e.g.*, soil permeability, temperature), and stream properties (*e.g.*, flow, water time of travel). The model separately estimates the quantities of nutrients delivered to streams and the outlets of watersheds from point and diffuse sources. Spatial referencing of land-based and water-based variables is accomplished via superposition of a set of contiguous land-surface polygons on a digitized network of stream reaches that define surface-water flow paths for the region of interest. Water-quality measurements are available from monitoring stations located in a subset of the stream reaches. Water-quality predictors in the model are developed as functions of both reach and land-surface attributes and include quantities describing nutrient sources (point and nonpoint) as well as factors associated with rates of material transport through the watershed (such as soil permeability and stream velocity). Predictor formulae describe the land-to-water transport of nutrient mass from specific sources in the watershed surrounding each reach, and in-stream transport from reach to reach in downstream order. Loss of nutrient mass occurs during both land-to-water and in-stream transport. In calibrating the model, measured rates of contaminant transport are regressed on the set of predictor formulae evaluated at the locations of the monitoring stations, giving rise to a set of estimated linear and nonlinear coefficients from the predictor formulae. Once calibrated, the model can be used to estimate contaminant transport (and concentration) in all stream reaches under mean flow conditions. In addition, because the nutrient contribution from each source is tracked separately in the model, the percent contribution from each source category (*e.g.*, fertilizer, animal agriculture, etc) can also be computed for each reach. A study of model reliability is given in Alexander *et al.* (*in press*).

SPARROW has been applied nationally in the conterminous United States (Smith *et al.* 1997) with separate studies of nitrogen flux in the Chesapeake Bay watershed (Preston and Brakebill, 1999), the Mississippi River and its tributaries (Alexander *et al.* 2000), the watersheds of major U.S. estuaries (Alexander *et al. in press*), and watersheds of New Zealand (Alexander, R.B., U.S. Geological Survey, written comm., 1999).

Data sources and methods

Detailed descriptions of the data sources and calibration results for the SPARROW total nitrogen (TN) and total phosphorus (TP) models used in this study are given in Smith *et al.* (1997). Observations of in-stream nutrient transport (i.e., the dependent variables in model calibrations) were based on U.S. Geological Survey (USGS) long-term stream monitoring records of TN and TP for the period 1974 to 1989 for 414 (TN) and 381 (TP) sites in the conterminous United States. Data for nutrient sources were developed for five major source categories: (1) municipal and industrial point sources, (2) commercial fertilizer, (3) animal agriculture, (4) nonagricultural runoff, and (5) atmospheric deposition (TN model only). Watershed inputs of nutrients for the source category fertilizer are based on fertilizer sales data. Nitrogen contributions from leguminous crop fixation are assumed to be reflected in the estimated coefficient for the fertilizer source category. Nutrient inputs for the source category animal agriculture are based on federal surveys of animal populations and literature data on animal-waste production and the nutrient content of animal wastes. Atmospheric deposition sources are based on measured inputs of wet nitrate deposition, which are scaled by the model to reflect additional atmospheric contributions from such sources as wet deposition of ammonium and organic nitrogen and dry deposition of inorganic nitrogen. The source category nonagricultural runoff is scaled according to nonagricultural land area, and includes remaining nutrient sources unaccounted for by the other categories. This source may include surface and subsurface runoff from wetlands and urban, forested, and barren lands.

Data on the source inputs and terrestrial characteristics, which are available for nearly 20,000 land-surface polygons, were referenced to approximately 60,000 stream reaches in a digital stream network using conventional spatial disaggregating methods in a geographic information system [see Smith *et al.* 1997]. The surface-water flow paths, defined according to a 1:500,000 scale digital network of rivers for the conterminous United States, cover nearly one million kilometers of channel, and are obtained from the

U.S. Environmental Protection Agency River Reach File 1 (RF1). The river reach network provides the spatial framework in the model for relating in-stream measurements of nutrient flux at monitoring stations to landscape and stream channel properties in the watersheds upstream from these stations. The median watershed size of the reaches is 82 km^2 with an interquartile range from 40 to 150 km^2. Stream attributes of the digital network include estimates of mean streamflow and velocity from which water time of travel is computed as the quotient of stream length and mean water velocity.

Model predictions of nutrient export were developed for each of the 2,057 nontidal watersheds (hydrologic cataloging units; see Seaber *et al.* 1987) comprising the major water-resources regions of the conterminous United States (see Smith *et al.* 1997; model output is available at http://water.usgs.gov/nawqa/sparrow/wrr97/results.html). These watersheds are a logical choice for national level water-quality characterization because they represent a systematically developed and widely recognized delineation of U.S. watersheds, and provide a spatially representative view of water-quality conditions (Smith *et al.* 1997; Seaber *et al.* 1987).

Results and discussion

A statistical summary of TN and TP export from the watersheds of the major water resources regions of the conterminous United States is given in Tables 1 and 2. The tables give median total export and the median and quartile percent contributions to export from each of the five source categories. According to Table 1, for example, the estimated median TN export from the watersheds in the Mid Atlantic region is 9.0 kg ha^{-1} yr^{-1} . The median contribution to TN export from animal agriculture in the same region is 15.5 percent with quartile (i.e., 25th and 75th percentile) values of 8.2 and 23.0 percent.

Median export of TN and TP varies among the regions by more than an order of magnitude, with the highest rates for both elements occurring in the Upper Mississippi and Ohio regions and the lowest occurring in the Great Basin and Rio Grande regions. Recognizing that these figures refer to the median rate in each region, it is clear that the total range of variation in nutrient export rates among all watersheds is much larger.

From Tables 1 and 2, it is also clear that the relative importance of the different categories of nutrient sources in watersheds varies greatly from one region to another. Not surprisingly, point sources, which generally represent the smallest contributors to nitrogen and phosphorus export from watersheds, are seen to reach their highest importance in the densely populated Northeast, Mid Atlantic, and Great Lakes regions. In the Northeast region, in fact, point sources contribute more than half of the total phosphorus export in at least 25 percent (i.e., upper quartile) of the watersheds. Fertilizer is a large contributor to nutrient loads in the high-export Upper Mississippi and Ohio regions, but makes its highest contribution in percentage terms (median TN=75 percent; median TP=64 percent) in the Red-Rainy basin in the northern plains where total export is low. In the southwestern regions, where total export is also low, nonagricultural runoff from forest, barren, and range lands contributes the largest percentage to watershed export of nutrients. Atmospheric nitrogen contributes more than a quarter of the total nitrogen export in a majority of watersheds in the northeastern quadrant of the United States, and is the dominant source in the Great Lakes and Mid-Atlantic water-resource regions.

The importance of animal agriculture as a nutrient source in watersheds is presented in the regional summaries in Tables 1 and 2 and also in map form in Figures 1a and 1b, which show the percentage contribution made by animal agriculture to TN and TP export from each of the 2,057 hydrologic units. For total nitrogen, the median contributions of animal agriculture in the water resource regions range from about 5 to 23 percent (Table 1). The highest contributions (median=19 to 23 percent) are found in the Tennessee, Upper Mississippi, Missouri, Arkansas-Red, and Texas-Gulf regions. Figure 1a indicates that in many watersheds in the states of Wisconsin, Iowa, Missouri, Oklahoma, and Texas, animal agriculture contributes from 20 to 58 percent of TN export. Although animal agriculture in the Mid-Atlantic and Southeast regions contributes a median of only about 8 percent to export (Table 1), farm animals contribute more than 20 percent of the exported nitrogen from many individual watersheds within these regions (Figure 1a). The lowest contributions of animal agriculture (i.e., less than 10 percent) are found in the Northeast, Great Lakes, and many western water-resources regions.

For total phosphorus, the median percentage contributions of animal agriculture in the major water-resource regions range from about 7 to 48 percent (Table 1) or approximately twice the contributions estimated for total nitrogen. The highest contributions occur in the Upper Mississippi, Arkansas-Red, Missouri, and Texas-Gulf regions, including watersheds in the states of Wisconsin, Iowa, Nebraska, Missouri, Kansas, Arkansas, Oklahoma, and Texas (Figure 1b). The water-resource regions with the lowest contributions of animal agriculture to stream phosphorus (i.e., less than 20 percent) are similar to those found for total nitrogen, and include the Northeast, Great Lakes, and many western regions.

Summary and Conclusions

Estimating the importance of animal agriculture as a source of nutrients in watersheds is made difficult by the diverse and ubiquitous nature of nitrogen and phosphorus forms in the environment. The relative importance of nutrient sources is most meaningfully expressed in “in-stream” terms rather than as raw inputs. However, the contribution of individual nutrient sources to in-stream water quality is not directly measurable in large watersheds, and must therefore be estimated using a watershed model. The results of recent research indicate that spatial referencing of variables improves the accuracy of watershed nutrient models. SPARROW models of TN and TP have been calibrated with stream monitoring records from 414 locations across the conterminous United States. These models were used here to estimate nutrient contributions from five source categories for the 2,057 cataloging unit watersheds comprising the major water-resources regions.

The relative importance of the different categories of nutrient sources in watersheds varies greatly from one region to another reflecting differences in human activities. Point sources generally contribute little to nutrient export from most of the nation’s watersheds, but contribute a majority of the total phosphorus export from many watersheds in the densely populated northeastern United States. Atmospheric deposition is the largest contributor to stream export of nitrogen in more than half of the watersheds in the northeastern United States. In the southwestern United States, nonagricultural runoff is the predominant source of both nitrogen and phosphorus in watershed export. Fertilizer is an important contributor to nutrient export in many watersheds throughout the central United States, and is the largest contributor in most watersheds in the Ohio Valley and Midwestern states. Animal agriculture is also an important contributor of both nitrogen and phosphorus in watersheds in the same regions, but animal wastes constitute a much larger fraction of phosphorus export than nitrogen export in these areas.

References

Alexander, R.B., Smith, R.A., and Schwarz, G.E., Effect of stream channel size on the delivery of nitrogen to the Gulf of Mexico, *Nature* **403**, 758-761 (2000).

Alexander, R.B., Smith, R.A. Schwarz, G.E., Preston, S.D., Brakebill, J.W., Srinivasan, R., and Pacheco, P.A., Atmospheric nitrogen flux from the watersheds of major estuaries of the United States: An application of the SPARROW watershed model, *in Assessing the Relative Nitrogen Inputs to Coastal Waters from the Atmosphere*, American Geophysical Union Water Monograph, Valigura, R., Paerl, H.W., Meyers, T., Castro, M.S., Turner, R.E., Alexander, R.B., Brock, D., and Stacey, P.E. (editors) *in press.*

Caraco, N.F., and Cole, J.J., Human impact on nitrate export: An analysis using major world rivers, *Ambio.* **28**, 167-170 (1999).

Carpenter, S.R., Caraco, N.F., Correll, D.L., Howarth, R.W., Sharpley, A.N., and Smith, V.H., Nonpoint pollution of surface waters with phosphorus and nitrogen, *Ecological Applications.* **8**, 559-568 (1998).

Howarth, R.W., G. Billen, D. Swaney, A. Townsend, N. Jaworski, K. Lajtha, J.A. Downing, R. Elmgren, N. Caraco, T. Jordan, F. Berendse, J. Freney, V. Kudeyarov, P. Murdoch & Zhu Zhao-liang, Regional nitrogen budgets and riverine N & P fluxes for the drainages to the North Atlantic Ocean: natural and human influences, *Biogeochem.* **35**, 75-139 (1996).

Jaworski, N.A., Groffman, P.M., Keller, A.A. & Prager, J.C., A watershed nitrogen and phosphorus balance: the Upper Potomac River basin, *Estuaries* **15**, 83-95 (1992).

Johnes, P.J. Evaluation and management of the impact of land use change on the nitrogen and phosphorus load delivered to surface waters: the export coefficient modelling approach, *J. of Hydrology* **183**, 323-349 (1996).

Johnes, P.J. & Heathwaite, A.L., Modelling the impact of land use change on water quality in agricultural catchments, *Hydrological Processes* **11**, 269-286 (1997).

Preston, S.D. and Brakebill, J.W., *Application of Spatially Referenced Regression Modeling for the Evaluation of Total Nitrogen Loading in the Chesapeake Bay Watershed* (U.S. Geological Survey Water Resources Investigations Report 99-4054, Baltimore, Maryland, 1999), http://md.water.usgs.gov/publications/wrir-99-4054/ .

Puckett, L. J., Identifying the major sources of nutrient water pollution, *Environ. Sci. Techn.* **29**, 408-414 (1995).

Seaber, P.R., Kapinos, F.P. & G.L. Knapp, *Hydrologic Units Maps* (U.S. Geological Survey Water Supply Paper, 2294, Reston, Virginia, 1987).

Smith, R.A., G.E. Schwarz & R.B. Alexander, Regional interpretation of water-quality monitoring data, *Wat. Resour. Res.* **33**, 2781-2798 (1997), http://water.usgs.gov/nawqa/sparrow/wrr97/results.html .

Table 1. Point- and nonpoint-source contributions to total nitrogen export from watersheds in major water-resource regions of the conterminous United States. Total export is the median export from hydrologic cataloging units in each region. The median and quartile values for the source contributions within each region are expressed as a percentage of the total export.

Region	Total Export (kg ha^{-1} yr^{-1})	Percentage of Total Export									
		Point Sources		Fertilizer		Animal Agriculture		Atmosphere		Nonagricultural Runoff	
		Median	Quartiles	Median	Quartiles	Median	Quartiles	Median	Quartiles	Median	Quartiles
Northeast	6.7	4.3	1.2 – 19	6.2	3.6 – 13	5.8	2.8 – 9.3	30	25 – 38	38	27 – 52
Mid Atlantic	9.0	4.1	1.6 – 20	14	10 – 22	16	8.2 – 23	32	20 – 40	22	14 – 28
Southeast Atlantic-Gulf	5.9	2.7	1.1 – 8.2	26	17 – 38	14	8.8 – 21	21	15 – 28	26	19 – 34
Great Lakes	8.0	4.3	1.3 – 12	22	7.8 – 41	10	4.6 – 17	25	16. 34	17	6.5 – 40
Ohio	11	1.8	0.7 – 7.0	30	9.2 – 58	14	9.2 – 20	25	15 – 42	13	6.4 – 23
Tennessee	8.3	2.7	0.6 – 7.2	22	16 – 29	19	15 – 25	26	21 – 33	24	18 – 28
Upper Miss.	13	0.8	0.5 – 1.6	55	40 – 66	21	15 – 27	13	11 – 17	3.6	2.1 – 10
Lower Miss.	7.6	2.3	1.0 – 11	40	14 – 64	6.3	3.2 – 10	22	14 – 28	18	8.0 – 28
Red Rainy	3.5	0.3	0.1 – 0.6	75	57 – 81	5.2	2.8 – 9.0	9.3	7.4 – 14	7.2	3.4 – 20
Missouri	2.1	<0.1	<0.1 - <0.1	30	8.8 – 51	20	15 – 25	16	12 – 20	29	9.5 – 55
Ark-Red	3.9	0.8	0.2 – 1.9	29	20 – 46	23	17 – 29	18	14 – 23	20	12 – 28
Texas-Gulf	3.7	0.9	0.1 – 5.3	30	18 – 41	19	14 – 26	18	14 – 21	23	13 – 37
Rio Grande	1.0	<0.1	<0.1 - < 0.1	1.7	0.6 – 5.1	11	6.2 – 14	13	8.9 – 16	71	63 – 80
Upper Colorado.	1.9	0.1	<0.1 – 0.4	2.0	1.1 – 4.5	8.7	5.3 – 12	17	14 – 20	72	64 – 76
Lower Colorado	0.7	<0.1	<0.1 – 0.4	1.6	0.7 – 16	6.6	2.9 – 10	8.6	5.0 – 9.9	78	65 – 84
Great Basin	0.9	<0.1	<0.1 - <0.1	3.6	0.9 – 9.2	9.3	5.6 – 15	6.4	5.4 – 8.1	78	61 – 86
Pacific NW	4.2	<0.1	<0.1 - <0.1	12	5.5 – 30	11	7.3 – 14	13	8.0 – 16	57	34 – 69
California	4.8	1.2	0.3 – 6.7	21	8.9 – 52	12	7.6 – 17	8.7	5.5 – 13	35	16 – 62
United States	4.7	0.8	0.5 – 3.4	22	7.5 – 45	14	8.2 – 21	16	11 – 23	28	13 – 56

Table 2. Point- and nonpoint-source contributions to total phosphorus export from watersheds in major water-resource regions of the conterminous United States. Total export is the median export from hydrologic cataloging units in each region. The median and quartile values for the source contributions within each region are expressed as a percentage of the total export.

Region	Total Export (kg ha^{-1} yr^{-1})	Percentage of Total Export							
		Point Sources		Fertilizer		Animal Agriculture		Nonagricultural Runoff	
		Median	Quartiles	Median	Quartiles	Median	Quartiles	Median	Quartiles
Northeast	0.41	18	7.1 – 55	7.7	4.1 – 13	6.8	3.1 – 14	54	28 – 68
Mid Atlantic	0.68	14	5.6 – 45	19	14 – 26	25	13 – 38	22	12 – 37
Southeast Atlantic-Gulf	0.54	7.9	3.4 – 22	23	11 – 32	30	20 – 40	29	18 – 40
Great Lakes	0.49	13	4.7 – 24	26	12 – 41	18	8.0 – 29	22	6.6 – 59
Ohio	0.93	7.3	2.6 – 21	30	15 – 45	30	20 – 41	14	6.2 – 33
Tennessee	0.67	7.2	2.3 – 16	24	18 – 30	33	26 – 43	23	16 – 34
Upper Miss.	1.1	3.6	1.7 – 6.8	37	30 – 44	47	35 – 55	3.6	2.1 – 10
Lower Miss.	0.53	9.6	4.7 – 27	29	6.7 – 58	15	8.9 – 25	27	13 – 39
Red Rainy	0.22	1.7	0.9 – 3.6	64	45 – 77	12	7.8 – 22	11	5.1 – 23
Missouri	0.19	1.0	0.3 – 2.4	20	6.8 – 30	42	28 – 55	29	14 – 60
Ark-Red	0.36	2.7	1.0 – 5.4	18	10 – 29	48	38 – 56	24	13 – 33
Texas-Gulf	0.38	2.7	0.5 – 14	18	8.6 – 25	39	29 – 49	29	16 – 46
Rio Grande	0.12	<0.1	<0.1 - < 0.1	0.9	0.3 – 2.7	16	11 – 20	81	73 – 87
Upper Colorado	0.14	0.4	<0.1 – 1.8	1.1	0.6 – 2.6	16	10 – 21	81	75 – 88
Lower Colorado	0.10	0.3	<0.1 – 1.3	1.0	0.4 – 7.7	12	4.9 – 18	83	69 – 91
Great Basin	0.09	0.2	<0.1 – 2.1	3.5	1.7 – 8.1	14	8.4 – 20	79	65 – 88
Pacific NW	0.30	1.5	0.2 – 8.9	7.1	2.9 – 18	19	12 – 25	65	43 – 78
California	0.41	4.0	1.1 – 19	9.5	3.7 – 30	19	12 – 29	40	20 – 71
United States	0.37	3.0	0.7 – 11	17	5.5 – 31	26	15 – 42	33	15 – 65