Dynamic phosphorus mass balance modeling of large watersheds: long-term implications of management strategies

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Abstract The principles of mass balance, compartment-flux diagramming, and dynamic simulation modeling are integrated to create computer models that estimate phosphorus (P) export from large-scale watersheds over long-term futures. These Watershed Ecosystem Nutrient Dynamics (WEND) models are applied to a 275,000 ha dairy-documented watershed and a 77,000 ha poultry-dominated watershed in northeastern USA. Model predictions of present-day P export loads are consistent with monitoring data and estimates made using P export coefficients. For both watersheds P import exceeds P export and P is accumulating in the agricultural soils. Agricultural and urban activities are major contributors to P export from both watersheds. Continued urban growth will increase P export over time unless wastewater management is substantially enhanced and/or rates of urban growth are controlled. Agriculture cannot rely solely on the implementation of increasingly stringent conservation practices to reduce long-term P export but must consider options that promote P input/output balance. The WEND modeling process is a powerful tool to integrate the diversity of activities in watersheds into a holistic framework. Model outputs are suited to assist managers to explore long-term effects of overall watershed management strategies on P export in comparison to environmental and economic goals.

Keywords Watersheds; phosphorus; dynamic simulation; modeling; management strategies

Introduction

Watersheds are complex ecosystems in which people live, work and play. While natural unimpacted watersheds in temperate climates are largely forested, the landscape of developed watersheds consists of agricultural lands and urban areas with only fragments of the original forests remaining. Phosphorus exported from watersheds can impair the water quality of the receiving water body. In natural watershed ecosystems both P inputs and outputs are low and water quality impacts are often minimal. In most developed watersheds substantial amounts of P are imported so that more P is imported than exported (Cahoon *et al.*, 1999) causing increased P storage in watershed soils and higher P export (Sharpley *et al.*, 1994). Furthermore, as agricultural and urban development in watersheds intensifies over time the natural biological, chemical, physical processes that control the storage and processing of P in natural watersheds often are overwhelmed so that the manner in which watersheds process P is changed.

It is useful, from a mass balance point of view, to consider large-scale developed watersheds as consisting of three sectors: forest, agriculture, and urban. Phosphorus storage, movement, and export differs among these sectors because the use of P is different in each sector. Individual sectors also relate differently to the outside world. Because developed watersheds contain all three sectors, a watershed-scale P mass balance analysis must simultaneously consider how P is processed by each individual sector. Furthermore, in large-scale watershed ecosystems, the individual sectors that store and process P interact

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with each other and cannot be considered in isolation. For example, people living in the urban sector eat food produced in the agriculture sector while products and waste residues produced in the urban sector are consumed in the agriculture sector.

Ecologists developed the compartment-flux diagram (CF diagram) to map how complex ecosystems process nutrients (Odum, 1960; 1964; 1971) and use them to study how material (or energy) is stored, moved, and exported in ecosystems. Systems analyses developed dynamic simulation modeling techniques to study how various elements within complex systems interact and how such complex systems respond dynamically (over time) to perturbation. Compartment-flux diagrams and dynamic simulation are tools well adapted to mass balance analysis. In this work we combine CF diagrams and dynamic simulation techniques with mass balance concepts to create models that predict how the storage, movement, and export of P from watersheds change over time in response to alternative scenarios for managing the resources and human activities in the forest, agriculture, and urban sectors. The result is the Watershed Nutrient Dynamics Model (WEND model). These models suggest how average P loadings from watersheds change over decades after implementation of watershed management strategies. Two large agriculturally impacted watersheds in northeastern USA are used to test the WEND modeling concept: the relatively mountainous Winooski River watershed in Vermont, and Delaware's coastal Inland Bays watershed.

Process of model development

Each WEND model is developed to competently describe the import, storage, movement and export of P for a particular watershed. Several fundamental principles are applied including: (a) every watershed ecosystem possesses defined boundaries across which P moves to either enter or leave the watershed; (b) all watershed ecosystems contain one or more sectors in which P is stored (WEND models in this paper contain the forest, agriculture, and urban sectors); (c) all sectors are connected so P can move from one sector to another so that individual sectors function in concert with the other sectors in the watershed ecosystem; (d) the manner in which P is processed within each sector is defined by a unique set of activities that occur within that sector; and (e) the principles of mass balance are applied simultaneously to the inputs and outputs of P for each sector and the overall watershed ecosystem.

The CF diagram in Figure 1 depicts a watershed ecosystem. Three sectors are inside the watershed boundary. The arrows are fluxes or pathways through which P cycles inside and moves across the watershed and sector boundaries. The structure in each sector is a set of unique pathways through which P cycles within the sector. The three arrows pointed downward are the fluxes (or loads) of P exported from each sector to the network of streams and rivers in the watershed. The sum of these fluxes is equal to P export from the watershed only when P is not permanently stored in the watershed drainage net.

The magnitude of P storage and the arrangement of pathways through which P is cycled is unique to each sector and watershed. Thus, it is necessary to identify specific sectors and pathways through which P moves for each watershed to which the WEND model is applied. The network of pathways within each sector must include all the major natural or anthropogenic processes that transport P from one location to another. This structure is represented as a CF diagram and used to understand the unique P infrastructures of the sectors and watershed. Figure 2 is an example detailed CF diagram for the urban sector of the Inland Bays watershed. It represents the complex infrastructure through which P moves within the urban areas of the Inland Bays watershed. Because urban areas are unique the Inland Bays urban CF diagram (Figure 2) differs from the infrastructure that is used to describe the urban CF diagram for the Winooski River watershed. Detailed CF diagrams are also constructed to establish the unique P infrastructures for the forest and agriculture sectors for each watershed to which WEND is applied.

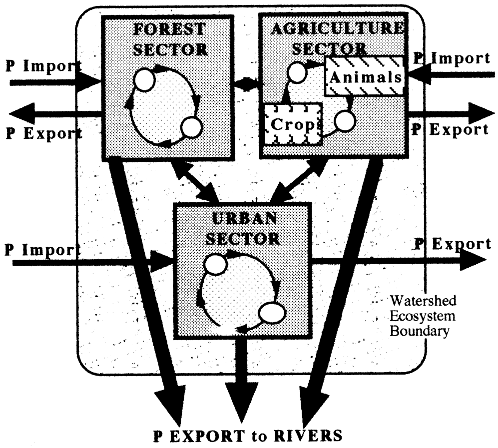

Figure 1 Phosphorus compartment-flux diagram for a complex watershed ecosystem

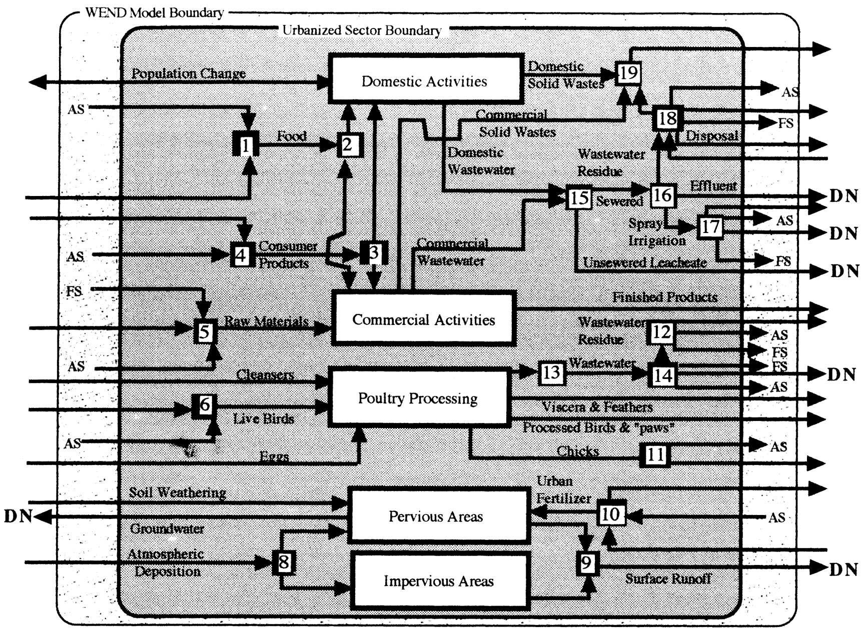

Figure 2 Phosphorus CF diagram for the urban sector of the Inland Bays watershed. Phosphorus is stored in the rectangles and moves through the arrows. Arrows crossing the WEND model boundary are P imports and exports. Arrows crossing the urbanized sector boundary are P inputs and outputs for the urban sector. The small rectangles that contain numbers are "decision nodes" which allow the modeler to assign a pattern of P flows in the sector to model different management strategies. *FS* is the forest sector and *AS* is the agriculture sector. Arrows directed to **DN** are P fluxes that enter the watershed drainage net to be ultimately exported from the watershed

The necessary process of creating customized CF diagrams for each sector and watershed is extremely valuable because it contributes to a holistic understanding of the overall watershed P infrastructure. A holistic comprehension of watershed infrastructures is rare among government officials, managers, and most scientists yet is absolutely essential to understanding the real long-term impact of implementing management programs. The construction of P infrastructures for the forest, agriculture, and urban sectors requires consultation with a wide array of expertise and locally knowledgeable individuals including: local government agents responsible for waste management, urban development, recycling, etc.; state and federal officials responsible for water quality monitoring, land management programs, and economic development, etc.; resource and economic planners at all levels; demographers; business leaders; tourism agencies; industrial and commercial establishments; extension agents; farmers; foresters; and scientists from local and state universities. Through this process of consultation, an extremely diverse set of data is obtained upon which a custom CF diagram is built for each specific watershed. Algorithms also are identified to describe each important pathway and storage location for the WEND model. Another outcome of the customization process is identification of a cadre of individuals who become involved in how their watershed is studied, develop an understanding of the capabilities of the WEND model and its outputs, and begin to think more holistically about their watershed ecosystem. Some of these individuals may serve as an advisory panel to assure that study conditions and evaluated scenarios are relevant to the local politic. Ultimately local experts may apply the finished model to analyze additional scenarios.

Once the important compartments for P storage and pathways for P movement, export, and import are established and competent algorithms are assigned to each pathway the code for the WEND model is built. All model code is formulated in STELLA (HPS, 1996), an object oriented dynamic simulation programming language derived from the basic notions of systems analysis (Forrester, 1968). Basic to STELLA modeling is: (a) definition of system boundaries, (b) definition of system compartments, and (c) establishment of the appropriate pattern of intercompartmental connections. Once the system and compartmental boundaries are established the model is constructed to provide a complete mass balance accounting of all P pathways that cross all boundaries. WEND models are created directly on the computer screen as structures consisting of four basic objects: stocks, flows, converters, and connectors consistent with STELLA. The skeleton of these on-screen structures closely emulate the CF diagrams for the various sectors. It is possible to incorporate feedback mechanisms and both linear and non-linear algorithms into these structures so that the resulting model algorithms can be quite complex. The models are built to conveniently allow input data to be changed so that various management scenarios can be emulated, including the internal recycling of P within the watershed.

Final WEND models of watersheds are hierarchical in that they contain several different levels of complexity. WEND models are built from the bottom up, from the simple to the complex. That is, modeling begins with individual algorithms, a number of these algorithms are combined to represent a single process, several of these processes are integrated to describe a sector, and lastly the sector models are connected together to form the complex structure that emulates Figure 1. All WEND models assume the input data that define each sector are average or typical values for the activities in that sector, that is, each sector is homogeneous. For example, even though soils are known to be spatially variable over a watershed, the algorithms in WEND that define how soil processes P are based on data for the typical or average soil condition in the watershed. Since there is no spatial explicitness in WEND models the data requirements are substantially less than for models driven by geographic information systems. All computations in the WEND model are carried out over decades with an annual time step. Consequently, WEND models are not useful in examining P export due to specific runoff events nor variation in P export over season.

Case study results

In this paper WEND models are applied to two relatively large and very different watersheds in northeastern USA. The long-term consequences of alternative resource and environmental management strategies on P export from both watersheds is analyzed. Vermont's Winooski River watershed discharges into Lake Champlain whose quality is impacted by high P loading.

Table 1 Characteristics of study watersheds

Characteristic	Winooski River	Inland Bays
Land Area (ha)	275,399	77,000
% Urban	8	12
% Agriculture	13	36
% Forested	74	24
% Water, other	5	28
Overall terrain	Hilly, mountainous	Flat, highly drained
Resident population (No.)	~153,000 (est. 1995)	~36,000 (est. 1998)
Tourism (visitor-days/year)	~300,000 (est. 1995)	~5,200,000 (est. 1998)
Character of agriculture		
Dominant animal	Cattle (dairy)	Poultry (broilers)
Animals (No.)	~54,000	~13,000,000 (5.5 flocks/yr)
Dominant cropland	silage corn, hay, pasture	corn-wheat-soybean rotation

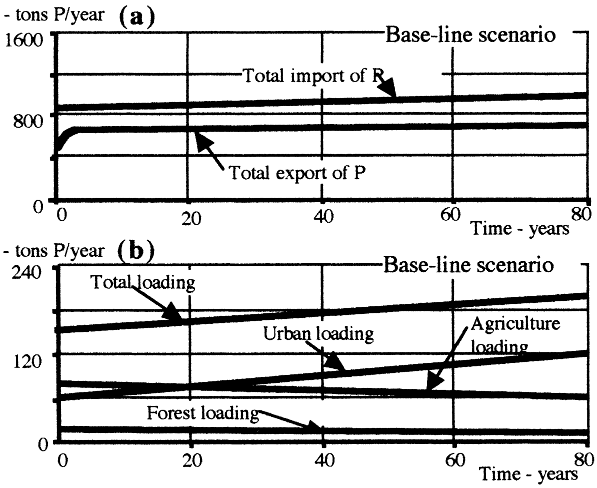

Figure 3 Dynamic patterns of P import, export, and loading to Lake Champlain from the Winooski River watershed as estimated by the WEND model

Delaware's Inland Bas watershed discharges into the polluted, shallow, brackish Inland Bays that flow into the Atlantic ocean. The characteristics of each watershed are in Table 1.

The Winooski River watershed

This urbanizing watershed is currently the source of about 20% of the total load of P to Lake Champlain (VTDEC and NYDEC 1994) and supports a dairy agriculture that is presently in decline. Initially, a Base-line simulation was run in which assumed that current conditions in the Winooski River watershed remain constant over the 80 year period (Casell *et al.*, 1998). To assess how different management scenarios influence the long-term patterns for P export from the watershed, several 80 year simulations were run with the WEND model. These simulations emulated management strategies that ranged from an aggressive environmental scenario to a rapid economic growth scenario. The conditions for these scenarios were implemented between years 20 and 30.

Figure 3a shows the 80 year dynamic patterns in the import and export of P for the Base-line scenario. The total amount of P imported to the watershed (i.e. P in human food, raw materials, atmospheric deposition, animal feeds, etc.) increases over time due to population growth and is always greater than the total amount of P exported (i.e. P in finished products, liquid and solid

Table 2 Scenario conditions for Winooski River watershed simulations

Characteristic	Base-line scenario	Rapid growth scenario	Environmental scenario
% Population unsewered	41	25	35
% Urban area impervious	10	10	5
Urban growth (%/yr)	0.8	1.2	0.6
Waste treatment level index	2.8	2.8	4.0
Ag fertilizer applied (kg TP/ha/yr)	3.2	3.2	0.0
Ag herd growth rate (%/yr)	2	2	0
Ag harvest (kg TP/ha/yr)	15.4	15.4	12
Use of no-till	NO	NO	YES
Ag % cropland in grass	90	90	70
Urban % food from ag sector	5	5	15
Urban % raw material from ag sector	25	15	45
Urban % lawn fertilizer imported	70	70	20
Urban % lawn fertilizer from recycled wastes	10	10	30

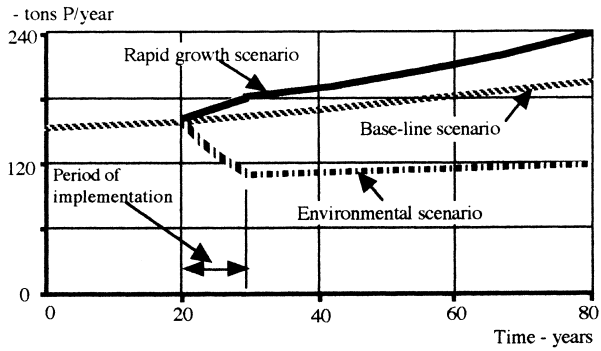

Figure 4 Total phosphorus loads from the Winooski River watershed for various management scenarios as estimated by the WEND model

wastes, diffuse pollution, etc.) Each year the watershed accumulates about 200 tons of P (primarily in the watershed soils) because imports exceed exports (Figure 3a). Figure 3b displays the P loading from each sector that enter the stream and river network of the watershed and are ultimately exported to Lake Champlain. At time 0 the predicted total loading is about 150 t/yr which compares favorably to recent monitoring data (153 t/yr) (VTDEC & NYDEC, 1994).The P loading from the urban sector increases over time while that from agriculture decreases as urban growth displaces agriculture. The loading from the forest sector is low compared to the other sectors. If current conditions prevail in the Winooski River watershed, the watershed will become more urban and unless management actions are taken, the watershed will provide increasing loading of P to Lake Champlain over the next eight decades.

Figure 4 compares the loading of P from the watershed to Lake Champlain among three scenarios: the Base-line scenario, the Rapid economic growth scenario, and the Environmental scenario. The conditions for these scenarios are summarized in Table 2 and are implemented between years 20 and 30 of the simulation and then maintained constant until year 80. For the Rapid growth scenario the P loading to the lake increases above the Base-line between years 20 and 30 and remains higher for the duration of the simulation run. However, for the Environmental scenario, the P loading decreases below the Base-line scenario between years 20 and 30 and remains lower for the duration of the simulation. The WEND model suggests that different watershed management alternatives can materially impact the annual mass of P that exits the watershed in river discharge.

Table 3 Scenario conditions for the Inland Bay

Simulation Name	Conditions for scenario
1. Base-line	Current (1996–1998) conditions
2. Phytase	Add phytase to poultry feed to reduce P content of feed
3. Comprehensive ag	Add phytase to poultry feed
	+ Export 20% of litter production
	+ Implement stringent ag land management practices
4. Comprehensive urban	Enhance P removal of waste treatment plants
	+ Implement stringent urban land management practices
5. Watershed practices	Comprehensive ag practices
	+ Comprehensive urban practices
6. Growth management	Comprehensive ag practices
	+ Comprehensive urban practices
	+ Reduced urban growth rate
	+ 10% reduction in poultry production capacity by year 10

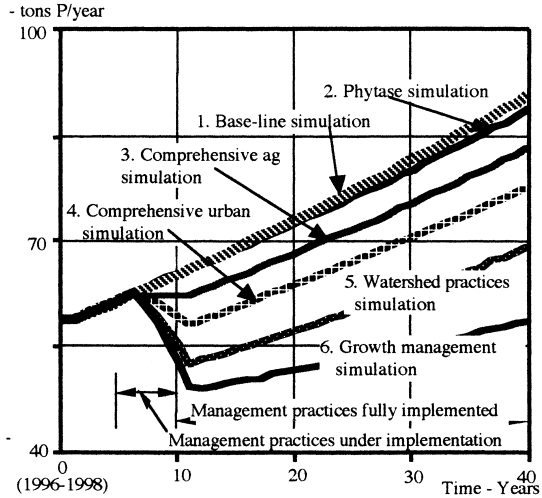

Figure 5 Phosphorus export to the Inland Bays for various watershed management scenarios as estimated by the WEND model

Inland Bays watershed

This urbanizing watershed is very flat and much agricultural land is artificial drained. Agriculture is dominated by intensive broiler production facilities while some areas of the watershed support a large tourism industry. These watershed activities contribute large amounts of nitrogen and P to the Inland Bays. In the recent past agricultural and urban-based activities in the watershed have increased each year.

The WEND model was customized to capture the uniqueness of the urban and agricultural economy, and the resource base of the Inland Bays watershed (Cassell and Meals, 1999). A Base-line simulation in which input data define current watershed conditions was first run to provide a basis for comparing the efficacy of various other management scenarios for reducing the P loadings to the Inland Bays. The conditions for the scenarios reported here are summarized in Table 3.

Figure 5 shows the 40 year pattern for the export of P from the watershed to the Inland Bays for the Base-line scenario as well as the other management scenarios listed in Table 3. For the Base-line simulation the P loading at time = 0 is the present-day loading to the Inland Bays which is estimated by the WEND model to be 58.7 t/yr or only about 2% of the total amount of

P imported into the watershed. About 52% (30.5 t/yr) and 36% (21.1 t/yr) of the present-day loading is derived from the agriculture and urban sectors, respectively. The agriculture sector loading estimated by Ritter (1986) using P export coefficients is 25.6 t/yr while the 1990 urban loading is estimated by DDNREC (1998) to be 11.2 t/yr. For this Base-line scenario the P loading to the Inland Bays increases gradually so that in just 20 years it is about 125% of current loadings (Figure 5) due to continuing urban and agricultural growth.

Five other simulations are also shown in Figure 5. For all these simulations the scenario conditions are implemented between years 5 and 10 and then remain fully implemented until the end of the 40 year simulation period. Simulations 2–5 all emulate policies in which one or more watershed simulation conservation practices are implemented. For all these scenarios, except for simulation 2, there is an immediate reduction in P export but after implementation is complete (after about year 11) P export begins to again increase so that by the end of 40 years being exported exceeds current day export. It would appear that additional management action is needed if a long-term reduction in P export is to be achieved. Simulation 6 displays the trend in P export when conservation practices are fully implemented AND the rate of urban growth is modestly reduced AND poultry production capacity is reduced by 10%. Simulation 6 is the only simulation that shows the export of P to be lower after 40 years than it is presently. Similar long-term reductions in P export could be achieved by: exporting higher fractions of the poultry litter from the watershed, substantial reductions in the urban growth rate, and reduction in the poultry production capacity in the Inland Bays watershed.

Discussion

The present-day export of P discharged from both study watersheds predicted by the WEND models is consistent with values obtained from monitoring studies and P export coefficients. Because WEND models estimate P export through a comprehensive mass balance analysis in which neither water quality data nor P export coefficients play a role, this one-point-in-time verification of P export suggests that a dynamic simulation mass balance modeling concept may be useful to estimate P loading from large watersheds.

The data upon which WEND depends are of three types: (a) demographic type data including numbers of people and animals, area and land use, crop types, etc.; (b) resource data including annual rainfall, runoff, and infiltration amounts and knowledge of how P interacts with the soil resource; and (c) resource management data such as intensity of forest harvesting, type and amount of commercial and industrial activities, crop type and tillage practices, waste management functions, recycling programs and material transportation and movement, etc. The WEND model is a lumped model as all input data are watershedwide averages defining typical conditions for each sector (Cassell and Clausen, 1993; Cassell *et al.*, 1998). This substantially reduces data requirements and model complexity in comparison to modeling approaches that incorporate spatial variability. Furthermore, because the WEND model performs calculations on an annual time step the data requirements are low compared to models that examine short-term phenomena. Thus, the WEND model calculates long-term patterns in P export using diverse data similar to that gathered for economic and resource inventory studies and for management program evaluations. This approach for describing watersheds allows WEND models to be applied to different watersheds provided the models are based on CF diagrams that are customized to reflect the uniqueness of each watershed.

The creation of a WEND model for a watershed requires defining P storage compartments and pathways through which P moves. Although the data requirements are diverse the consultation process necessary to gather the needed information builds a detailed understanding of the infrastructure in which P is stored and through which P moves. This process not only promotes an understanding of the watershed at a holistic level but serves as a procedure to organize multi-disciplinary knowledge relevant to the watershed. As long-term goals for watershed management become more complex and inter-related it will become increasingly important to capture and organize diverse multi-disciplinary information. WEND models incorporate numerous decision nodes that allow pathways for the transport of P through sectors and watersheds to be changed (see Figure 2). These changes are made so simulations emulate how various strategic watershed management options influence the movement of P through a given watershed. The effect of different management strategies on long-term patterns of P export can be determined within the framework of some overall management goal and/or compared to some allowable load of P for the impacted receiving body of water.

WEND simulations for the Winooski River watershed indicated that an environmental strategy (the Environmental scenario) results, over the long-term, in the export of less P than either the Base-line or Rapid growth scenarios. However, it was also apparent that even the Environmental scenario will not reduce P export below about 120 t/yrr. Is this export low enough to meet some management goal? The Base-line and Rapid growth scenarios demonstrate a watershed that is becoming increasingly urban over time resulting in an ever increasing P export. Can such management strategies be implemented within environmental limitations? The running of additional simulations with the WEND model that emulate other management strategies may be helpful in answering such questions before a particular management strategy is implemented.

The Inland Bays watershed is heavily impacted by an intensive poultry agriculture and a large tourism industry. Consequently large amounts of P, about 59 t/yr, are exported to the Delaware's Inland Bays. WEND simulations suggest that it will be difficult to reduce the long-term P export below present-day levels. Implementation of traditional conservation practices only temporarily reduces P export (scenarios, 3, 4, an d 5) before continuing growth overcomes these temporary effects (Figure 5). Thus the application of conservation practices alone appear insufficient to accomplish long-term reduction in P export for the Inland Bays watershed. This pattern exists for scenarios 1–5 because the import of P to the watershed is substantially greater than the total amount of P exported. Consequently, the soils of the watershed are accumulating P and becoming increasingly rich in P. As a result surface runoff and groundwaters are also becoming richer in P, increasing P export.

The WEND model suggests that the long-term reduction in P export from the Inland Bays can be achieved only when the rate of urban growth and/or poultry production capacity is reduced and/or larger amounts of poultry litter are removed to outside the watershed such as in simulation (Figure 5). All the strategies in simulation 6 either reduce the import of P or increase the export of P for the watershed so that the excess of P inputs over P outputs is reduced. Consequently, the rate of P accumulation in the watershed is also reduced. However, these may be difficult, if not impossible, to implement since the economic impacts may be great and politically controversial. As with the Winooski River watershed modeling results, it would be instructive to run additional WEND simulations that emulate other management strategies before committing to a particular strategy with uncertain consequences for the future.

Thus far the WEND model has been applied to two large watersheds. In both cases, as mentioned above, WEND's computed present-day P export approximated monitoring results and/or estimates from P export coefficients. However, what may be the effect of watershed scale on the usefulness of the WEND model? In small watersheds the location of an individual feature may so completely dominate P export that the remaining sources of P may appear to be insignificant. This condition violates our basic premise of homogeneity and the use of sector or watershed-wide average values and suggests an accounting of the spatial organization of the watershed is necessary. However, in larger watersheds one individual source of P probably would not contaminate the export of P but if it did (like a very large urban area in a watershed) it could be considered to be typical of the entire watershed. Thus, in larger watersheds we believe it is appropriate to integrate, average, and lump the sources of P and the pathways of P movement to define the overall nature of the watershed.

The process of defining P storage locations and pathways for P movement and incorporating them into a CF diagram that describes a particular watershed is referred to as WEND model customization. This customization process builds an understanding of how the resources and activities in the watershed function to process P or possibly some other nutrient such as nitrogen, etc. Regardless of the material being considered the resulting understanding is comprehensive as it crosses many disciplinary, cultural, and economic sector boundaries. It becomes a basis to view watershed resources and activities holistically and to consider how what we do today may impact tomorrow's world of our children and grandchildren.

Conclusions

Generally, dynamic phosphorus mass balance modeling of large watersheds (WEND models) can be a useful tool to assist resource managers and planners peer into the future to examine the long-term implications of management decisions being made today on patterns of P export from watersheds.

More specifically, WEND models have been customized and applied to two large watersheds, the Winooski River and Inland Bays watersheds in northeastern USA. In both cases:

1. WEND models compute a present-day P export load that is consistent with other estimates,
2. WEND model simulations suggest that different strategies for management watershed resources and activities have a substantial impact on the long-term future of P export, and
3. WEND model simulations suggest that for developed watersheds the most effective way to reduce the export of P to receiving bodies of water over the long-term is to implement policies that promote a closer balance between the total amount of P imported and exported from the watershed.

Lastly, the process of formulating and customizing WEND models to describe P dynamics for particular watersheds promotes a comprehensive understanding of how the resources and activities in the watershed function, thus providing a framework through which multi-disciplinary expertise can be organized and integrated as a basis for decision making.

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