An Environmental Accounting System to Track Nonpoint Source Phosphorus Pollution in the Lake Champlain Basin

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First Year Report

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1. Introduction and Overview of the Report

Over the last fifteen years, huge investments have been made to improve water quality in Lake Champlain. Many of these investments have focused on reducing phosphorus inputs to the lake because this essential nutrient acts like a fertilizer, stimulating noxious algae blooms that can disrupt the lake's ecology and interfere with recreational use and enjoyment of its waters. In 1996, the Lake Champlain Basin Program (LCBP) ranked reducing phosphorus pollution as one of its highest management priorities in its comprehensive management plan *Opportunities for Action*. In 2003, Governor Douglas initiated his *Clean and Clear Action Plan*, an ambitious agenda for reducing phosphorus that is linked to the LCBP's efforts and to the Lake Champlain Total Maximum Daily Load (TMDL) allocation for phosphorus required by the US EPA and the Clean Water Act. All three of these plans acknowledge that the current phosphorus concentrations in Lake Champlain are too high and must continue to be reduced. All three also specify phosphorus concentrations goals, or standards for water quality, that should provide for a healthier lake. Despite the best efforts of many agencies and individuals, these water quality goals have not been achieved in most segments of Lake Champlain.

In order to determine why we have not yet reached the in-lake phosphorus concentration goals managers have established for the lake, and to make good decisions about the strategies necessary to get there, we need good scientific information about the sources, transport, and potential for reduction of phosphorus throughout the Lake Champlain basin. We also need an overall accounting system to track this phosphorus and explore reduction scenarios. Our project is designed to provide such information.

The stated goal of our project is to develop a framework and model that can be used to account for major sources and potential reductions of phosphorus across the landscape. As part of our literature review and framing of the issues, we evaluated the relative magnitude of phosphorus sources and transport pathways in the watershed. Our literature review also includes a summary of the relative reductions in phosphorus that might be achieved using various BMPs in both agricultural and urban/suburban land areas. This information appears in Section 2 of the report.

We chose to start our work with a focus on the Missisquoi watershed. Because agriculture is estimated to be about 70% of the nonpoint source phosphorus in this watershed, we also chose to begin by developing an agriculturally focused tool. In order to accumulate phosphorus across the watershed and consider the relative importance of landscape factors like slope, soil type, and specific land use; contiguities and connections in the riparian corridor and stream network; and specific management practices, we needed to use a watershed model. We selected SWAT (Soil and Water Assessment Tool) for this purpose.

We will use SWAT to account for phosphorus across the landscape and transport it to Lake Champlain. Our watershed modeling approach will also allow us to find critical

source areas and evaluate the most effective ways to control and/or reduce phosphorus losses in these areas. The development of an accounting system and use of that system to examine critical sources and potential reduction scenarios are essentially highly related tasks and both are included in our efforts. Our overall framework for phosphorus accounting and critical source area identification for agricultural land uses appears in Section 3. Our approach includes the development of both a watershed-level accounting tool and a farm-level accounting tool.

Because of the logistical challenges associated with starting with a watershed the size of the Missisquoi and data availability to calibrate the SWAT model, we have begun our modeling efforts by focusing on the Rock River Watershed. This smaller watershed will allow us to examine in detail the sources and transport of phosphorus and to develop an overall approach to accounting and targeting critical source areas that then can be applied throughout the basin. In Section 4, we describe our modeling methods and the modeling results to date.

The single greatest problem with the current TMDL implementation plan is the lack of clearly defined and measurable objectives for the nonpoint sources. Our goal is to produce tools that can be used to account for the phosphorus reductions that might be associated with various management actions on agricultural land. In addition to telling us where we stand, these comparative values can be used to explore which management interventions, in which places, offer the greatest potential for reducing the phosphorus load to Lake Champlain.

Our proposed work plan for year 2 is described in Section 5 of the report. At the end of the second year of our project, we will have a management tool that can be used in an adaptive implementation strategy to answer four critical questions relative to agricultural land uses:

- Where do we stand right now?
- What are the critical sources and source areas we need to address?
- What interventions will provide the greatest phosphorus reductions in these areas?
- What are realistic expectations of outcomes once we do intervene (in terms of both the phosphorus balance and the timeline for response)?

2. Literature Review

Introduction

Phosphorus enrichment has been identified one of the main causes of the algae blooms and aquatic plant growth in the Lake Champlain. More than 90% of the phosphorus entering Lake Champlain comes from non-point sources, while the remaining <10% of the phosphorus entering the Lake is attributed to point source origins, specifically, waste water and sewage treatment plants (Lake Champlain Basin Program, 2006; 2008). Non-point sources include phosphorus losses that originate from many sources across the landscape, including agricultural areas and urban and suburban areas. The importance of this agricultural and urban/suburban nonpoint source phosphorus loss and its profound impacts to the Lake are well recognized. There is a critical need for creative efforts to translate this recognition into effective practices and planning that will lead to identifying and controlling phosphorus sources and eventually restoring the quality of the Lake.

Depending on the type of dominant land use activities, the proportion of phosphorus loss from agricultural and urban/suburban areas varies among watersheds in the Lake Champlain Basin. For watersheds in which agricultural land use and livestock production are the dominant land use activities, phosphorus losses from manure and fertilizers applied to agricultural fields pose a major threat to receiving water bodies. On the other hand, for watersheds experiencing land use conversion from agricultural and forest lands to developed land uses, non-point phosphorus source loads contributed by these urban/suburban sources becomes an important proportion. In either case, understanding the sources and the processes involved in the transport of phosphorus is crucial in planning effective mitigating measures. Thus a literature review is required to explore the state of knowledge and provide scientific information on the phosphorus sources and control measures and their effectiveness.

The following sections present synopses of reviews on non-point source phosphorus losses, transport processes, and management practices and their effectiveness. The literature review presented herein is also part of an agreement with State of Vermont representatives to include in this project a review of phosphorus in the landscape and an evaluation of the effectiveness of various management practices.

Phosphorus and Water Quality

Phosphorus is an essential nutrient required for plant and animal growth. However, excessive phosphorus input to streams and lakes accelerates eutrophication, excessive growth of algae and aquatic vegetation, which in turn leads to reduced aesthetic and recreational values of lakes and other water bodies. Moreover, reduced water clarity and objectionable odors may result from excessive phosphorus loadings and the associated plant growth. No clear guidelines exist concerning the critical concentration values of phosphorus in water that will accelerate eutrophication. However, numerous data exist

regarding the critical phosphorus concentration values that accelerate eutrophication. Examples are:

1) Sawyer (1947) and Vollenweider (1968) reported 0.01 ppm and 0.02 ppm of dissolved and total phosphorus, respectively, as a critical concentration for lakes and streams that accelerate eutrophication.
2) Correll (1998) reported a 0.02 ppm of total phosphorus as a critical concentration for lakes and streams that accelerate eutrophication.
3) USEPA (2000) reported a 0.01 ppm of total phosphorus as a critical concentration for lakes that accelerate eutrophication.

Sources of Phosphorus

Natural: Phosphorus occurs naturally in soil, water and all living organisms. Residues of vegetation, both perennial grasses and agricultural crops, can be a source of phosphorus in runoff. A study by Wendt and Corey (1980) reported phosphorus losses in spring runoff from residues of alfalfa, grasses, and crops. A study by Singer and Rust (1975) also indicated forest leaf litter to be a contributor of phosphorus loss in runoff. In colder climates, phosphorus, dominated by the dissolved form, is released from the tissues of vegetation as freezing and thawing processes break plant cells (Daniel et al., 1998). Moreover, Correll et al. (1992) and Menzel et al. (1978) reported phosphorus inputs from precipitation. However, the magnitudes of phosphorus losses found from these sources, and specifically from forested lands, are significantly lower than those losses from land uses where agricultural activities are dominating (Vaithiyanathan and Correll, 1992).

Fertilizer and Manure: Application of fertilizer to crops is the greatest phosphorus use in agriculture (Mullins, 2000). The original source of most of phosphorus fertilizers in the U.S. is rock phosphate (Schulte and Kelling, 1992). Many forms of phosphorus fertilizers are commercially manufactured by blending phosphorus with nitrogen, potassium, or both to form mixed fertilizer blends (Schulte and Kelling, 1992). The long-term application of manufactured fertilizers to crops and lawns increases the availability of phosphorus for runoff losses, especially when the applications are beyond the levels that are necessary for crop growth.

Land application of manure to cropland also adds phosphorus to the soil. Often, manure is applied to cropland at rates that meets the nitrogen need of the crop. The relative proportions of phosphorus and nitrogen in dairy manure are about equal. The nitrogen need of crops is, however, greater than the phosphorus need of the crops. For example, the nitrogen need for corn is about 5 times greater than its phosphorus need. When manure is applied to meet the nitrogen need of crops, the amount of phosphorus applied will exceed crop removal, which leads to phosphorus build-up in the soils, which in turn, increases the potential for phosphorus losses via runoff and soil erosion. In areas where concentrated livestock operations are common, long-term manure applications have elevated the soil phosphorus concentrations of many soils above the range necessary for optimum crop growth (Sims, 1993).

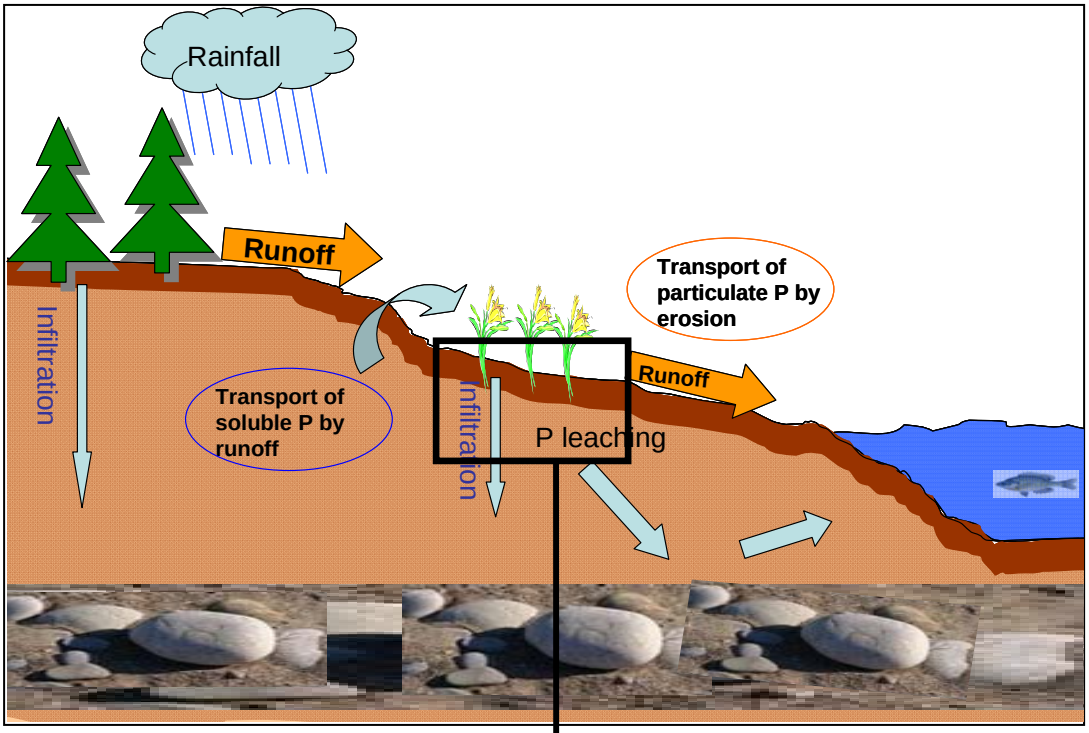
Phosphorus Cycle, Processes, and Transport

Phosphorus in soil originates from the weathering of minerals and from additions of phosphorus in the form of fertilizers, animal manure, plant residues, and precipitation. Phosphorus exists in many different forms in soil: plant available inorganic phosphorus, and three forms which are not plant available, organic phosphorus, adsorbed phosphorus, and primary mineral phosphorus. Practically, all soluble phosphorus from fertilizer or manure is converted to soil-bound phosphorus within a few hours of application (Schulte and Kelling, 1992).

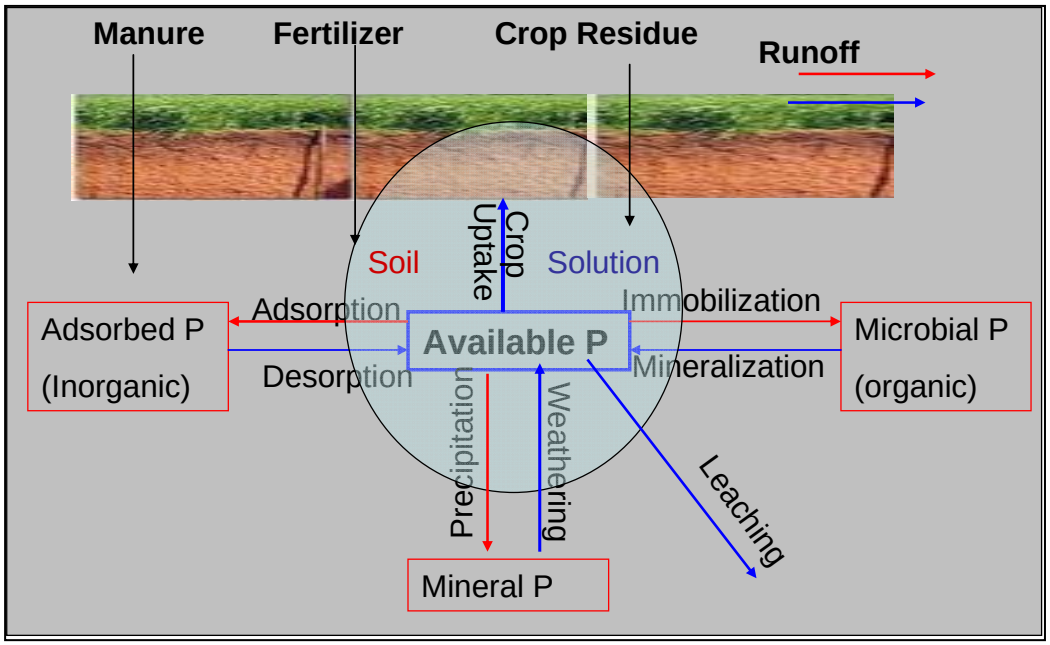
Phosphorus, like most soil nutrients, moves through a sequence of cycles from soil to plant to animal. The phosphorus cycle consists of a complex relationship of chemical and biological reactions that control the availability of phosphorus. The phosphorus cycle in Figure 2-1 shows these phosphorus forms and the pathways by which the phosphorus may be taken up by plants or leave the site as phosphorus runoff or leaching. The general phosphorus transformation processes are: weathering and precipitation, mineralization and immobilization, and adsorption and desorption. Weathering refers to breaking down of mineral phosphorus to a plant available form, as opposed to precipitation where available phosphorus is transformed into a mineral form. Mineralization is the microbial conversion of organic phosphorus into forms that are available to plants (orthophosphates). Immobilization occurs when these plant-available phosphorus forms are consumed by microbes, turning the phosphorus into organic phosphorus forms that are not available to plants. The microbial phosphorus will become available over time when the microbes die. Adsorption is the chemical binding of plant-available phosphorus to soil particles, which makes it unavailable to plants. Desorption is the release of adsorbed phosphorus from its bound state into the soil solution. Overall, weathering, mineralization and desorption increase plant available phosphorus; whereas, immobilization, precipitation and adsorption decrease plant available phosphorus.

Plant roots adsorb dissolved or soluble phosphorus from the soil solution in the form of orthophosphate ($H_2PO_4^-$ or $HPO4^{=}$). The solubility of phosphorus is controlled by the concentrations of calcium (Ca), iron (Fe), aluminum (Al), and manganese (Mn) in the soil solution and by the nature and amount of soil minerals. Therefore, knowing soil minerals and these metallic elements is critical in understanding the processes that affect the release of phosphorus to a form available to plants.

Phosphorus can be removed or lost from soil by crop uptake and subsequent harvest, soil erosion, and runoff. As rainfall or snowmelt travels along the landscape, the water interacts with the topsoil and any materials on the soil surface. During this process, phosphorus can be added to the runoff water from soil, plant material, and manure, and it enters lakes and streams mainly in runoff and erosion from landscapes draining to them (Figure 2-1). In some instances, phosphorus can also be removed through leaching, particularly in areas of very sandy soils, high organic matter soils, or phosphorus saturated soils (Sims et al., 1998). However, phosphorus leaching is relatively rare because phosphorus is tightly held by soil particles (Heckrath et al., 1995; Sims et al., 1998; Hesketh and Brookes, 2000).



Phosphorus Movement in a Landscape



Phosphorus Cycle

Figure 2-1. Diagrams showing the overall phosphorus cycle and phosphorus movement in the landscape.

Overall, sediment-attached phosphorus loss is the major portion of the phosphorus removed from agricultural land. Sharpley et al. (1992) estimates sediment-attached phosphorus loss makes up 60 to 90% of the total phosphorus load transported in runoff from cropland. However, the impact of the soluble phosphorus portion of runoff can be immediate on algae and aquatic weeds in lakes and streams (Sharpley et al., 1996).

Runoff that contains sediment and associated phosphorus and that reaches waterbodies often originates from limited areas within a watershed. These areas vary in location and magnitude of phosphorus contribution due to climatic conditions, such as the intensity and duration of rainfall, as well land characteristics such as soil moisture conditions, soil erodibility, soil water storage capacity, slope, topography, and others (Gburek and Sharpley, 1998). Identifying these factors influencing phosphorus movement from the landscape is critical in predicting phosphorus loss and in developing effective water quality protection practices and programs.

Nonpoint Source Phosphorus Pollution and Management Practices

Phosphorus is an essential nutrient required for crops, lawns, gardens, and animal production. However, application of phosphorus either as commercial fertilizer or manure in excess of plant needs can lead to accumulation in the soil, which eventually increases the risk of phosphorus loss in runoff (Sharpley, 1995). Urban runoff may also contain high phosphorus concentrations from use of phosphorus in lawn and garden fertilization, and from other sources. The link between the continuous transport of phosphorus in runoff and the resulting eutrophication problem in water bodies is already well-established (Carpenter et al., 1998; Daniel et al., 1998; Correll, 1998). Efforts are being directed towards identifying strategies for minimizing phosphorus loading to water bodies.

Management strategies, collectively called best management practices (BMPs), to reduce phosphorus losses from agricultural land to water bodies can be grouped into source management, transport management, and managements that interfere with phosphorus delivery to the stream (Baker and Johnson, 1983; Dillaha, 1990; Novotny and Olem, 1994; Sharpley, 1995). These practices can be structural or non-structural (management based practices) strategies.

The source management strategies for agricultural land uses attempt to minimize accumulation of phosphorus at the soil surface. Source management attempts to minimize phosphorus build-up in the soil surface so that an optimum agronomic level is maintained while reducing the amounts available for wash off at the surface. These BMPs include: manipulating animal dietary phosphorus to match animal requirements, controlling the amount of phosphorus in manure and fertilizers applied to the agricultural land (placement, rate, timing, form and chemical composition, hence, applying manure to crops based on the manure and soil phosphorus content and crop requirement), decreasing the solubility of phosphorus in manure with chemical amendments or physical treatment exporting excess manure nutrients, and reducing the amount of phosphorus

input to the farm/watershed by producing more home grown animal feeds and hence purchasing less off-farm animal feeds. Increasing productivity of forage also promotes increased utilization of soil phosphorus. Hence, increasing productivity of homegrown forage promotes recycling and re-use of phosphorus on the farm (Lanyon, 1992). For areas with higher soil phosphorus contents, increasing crop yields to increase crop phosphorus harvest has been widely practiced on dairy farms throughout Europe (Sibbesen and Runge-Metzger, 1995), as has implementing appropriate tillage practices that involve incorporation of phosphorus-containing surface material into the soil.

The transport management strategies are efforts that interfere with phosphorus movement from soil to water bodies. These BMPs reduce runoff volumes and velocity and soil losses from the land surface, thus controlling the movement of phosphorus from the soil to water bodies. Runoff and erosion control practices include conservation tillage, crop rotation, crop residue management, terraces, buffer strips, filter strips, riparian buffers, cover crops, and impoundments (such as sedimentation basins). Runoff and erosion control practices, including cover crops, crop rotation, conservation tillage, and crop residue management, are BMPs implemented to limit or contain soil movement. BMPs such as terraces and filter strips are structural devices installed or constructed to trap runoff and thereby reduce the amount of sediment and pollutant entering streams.

The off-site remediation BMPs are efforts that interfere with phosphorus delivery to the waterbodies. In order to link changes of agricultural management with the receiving downstream waterbodies, understanding of in-channel phosphorus transport processes and the impact of transported phosphorus are necessary. These practices are mostly situated between the landscape where phosphorus flows overland and the receiving waterbodies. BMPs in this group include sedimentation basins, filter strips, terraces, and waterways (Baker and Johnson, 1983; Dillaha, 1990).

As described previously for agricultural areas, urban BMPs can also be structural or non-structural in nature. Depending on their purpose, urban BMPs can also be categorized as source control and off-site treatment (Roesner, 1999). Source control urban BMPs include porous and permeable surfaces, infiltration drains (e.g., as in the use of residential lawns to filter storm water runoff from roof tops), filter strips, and others. The off-site treatment controls include structures such as retention ponds, detention basins, wetlands, and infiltration basins.

Research and implementation have identified phosphorus management practices by separately addressing the source or transport factors ((Sharpley et al., 1994; Bottcher et al., 1995). However, studies have also indicated that implementation of these measures over broad areas of a watershed do not result in expected reductions in phosphorus losses (Meals, 1993; Sharpley and Rekolainen, 1997). Pionke et al. (1997) suggested that effective mitigation of phosphorus losses from non-point sources, particularly from agriculture, must focus on defining, targeting, and remediating critical source areas (**CSA**) of phosphorus loss. CSA of phosphorus loss result from overlapping of areas of high levels of phosphorus availability (source areas) with areas of high potential for

phosphorus movement (transport areas). These areas in the landscape are those that pose the greatest risk for phosphorus loss to receiving waters.

Documented Best Management Practice (BMP) Effectiveness for Phosphorus Control

For the purpose of this report, reviews of the effectiveness of BMPs are categorized into Agricultural and Urban BMPs groups.

Agricultural non-point source BMPs

Collection of BMPs effectiveness data documented in the literature was carried out in an effort to organize and compile these effectiveness data in user-friendly database. While searching for BMPs effectiveness data, however, an already compiled BMPs effectiveness database developed by Gitau et al. (2005) was found in a peer-reviewed journal. This database focuses on the effectiveness of agricultural BMPs for nonpoint source pollution. It includes literature reviews conducted prior to its publication. Hence, our original intention to develop a BMP effectiveness database was instead re-focused to acquire the database from the authors and make it available for future use and references, and to gather other agricultural BMPs effectiveness data that were not included in this database. Other BMPs effectiveness data that were not included in the database by Gitau et al. (2005) include BMPs effectiveness related to animal feeds and fencing livestock from water bodies. We include in our report the database by Gitau et al. (2005), as well as summaries of other agricultural BMP effectiveness data that were not included in this database.

BMP effectiveness tool (Gitau et al., 2005): Many studies exist reporting on the effectiveness of agricultural BMPs for nonpoint source pollution control. However the database developed by Gitau et al. (2005) is an interactive BMP database developed from large amounts of BMP effectiveness data that were gathered from literature. Hence this database allows users to obtain effectiveness estimates for about 32 agricultural BMPs. The interactive database provides end-users with average reduction efficiencies for general location and/or reduction efficiencies for their respective site soil and slope conditions to control phosphorus pollution. A list of BMPs included in the database is presented in Table 2-1. Tables 2-2 and 2-3 present ranges in effectiveness of the various BMPs in reducing dissolved, particulate, and total P loss in overland flow based on published information (adapted from Gitau et al., 2005). Table 2-2 presents descriptive statistics for all BMP effectiveness data (adapted from Gitau et al., 2005), while Table 2-3 presents examples of BMP effectiveness obtained from the tool for selective site soil and slope conditions.

Table 2-1. List of best management practices (BMPs) included in the BMP tool developed by Gitau et al. (2005)

BMP class	description
Animal waste systems, AWS	Systems designed for the proper collection, transportation and storage of livestock manure and their animal waste.
Barnyard runoff management, BYRM	Exclusion of clean water runoff from the barnyard and disposal of the remaining barnyard runoff in a way that minimizes its pollution
Conservation tillage, CONST	Any tillage and planting system that leaves a minimum of 30% of the soil surface covered with plant residue after the tillage or planting operation (i.e. reduced-till, no-till..
Contour strip crop, CSC	Alternating strips of a row crop with a small grain or forage, planted on the contour (Contour strip cropping) or across the slope (Field strip cropping).
Crop rotation, CR	A planned sequence of annual and/or perennial crops.
Filter strips, FS (as filters for barnyard runoff)	Strips of perennial grasses, planted across the slope, established adjacent to areas of high pollutant potential and managed for pollutant removal by overland flow.
Nutrient management plan, NMP	Managing the rate, timing, and placement of fertilizers, manures and other nutrient sources to encourage maximum nutrient recycling and minimize nutrient runoff and leaching.
Riparian forest buffers, RFB	Areas of trees, shrubs and grasses located adjacent to ponds, lakes, and streams that filter out pollutants from runoff, as well as providing shade for fish and wildlife.

Table 2-2. Descriptive statistics of best management practices (BMPs) effectiveness (adapted from Gitau et al., 2005).

BMP class	Va	Average %	Std.Dev. %	Min. %	Max %	Number	Reference number
Animal waste systems, AWS	DP	-13*	71	-117	40	4	3, 21
	TP	42	24	21	90	7	3, 5, 16, 20, 21
	PP	59	21	35	72	3	3
Barnyard runoff management,	DP	30	35	5	81	4	4, 28
BYRM	TP	53	23	23	82	7	4, 22, 28
	PP	33	--	33	33	1	21
Conservation tillage, CONST	DP	-167	262	-889	73	18	1, 2, 11, 13, 15, 17, 27, 29, 32
	TP	62	29	-22	95	21	2, 5, 11, 14, 15, 17, 20, 21, 22, 32
	PP	63	20	15	92	17	1, 11, 13, 15, 29, 32
Contour strip crop, CSC	DP	45	28	20	93	5	11, 13
	TP	44	25	8	93	22	14, 21, 22
	PP	60	11	43	76	6	6, 11, 13
Crop rotation, CR	DP	50	17	30	75	6	5, 6, 13, 22
	TP	30	--	30	30	1	21
	PP	65	4	60	70	4	13, 22
Filter strips, FS	DP	26	25	-56	59	18	8, 9, 10, 21, 30
	TP	56	18	22	93	23	6, 8, 10, 11, 14, 19, 22, 24, 30
	PP	41	4	38	43	2	10
Nutrient management plan, NMP	DP	26	41	-66	94	14	23, 31, 33
	TP	47	24	14	91	9	4, 22, 23, 31
	PP	46	4	42	50	3	31
Riparian forest buffers, RFB	DP	62	26	28	99	8	7, 9, 12, 18, 26
	PP	84	--	84	84	1	26
	TP	43	36	2	93	9	12, 18, 21, 25

Va = variables; DP = dissolved phosphorus; TP= total phosphorus; PP = particulate phosphorus; negative values indicate increase in P losses.

#	Reference
1	Baker and Laflen, 1983
2	Berg et al., 1988
3	Brannan et al., 2000
4	Brown et al., 1989
5	Chesapeake Bay Program, 1987
6	Clark et al., 1985
7	Corley et al., 1999
8	Daniels and Gilliam, 1996
9	Doyle et al., 1977
10	Eghball et al., 2000
11	EPA, 1993
12	Franco et al., 1996
13	Haith, 1979
14	Hamlett and Epp, 1994
15	Hansen et al., 2000
16	Hession et al., 1989
17	Laflen and Tabatabai, 1984
18	Lee et al., 2000
19	Magette et al., 1989
20	Mostaghimi et al., 1989
21	Novotny and Olem, 1994
22	NYSDEC, 1991
23	Osei et al., 2000
24	Parsons et al., 2001
25	Perry et al., 1999
26	Peterjohn and Correll, 1984
27	Phillips et al., 1993
28	Robillard et al., 1983
29	Romkens et al., 1973
30	Schmitt et al., 1999
31	Schuman et al., 1973
32	Sharpley et al., 1991
33	Walter et al., 2001

Table 2-3. Best management practices effectiveness obtained from BMP tool developed by Gitau et al. (2005)

Management practices	Soil group	DP	PP	TP	Slope ranges
Filter strip for barn runoff	B	26	41	55	8-15%
Conservation Tillage	B	-244	55	58	3-8%
	C	25	55	47	3-8%
	D	59	89	87	0-3%
Contour strip Crop	B	25	58	--	3-8%
	C	45	65	59	3-8%
Crop Rotation	B	43	63	--	3-8%
	C	75	70	--	3-8%
Riparian Forest Buffers	B	62	--	73	3-8%
Nutrient management plan	B	50	46	48	8-15%
	C	64	--	56	3-8%

DP = dissolved phosphorus; TP= total phosphorus; PP = particulate phosphorus

As one example of how effectiveness varies across published reports, general trends in the phosphorus reduction efficiency of conservation tillage implementation suggest that total phosphorus and particulate phosphorus losses are significantly reduced (average 67% and 63% respectively; Table 2-2). However, dissolved phosphorus loss increased after adoption of conservation tillage by an average of 167%. There are also a wide range of efficiency values resulting from site-specific factors (Table 2-3). With site specific information, average phosphorus reduction effectiveness of conservation tillage for a "C" soil group and 3-8 % slope are 25%, 55%, and 47% for dissolved phosphorus, particulate phosphorus, and total phosphorus losses, respectively (Table 2-3).

An electronic file that contains the interactive BMP effectiveness tool (Gitau et al. 2005) is included with this report. We are grateful to the lead author, Dr. Gitau M. Margaret, for providing the electronic file of this database. In addition, hard copies of the BMP tool documentation and the peer-reviewed manuscript of this tool are included in Appendix 1 and Appendix 2, respectively. Should any one be interested to get effectiveness estimate data of any particular BMP, the BMP tool can be used. The BMP tool documentation also provides step by step guidelines on how to use the tool in obtaining effectiveness estimate and references of studies in which the estimate data were obtained.

Feed BMPs: Phosphorus is required in the diet of animals; however, if animals are overfed or feed is mismanaged, phosphorus can contaminate the environment and water supplies. Feed BMPs are practices that involve manipulating animal dietary phosphorus to match animal requirements, and hence the goal is to avoid excess feeding of phosphorus to animals, which in turn, prevents enrichment of livestock manure with

excess phosphorus. Application of manure with higher concentrations of phosphorus and in excess of plant needs can lead to accumulation in the soil, which eventually increases the risk of phosphorus loss in runoff.

Dietary phosphorus is managed differently for ruminants and non-ruminants. For example, cereal grains fed to poultry or livestock contain phytate-bound phosphorus. Phytate-bound phosphorous is digestible by ruminant animals such as cows, sheep, and goats, but it cannot be digested by non-ruminants animals, such as swine and poultry. Therefore for ruminants, management options may mostly include balancing dietary phosphorus to meet the animal requirement. However, for non-ruminants, additional options include selecting feeds with readily available phosphorus, utilizing enzymes (such as phytase that break down phytate in grains and release digestible phosphorus) selective crop hybrids to enhance utilization. Moreover, after manure is excreted, chemical amendments or physical treatment can be carried to decrease the solubility of phosphorus in manure. The following paragraphs focus on dairy-based feed BMP effectiveness estimates.

According to the National Research Council (NRC 2001), a lactating dairy cow requires between 0.35 and 0.38% phosphorus in the diet. Previous dairy feeding practices included as high as 0.55% or 0.60% phosphorus in the diet (NRC, 2001; Dou et al., 2003). Reducing this excess intake of phosphorus by dairy cows has been shown to have a significant impact on phosphorus excretion (Satter and Wu, 1999; Ebeling et al., 2002; Dou et al., 2002; Dou et al., 2003; Cerosaletti et al., 2004; Ghebremichael et al., 2007).

For example, a field study by Cerosaletti et al. (2004) for two farms in Cannonsville Reservoir Watershed, New York (a New York City drinking water supply reservoir), in which excess feed phosphorus intake was decreased by 25%, resulted in 33% reduction in manure phosphorus and in the 49% reduction in mass phosphorus balance (imports minus exports). A study by Ghebremichael et al. (2007) also reported 21% decrease in the excreted manure phosphorus and a reduction of 51% in mass phosphorus balance by reducing excess dietary phosphorus by 25%. These results were equivalent to average annual manure phosphorus reductions of 6 kg/cow considering only the mature cows of the farms studied. Both studies also indicated an increase in farm profitability as a result of decreased purchases in supplemental phosphorus.

Fencing: Studies have reported benefits of fencing livestock out of riparian zones and streams in reducing nutrient loading to water bodies. Examples include:

- A study by Jones and Knowlton (1999) on a Virginia farm reported 52 % reductions in downstream total phosphorus by implementing fencing dairy cows and calves out of a stream and providing alternative water.
- A study by Line et al. (2000) to a North Carolina stream noted a 76 percent reduction in total phosphorus when dairy cattle were protected from going to the stream.

- A study by Meals (2000) in a Vermont watershed documented significant reductions in total phosphorus concentration (15 percent) when cattle were fenced out of streams.
- A study by James et al. (2007) in Cannonsville Reservoir Watershed, New York, highlighted the importance of stream bank fencing programs in controlling phosphorus loadings from pastured cattle. In their study, James et al. (2007) were able to estimate fecal phosphorus contributions to streams, with 30% of all fecal deposits reportedly fell on land within 40 m of a stream and 7% reportedly fell directly into streams. Using these field observations, James et al. (2007) also developed a generalized set of equations predicting fecal phosphorus distribution within the pastures of the watershed encompassing the field studied.

Urban/suburban nonpoint source BMPs

Effectiveness data related to urban (sub-urban) BMPs to control phosphorus loss are well documented on on-line sources. The Urban BMPs database currently in existence is the National Storm Water BMP Database (http://www.bmpdatabase.org). This database is developed for storm water BMPs and it is the most comprehensive of available BMP databases. The database contains data pertaining to the characteristics and effectiveness, BMP design and layout, and monitoring and instrumentation. The database provides information based on location, watershed size and general BMP categories. Moreover, in most instances, the database provides costs spent in designing and implementing these BMPs. This database was intended to provide a consistent and scientifically defensible set of data on BMP designs and related performance.

Examples of urban BMP included in the National Storm Water BMP Database are: detention basins, manufactured devices, retention ponds, infiltration basins, percolation trenches/dry wells, porous pavement, wetland basins, wetland channels/swales, grass filter strips, media filters, and green roofs.

Table 2-4 is presented to show the type of BMP reduction effectiveness data that can be generated from this Urban BMP database. For demonstration purposes, a wetland basin is taken as an example. Based on the three studies obtained from the Urban BMP database (presented in Table 2-4), average effectiveness estimates of a wetland basin for phosphorus removal ranges from 23.41% to 55.62% for total phosphorus, and from 5.25% to 46.09% for dissolved phosphorus.

Table 2-4. Urban best management practices (BMPs) effectiveness for nutrient removal generated from National Storm Water BMP Database (http://www.bmpdatabase.org), taking wetland as an example.

SITEID	BMP Name	Parameter Name	Mean Concentration mg/L		Average Pollutant Removal %
			Inflow	Outflow	
1	Lake McCarrons Wetland	Nitrate Nitrogen, Total	0.62	0.29	53.62
2	Tanners Lake Wetland	Nitrate Nitrogen, Total	0.47	0.37	21.82
1	Lake McCarrons Wetland	Nitrogen, Kjeldahl, Total	2.82	1.24	56.05
2	Tanners Lake Wetland	Nitrogen, Kjeldahl, Total	1.80	1.61	10.57
3	Franklin Wetland	Nitrogen, Kjeldahl, Total	1.57	1.36	13.44
1	Lake McCarrons Wetland	Nitrogen, Total	3.47	1.54	55.70
2	Tanners Lake Wetland	Nitrogen, Total	2.27	2.03	10.50
3	Franklin Wetland	Nitrogen, Total	2.68	2.59	3.15
1	Lake McCarrons Wetland	Phosphorus, Dissolved	0.20	0.11	46.09
2	Tanners Lake Wetland	Phosphorus, Dissolved	0.21	0.17	19.05
3	Franklin Wetland	Phosphorus, Dissolved	0.25	0.24	5.25
1	Lake McCarrons Wetland	Phosphorus, Total	0.51	0.23	55.62
2	Tanners Lake Wetland	Phosphorus, Total	0.55	0.39	28.70
3	Franklin Wetland	Phosphorus, Total	0.39	0.30	23.41

Biography and source of BMP data listed in the table above.

Site ID Code	**1**	**2**	**3**
State	MN	MN	VA
Date Added to BMP Database	1999	1999	1999
Study Site BMP	Lake McCarrons Wetland Treatment System-Wetland	Tanners Lake Wetland	Franklin Farm Pond - Created Wetland
Published Title or Data Source	The effectiveness of a detention/wetland treatment system and its effect on an urban lake, 8. ANNUAL INTERNATIONAL SYMPOSIUM ON LAKE AND WATERSHED MANAGEMENT., 1988., p. 29	The Water Quality Performance of Select Urban Runoff Treatment Systems, prepared for the Legislative Commission on Minnesota Resources, Metropolitan Council, St. Paul, Minnesota	
Authors/Data Source	Oberts, G; Osgood, R	Oberts, G.L.	
Sponsoring Agency	Metropolitan Counc., St. Paul, MN, USA; North American Lake Management Soc., Arlington, VA (USA)	Legislative Commission on Minnesota Resources	Northern VA Soil and Water Conservation District
Data Provider	International Stormwater BMP Database 1999; Extracted from Literature	International Stormwater BMP Database 1999; Extracted from Literature	International Stormwater BMP Database 1999; Extracted from Literature
Year of Publication	1988	1989	

Conclusions

Effective mitigation of phosphorus losses from non-point sources must focus on defining, targeting, and remediating critical source areas (**CSA**) of phosphorus loss. CSA of phosphorus loss are areas within a landscape with high levels of phosphorus availability (source areas) and high potential for phosphorus movement (transport areas). In general, these critical source areas of phosphorus loss result from combinations of high hydrologic activity due to climate, topography and geology with high phosphorus loss potential (soils with high level phosphorus) resulting from intensive agricultural activity. Priorities for mitigating phosphors loss problems must be given primarily to these areas in the landscape because these areas pose the greatest risk for phosphorus loss to receiving waters.

Various best management practices (BMPs) have been implemented to reduce phosphorus losses to water bodies. Many studies have been carried out with the aim of determining the effectiveness of the various phosphorus control measures. This report included some of these previously reported BMP effectiveness data. It must, however, be recognized that BMPs effectiveness is site-specific and weather specific. Nevertheless, such BMPs effectiveness estimates that are compiled from peer reviewed performance assessment techniques can be used to determine anticipated improvements in water quality due to previously implemented practices, and to collect information that could be used to refine future estimates of phosphorus reductions in Lake Champlain Basin.

3. Modeling Framework

Critical Source Area for Phosphorus Loss

Major concerns remain regarding continuing phosphorus inputs to the Lake Champlain because excess phosphorus loading continues to exacerbate eutrophication problems (Lake Champlain Basin Program, 1979; 2006; 2008). Much of this phosphorus input (90%) to the Lake is identified to be from nonpoint sources within the Lake Champlain Basin. This project focuses on the agricultural nonpoint source phosphorus loss areas because these areas pose a tremendous challenge in the northern watersheds of Lake Champlain, a current focus of management efforts.

It is well-recognized that efforts aiming in effective mitigation of nonpoint source phosphorus loss must focus on identification, targeting and remediating critical source areas of phosphorus loss. These critical source areas of phosphorus loss (Figure 3-1) represent areas with high availability of phosphorus (phosphorus source) that is at high risk for runoff (phosphorus transport). Thus, in a watershed, runoff water quality is governed by the combined effect of source and transport factors.

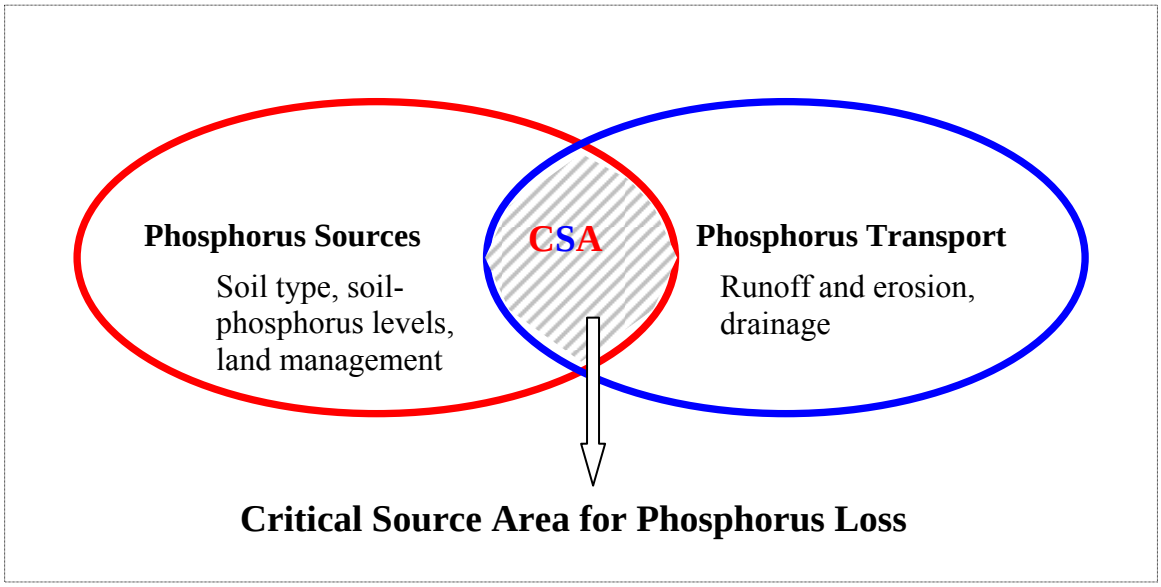


Figure 3-1. The source and transport factors that control phosphorus losses.

Phosphorus source areas are characterized by particular soil types; soil phosphorus levels; tillage; cover; phosphorus application rates, methods and times; and rainfall conditions. In areas of livestock production, elevated soil phosphorus levels may occur as a result of farm phosphorus imbalances. Farm phosphorus imbalances are caused when farm phosphorus imports (as purchased feed and fertilizer) exceed phosphorus exports (as milk

or meat or off-farm sales of harvested crops or other products). Phosphorus transport is controlled by landscape and stream hydrologic processes. These transport processes connect source areas to water bodies. Identification of critical source areas for phosphorus loss is crucial in order to ensure that phosphorus pollution abatement strategies are focused on the highest priority sources in the most cost-effective manner possible.

Three-phase Methodology

For the purpose of identifying critical source areas for phosphorus loss and evaluating potential management practices, a modeling frame work consisting of a three-phase methodology is being developed (Figure 3-2). This modeling framework employs model-based techniques that include watershed-level accounting system and farm-level accounting system tools that can be used for identifying sources and transport processes of phosphorus, and assessing benefits of appropriate strategies in reducing phosphorus losses while maintaining sustainability of agricultural production.

The watershed-level phosphorus accounting system (Phase I) is the major part of the project, however, a farm-level phosphorus accounting system (Phase II) is included in this project in order to account for farm-level phosphorus imbalances, which are the root cause of phosphorus build-ups on farms. The watershed-level phosphorus accounting system will provide locations of critical sources areas within the watershed, highlight areas for management practices, and evaluate the effectiveness of these practices. The farm-level accounting system is expected to identify phosphorus sources in a farming system, highlight the need for alternative farm system strategies, and evaluate the benefits of these strategies.

Finally, Phase III of the methodology integrates both watershed- and farm-level accounting system studies in order to provide a more comprehensive picture of environmental and economic impacts from implementing management strategies.

Phase I: Watershed-level phosphorus accounting system

Phase I involves the development and application of a watershed-scale tool. This tool will aid in (1) identifying individual land response units (unique land use, soil, and slope, and management combinations) with regard to phosphorus losses, and (2) assessing the effectiveness of management solutions in minimizing phosphorus losses. The watershed-level phosphorus accounting system accounts for nonpoint sources and transport of phosphorus across the landscape, at the field edges, and at the outlet of the watershed.

Often times, the potential expenses and time involved in the field assessment of critical source areas for phosphorus losses and field evaluations of management strategies for phosphorus loss reductions are enormous. Hence, a model-based approach can be used to provide a more efficient and feasible means of identifying phosphorus sources and transport factors and evaluating management alternatives.

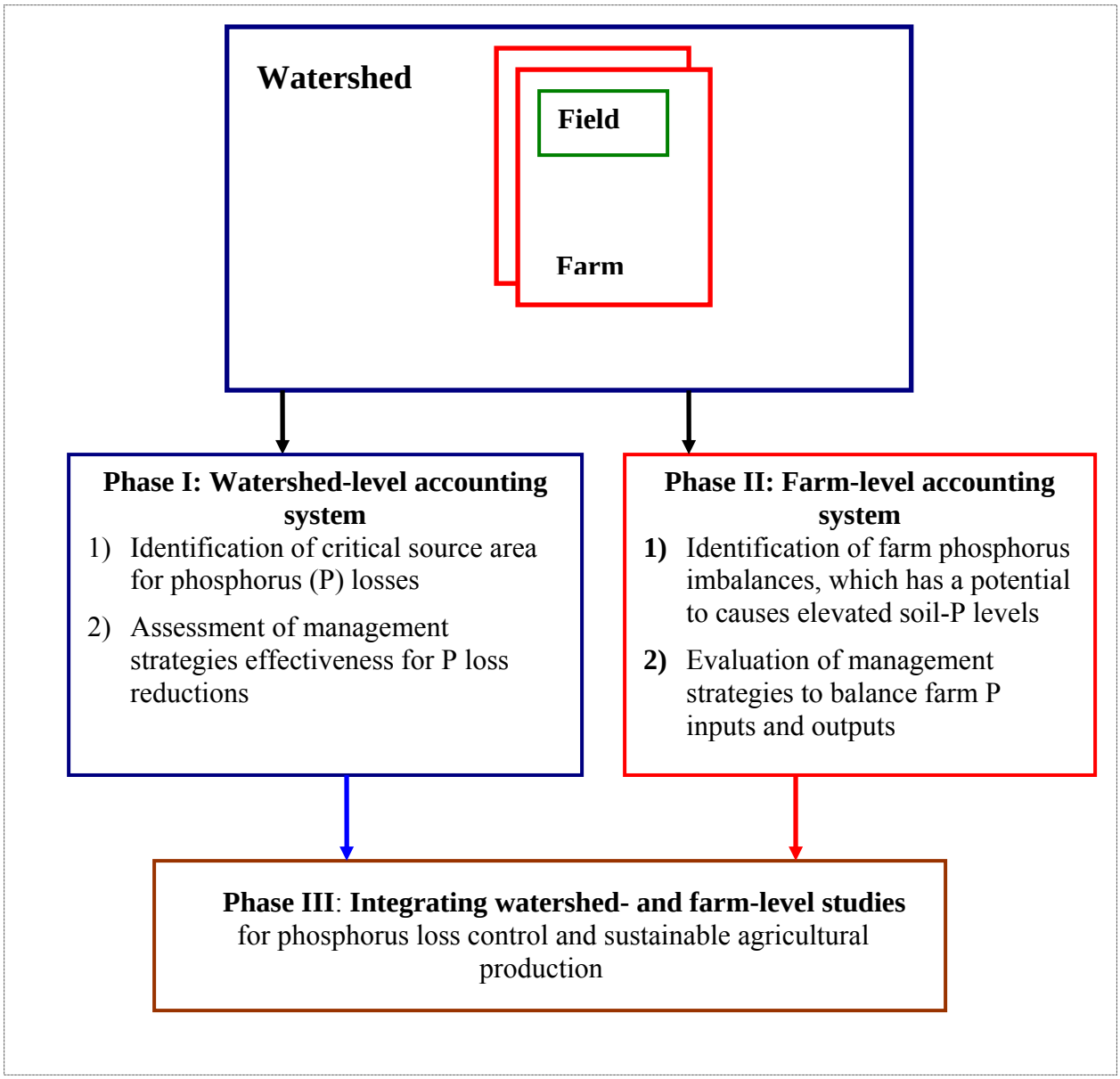


Figure 3-2. A three-phase work-plan for accounting critical source area for phosphorus imbalances and losses and evaluation of remediation management strategies.

In the Lake Champlain Basin, several strategies have been used in identifying areas within a landscape that have a higher potential for phosphorus loss. For instance, an export coefficient approach was used by Meals and Budd (1998) and Hegeman et al. (1999) to estimate nonpoint source phosphorus loads to Lake Champlain by combining exiting land use data and a land use-based phosphorus concentration coefficient with hydrologic data. A follow-up by Troy et al. (2007) also applied the same export coefficient approach, except they used more updated land use data. In all these export coefficient-based studies, relative contributions of phosphorus loadings from different land uses (forest, agriculture, and urban land) were identified so as to guide planners in targeting land uses requiring management measures. Compared to more detailed, process-based modeling approaches, the export coefficient approach is relatively simple and allows the significance of sources (e.g., diffuse versus point source) to be assessed (Johnes, 1996). The export coefficient approach has long been used to provide simple budgets of nutrient loads entering waterbodies (Johnes and Heathwaite, 1997). In contrast to their advantage in simplification, however, such approaches make no attempt to explain the processes involved in generating nutrient losses from a set of parameters related to landscape, field-specific management, and hydrological characteristics within a specific watershed.

Another approach being applied to assess areas of phosphorus pollution potential in Lake Champlain Basin includes the Vermont Phosphorus Index (VT P-index). The VT P-index was developed to assess potential for phosphorus runoff from individual fields based on detailed data related to soil (e. g. soil phosphorus test, soil type), field characteristics (e.g., slope, land use), and management practices (e. g. fertilizer and manure applications, rates and timing). The P-index also applies standard contributing distances, calculated with respect to receiving waters, to account for phosphorus transport areas. This P- index approach is designed to offer a comprehensive assessment of phosphorus sources and transport areas at a field scale, which, in turn, can be used to direct farmers and land managers to identify CSAs of phosphorus loss and direct remediation measures to those specific locations within the watershed. Although, the P-index approach requires detailed field-based data, it is designed to provide a simple, practical, user-oriented tool by both ranking fields for their phosphorus loss potential and focusing remediation measures. However, the validity of this VT P-index has not been thoroughly evaluated in the field.

Recently, the United States Department of Agriculture, Natural Resources Conservation Service (USDA-NRCS) in Vermont has combined the use of available GIS spatial datasets and simple erosion and phosphorus indices in developing a watershed-based approach of identifying areas where conservation interventions are likely to have the greatest impact (USDA-NRCS, 2008). The study was focused in the Missisquoi Sub-basin of the Lake Champlain Basin, which includes the Vermont portions of the Missisquoi River, Rock River, and Pike River watersheds. In this watershed-based approach, geospatial analyses, such as soil and slope characteristics, were used to identify and prioritize cropland areas (corn and hay crops) and stream reaches with higher potential for sediment and phosphorus losses. In addition, a combination of erosion prediction tool (RUSLE2) and VT P-index was applied to evaluate management strategies for their phosphorus reduction effectiveness. Although RUSLE2 and the VT P-

index are not validated in the field, their predictions of phosphorus losses may have relative significance. The USDA-NRCS (2008) study provides a direct and an informal means of identifying the relative importance of crop lands and streams with respect to phosphorus pollution potential and potential reductions that may come from management strategies. This approach made good use of available GIS data and technology for its assessment; however, it does not capture the complex physical and hydrological processes involved in generating phosphorus losses from the landscape.

In our study, a process-based watershed model, Soil and Water Assessment Tool (SWAT; Neitsch et al., 2002) was selected for the purpose of identifying critical source areas of phosphorus loss and evaluating management strategies. The SWAT model was selected for our study because it has a long history of successful application in hydrologic watershed response and in the study of impacts of land management and climate on water quantity and quality in USA and internationally. Summaries of over 250 peer-reviewed SWAT publications are presented in Borah and Bera (2004) and Gassman et al. (2007). The SWAT model is also a comprehensive model that integrates information over a watershed scale, helping to define watershed scale processes relevant to phosphorus transport, highlighting appropriate management strategies, and identifying critical source areas where BMPs are most likely to affect watershed-scale phosphorus losses.

Figure 3-3 presents details involved in the Phase I watershed-level phosphorus accounting system. As shown in the Figure 3-3, a scientifically defensible tool, the SWAT model, is used in identification of critical source area for phosphorus losses. By identifying critical source area for phosphorus sources, it is possible to 1) plan appropriate management strategies and evaluate their potential for phosphorus reduction and 2) gain understanding on the hydrologic and phosphorus transport responses of the combinations of landscape characteristics such as slope, soil, and land use management practices that may help in applying these understanding in other similar watersheds within the Lake Champlain Basin with similar settings.

Another important task in Phase I is to determine potential management practices for the various identifiable critical source areas. Several best management practices that have the potential to reduce phosphorus losses can be found from the literature, however, involvement of stakeholders in the process of selection of best management practices may help to focus on those best management practice that have the highest potential for implementation.

Work related to this phase is in progress and details are presented in the next section of this report.

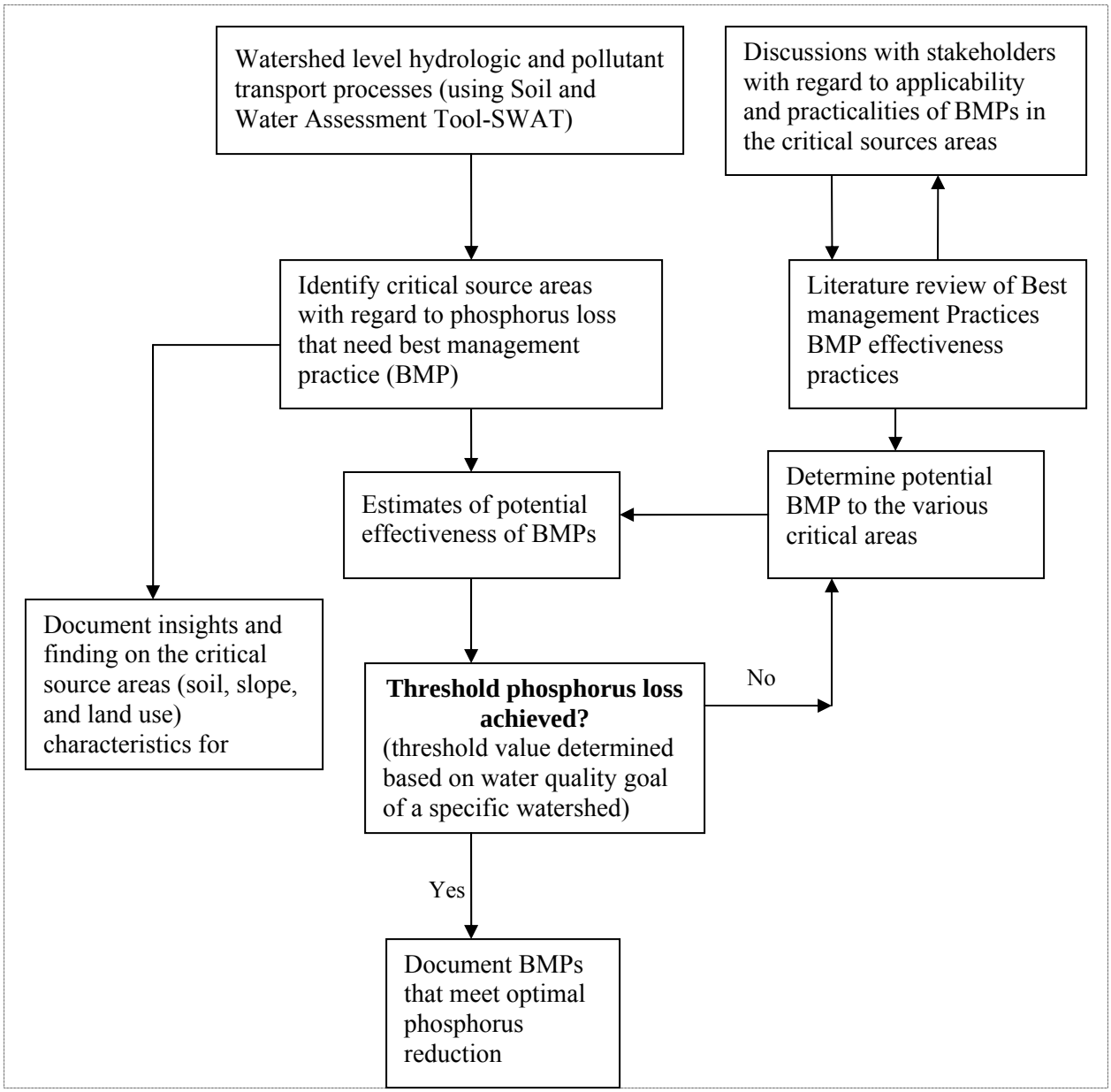


Figure 3-3. Phase I-watershed-level phosphorus accounting system: identification of critical source area for phosphorus loss and assessment of BMP effectiveness to control phosphorus losses.

Phase II: Farm-level accounting system

Phase II will involve the application of a farm-scale tool that aids in (1) estimating phosphorus balances of farms and associated farm management systems and (2) assessing farm system strategies that balance farm phosphorus inputs (in purchased feed and fertilizers) and farm phosphorus outputs (in milk, meat, or off-farm sales of harvested crops or other products) while maintaining farm profitability.

A farm-level phosphorus accounting system accounts for the farm phosphorus imbalances (surplus). When there is a surplus of phosphorus on the farm, the phosphorus levels of soils may be elevated, and as a result, risks of phosphorus loss in runoff may increase (Figure 3-4). Fields with higher soil phosphorus levels have higher risks of phosphorus losses in runoff and erosion.

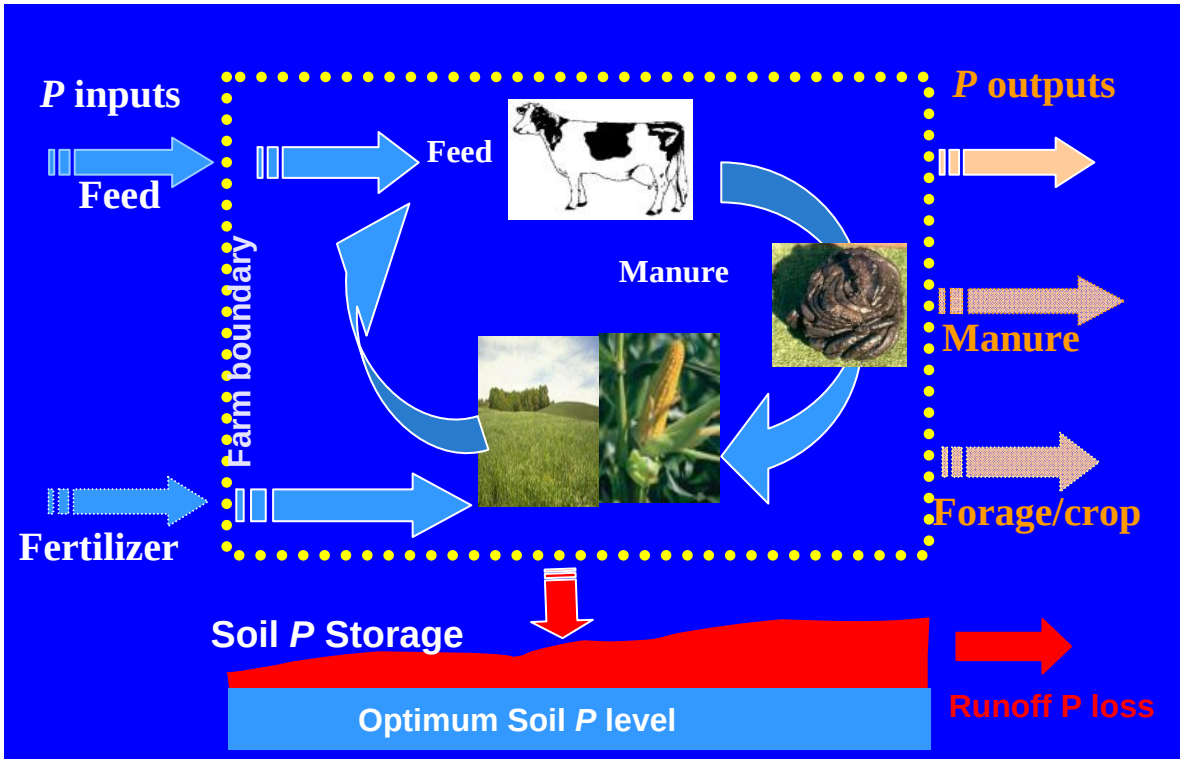


Figure 3-4. Diagram showing phosphorus balances and losses considering dairy farm as an example.

The farm phosphorus imbalance problem is caused when phosphorus imports in purchased feed and fertilizer exceed phosphorus exports in milk or meat or off-farm sales of farm products. In Lake Champlain Basin, as in much of Vermont and Northeastern U.S., farming operations often import feed grain and supplements from the Midwestern U.S. Through this accounting system, phosphorus levels of livestock rations and excreted manure will also be assessed. Overall, this farm-level phosphorus accounting system is expected to provide important information in identifying critical points of phosphorus imbalances. As a result, it will be possible to evaluate phosphorus feeding levels and to identify the critical control points pertaining to phosphorus management in livestock production. For this farm-level phosphorus accounting system project, a farm scale model, Integrated Farm System Model (IFSM; Rotz and Coiner, 2006) has been selected.

The IFSM model is a comprehensive farm-scale model that simulates long-term environmental impact and farm profitability for various technologies and management strategies applied to a farm system. IFSM has been widely used in studying farm planning strategies mainly in the Northeastern and Central U.S. and Canada (Rotz et al.,

1999a; Rotz et al., 1999b; Rotz et al., 2001; Andersen et al., 2001; Soder et al., 2001; Sanderson et al., 2001; Rotz et al., 2002, Ghebremichael et al., 2007). The IFSM farm simulation model integrates models of crop growth, harvest, storage, feeding, animal (dairy or beef) production, and manure handling to determine long-term (up to 25 years of weather data) performance and environmental and economic impacts of a farm enterprise.

The environmental component of IFSM predicts nutrient balances (phosphorus, nitrogen, and potassium) as well as off-farm erosion and nutrient losses. The quantity and characteristics of phosphorus produced in the manure is calculated as a function of the quantity and phosphorus content of the feed consumed. In other words, phosphorus that is consumed but not used within the body for maintenance, growth, milk production, or reproduction will be excreted directly in manure. The economic component of IFSM uses a simple accounting of production costs and incomes to compute net-return of a farm enterprise. The production cost includes costs of crop production, harvest, storage, feeding, and other production-related activities. The farm income includes receipts from sales of milk, animals, and crops.

Major tasks involved in Phase II of the modeling frame work are presented in Figure 3-5. Using IFSM model, phosphorus balance status of farms and current farming systems will be identified. Several farm strategies that have the potential to balance the input and outputs of farm phosphorus are available in literature, however, involvement of stakeholders in the process of selection of practical strategies is recommended so as to focus on those farm system strategies that have highest potential for implementation. Work related to this phase is planned for the second year of this project.

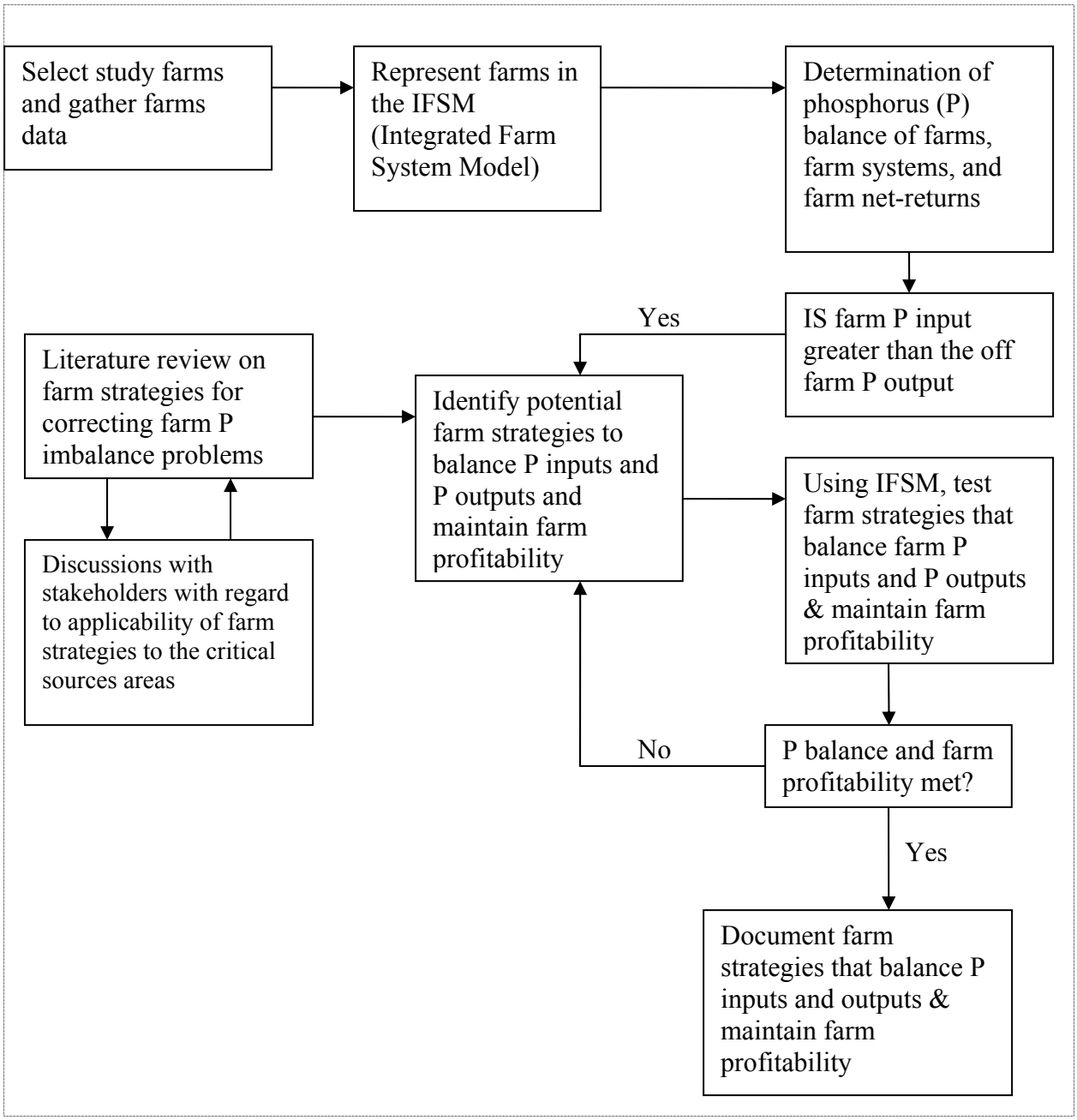


Figure 3-5: Flow chart showing tasks involved in Phase II-farm phosphorus accounting system: Identification of farm phosphorus imbalances and farm strategies to reduce farm phosphorus surplus and maintain farm profitability.

Phase III: Integrating watershed- and farm-level accounting systems

Phase III of the project will involve integrating Phases I and II (watershed-scale tool and farm-scale tool). By integrating the watershed-scale and farm-scale tools the smallest management unit (farm management plan) can be assimilated into a watershed plan and vice-versa. Also, by including farm-level management planning, assessment of economically viable and practical solutions for permanent reduction of P losses from nonpoint sources to the Lake Champlain may be possible.

This phase of the project will integrate findings of the two phases (Phases I and II) described previously to identify critical sources areas of phosphorus and make recommendations on best management strategies helpful in mitigating phosphorus loss problems. Work related to this phase (Figure 3-6) is planned for the second year of this project.

The lessons learned from the application of this methodology to the Rock River watershed and its farms will be generalized to provide a common strategy for phosphorus CSA identification and phosphorus accounting for the entire Missisquoi Bay watershed and the Lake Champlain Basin. Although the specifics of watershed topography, hydrology, soils, farm locations, and land management practices vary from basin to basin, the combinations of factors that generate P losses and the potential for remediation using the approach and accounting method will be discussed. These principles can then be applied to estimate phosphorus balances and potential improvements that might come in other areas.

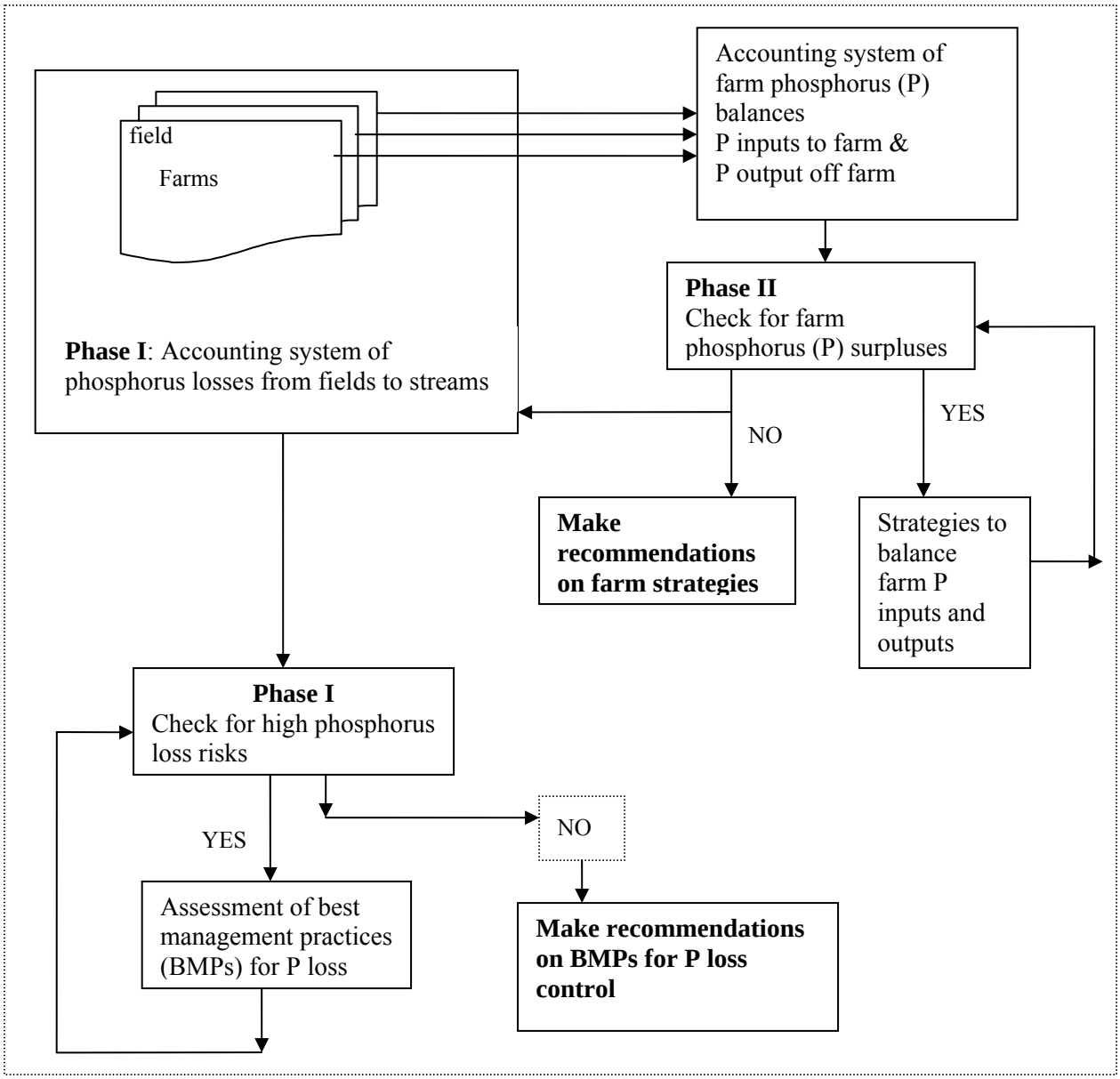


Figure 3-6: A flow chart showing tasks involved in Phase III of the modeling frame work: Integrating farm- and watershed-level planning for phosphorus control and sustainable agricultural production.

Summary

A modeling framework consisting of three parts has been developed for the purpose of identifying critical source area for phosphorus loss and evaluating potential management strategies. The modeling framework employs watershed- and farm-level accounting system tools as a means of identifying and targeting critical source areas of phosphorus loss. Work related to the first and major part of this modeling framework, Phase I, is in

progress and details are presented in the next section of this report. Work related to Phases II and III are planned for the second year of this project.

Although a similar approach might be applied to develop an accounting system and to examine what might be achieved in urban/suburban areas, differences do exist. Land generation of phosphorus must consider infrastructure as well as many of the same factors considered on agricultural land. BMP effectiveness will be highly site-specific and must reflect targets of opportunity for retention and infiltration combined with good municipal and citizen practices. Stream restoration must also eventually be included in the modeling framework and accounting system, however, phosphorus on the land must be controlled first and restoring water and sediment balances (Lane's balance) should precede active channel modification.

4. Phase I: Watershed-level Phosphorus Accounting System

SWAT Model Description

Soil and Water Assessment Tool (SWAT) is a hydrologic and pollutant model that was developed by the Agricultural Research Service of the United States Department of Agriculture (Neitsch et al., 2000a). SWAT is a process-based, distributed, and continuous daily time-step watershed model that simulates the transport of sediment, runoff, phosphorus, nitrogen, and pesticides as a function of land use at the subwatershed and watershed scales. SWAT model has a long history of successful application in hydrologic watershed response and in the study of impacts of land management and climate on water quantity and quality in USA and internationally. Summaries of over 250 peer-reviewed SWAT publications are presented in Borah and Bera (2004) and Gassman et al. (2007). The SWAT model and its associated GIS interface have been integrated into the US Environmental Protection Agency's modeling framework of Better Assessment Science Integrating Point and Non-Point Sources (BASINS), which is being used in several states for total maximum daily load (TMDL) analysis (Diluzio et al., 2002).

The SWAT model allows a watershed to be divided into subbasins based on topographic criteria, with further subdivision of subbasins into hydrologic response units (HRUs) based on land use and soil type. SWAT allows the user to define management practices in every HRU. The user can also define the amount and timing of manure and fertilizer application in addition to other management operations. Geospatial data required for SWAT simulation include soil input map, digital elevation model, and land use coverage. Meteorological input data including precipitation, temperature, and solar radiation are also needed.

The model estimates relevant hydrologic components such as surface runoff, baseflow, evapotranspiration (ET), snowmelt, and soil moisture change for each HRU. SWAT uses runoff curve numbers to predict runoff volumes from daily rainfall and snow melt. The Soil Conservation Service's curve number is a function of the soil's permeability, land use, and antecedent soil water conditions. Curve numbers are recalculated daily, based on soil water content on that day. Ground water is calculated on a sub-basin basis, considering a shallow aquifer (contributes to stream baseflow) and deep aquifer (which does not contribute to streams) within the watershed. Algorithms are included in SWAT to represent water and nutrient movement in field with tile drainage. SWAT also includes snow melting and lake/wetland algorithms, which make the SWAT model a candidate in the study watershed where hydrology is significantly related to overwinter snow accumulation, snowmelt during spring, and surface and baseflow contributions.

Erosion caused by rainfall and runoff is estimated for each hydrologic response unit using the Modified Universal Soil Loss Equation, MUSLE (Williams and Berndt, 1977; Williams, 1995). MUSLE is a modified version of the Universal Soil Loss Equation (USLE) developed by Wischmeier and Smith (1978). USLE predicts average annual

gross erosion as a function of rainfall energy. In MUSLE, the rainfall energy factor is replaced with a runoff factor. The runoff factor represents energy used in detaching and transporting sediment. This allows the MUSLE equation to be applied to individual storm events and runoff, which in turn is a function of antecedent moisture condition and rainfall energy.

SWAT represents phosphorus dynamics using six pools: three organic phosphorus pools (fresh [associated with crop residue], active, and stable; the latter two are associated with humus) and three inorganic phosphorus pools (labile [solution], active, and stable). Phosphorus may be added to the soil by fertilizer, manure, or residue application. Neitsch et al. (2002a) details the various soil-phosphorus pools and interactions represented in SWAT. The organic phosphorus forms transform into inorganic phosphorus forms through the process of mineralization. Most of the mineral and organic phosphorus occurs in its adsorbed form. The inorganic phosphorus in the labile pool is in rapid equilibrium (several days or weeks) with the active pool. The active pool is in slow equilibrium with the stable pool. Phosphorus removed from the soil by plant uptake and runoff losses is taken from the labile phosphorus pool. The model estimates plant use of phosphorus using the supply and demand approach (Williams et al., 1984). Daily plant demand is estimated as a function of plant biomass and biomass phosphorus concentration. Depending on total plant biomass grown, or yield rate, the mass of phosphorus stored in plant biomass for each growth stage and the necessary plant uptake of phosphorus are determined. SWAT simulates crop growth and crop uptake of phosphorus for specified management, soil, and weather conditions. SWAT also simulates soluble phosphorus removed from the soil via runoff and particulate phosphorus removed with erosion.

With its detailed representation of the complex physical and hydrological processes, SWAT model is a suitable tool in identification of critical source areas for runoff and phosphorus losses within a watershed. By using SWAT watershed modeling as a critical source area identification tool, a list of key site factors that contribute most to phosphorus generation and transport can be developed. Examples of site factors that may be important include: presence of runoff contributing areas, proximity to surface waters, slope, soil characteristics, land use, and existence or lack of management practices.

Study Watershed Description

The Rock River Watershed is an approximately 70.9 km^2 rural watershed located in the Vermont's far northwestern corner (Figure 4-1). The portions of the Rock River we will model encompass the portion of the Rock River watershed between 3 and 10 miles inland from Missisquoi Bay. It has an average elevation of 101 meters, and is flat by Vermont standards, having been in glacial times the bed of Lake Vermont and the Champlain Sea, with the Rock River now incised within this landscape. The climate is humid with an average annual temperature of 6^0C and average annual precipitation of 1100 mm (based on 20 years data from meteorological station located at Enosburg, VT). Soils in the watershed are of glacial origins dominated by mainly silt loam or silty clay loam types.

The fertile periglacial lacustrine and alluvial soils support an intensive and increasingly consolidated dairy farming industry.

The Rock River Watershed was selected for our study because of 1) the availability of monitoring data of stream flow and phosphorus concentration at the outlet of the watershed that can be used for SWAT model calibration, 2) its agricultural-dominated land use makes it suitable in studying phosphorus transport processes in agricultural watersheds, and 3) it has high phosphorus loss per unit area and is ranked as number three among the watersheds in the Lake Champlain Basin for highest phosphorus loss per unit (Smeltzer and Simoneau, 2008). Hence, the Rock River Watershed is one of the watersheds in the Lake Champlain basin that is a high priority for watershed management activities.

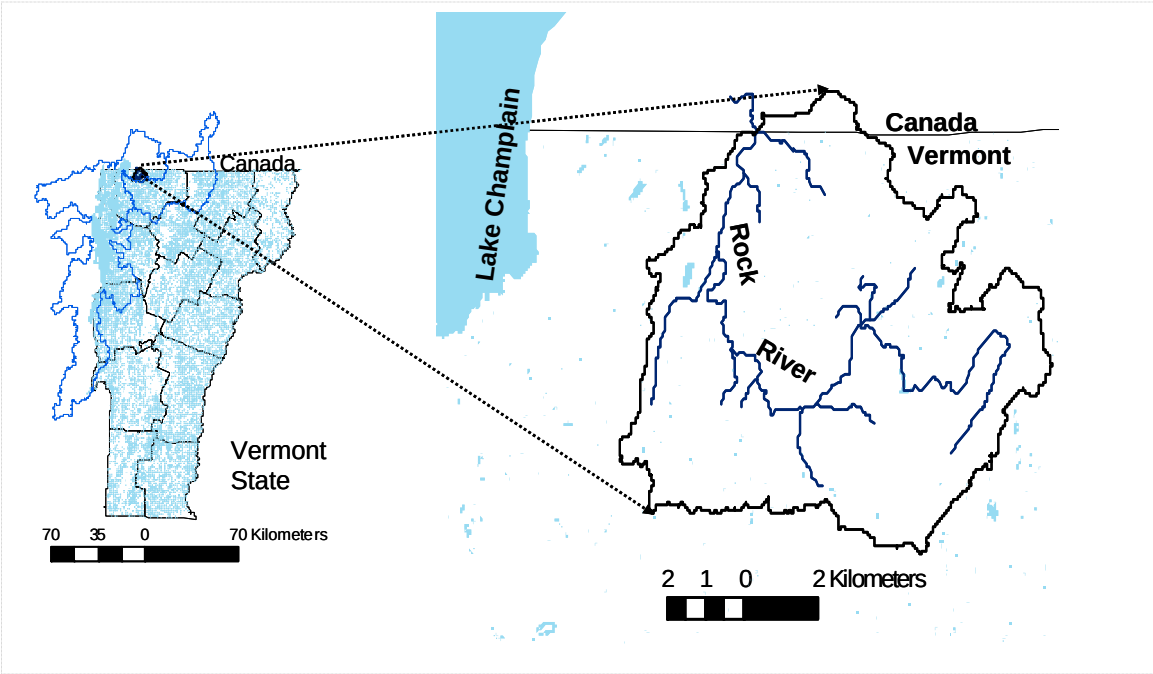


Figure 4-1. Map showing the location of Rock River Watershed.

Overview of tasks involved in Rock River SWAT modeling

This section covers general tasks involved in SWAT model application in the Rock River Watershed. These tasks include: 1) input data gathering and pre-processed as necessary, and then converting them into formats required by SWAT, 2) model calibrating and validation for hydrology and sediment and phosphorus, 3) analyzing of outputs for identifying critical sources area for runoff and phosphorus losses, and 4) application of the model for evaluating best management practices. The procedures used are summarized in Figures 4-2, 4-3, and 4-4.

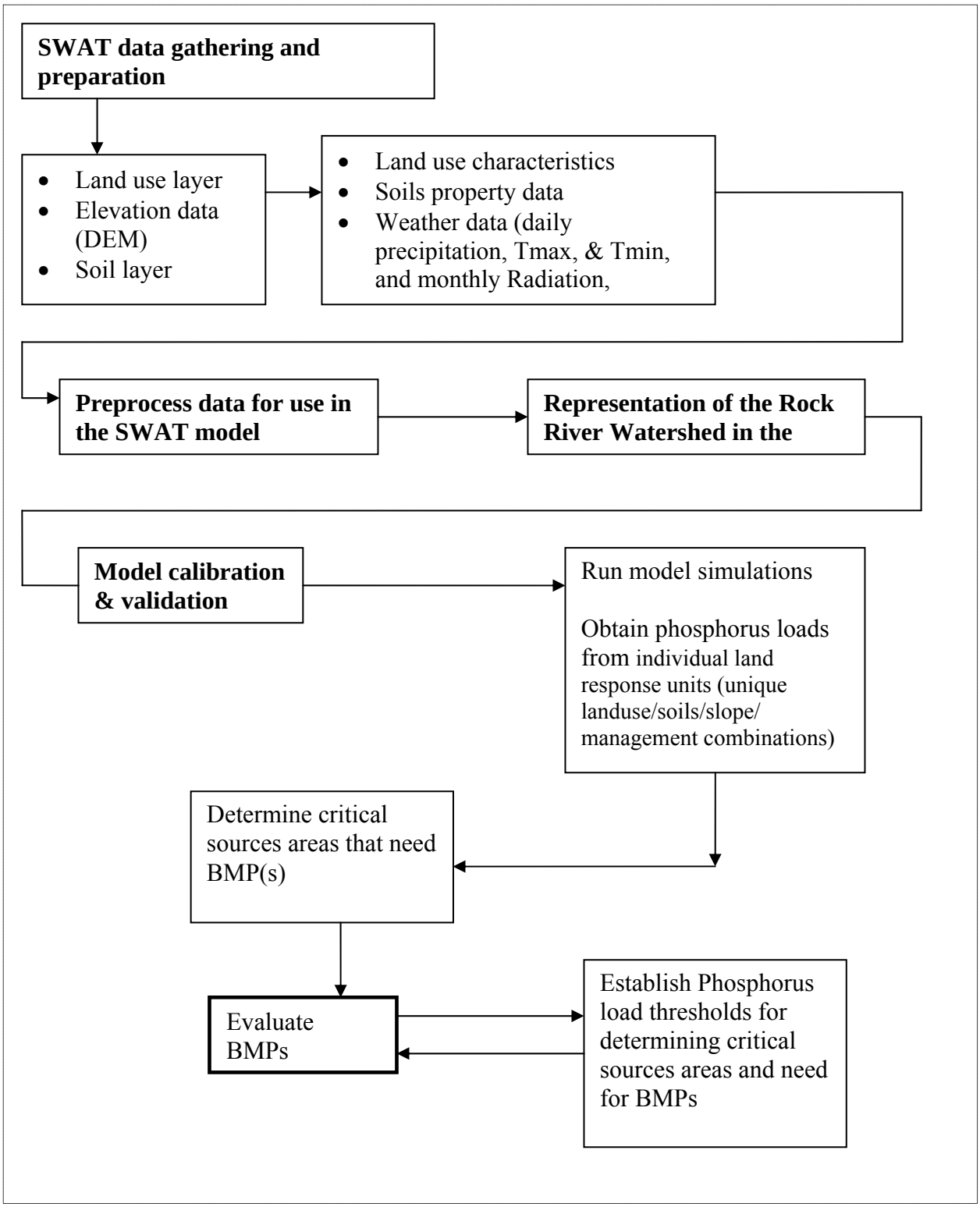


Figure 4-2. Chart showing SWAT model application for identification of critical source area of phosphorus loss, and evaluation of best management practices in the Rock River Watershed.

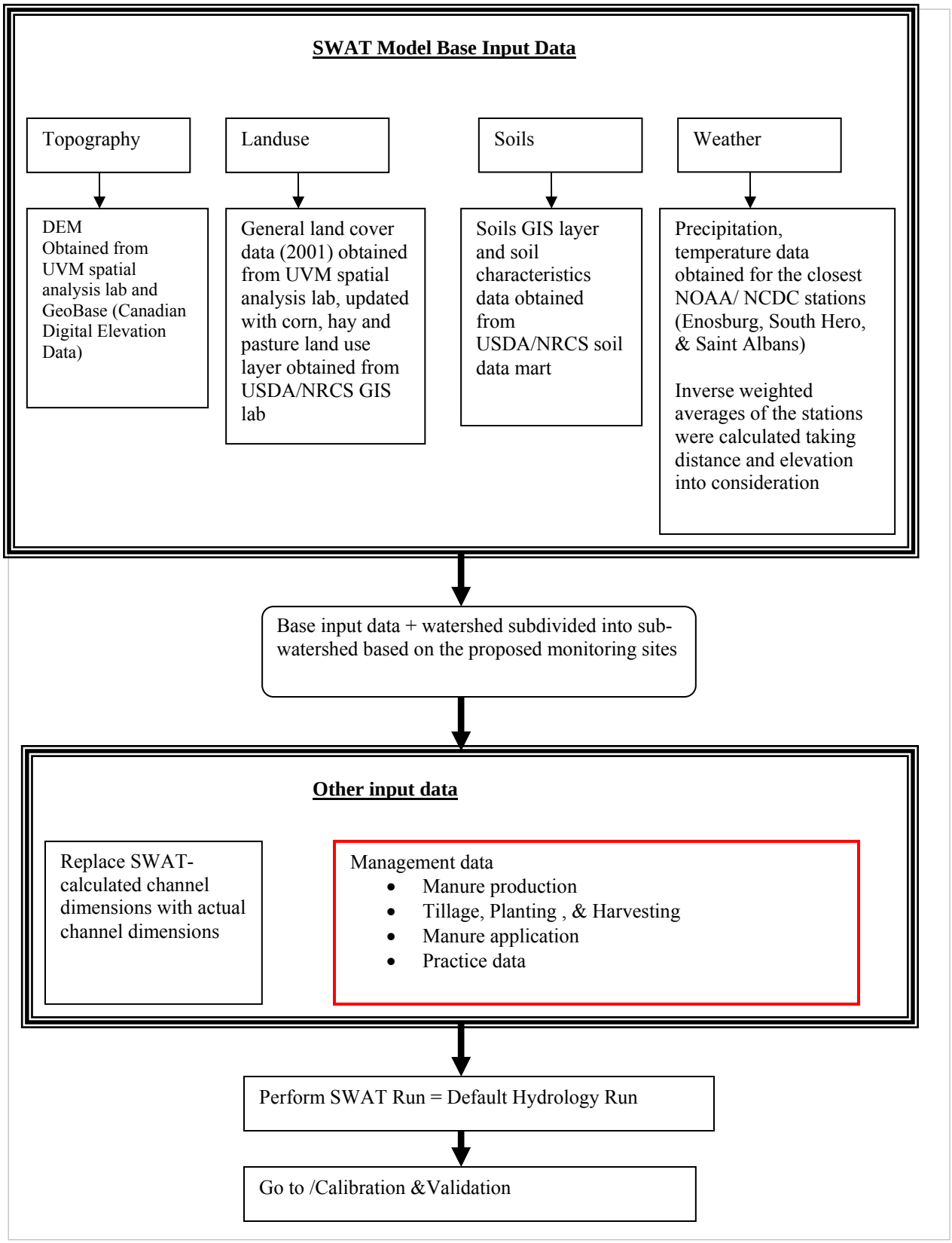


Figure 4-3. SWAT model input data preparation and representation of Rock River Watershed (text box that are colored red indicate tasks yet to be accomplished).

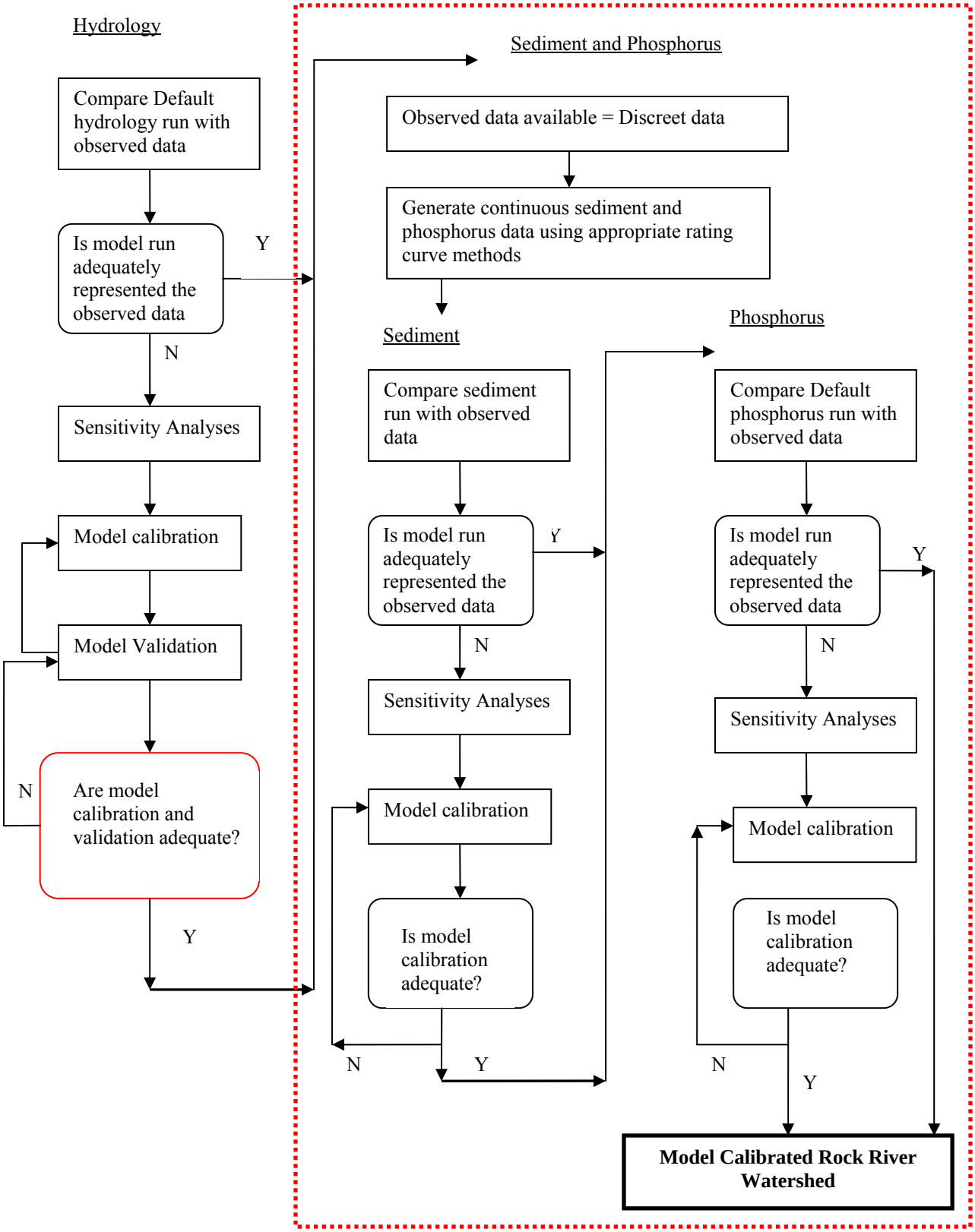


Figure 4-4. Chart showing steps in SWAT model calibration and validation processes (text box that are colored red indicate tasks yet to be accomplished).

SWAT Input Data

Digital Elevation Model (DEM) Data

DEM data of the Rock River Watershed were obtained from online data source of Vermont Center for Geographic Information VCGI (VCGI, 2007). The 10 m DEM data was abstained from this source for the entire area of Vermont State, and portion of the DEM data that covers the Rock River Watershed was clipped using GIS techniques and used for delineating this focus watershed. Since the outlet of the watershed is located in Canada just where you cross the border of Vermont State, a small portion of DEM data from Canada was needed for the watershed delineation processes. Hence DEM data of the Canadian part of the Rock River Watershed was acquired from online data source of Canadian Digital Elevation Data (CDED, 2007). These two data sets were mosaicked (joined) in Arc-GIS to make a single DEM raster data for the Rock River Watershed (Figure 4-5)**.** Based on this DEM data, mean elevation of the Rock River Watershed is 101 m above sea level (with maximum and maximum elevation above sea levels of 260 m and 29 m, respectively).

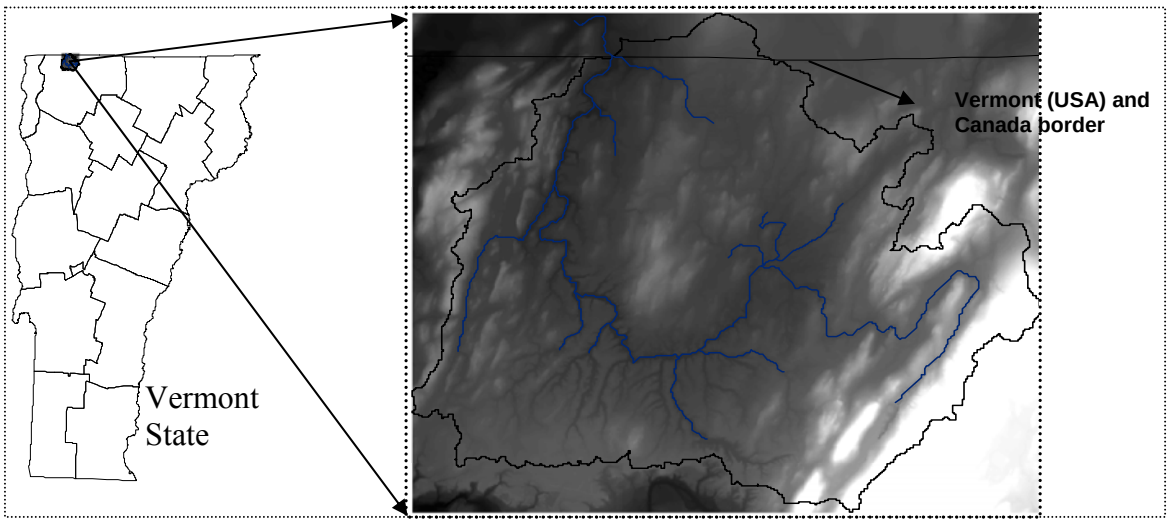


Figure 4-5. Digital Elevation Data (DEM) of the Rock River Watershed obtained from online digital elevation data sources of Vermont State (USA) and Canada.

Land Cover Data

For Rock River Watershed, there is no single layer data of land use cover data with distinct layers of crop lands, (corn, hay) pasture, forest, developed and others. Therefore, such land cover data for Rock River watershed was developed by combining several land use data sources using GIS techniques. The data sources used include digital land use/land-cover for the Lake Champlain Basin (LCB 2001), agricultural crops data layer, and pasture fields data layer.

1) Digital land use/land-cover for the lake Champlain Basin (LCB 2001): this LCB 2001 land cover data was developed by the University of Vermont (UVM) spatial analysis lab

(Troy et al., 2007) using the 2001 National Land Cover Database (NLCD), 2001 Landsat satellite imagery , and other Geographic Information (GIS) datasets.

Figure 4-6 shows the LCB 2001 land use data. The purpose of developing this LCB 2001 was to have an improved NLCD 2001 land use cover for estimating phosphorus loadings to the Lake Champlain (Troy et al., 2007). One of the improvements made to the NLCD 2001 database was to properly classify agricultural land uses and urban open lands. As shown in the Figure 5, eight general land uses categories (agriculture, barren, brush, developed, forest, open undeveloped, water, and wetland) were used. Despite its improvements, the LCB 2001 land use data aggregates different agricultural land uses together. Since identification of agricultural land uses, such as corn, hay, pasture, and others, is required for accurate representation of a process-based hydrological and phosphorus modeling, available data layers of different crops and pasture fields were used to update the LCB 2001 land use using GIS techniques.

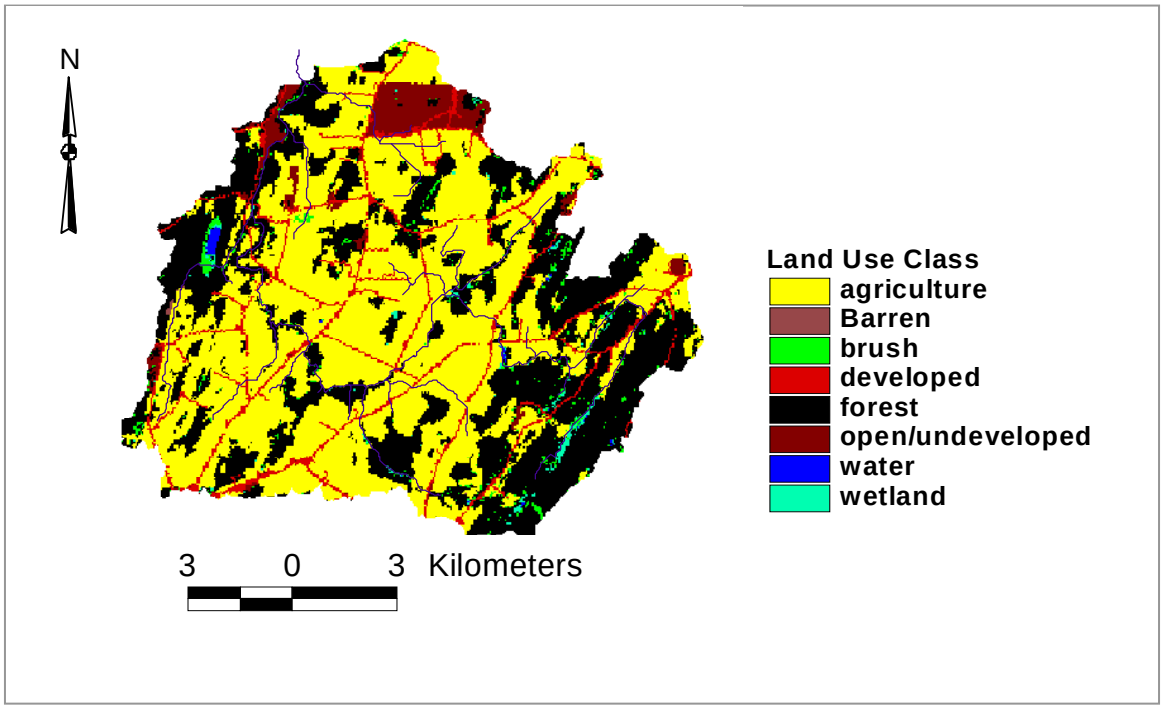


Figure 4-6: Rock River Watershed general land cover data (based on LCB 2001 land use classes).

2) Agricultural crops data layer: this data layer (Figure 4-7) includes corn, hay, other crops, and fallow crop cover types. This same data layer was obtained from both the University of Vermont spatial analysis lab and United States Department of Agriculture-Natural Resources Conservation Service (USDA-NRCS) GIS databases. Based on the metadata of this data layer, this crop cover data layer was developed from the National

Agricultural Imagery Programs' (NAIP) 2003, 1 m natural color orthophotographs and the USDA common Land Unit (CLU) boundaries obtained from the Farm Service Agency (FSA).

3) Pasture fields data layer: this data layer was also obtained from UVM spatial analysis lab. The pasture data layer was mapped from NAIP 1m true color imagery acquired in 2003. These fields include potential grassland areas that were not included in the agricultural crops data layer.

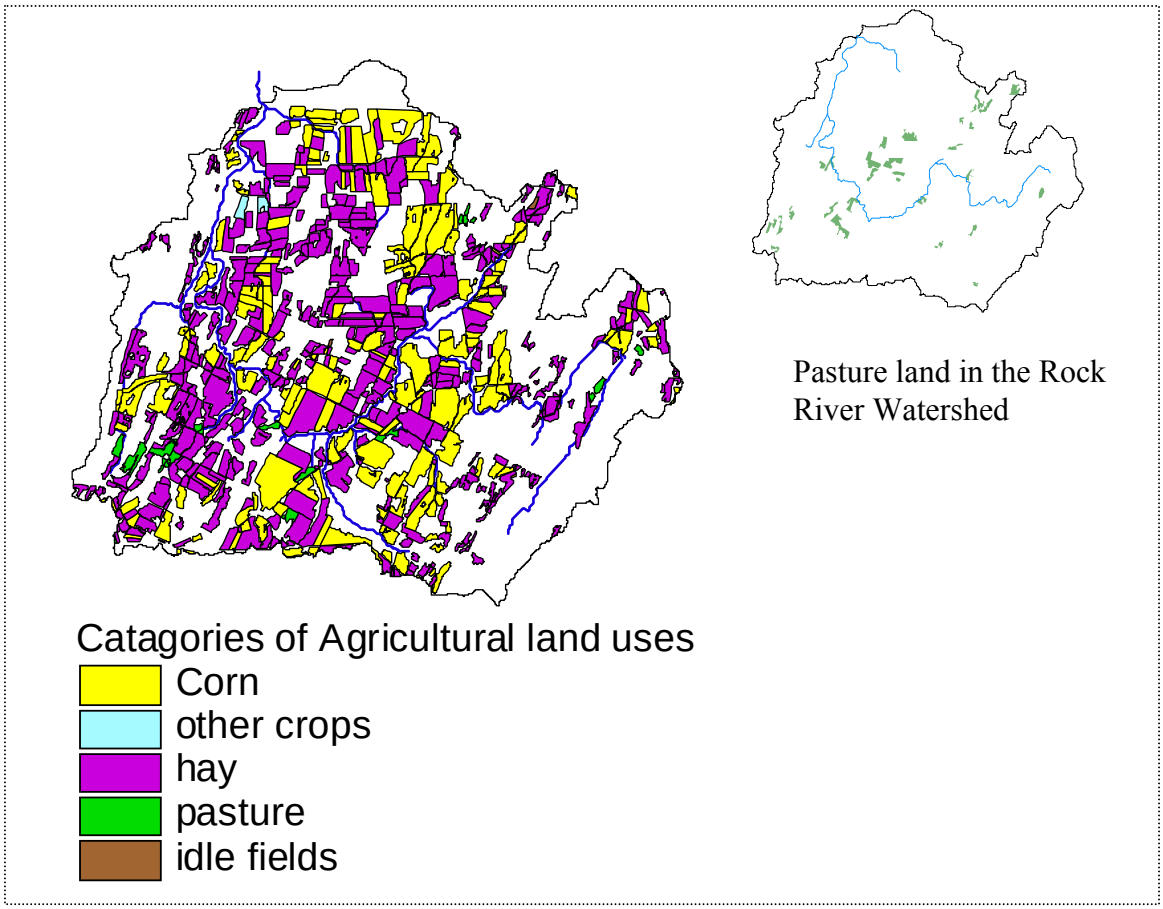


Figure 4-7. Digitized agricultural fields in Rock River Watershed: pasture, hay, corn and other crops.

Using GIS techniques, the latter two data, crop and pasture layer, were overlaid over the LCB 2001 land cover layer. As a result, good agreement between the agricultural land uses of the LCB 2001 and the boundaries of crops and pastures were obtained. Exceptions were some mismatches in the northeastern part of the Rock River Watershed (refer to Figure 4-8). In these areas, areas identified as open urban in the LCB 2001 were found to be in agricultural fields based on the data obtained from the 2003 NAIP 1 m natural color orthophotographs and the FSA common Land Unit (CLU) boundaries of

agricultural land uses. Though, these LCB 2001 and the 2003 agricultural field's boundary represent from different time period, the later was found to be accurate based on field visits of the area.

Therefore, a new land use layer was developed from these two data layers, hence used in this study (Figure 4-9). Percentage of areas of various land uses in the Rock River Watershed from both data layers, the LCB 2001 and the new updated land use layer (used herein this study) are presented in Table 4-1. Note that for the Rock River Watershed, the total agricultural land uses in the new updated land use data layer was 2% more than that of in the LCB 2001 land cover. The total area in developed and open urban was smaller (by 1.1%) in the new updated land use data layer compared to the LCB 2001 land cover data.

Soils Data

SSURGO level soils map (Figure 10) and data were obtained from the national soils data for the Franklin County, VT, in which the Rock River Watershed is located (http://soildatamart.nrcs.usda.gov). In addition, detailed soil components and layer properties, for each of the soil (map unit) in Rock River Watershed, were obtained from the USDA/NRCS soil data mart available on line (http://soildatamart.nrcs.usda.gov/State.aspx). Data required by SWAT includes the map unit symbol, hydrologic soil group, maximum rooting depth, and detailed layer properties, including; layer depth, bulk density, available water capacity, saturated hydraulic conductivity, organic carbon, clay, silt, and sand content, rock fragments, soil albedo, and the erosion K-factor. SWAT requires most of these data at map unit level, Table 4-2 presents a summary of soil property data for a MuB soil map unit. In addition, Table 4-3 is presented to show the types and percentages of various soils in the Rock River Waterhsed and their characteristics.

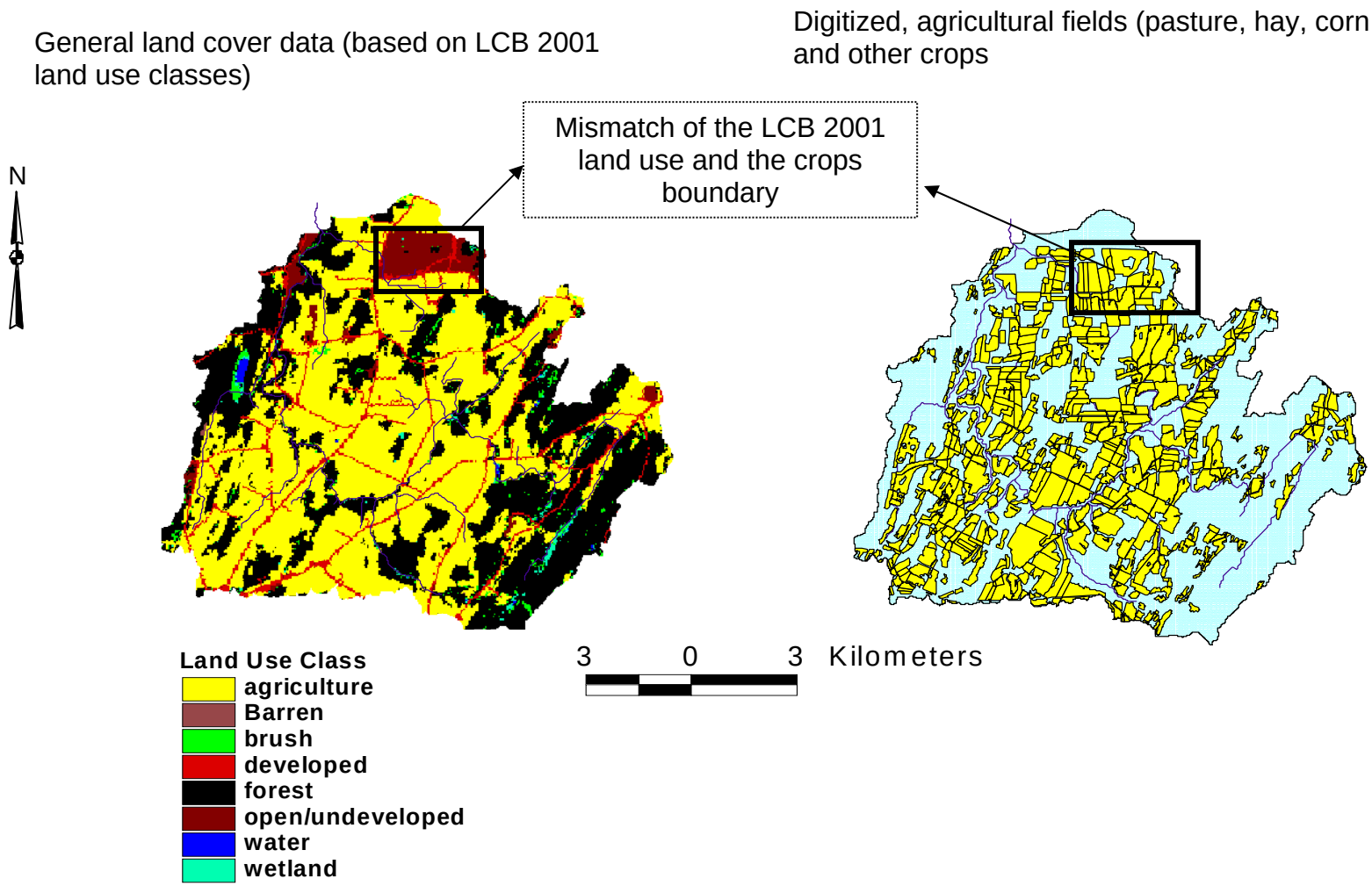


Figure 4-8. Maps showing LCB 2001 land cover data and digitized agricultural land uses developed from based on the data obtained from the 2003 NAIP 1 m natural color orthophotographs and the FSA Common Land Unit (CLU) boundaries of agricultural land uses.

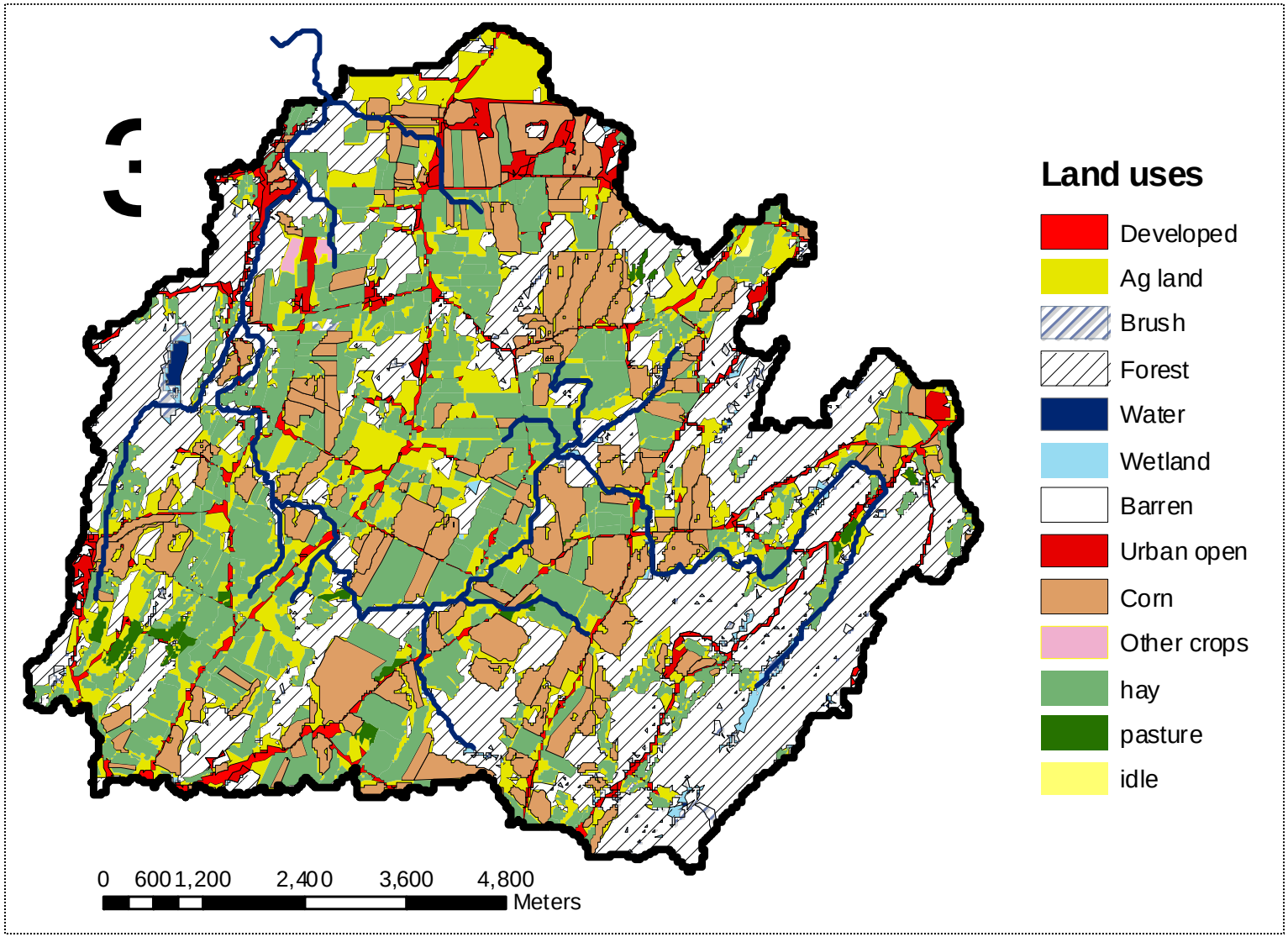


Figure 4-9. Rock River Watershed with new land use layer developed from Common Land Unit (CLU) and LCB 2001.

Table 4-1. Comparison of land areas of a new updated land use and the LCB 2001 land use of Rock River Watershed.

Land use codes	General land use Description	Percent areas in Updated land use data layer	Percent areas in LCB 2001 land use data layer	Detailed descriptions
1	Residential/developed	5%	5.6%	areas dominated entirely by constructed materials or a mix of constructed materials and vegetation.
8	Open	3.3%	3.8%	Urban-Open. Areas dominated by vegetation, typically lawn grass, where the use is anthropogenic. This includes many suburban and exurban properties with large lawns on former farm fields.
	Total urban/developed	8.3%	9.4%	
	Agricultural Land	55.3%	53.6%	land use dominated by the production of crops or for the grazing of livestock
2111	corn	14.7%		fields exhibiting the presence of corn or a failed corn crop
2118	Other raw crops	0.2%		the other crop category only includes row crops such as soybeans and grain crops such as winter wheat
2121	hay	23.9%		hay field assignment was limited to polygons that were actively managed as hay, not as pasture
2123	pasture	2.3%		potential pasture fields
2/2124	General Agricultural land use/idle	14.1%		general agricultural land use (idle, and unidentified agricultural land uses
3	Brush-Range	1.3%	1.4%	Areas in transition where early successional species dominate
4	Forest	34.4%	34.8%	areas dominated by tree canopy
5	Water	0.2%	0.2%	Open Water
6	Wetlands-Mixed	0.6%	0.6%	Areas dominated by wetland vegetation, often with saturated soils and standing water.
7	Barren	0.04%	0.04%	exposed soil or bare rock

Table 4-2. Sample Soil and Water Assessment Tool (SWAT) soil data file.

Soil name	MuB	Munson silt loam	
Soil Hydrologic Group	D		
Maximum rooting depth, mm	1525		
Crack volume potential for soil	0.5		
	Layer 1	**Layer 2**	**Layer 3**
Depth, mm	203.2	355.6	1524
Bulk Density Moist, g/cc	1.300	1.100	1.600
Ave. avail. Water Incl. Rock Frag, m/m	0.215	0.180	0.170
KSAT,mm/hr	33.012	27.432	2.538
Organic Carbon, weight %	1.160	1.015	0.290
Clay, weight %	6.5	9.5	47.5
Silt, weight %	60.0	60.0	50.0
Sand, weight %	33.5	30.5	2.5
Rock Fragments, vol. %	2.500	2.500	2.500
Soil Albedo (Moist)	0.250	0.250	0.250
Erosion K	0.490	0.490	0.490
Salinity (EC)*	0.0	0.0	0.0

* Not currently used by SWAT

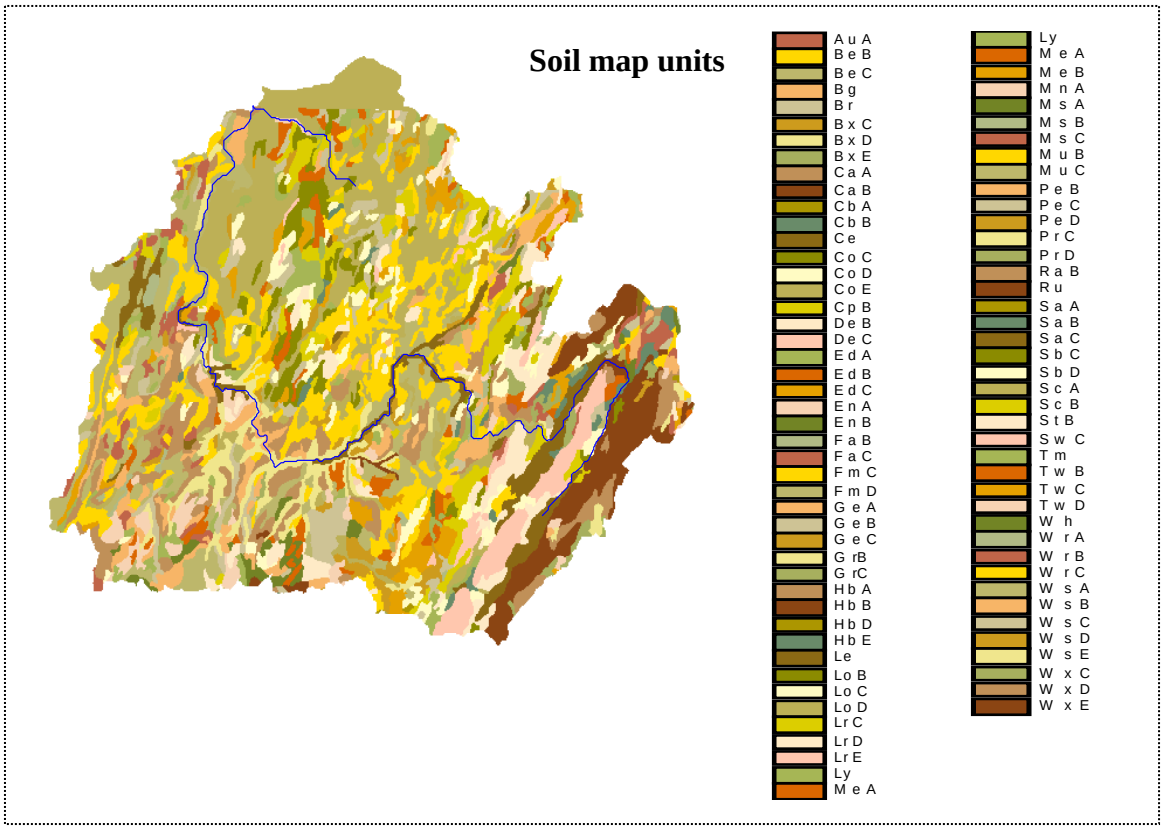


Figure 4-10. Rock River Watershed Soil data map with a map-unit level classification (Table 4-3) (soil map units are represented by the first two letters (e.g. Au in AuA represents a unique map unit, and any third letter following represents slope; A or null represents slopes with 0-2 % slope; B = represent 2-8% slope, C = 8-15 %, D= 15-25 %, and E = above 25%).

Table 4-3. Rock River Watershed Soils, percentages of soil map unit, characteristics, and suitability for farming in the Rock River Watershed. Soil characteristics and suitability information is obtained from USDA/NRCS soil database.

Soil Map Unit	% area	Name and composition	Susceptibility to Erosion	Suitability for farming
Sc	13.8	Scantic silt loam	Not potentially erodible	Farmland of statewide importance
Mu	12.4	Munson silt loam	Potentially highly erodible land	Farmland of statewide importance
Lr	10.7	Lordstown-Rock outcrop complex	Potentially highly erodible land	Not prime farmland
Lo	6.7	Lordstown loam, rocky,	Potentially highly erodible land	All areas are prime farmland
Wx	6.1	Woodstock-Rock outcrop complex,	Potentially highly erodible land	Not prime farmland
Ra	5.5	Raynham silt loam	Potentially highly erodible land	Prime farmland if drained
Bx	4.6	Buxton silt loam	Potentially highly erodible land	Farmland of statewide importance, for slope < 15%
Fm	4.5	Farmington-Rock outcrop complex	Potentially highly erodible land	Not prime farmland
Ed	4.0	Eldridge loamy fine sand	Not highly erodible land	All areas are prime farmland
Bg	3.5	Binghamville silt loam	Not highly erodible land	Prime farmland if drained
Me	2.9	Massena stony loam	Not highly erodible land	Prime farmland if drained
Ws	2.7	Windsor loamy fine sand	Not highly erodible land	Farmland of statewide importance
En	2.6	Enosburg loamy fine sand	Not highly erodible land	Prime farmland if drained
Ge	2.6	Georgia stony loam	Potentially highly erodible land	Farmland of statewide importance
Ce	2.5	Carlisle muck	---	Not prime farmland
Be	2.1	Belgrade silt loam	Potentially highly erodible land	Farmland of statewide importance
Fa	1.5	Farmington loam, very rocky,	Potentially highly erodible land	Farmland of statewide importance
Br	1.2	Birdsall silt loam	Not highly erodible land	Not prime farmland
Le	1.1	Limerick silt loam	Not highly erodible land	Farmland of statewide importance
Wr	1.0	Westbury stony fine sandy loam	Not highly erodible land	Farmland of statewide importance
Sa	1.0	St. Albans slaty loam	Not highly erodible land	All areas are prime farmland
Tm	0.9	Terric Medisaprists	----	Not prime farmland
Ly	0.9	Lyons stony loam	Not highly erodible land	Not prime farmland
De	0.9	Deerfield loamy fine sand	Not highly erodible land	Farmland of statewide importance
Cb	0.6	Cabot extremely stony fine sandy loam	Not highly erodible land	Not prime farmland
Tw	0.6	Tunbridge-Woodstock fine sandy loams, very rocky,	Potentially highly erodible land	Not prime farmland
Pe	0.4	Peru stony fine sandy loam,	Potentially highly erodible land	All areas are prime farmland
Ru	0.4	Rumney variant silt loam	Potentially highly erodible land	Farmland of statewide importance
Mn	0.4	Massena stony loam	Potentially highly erodible land	Prime farmland if drained
Pr	0.4	Peru extremely stony fine sandy loam	Potentially highly erodible land	Not prime farmland
Sb	0.3	St. Albans very stony loam	highly erodible land	Not prime farmland
Au	0.3	Au Gres loamy fine sand	Not highly erodible land	Farmland of statewide importance
Hb	0.2	Hinesburg loamy fine sand	Not highly erodible land	All areas are prime farmland
Ms	0.2	Missisquoi loamy sand	Potentially highly erodible land	Farmland of statewide importance

Climate Data

Meteorological input data including precipitation, temperature, and solar radiation are required for SWAT modeling.

No long term meteorological data exists for the watershed. As proxy data, we used nearby National Weather Service (NWS) Cooperative Observer Stations for Enosburg, St Albans, and South Hero Vermont, and Canadian government data from Philipsburg, Quebec. Figure 4-11 shows the Rock River watershed relative to these stations. These stations bracket the Rock River geographically and in elevation and proximity to the lake. Table 4-4 lists these stations by NWS station code.

Table 4-4. Weather observation Stations closest to the Rock River Watershed

Station Name	Station ID Code	Elevation (meters)	Lat Long (degrees.dd)
Enosburg	432769	128.0	44.55/ 72.49
South Hero	437607	33.5	44.38/ 73.18
St Albans	437032	115.8	44.52/ 73.05
Philipsburg, PQ	7026040	53.3	45.03/73.08

Enosburg is located ten miles east and slightly south of the center of the Rock River watershed. St Albans is 12 miles to the south, slightly inland from the lake. South Hero is a low-lying island 25 miles southwest. Philipsburg is a community on Missisquoi Bay eight miles northwest of the center of the watershed.

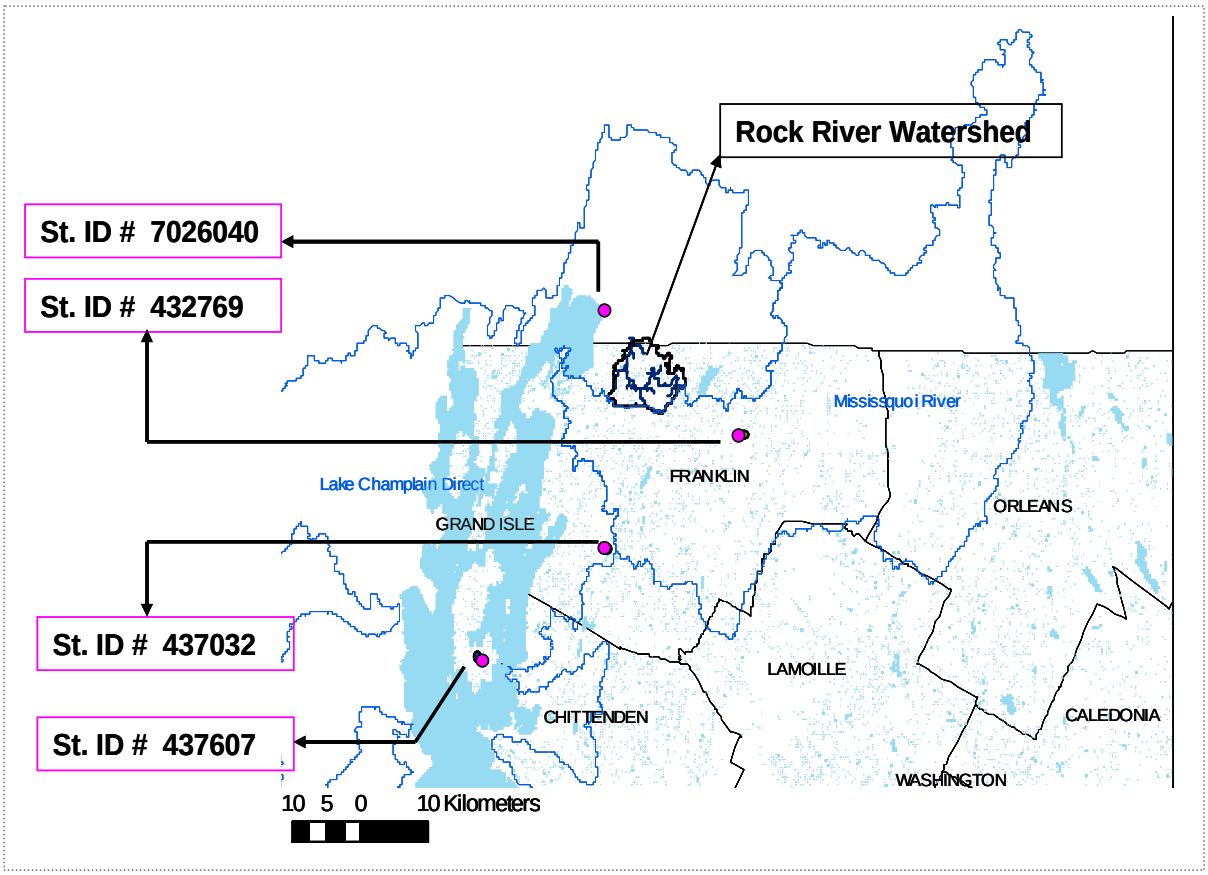


Figure 4-11. A map showing location of meteorological stations (used in this study) relative to the Rock River Watershed location. Station codes # 7026040, # 432769, # 437032, and # 437607 represent for stations in Philipsburg, PQ (Canada), Enosburg (VT), St Albans (VT), and South Hero (VT), respectively.

The portion of the Rock River watershed under consideration falls between 3 and 10 miles inland from Missisquoi Bay. It has an average elevation of 101 meters, and is flat by Vermont standards, having been in glacial times the bed of Lake Vermont and the Champlain Sea, with the Rock River now incised within this landscape.

Management Data

In general management data required for SWAT modeling study include, 1) data related to planting crop planting, tillage, and harvesting, grazing dates, 2) manure production, application, and scheduling, 3) fertilizer application, and scheduling and 4) management practices (such as crop rotation, cover crops, and others) that are currently implemented. Inventory of livestock production in the watershed is also needed in order to estimate manure production in the watershed.

Gathering these management data is still in progress. So far, data related to the number of livestock has been obtained for the 1 large farm and 4 medium farms in the Rock River watershed. Yet, similar data for the small farms is to be gathered. Other management data related to phosphorus fertilizer applications and land use management is also to be acquired.

Acquiring this kind of data is important in representing phosphorus sources in the SWAT model.

Observed (Measured) Data

Flow and water quality at the outlet of the Rock River near the border crossings of Vermont and Quebec, Canada, have been monitored by the Québec Ministère du Développement durable, de l'Environment et des Parcs (MDDEP). Stream flow data from the station # MDDEP 030425, located at Rivière de la Roche à Saint Armand in Canada (with 45.0217 Latitude ºN; 73.0161 Longitude ºW**)** was used in this study. Daily stream flow data at this station are available starting from October 1, 2001 to present. These daily stream flow data were used for model calibration and validation in the Rock River Watershed. For the hydrology model representation, the available data were divided into two data sets, with the first set (10/1/2001-9/30/2004) used for calibration, and the second set (10/1/2004-8/30/2008) used for validation.

SWAT Model Set-Up for the Rock River Watershed

In this study, a version of SWAT model with ArcView® interface (SWAT 2000) was employed. SWAT input data preparation and configurations were carried out following set up instructions in Neitsch et al. (2002b).

Watershed delineation

Processes included in the SWAT watershed delineation task are stream networks identification, watershed delineations, and sub-watershed delineations. These processes for the Rock River Watershed were performed using the watershed delineation tool built-in the SWAT ArcView® interface. A 10 m DEM data of the Rock River Watershed was used for this purpose. USGS digitized streams were also used to make sure the modeled modeled streams closely matched these data. The monitoring station mentioned previously (Lat = 45.02^0N, and Long = 73.02^0W) was used to define an outlet of the Rock River Watershed and the watershed was delineated based on this outlet data. In side the watershed, sub-watershed outlets were defined by SWAT based on the generated streams. Additional sub-watershed outlets were defined to match USDA/NRCS planned synoptic sampling sites within the watershed. In total, 38 sub-watersheds were produced for the watershed, as shown in Figure 4-12.

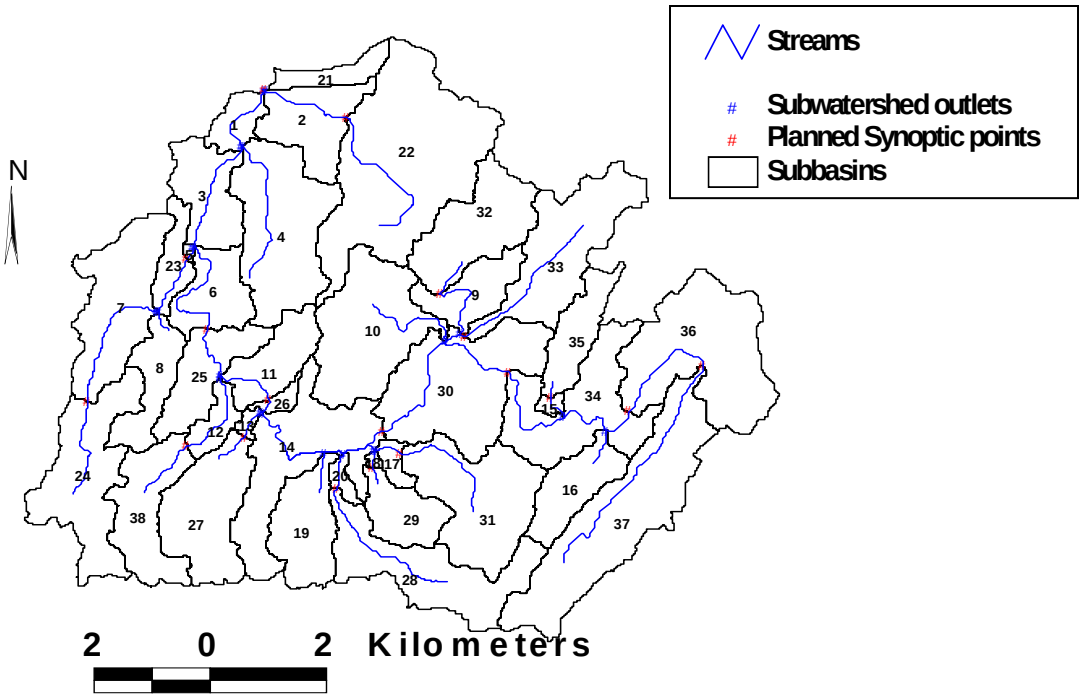


Figure 4-12. Sub-basins generated for the Rock River Watershed; stream network, sub-basin outlets, and synoptic points added in as sub-watershed outlets.

Hydrologic response units (HRUs)

Rock River Watershed land use and soil data described in the previous sections were added to SWAT interface using the SWAT land use and soil definition tool. SWAT subdivides each sub-watershed into unique hydrologic response units (HRUs) based on land use and soil combinations. For this study, individual land use and soil combinations located within each sub-watershed were generated using SWAT built-in HRU definition tool. Unique land use and soil combinations were preserved as a unique HRU by avoiding any lumping even if the percent of area is very small.

Calibration and Validation for Hydrology Simulations

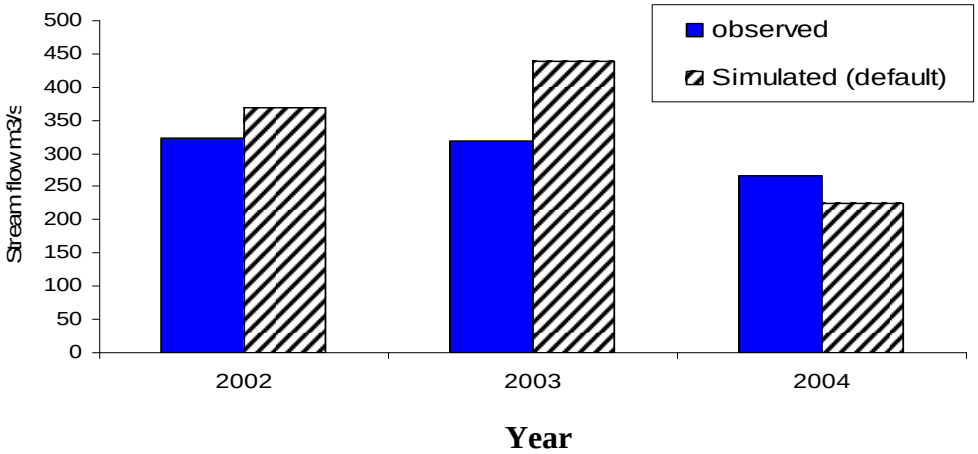
Once all input data had been prepared, the initial (uncalibrated) SWAT run, herein referred to as the default run, was performed. Model performance for the default run was assessed considering a comparison of descriptive statistics for measured and simulated runs, the Nash-Sutcliffe coefficient, NS (Martinez and Rango, 1989), and time series plots of simulated versus observed (measured) data were compared.

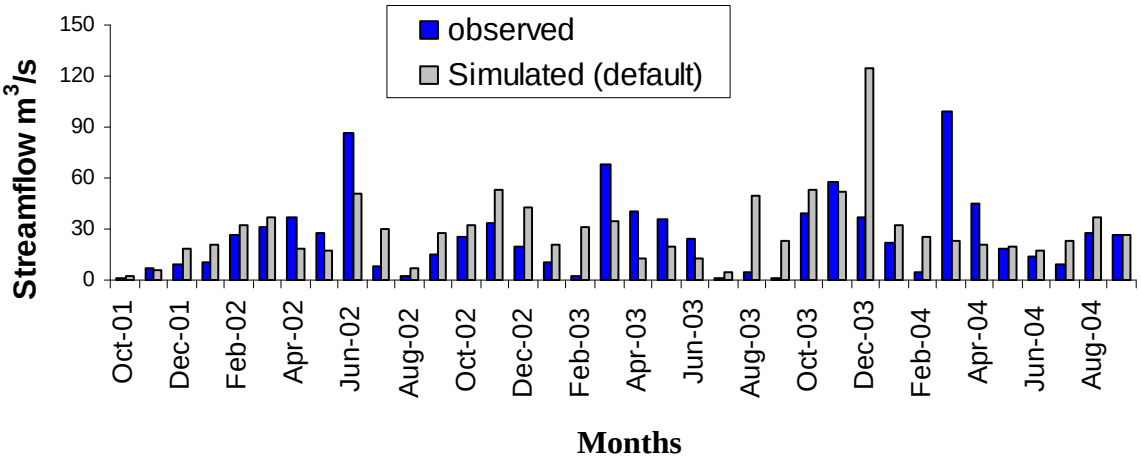
One measure of prediction strength commonly used when calibrating watershed-level hydrologic and water quality models is the Nash-Sutcliffe statistic (NS, Martinez and Rango 1989). The equation used to find NS value is presented in equation (1). NS values range from negative infinity to one, with values of NS close to 1 indicating improved model performance and a value of zero indicating that the simulated values provide no better prediction than the mean of observed values. The NS can be calculated on a daily, monthly, or yearly scale. A review of the watershed-level, water quality modeling literature by Morasai et al. (2007) found values of NS > 0.50 generally considered satisfactory with median monthly NS values across the reviewed calibration literature of 0.79 value for stream flow.

$$NS = 1 - \frac{\sum_{t=1}^{T}\left(Q_0^t - Q_m^t\right)^2}{\sum_{t=1}^{T}\left(Q_0^t - \bar{Q}_0\right)^2} \qquad \text{equation (1)}$$

where Q_0^t is observed discharge, $\bar{Q}_0$ is mean of observed discharge, and Q_m^t is modeled discharge.

Based on the results of the default run (Figure 4-13), it was observed that simulated stream flow rates were too high, as compared to measured data (except for the 2004 simulation period), while ground water flow rates were too low, based on the differences in recession, between the measured and simulated flows (daily time step). Simulated flow rates were generally low in the early summer months (May and June) and high in the late summer months (July, August and September) as evidenced from daily and monthly plots, and underestimated during most of the winter months, as evidenced from monthly plots. Additionally, there were peak flow rates on the simulation runs without corresponding peak flow rates on the measured data (daily time step).





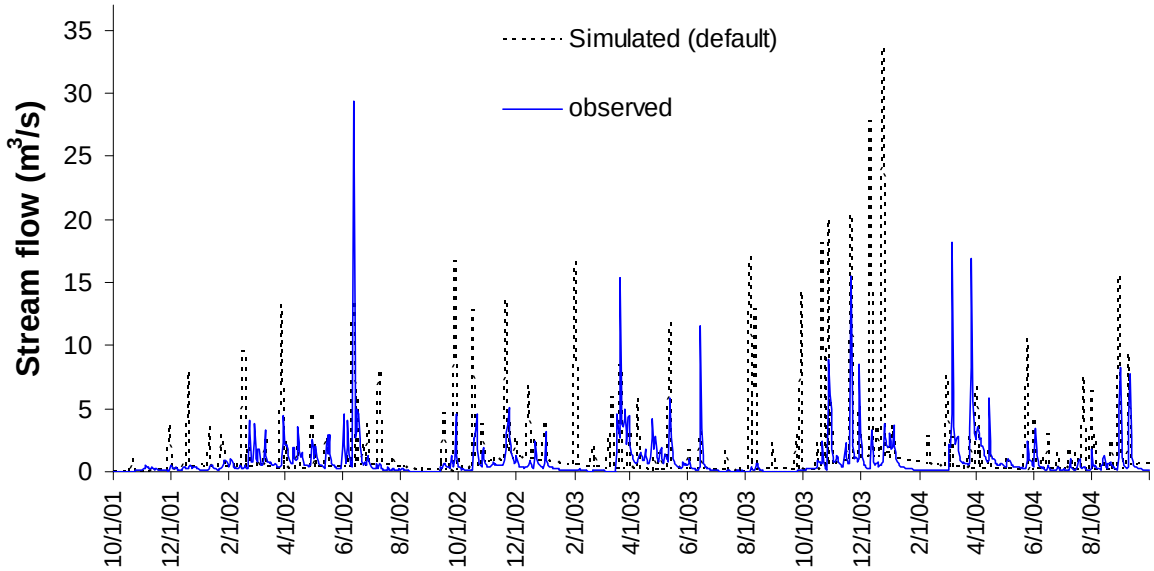


Figure 4-13. Default annual, monthly, and daily flows in comparison to observed flows.

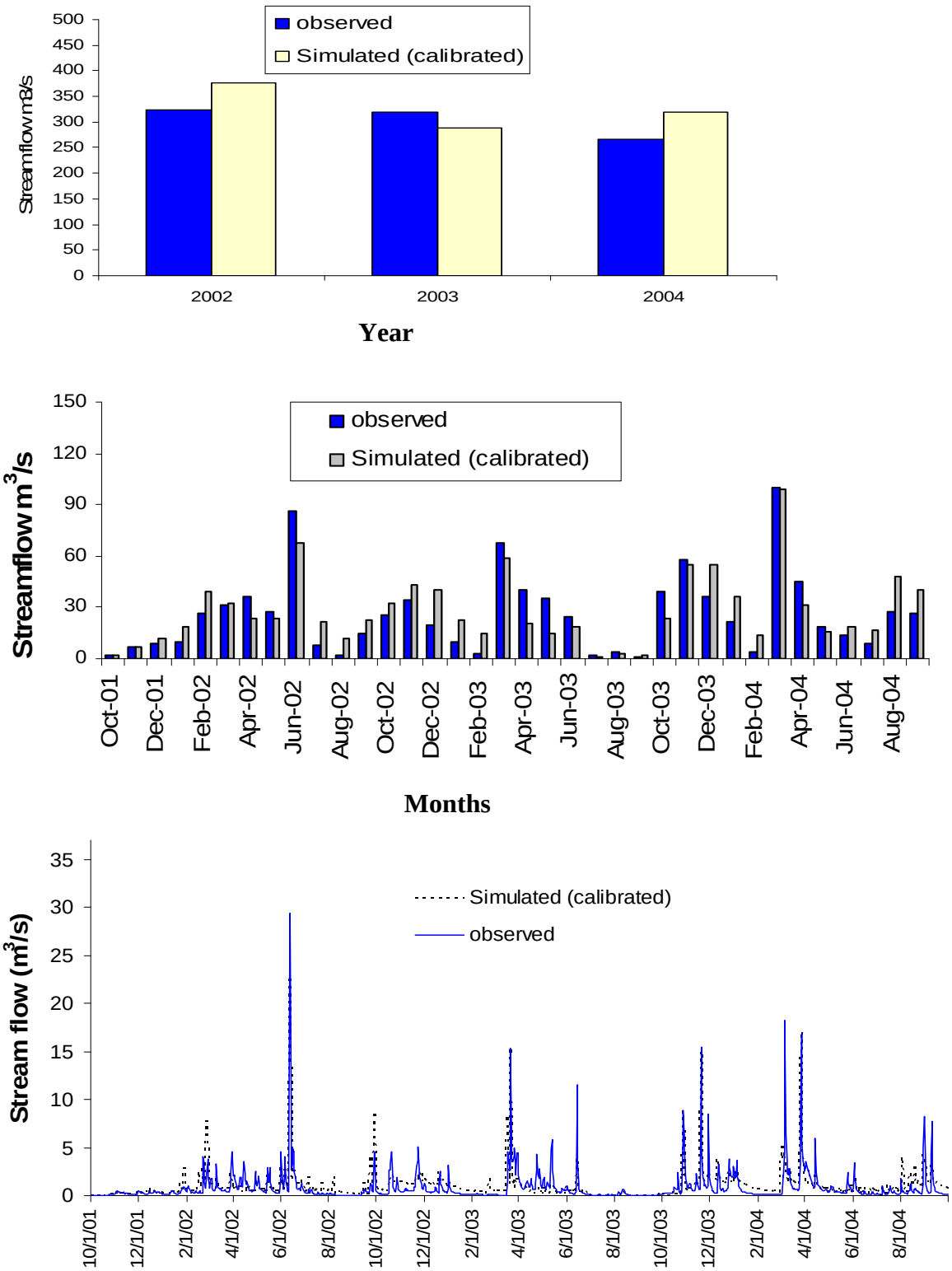


Figure 4-14. Calibrated annual, monthly, and daily flow rates in comparison to observed flow rates.

Table 4-5. SWAT model performance for hydrology calibrations (10/1/2001-9/30/2004). Stream flow in m^3/s.

		Stream flow		
Time Period	**Statistics**	**Measured**	**Default**	**Calibrated**
Monthly	Mean	25.75	29.43	27.92
	Standard deviation	23.28	21.32	20.92
	NS		-0.30	0.81
Daily (Including all data)	Mean	0.86	0.97	0.92
	Standard deviation	1.76	2.53	1.42
	NS		-0.84	0.61
Daily -Winter (Nov –April)	Mean	0.77	0.76	0.73
	Standard deviation	1.68	2.03	1.2
	NS		-1.16	0.51
Daily- Non-winter (Mar-Oct)	Mean	0.98	1.09	1.07
	Standard deviation	1.73	2.75	1.49
	NS		-0.44	0.70

Model performance measures for daily and monthly flow rates (NS = -0.83 and -0.30 respectively; Table 4-5) implied a need for thorough calibration on daily and monthly flow rates.

Therefore, sensitive hydrologic parameters (such as curve number, the available water capacity of the soil, and various base flow recession, ground water recharge, evapotranspiration, and snow melt factors) were adjusted during model calibrations. Performance measures were re-computed for calibration runs, and annual, monthly and daily time series plots made to further determine the suitability of the model calibrations. Model calibration results are presented in Figure 4-14 and Table 4-5. As shown from the time series plots of Figure 4-14 and performance measures, accuracy of simulated results much better than the default run.

After calibration, model performance measures, NS values, for daily and monthly flow rates were 0.61 and 0.81 respectively; Table 4-5. NS value was also re-computed for winter and non-winter months, and the NS values were 0.51 for winter and 0.70 non-winter months. Though these values are above the 0.50 NS value that was considered satisfactory for hydrology calibration (Morasai et al., 2007), more model calibration is needed to improve the accuracy of the stream flow predictions, especially during winter seasons. Hence, further adjustments of sensitive hydrologic parameters, especially those that control winter hydrology and stream flow in the reaches are yet to be accomplished. Moreover, validation procedures will be accomplished to make sure results are repeatable for different conditions. Therefore, simulation results presented herein this report should be taken as preliminary results.

Determination of Critical Source Area for Runoff Loss

From the SWAT preliminary calibration results, a spatial data of annual stream flow can be generated using GIS techniques. Spatial data for the 2001 is presented in Figures 4-15 and 4-6 for demonstration purposes. Map on Figure 4-16 represent for only one of subbasins in the Rock River Watershed (shown in Figures 4-15). Such spatial data obtained from the SWAT model, shown in the Figures 4-15 and 4-16, indicates model's ability to represent runoff generation areas at a watershed scale. These data represent different runoff generations from various response units of different land use, soil, and slope combinations. Areas shaded with darker (red) showing higher runoff generation areas, while areas with lighter (white) showing low runoff generating areas. Using this type of spatial representation, areas with higher runoff generation can be identified.

These spatial data represent only for overland runoff flow. These overland flows of the hydrologic cycle control the amount of water, sediment, and phosphorus loadings to the main channel in each subbasin. However, ones analysis of stream flow in reaches for each sub-basin (Figure 4-12) is done, similar maps that show the different routing processes of flow in reaches can be developed. The routing phase of the hydrologic cycle depicts the movement of water, sediments, and phosphorus through the channel network of the watershed to the outlet.

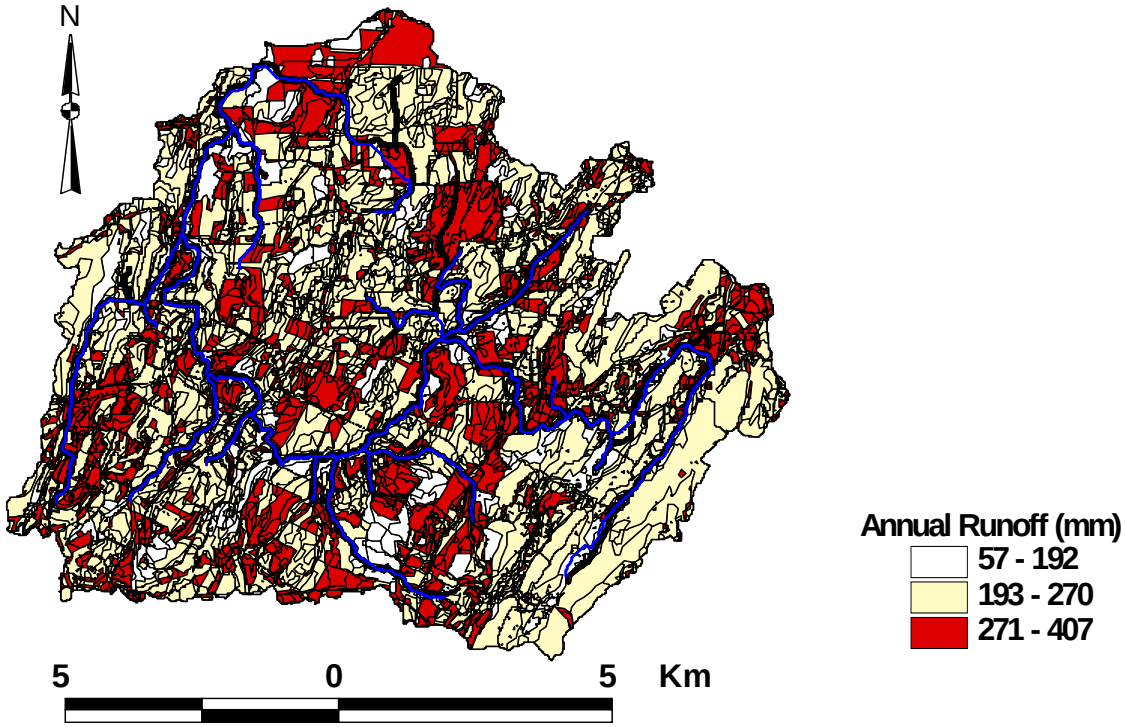


Figure 4-15: Hydrologic response area representing runoff generation areas.

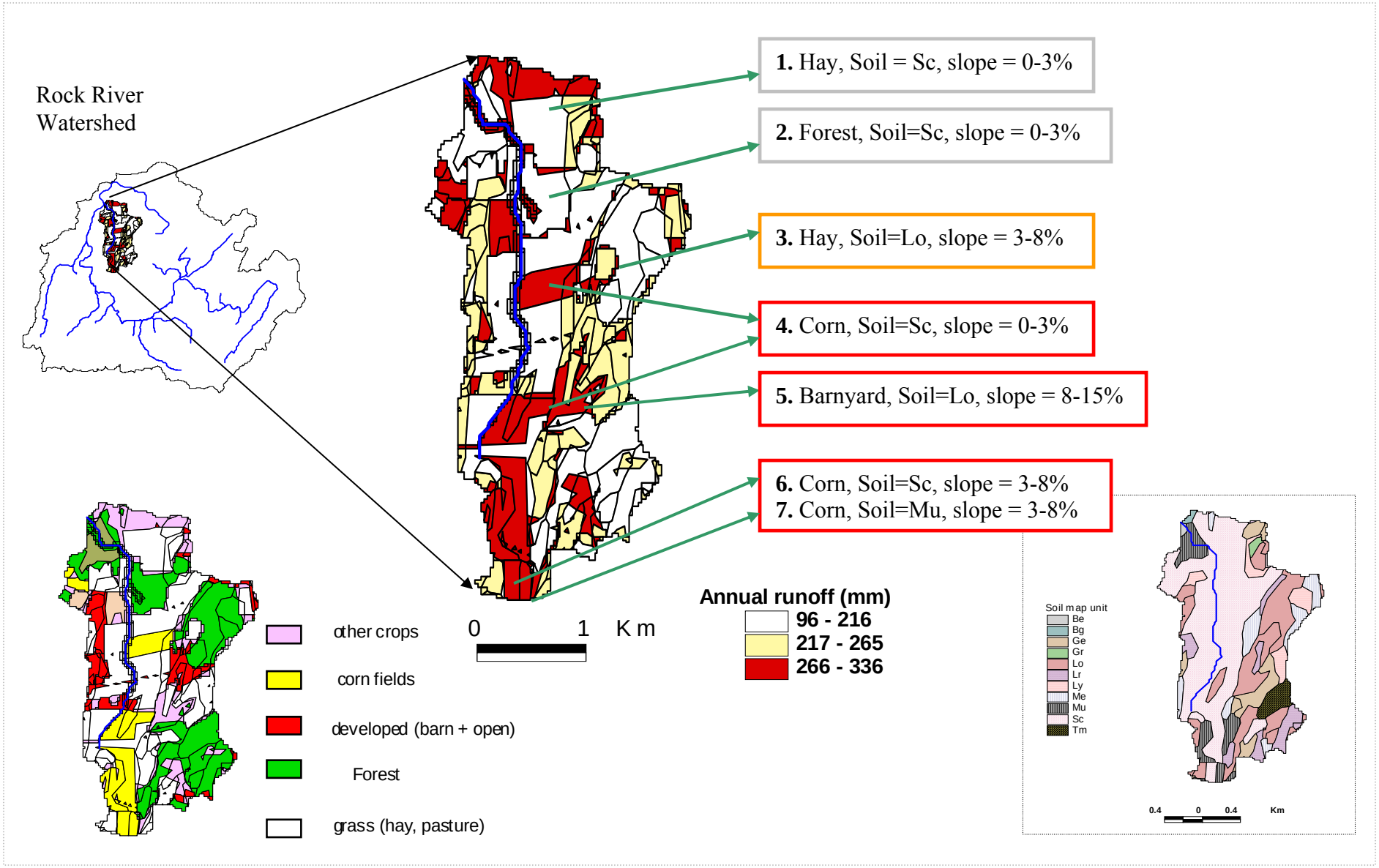


Figure 4-16. Spatial representation of runoff generation areas of one subbasin in the Rock River Watershed, with bottom maps of land use and soil data.

From the overland flow map shown in Figure 4-16, for example, runoff generation appeared to be more sensitive to land use than soils. SWAT uses a Curve Number (CN) method in estimating runoff volume. Since CN values, in general, are larger for agricultural land use than forest, agricultural land tends to produce more runoff in SWAT than forest for the same soil types (Figure 4-16). Moreover, SWAT identified large corn fields (box # 4 in Figure 4-16) to right side of the stream as major runoff source areas (compare the dark colored area presented in Figures 4-16). These fields had gentler slope near the ridge (< 3 percent) and steeper slopes near the stream (approximately 25 percent). Because of the large slope and corn land use type, SWAT identified these fields to be major runoff source areas.

The spatial runoff generation map also demonstrates difference in runoff contributions from two fields of the same land use types but with different soils and slope. For example, runoff generation from two fields with hay crop, indicated in box #1 and #2 of Figure 4-16, is different because of their difference in soils and slope. This also indicates how this type of spatial map of runoff generation helps to identify fields with the same land use type requiring different priorities for management practices depending on their slope and soil type.

In addition, the spatial representations of runoff generation areas help to prioritize management strategies to fields closer to streams. For corn fields represented by box #4 vs. box #6 and #7 of Figure 4-16, for example, corn fields represented by box #4 are more likely to benefit from applying management practices compared to fields represented by box #6 and #7, though all fields are simulated to have the same potential for runoff generation. This is because fields closer to stream are more active during storm events, producing the majority of storm flow. Hence, fields closer to streams makes them to have higher potential threat of runoff, erosion and associated phosphorus losses.

Approach to Phosphorus Critical Source Area Identification

Once the hydrology calibration and validations processes are completed, calibration and validation procedures will be run for SWAT predictions of sediment and phosphorus losses. The procedures will be run until the simulated and observed loadings matched as closely as possible. Following these procedures, spatial pattern of phosphorus loss generating areas, similar to these runoff generating areas presented in Figures 4-15 and 4-16 will be generated for phosphorus loss on a yearly and a seasonal basis. These generated maps showing critical source area for phosphorus loss can then be used to design and focus management practices within specific fields. Following this, the effectiveness of these potential management practices in reducing phosphorus losses will be evaluated. We anticipate this work to progress shortly as part of the second year's work plan.

Comments on Anticipated Results of the Phase I

The following points summarize key accomplishments expected from completion of the Phase I of the project.

- Critical areas of runoff and phosphorus losses in the Rock River Watershed will be identified.
- Critical areas of runoff and phosphorus loss characteristics will be grouped by common land use, soil, slope, distance to streams, and management activities.
- Potential management practices appropriate to these specific combinations of land uses will be identified and management practices will be assessed for their effectiveness in the Rock River Watershed.

The following points summarize potential applications of the findings listed above beyond their application to the Rock River Watershed

.

- Insights and finding from the results will help identify factors that can be used to find critical source areas for phosphorus loss, such as land use, soil, slope, distance to streams, and management activities for scaling up in agricultural watersheds throughout the Lake Champlain Basin.

- The evaluation technique used in the Rock River Watershed will help to extrapolate the various factors (land use, soil, slope) and potential management practices envisioned and their effectiveness at a larger scale and under time-varying climatic conditions. Such evaluations can only be made by development and application of model(s) appropriate to the questions being asked.

- We recognize the potential of VT P-index tool to offer a comprehensive assessment of phosphorus sources and transport areas at field and farm scales that can be directly used to help farmers and land managers to identify critical phosphorus loss areas and direct remediation measures to those specific locations within the watershed. We also recognize the need for field validation to confirm its reliability as a risk assessment tool. To this end, we envision a great potential for using the field-by-field based phosphorus runoff losses from Rock River Watershed predicted by the SWAT model for validating the phosphorus transport component of VT P-index.

5. Second Year Project Work Plan

The stated goal of our project is to develop a framework and model that can be used to account for major sources and potential reductions of phosphorus across the landscape. In Phase 1, we conducted a literature review and framed the issues. We summarized the relative reductions in phosphorus that might be achieved using various BMPs in both agricultural and urban/suburban land areas.

We chose to start our project with a focus on the Missisquoi watershed. Because agriculture is estimated to be about 70% of the nonpoint source in this watershed, we also chose to begin by developing an agriculturally focused tool. In order to accumulate phosphorus across the watershed and consider the relative importance of landscape factors like slope, soil type and specific land use, contiguities and connections in the riparian corridor and stream network, we needed to use a watershed model. We selected SWAT (Soil and Water Assessment Tool) for this purpose.

In order to identify critical source areas of phosphorus, it is essential to have a way to account for phosphorus across the landscape and transport it to Lake Champlain. Critical source area identification and evaluation of the most effective ways to control and/or reduce phosphorus losses in these areas are the primary uses of an accounting system, and thus a second endpoint of our project. The development of an accounting system and use of that system to examine critical sources and potential reduction scenarios are essentially highly related tasks and both are included in our efforts.

Because of logistical challenges associated with starting with a watershed the size of the Missisquoi and data availability to calibrate the SWAT model, we have begun by focusing on the Rock River watershed. This smaller watershed will allow us to examine in detail the sources and transport of phosphorus and to develop an overall approach to accounting and targeting critical source areas that then can be applied throughout the basin.

The single greatest problem with the current TMDL implementation plan is the lack of clearly defined and measurable objectives for the nonpoint sources. Our goal is to produce a tool that can be used to account for the phosphorus reductions that might be associated with various management actions on agricultural land. In addition to telling us where we stand, these comparative values can be used to explore which management interventions, in which places, offer the greatest potential for reducing the phosphorus load to Lake Champlain.

In year two, we will focus explicitly on developing a management tool that can be used in an adaptive implementation strategy to answer four critical questions relative to agricultural land uses:

- Where do we stand right now?

- What are the critical sources and source areas we need to address?
- What interventions will provide the greatest phosphorus reductions in these areas?
- What are realistic expectations of outcomes once we do intervene (in terms of both the phosphorus balance and the timeline for response)?

The following sections outline the major tasks remaining in the project.

Tasks to be accomplished in **Phase I** of the project

The majority of the Year 2 work plan involves continuation of the Tasks listed in **Phase I** of the report (Year 1 report, Figures 4-2, 4-3, and 4-4). Major tasks of **Phase I** involve:

1. Data gathering (base input data, management data) and pre-processing to support the SWAT model.

Basic input data such as, land use, soils, elevation, weather data (daily precipitation, Tmax, & Tmin, and monthly Radiation) have been gathered and pre-processed to fit the format requirement by SWAT model.

The SWAT model allows a watershed to be divided into sub-basins based on topographic criteria and user defined streams. A 10 m DEM data of the Rock River Watershed was used to define stream networks, and a USGS digitized streams layer was also used to make sure the modeled streams closely matched these data. In addition, stream networks were defined to match the VT DEC planned synoptic sampling sites within the watershed. The sub-watershed and stream net-works generated in our SWAT modeling are as presented in the Year 1 report. However, stream networks representation in SWAT can be modified should there exist actual drainage networks data. We are not aware of existence of any other data related to drainage networks and we plan to work on these stream net-works and sub-watersheds defined and presented in the Year 1 report.

In the SWAT model, hydrologic response units (HRUs) within each sub-watershed are defined based on the combinations of land use, slope, and soil types. In order to simplify SWAT runs, areas of a particular land use, slope, and soil type within a sub-basin are combined together to form one HRU without any consideration to individual fields and with no significance to their spatial location. However, in this project, we are planning to minimize lumping of land areas with similar combinations of land use, slope, and soils by performing some modification of the SWAT model input data format and by uniquely coding the FSA Common Land Unit (CLU) fields. The distinct representation of fields is useful during the process of HRU formation to avoid lumping of similar land use, slope, and soil combinations of different fields within a sub-basin into one HRU. Once the field boundaries are taken into account in the process of HRU development, amounts of runoff and associated sediment and nutrient loadings for each field can then be extracted from the outputs of HRUs that are distinct to each field.

We will also gather as much information as we can on tile drainage and ditching. SWAT has a standard routine for representing tile drainage. Colleagues in Canada (IRDA) who are also working on SWAT applications in the Lake Champlain Basin have also developed a SWAT version with a modified tile drainage module that captures their study area. We plan to test the suitability of both these SWAT versions. It is possible to use SWAT to represent hydrologic modifications in the landscape due to ditches. Hence, if the data can be acquired, we will examine the impacts of both tile drainage and ditching using SWAT.

Input data concerning management are not completely acquired and hence we will continue to gather these data as part of the Year 2 work plan. Management input data required include: 1) inventory of livestock, which will be used to estimate the amount of manure production, 2) data related to crop planting, tillage, and harvesting, grazing dates, 3) typical manure application rates and scheduling, 4) fertilizer application, and scheduling, and 4) management practices (such as crop rotation, cover crops, and others) that are currently implemented. These data are required by the model in order to appropriately simulate sediment and phosphorus losses. Other input data that may help in improving data representation and validating model predictions include, among others, soil phosphorus test, manure analysis results (% of phosphorus in manure).

So far, data related to the number of animals have been obtained for the 1 large farm (LFO) and 3 medium farms (MFOs) in the Rock River watershed. Similar data for the small farms still must be gathered. Details of input data, their sources and level of specificity and importance are presented in the table below.

Table showing details of input data for Phase I of the project
(information will continue to be updated and refined as the project proceeds)

Data Item	Source of Data	Data Status	Level of Specificity	Level of importance and purpose
		(a) already obtained by investigators, or (b) promised by agency (specify), or (c) will be obtained by investigators (d) other	(a) farm or field-specific, or (b) generalized for watershed (c) other (specific)	
Measured data Stream flow, sediment, & Phosphorus	Canada: Québec Ministère du Développement durable, de l'Environment et des Parcs (MDDEP)	(a)	(c) Data at the outlet of the Rock River Watershed	Required for model calibration/validation
Synoptic sampling data within the Rock River watershed.	VT DEC	(b)	(c) Data within the subwatersheds of the Rock River Watershed	Optional data, if available, important for validating SWAT predictions across the subwatersheds
DEM	1) Vermont Center for Geographic Information VCGI 2) Canadian Digital	(a)	(b)	Required input for SWAT model: used to generate stream networks, slope calculations, and other

	Elevation Data)			watershed characteristics.
Land use General land cover data (2001) FSA Common Land Unit (CLU) fields Active farmstead areas	University of Vermont (UVM) spatial analysis lab USDA/NRCS GIS lab	(a)	(a) and (b)	Required input for SWAT model: used to represent land cover characteristics of crop and animal production area.
Soils map & Soil characteristics	USDA/NRCS	(a)	(a)	Required input for SWAT model: used to represent soil- water movement
Climate data: Precipitation, temperature	NOAA/ NCDC stations (Enosburg, South Hero, & Saint Albans) Canada (Philipsburg) - Banque de données climatologiques - données préliminaires et approuvées, Québec, Ministère du Développement durable, de l'Environnement et des Parcs, Direction du suivi de l'état de l'environnement.	(a)	(c) Station-specific daily data	Required input for SWAT model: used to represent water balances and initiate water-soil movement
Crop planting, tillage, harvesting, grazing	NRCS, Nutrient management planners, VT AAFM, Farmers Watershed Alliance, USDA-NASSS data	(d) We will set a meeting with these agencies to figure out from where exactly to find this data	(a) -Best will be to find field specific data If not, (c) crop-specific typical data	Required input data for SWAT model in representing crop production
Inventory of Large and Medium Farm operations	*Vermont* Agency of Natural Resources	(a)		Required to estimate manure production input to SWAT model.
Inventory of Small Farm operations	UVM extension, NRCS, Nutrient Management planners, VT AAFM, Farmers Watershed Alliance, USDA-NASSS data	(d) We will set a meeting with these agencies to figure out from where exactly to find this data	(c) preferred to find, # of small farms, and # livestock of each farm	Required to estimate manure production input to SWAT model.
Manure application rates and scheduling	NRCS, Nutrient management planners, VT AAFM, Farmers Watershed Alliance, USDA-NASSS data	(c)	(a) Best will be to find field specific data; If not, (c) crop-specific typical data	Required input data for SWAT model: used to estimate input sources of phosphorus in manure
Type of manure produced (liquid, sold, mixed	Nutrient management planners	(c)	(b)	Input data for SWAT model.
Manure analysis	Nutrient management planners, or	(c)	(b)	Input data for SWAT model.
Fertilizer application, and scheduling	NRCS, Nutrient management planners, VT AAFM, Farmers Watershed Alliance, USDA-NASSS data	(c)	(a) Best will be to find field specific data; If not, (c) crop-specific typical data	Required input data for SWAT model: used to estimate input sources of phosphorus in fertilizer
Management	NRCS, Nutrient	(c)	(a) Best will be	Required input data for

practices (such as crop rotation, cover crops, and others)	management planners, VT AAFM, Farmers Watershed Alliance, USDA-NASSS data		to find field specific data; If not, (c) crop-specific typical data	SWAT model: used to represent existing management efforts
Soil Phosphorus test	NRCS, Nutrient management planners	(c)	(a) Best will be to find field specific data; If not, (c) crop-specific typical data	Optional data, if available, important for validating SWAT predictions of soil phosphorus
Tile drained fields (and ditches)	UVM extension, NRCS, Nutrient Management planners, VT AAFM, Farmers Watershed Alliance, USDA-NASSS data	(c)		Required input data for SWAT model: used to represent the hydrological modifications due to tile (ditches) drainage.

2. Model calibrating and validation for hydrology, sediment and phosphorus.

Observed flow and water quality data required for calibration and validation the SWAT model is being acquired from the Québec Ministère du Développement durable, de l'Environment et des Parcs (MDDEP). Stream flow data obtained is from the station # MDDEP 030425, located at Rivière de la Roche à Saint Armand in Canada (with 45.0217 Latitude ºN; 73.0161 Longitude ºW**).** Sediment and phosphorus data gathered are from the station # MDDEP 03040112, located at Rivière de la Roche, north of border in Canada (with 45.0177 Latitude ºN; 73.0519 Longitude ºW**).**

So far, preliminary calibration of hydrology is completed. As part of the Year 2 work plan, we plan to improve hydrologic predictions by calibrating sensitive hydrologic model parameters, such as Curve Numbers and Snow-melt factors and also by improving actual hydrologic response areas such as representing the existing tile drained fields.

In addition, in Year 2 we will calibrate and validate the sediment and phosphorus loss predictions. As a result, critical source areas will be identified within the Rock River Watershed for runoff, sediment, and phosphorus losses.

3. Application of the model for representing and evaluating best management practices.

The effectiveness of potential best management practices within the Rock River Watershed will be quantitatively evaluated.

<u>Tasks to be accomplished in **Phase II** of the project.</u>

1. Select two (or three) representative farms and gather data required for IFSM model simulation.

Though detailed soil phosphorus test data for Rock River Watershed fields are not available, considerable agricultural fields in Lake Champlain Basin were reported in the "*State of the Lake 2008*" to have high and very high soil phosphorus levels that are above the crop's phosphorus requirements. Similar soil phosphorus levels may be presumed in the Rock River Watershed in which the phosphorus loss per unit area is high. There may be many contribution factors to these higher soil phosphorus levels. Excess feeding of phosphorus to animals may enrich livestock manure with excess phosphorus. Application of manure with higher phosphorus content to cropland has the potential to cause phosphorus accumulation in the soil. In addition, application of manure to agricultural crops, with manure application rates based on field-specific nitrogen (N) requirements, increases soil phosphorus build-up and the risk for runoff phosphorus loss.

As stated previously, we are using a modeling approach to account for and track P (for its sources and movements) across the landscape. In Phase I of the project presented previously, we plan to use SWAT model in accounting and tracking P sources and transport factors in the landscape. SWAT model representation of P sources and transport mechanisms and management strategies for remediation is the major part of the project, and it is expected to take the major part of the time in the Year 2. However, for comprehensive P accounting system, there is a need of P accounting in the animal production part of the agricultural production, which won't be accounted using the SWAT model. SWAT model doesn't have components, such as an animal model, that represents P processes in cows and farm phosphorus inflows (in feed concentrates, minerals, and forage) and outflows (in milk, and crops and animals sold). Also, the SWAT model does not have a model component for predicting the amount of manure produced, manure P contents, P imports and exports and other important farm factors for specific farm strategies. Hence, using the IFSM model becomes helpful in order to account for this P in animal production that would not otherwise be included in the SWAT model. Hence IFSM model is expected to provide information that can't be acquired by using the watershed scale model, the SWAT model. Conjunctive use of both SWAT and IFSM models is helpful in order to perform comprehensive accounting of the P sources and transport processes. However, by integrating the use of both models, information acquired from one model can also be used to instruct the other model in testing management strategies that address P problem issues in both animal and agriculture production areas.

The IFSM has model components that can be used to examine farm dietary P and farm P balances among others. Accounting for dietary P and farm P balances (or imbalances) will help to estimate surplus P in resulting from the existing set of farm strategies. As part of the accounting system and using this system to target management practices to these practices, we feel that it is important to identify potential root causes of the phosphorus imbalance at the farm level.

Best management practices, which are typically structural or management based, are designed to control off-field P transport to streams, but they do not address long-term, on-farm P imbalances. Over time, the effectiveness of such BMPs may be limited as soil-P

build-up continues. Hence, identifying and targeting the root cause of the P imbalance is critical to the long-term health and quality of the Lake Champlain.

Because of Lula's experience on successful use of IFSM in New York farms in identifying and targeting the root cause of the P imbalance, we know what set of input data need and how to robustly run the model to represent farm strategies. We are also planning to bring a student to facilitate data collection and model data entry.

The 2002 CENSUS OF AGRICULTURE - USDA, National Agricultural Statistics Service (presented in table below) shows that about 42% of the cows in Franklin county are owned by small farm operations; 26% of the cows are owned by medium farm operations (MFO), and 31% of the cows are owned by large farm operations (LFO). Based on the Vermont's farm size categorization, a farm having cows that are less than 199 is considered to be small farm; farms with number of cows greater than 200 but less than 499 are categorized as MFO; and farms with number of cows greater than 500 are categorized as LFO.

Table showing Cattle Inventory of 2002 in Franklin County, VT
(source USDA, National Agricultural Statistics Service)

Farms by inventory	# cows	# of farms	Percent of farm sizes in the county
1-9	216	41	0.3%
10-19	596	44	1%
20-49	2,154	69	3%
50-99	6,221	83	9%
100-199	19,332	139	29%
200-499	17,832	59	26%
>500	21,020	24	31%

In Rock River Watershed, there are 3 MFO, with 380 cows (plus 200 young stock), 250 cows, and 206 cows (135 young stock). Also there is one farm categorized as a large farm operation (LFO) with 95,000-100,000 chickens. The majority of the farms in the Rock River Watershed fall under small farm operations category.

Therefore, for our study, we plan to select 1 MFO farm and another 2 farms from small farm operations with 100-199 cows as representative farms. Though these are our criteria for selecting representative farms, the numbers of farms and actual farms to be studied are dependent upon finding volunteer farmers. We plan to consult with a variety of agricultural professionals to help find willing farmers.

We will also use meetings with farm practitioners and advisors to help guide our farm input scenarios. In addition to nutrient management planners and UVM extension faculty and staff, we will also consult with the Farmer's Watershed Alliance, NRCS, and VT AAFM. We are also aware that farm data is being acquired through Heather Darby's oilseed demonstration project. We will assess the possibilities of involving this farm as

one of our pilot (representative) farms in assessing P inflows and outflows and in testing benefits of potential farm strategies in balancing farm P.

Model Input data: IFSM model requires three input data files, such as farm, machinery, and weather input data to represent the farm system. The farm data consist of detailed information that describes a farm enterprise. These are crop types and their area, generalized soil type and slope, type of animal (Holstein, Jersey, and others), number of cows of different ages, typical feed rations, manure handling strategies, equipment and structures used, and prices of farm commodities produced, purchased feeds, and farm products sold off-farm.

The machinery file contains data for machinery used, including parameters related to machine type, size and associated costs. Finally, the weather file consists of weather data required by the IFSM model. These data include daily values of total precipitation, maximum and minimum temperatures, and solar radiation.

Data sources: most of the data related to farm and machinery use will be collected from the specific farms. However, data related to weather data, slope, and soils that have already been gathered in Year 1 will be used as input to the IFSM model.

2. Once these farm inputs are gathered and entered in the IFSM model, the model will be used, among others, to assess feed production and utilization, determine phosphorus mass balance and the economic status of the farms, and determine dietary phosphorus in the ration.

3. Using the model outputs, the need for a change in farm system strategies, such as on-farm feed production and feeding strategies will be evaluated for farms with surplus phosphorus.

4. Finally, benefits of various potential changes in farm strategies will be evaluated for reducing surplus phosphorus.

Tasks to be accomplished in **Phase III** of the project

This section of the project involves integrating findings of modeling systems developed in Phase I and II, the watershed-scale and farm-scale models and accounting systems. This is essential for incorporating farm-based planning into watershed-scale management programs. Details of this task will depend on the results of Phases I and II. However, based on these analyses, we will:

- Identify critical areas of runoff and phosphorus losses in the Rock River Watershed.
- Group critical areas of runoff and phosphorus loss by characteristics such as common land use, soil, slope, distance to streams, and management activities.

- Identify potential management practices appropriate to these specific combinations of land uses and assess management practices for their effectiveness in the Rock River Watershed.

We will also extend the study farm results to selected watershed-scale scenarios designed to assess varying degrees of adoption of farm management systems by the dairy community and their potential impacts on the watershed phosphorus mass balance.

We recognize the particular interest in determining whether high soil P concentration is a critical source factor. Continued addition of fertilizer and manure in excess of crop nutrient requirements leads to a build-up of soil phosphorus levels in soils, which is a critical source factor in increasing the risk of adverse environmental effects from P loss to water. In addition to soil P, the load of P loss, however, depends on the runoff volume and erosion potential, which in turn, are related to climatic, agronomic, and tillage factors. By using SWAT, we expect to find out how different sets of situations, sources and transport factors contribute to high P loss. In short terms, using SWAT we expect to find where high build-up of soil P levels are occurring, and where the P losses to the water bodies are coming from.

Once the runoff, sediment and phosphorus losses are simulated using a SWAT model, we envision a great potential for using the field-by-field based P runoff losses from Rock River Watershed predicted by the SWAT model for validating the P transport component of VT P-index. However, such a full validation of the phosphorus transport component of VT P-index is beyond the scope of the Year 2 work plan. The processes of representing runoff, sediment, and phosphorus losses and management scenarios in the SWAT model will take the major part of the time in the Year 2.

Because there is basic uncertainty and some disagreement among the basin technical community about the relative importance of farm production areas and cropping areas as critical sources of phosphorus loading, we will examine this question using the combination of IFSM and SWAT modeling. In particular, data related to the location and size of the farm production areas will be collected in order to simulate P losses from active barn areas.

At the end of the project, we will develop overall guidance for a basin-wide system of phosphorus critical source area identification and accounting that can be scaled up for use in agricultural watersheds throughout the Lake Champlain Basin. We will use the lessons learned from the modeling to inform the development of this guidance. We hope to be able to generalize predictions from this process about the effectiveness of various potential management practices at a larger scale and over longer time frames.

Deliverables

The following deliverables will be produced as part of this project:

- A QAPP for secondary data
- A modeling system consisting of SWAT that will identify critical sources areas for phosphorus loss and that will quantify environmental impacts of variety of management practices by Rock River Watershed dairy farms.
- A modeling system consisting of IFSM that will identify points of farm phosphorus imbalances and that can quantify economic and environmental impacts of variety of management practices, with an application to Rock River Watershed dairy farms.
- Quarterly reports as required by the agreement.
- A comprehensive final report that includes methodologies and findings on the potential for reduction in phosphorus losses from the Rock River Watershed, a discussion of how the modeling system can be extrapolated to other similar watersheds throughout the Lake Champlain Basin, making clear the limits of extrapolation, and a discussion of how this approach might be integrated with a similar approach for urban/suburban land uses and to consider stream restoration for phosphorus reductions.
- Modeling results will also be analyzed, interpreted, and summarized for publication in the peer-reviewed literature although the submissions may occur after the end of the second year of the project.
- Presentations to the Lake Champlain Basin Program; the Vermont Agency of Natural Resources and Agency of Agriculture, Food, and Markets; and other interested parties.

Schedule

Complete QAPP for secondary data:	January 2009
Conduct and Complete Phase 1 tasks:	December 2008 – June 2009
Conduct and Complete Phase 2 tasks:	January 2008 – April 2009
Conduct and Complete Phase 3 tasks:	June 2009 – October 2009
Submit draft final report to VT ANR and LCBP:	October 31, 2009
Submit final report to VT ANR and LCBP	December 31, 2009

Budget

	VT C&C	LCBP
Personnel		
PI - Mary Watzin (2 weeks)		8,410
Post-doctoral associate – Lula Ghebremichael (full-time for one year)	28,000	12,385
Hourly wages		6,500
Fringe benefits	10,920	8,884
Supplies/Operating expenses	762	1,003
Travel		2,500
Subtotal	39,682	39,682
Indirect (26 %)	10,318	10,318
Totals	**50,000**	**50,000**

Budget Justification

Personnel. Full-time support is requested for Lula Ghebremichael, who will be responsible for all the SWAT modeling and the integration of the SWAT and IFSM models. Hourly wage support, for a new graduate student who will gather the data for IFSM is also requested. We have identified a student who has worked in the Watzin Lab previously, is an experienced farmer, and is familiar with the project s who will assist with data collection and other tasks as needed. About two weeks summer salary for the principal investigator is also requested to provide dedicated time to the project. Fringe benefits on the principal investigator and post-doctoral associate salaries are changed at the rate of 39.5%. Fringe benefits on hourly wages are charged at the rate of 9.5%.

Operating expenses. This will include miscellaneous expenses for the project such as computer supplies, mailing, phone service, and other expenses.

Travel. Funds are requested for travel for the coordination meetings with stakeholders in the region, and for travel for Ghebremichael to present the results of the project at a scientific meeting.

Indirect Costs: Indirect costs have been computed at UVM's standard off-campus rate of $26%.

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7. Appendices

A Tool for Estimating BMP Effectiveness for Phosphorus Pollution Control

Users' Manual

Margaret W. Gitau

Reference*: Gitau, M.W., W.J. Gburek, and A.R. Jarrett. 2005. A tool for estimating BMP effectiveness for phosphorus pollution control. J. Soil and Water Conservation, 60(1): 1-10.*

Disclaimer

The developers make no warranties express or implied, and assume no liability or responsibility whatsoever for any claims or damages that may result from the use of the tool and underlying database.

Content

Included in the package are:

- The BMP tool and underlying database, which is an access file (BMP Tool.mdb).
- An article giving technical information on tool development, data collection and analyses, and an example application. This article has been published in the Journal of Soil and Water Conservation (*Gitau, M.W., W.J. Gburek, and A.R. Jarrett. 2005. A tool for estimating BMP effectiveness for phosphorus pollution control. Journal of Soil and Water Conservation, 60(1): 1-10*).
- This file (Documentation), which the user documentation for the BMP tool.

The database

The database consists of three types of interlinked tables (Figure 1).

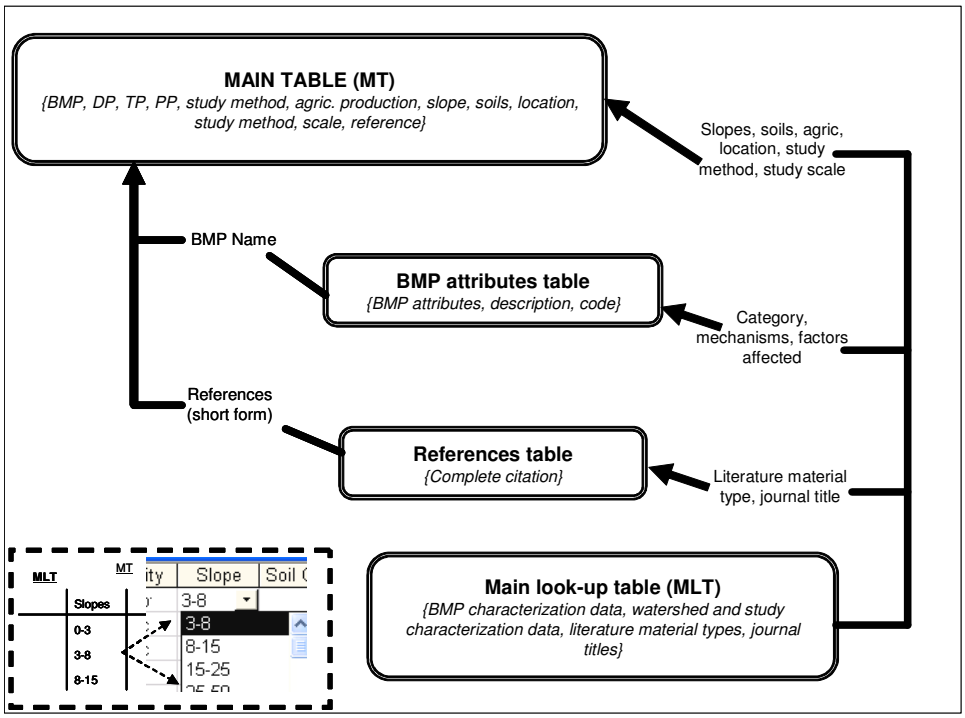

Figure 1: BMP database structure and component tables.

Main table

This table is named EffAnalysis. It holds all information related to effectiveness, including effectiveness values and corresponding site and study characteristics.

Secondary tables

These are the Attributes table and the References table. These tables hold information that occurs in more than one record within the main table, such as the BMP name and citation (represented by the short form of the citation, for example, "Hamlett and Epp, 1994"). These tables also hold supporting information that is not read into the main table but that is necessary to provide further information about the specific entry. For example, the short name field occurring within References, is read into EffAnalysis. Other information pertinent to the citation remains within References and is obtainable by querying the table.

Main look-up table

This table is named CHOICES. It contains items that can occur repeatedly within the database such as BMP names, slope classes, and journal titles. Entries in this table are look-ups, read through drop-down lists built into the other tables (see inset Figure 1).

The data

The database currently contains 32 BMPs grouped into three broad categories: barnyard management, erosion control, and nutrient management. Data includes literature-based BMP effectiveness values and associated study location, soils, slopes, and agricultural activities, study methods and study scale for particulate P (PP), dissolved P (DP), and total P (TP), nitrogen, sediment and runoff. Twenty one (21) of the BMPs have been further grouped into eight classes (animal waste systems, barnyard runoff management, conservation tillage, contour strip crop, crop rotations, filter strips, nutrient management plans, and riparian forest buffers, based on similarities in BMP operation mechanisms. It is upon these classes that the BMP tool has been developed. Tool capabilities have only been developed for phosphorus. Additionally, the nitrogen, sediment and runoff data have not been verified.

> ***To view the database, simply close the main interface using the red "X" on the right hand corner, and then use the navigation tools on the left-hand side of the database window. To return to the main interface click forms on the navigation bar to the left and double click on "main interface".***

Tool Structure and capabilities

The tool consists of four basic interfaces: the main interface, the estimates dialog box, the summary data access, and the update database interface.

Main interface

The main interface opens automatically at startup (Figure 2). It is the primary tool screen from which the other three interfaces can be accessed. It also provides background information on the database through the **About** button.

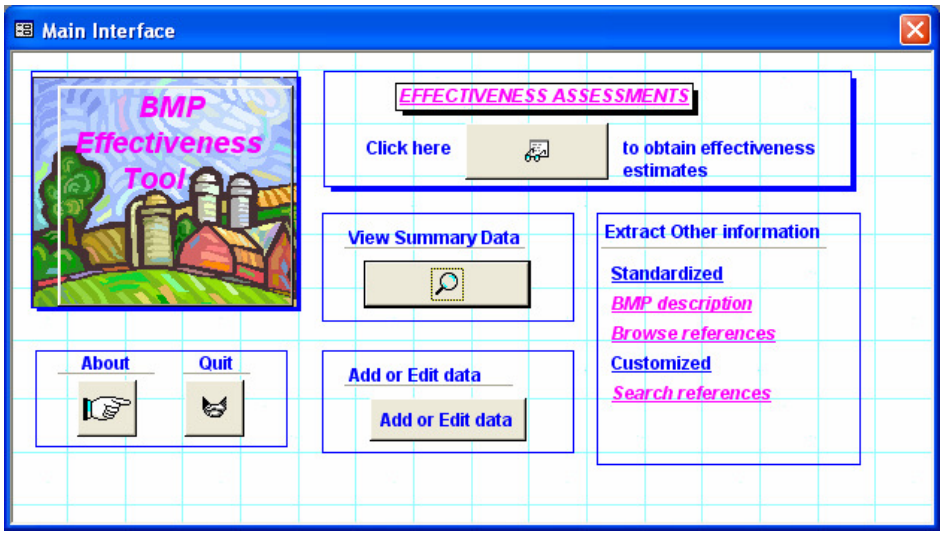

Figure 2: Main interface.

Estimates dialog box

The estimates dialog box forms the core of the BMP tool. By specifying soil and slope, as well as the category of BMP to be assessed (see example), a user is able to obtain BMP effectiveness estimates for DP, PP and TP, based on combined slope and soil effects.

Example

A cropland field has been categorized as high risk for phosphorus pollution, based on a site environmental review. This field is on hydrologic soil group C soils with a 3-8% slope. Farm planners feel that BMPs must be implemented on this field to prevent P losses. *Which BMP(s) should be implemented and how effective is it/are they likely to be in reducing P pollution?*

Step 1: Open the BMP tool by double clicking the file **BMP Tool.mdb**. For more efficient operation, save the tool to your hard-disk. *MS Access is needed to run the tool.*

Step 2: Click the Effectiveness button on the main interface as shown in Figure 3.

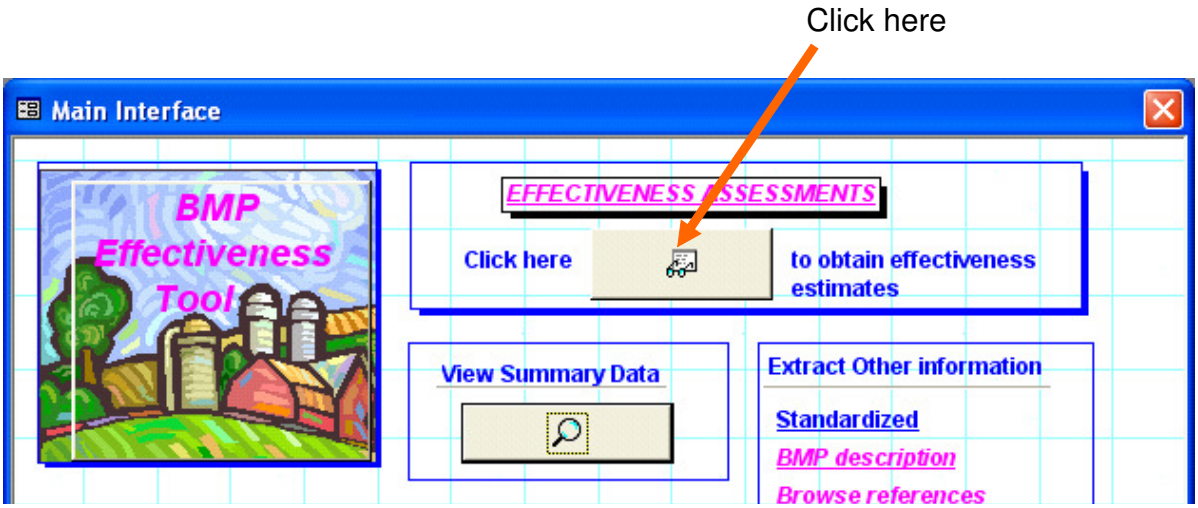

Figure 3: Accessing the estimates dialog box.

Step 3: The Estimates Dialog opens. Select "Erosion Control", "C", and "3-8" from the category, soil group and slopes drop-down lists respectively and click the **Do Estimates** button (Figure 4).

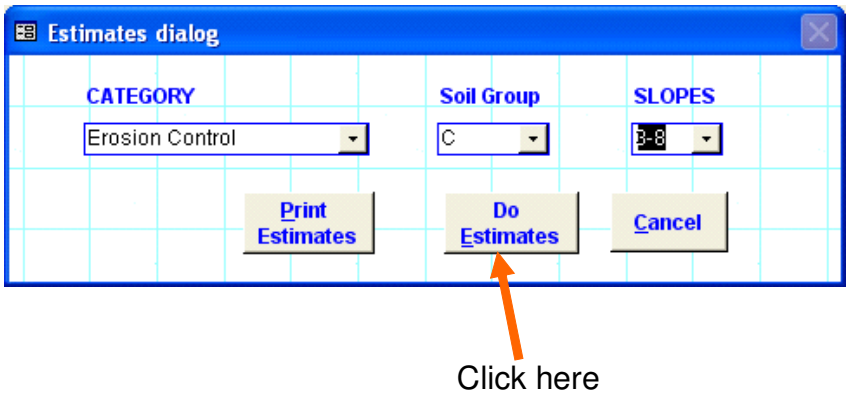

Figure 4: Getting the estimates.

The following result will be obtained:

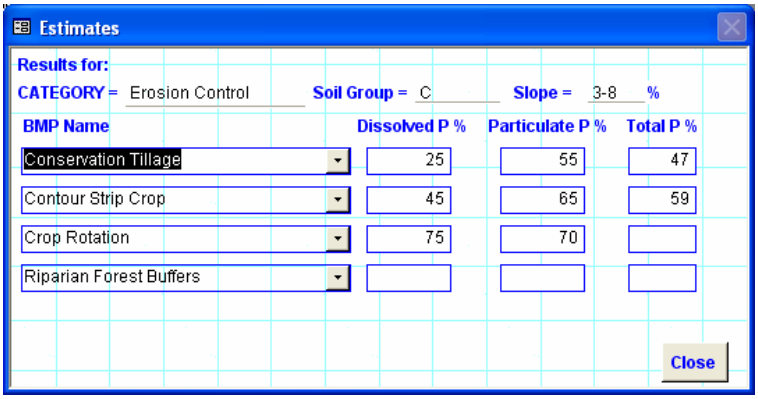

Figure 5: Tool output.

Interpretation: For example with conservation tillage, DP, PP, and TP can potentially be reduced by 25, 55, 47% over time, based on findings from the various BMP studies analyzed. Blanks (as in the output shown) will occur where sufficient data are currently not available to allow effectiveness estimates to be made based on both soil and slope, in such cases estimates can be made by averaging individually obtained slope-based and soil-based estimates for the BMP in question. These individual estimates are available within the summary data, accessible through the previously described *summary data interface*. Please refer to Gitau et al. (2005) for further details/information on interpreting and using BMP tool results.

Summaries interface

The summaries interface (Figure 6) is accessed by clicking the **view summary data** button on the main interface.

1. To view descriptive statistics for DP, PP and TP for each BMP select the appropriate option and click the **preview** button. In Figure 6, the DP summary option is checked; clicking the preview button will give a summary for DP (Figure 7). Summaries may also be viewed based on categories and by affecting factors.

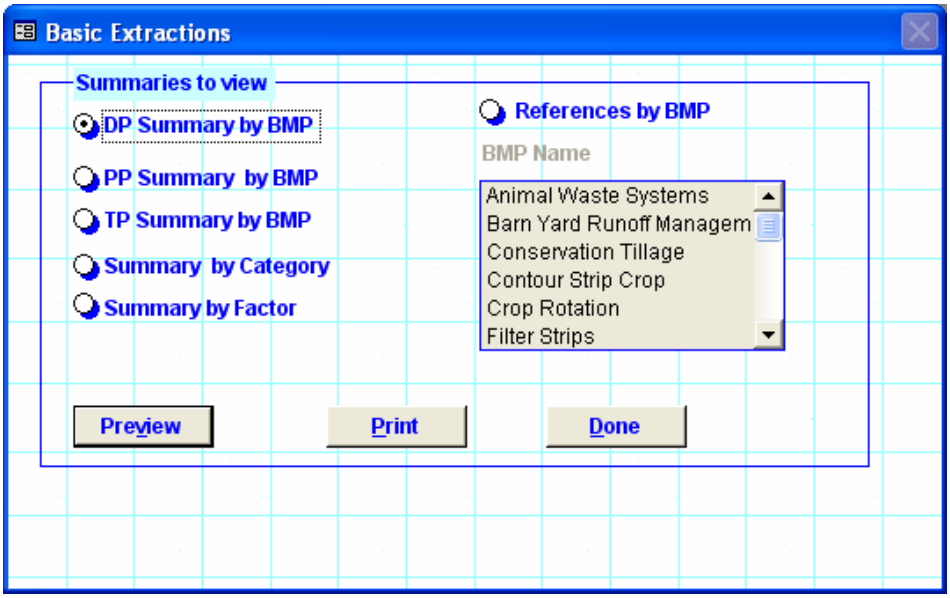

Figure 6: Summary data interface.

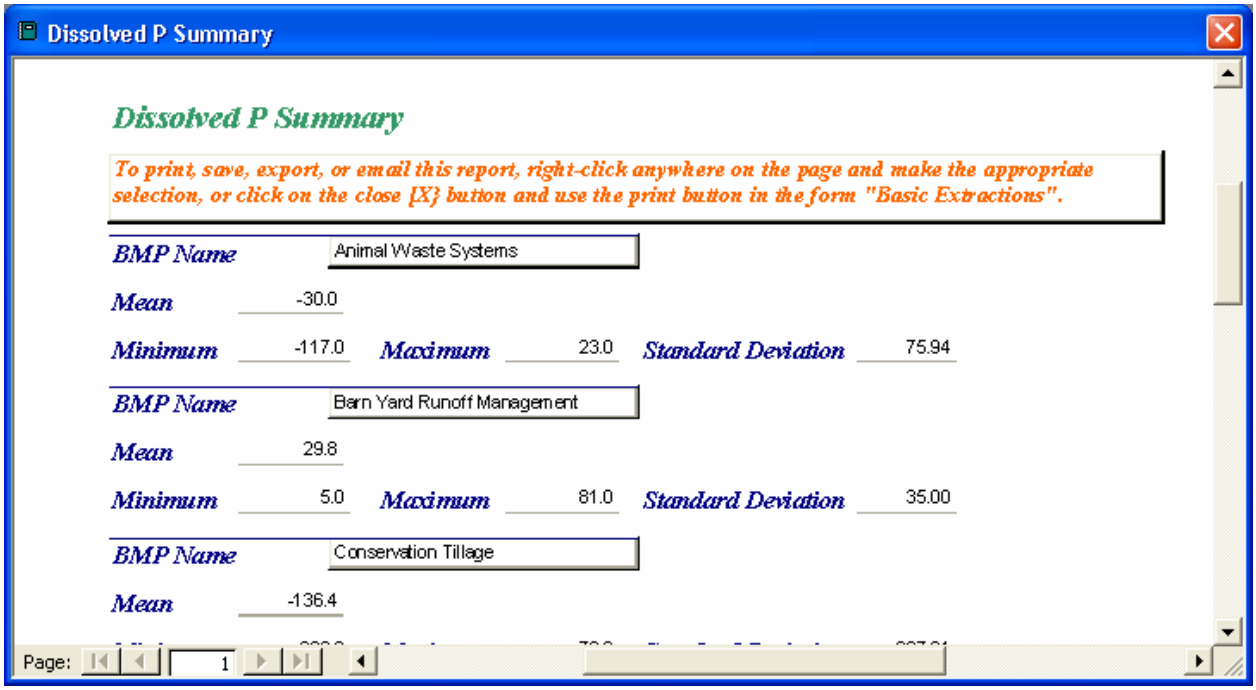

Figure 7: BMP summary data. Example: dissolved P.

2. To obtain complete citations of articles from which data for each BMP was obtained select the **Reference by BMP** option. The box labeled **BMP Name** will highlight (Figure 8) and constituent BMP names will be selectable.

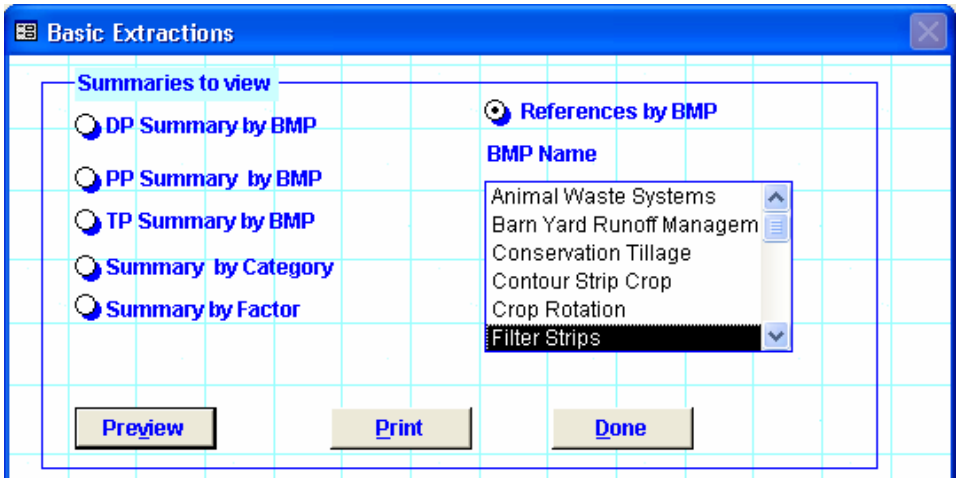

Figure 8: Accessing references for selected BMPs.

3. Select a BMP and click the **Preview** button. Filter strips are highlighted in Figure 8. Some of the references available for this BMP are as shown in Figure 9. Scroll down the page to view some more references.

References by BMP

Filter Strips

Chaubey et al, 1995. Effectiveness of vegetative filter strips in controlling losses of surface-applied poultry litter constituents. Transactions of ASAE,38(6) 1687-1692. . .

Clausen and Meals, 1989. Water quality achievable with agricultural best management practices. J. Soil and Water Cons.,6 593-596. . .

Daniels and Gilliam, 1996. Sediment and chemical load reduction by grass and riparian filters. Soil Sci. Soc. Am. J.,60 246-251. . .

Dillaha et al 1989. Vegetative filter strips for agricultural nonpoint source pollution control. Transactions of ASAE,32(2) 513-519. . .

Dillaha et al, 1988. Evaluation of vegetative filter strips as a best management practice for feed lots. J. Water Poll. Control Fed.,60(7) 1231-1238. . .

Doyle et al, 1977. Effectiveness of forest and grass buffer strips in improving the water quality of manure polluted runoff. ASAE Microfiche,77-2501 1-8. . .

Eghball et al, 2000. Narrowgrass hedge effects on phosphorus and nitrogen in runoff following manure and fertilizer application. J. Soil and Water Cons.,55(2) 172-176. . .

Gilley et al, 2000. Narrowgrass hedge effects on runoff and soil loss. J. Soil and Water Cons.,55(2) 190-196. . .

Hamlett and Epp, 1994. Water quality impacts of conservation and nutrient management practices in Pennsylvania. J. Soil and Water Cons.,49(1) 59-66. . .

Page: 1

Figure 9: References by BMP report. Example – Filter Strips.

Additions and Edits (updates) interface

To access this interface, click on the **Add or Edit data** button on the main interface. The interface is as shown in Figure 10.

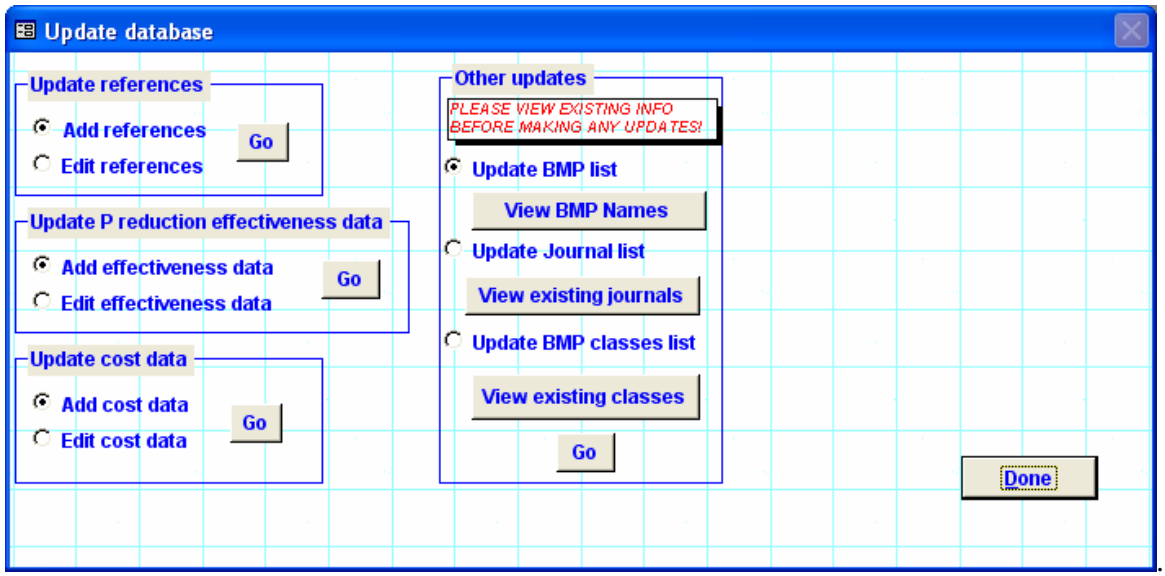

Figure 10: Updated interface.

1. To add articles (complete citations) to the database, select the **Add references option** and click on the **Go** button. A data entry form (Figure 11) opens.

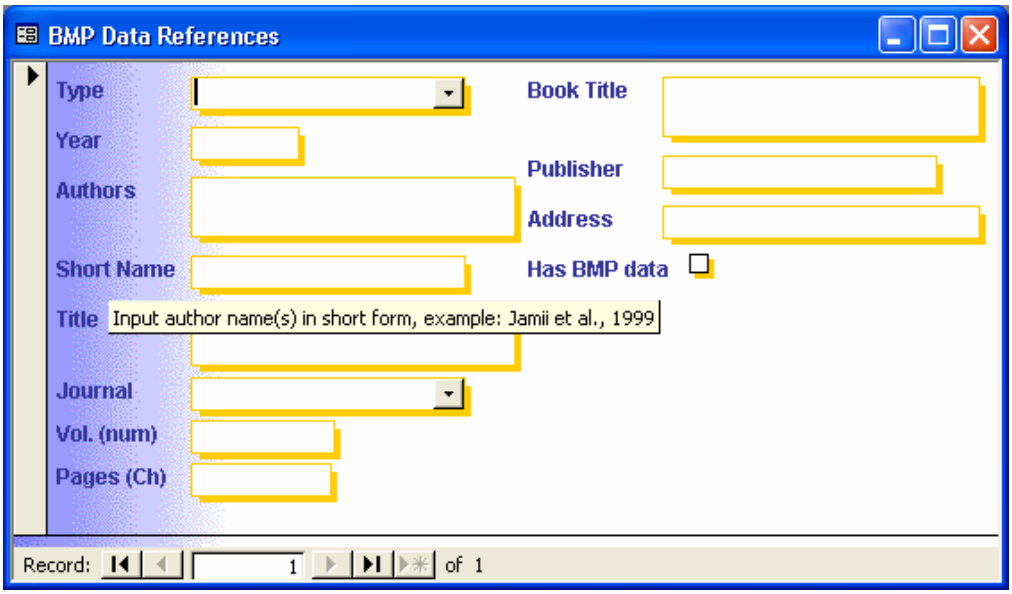

Figure 11: Data entry form allowing references to be added to the database.

2. To edit existing and newly input references select the **Edit references option** and click on **Go**. This brings up a form similar to that shown in Figure 11, except that you will be able to scroll through the references and make the necessary edits.
3. To add effectiveness data from the added articles, select the **Add effectiveness data** option and click on **go**. This will open up a dialog box as shown in Figure 12.

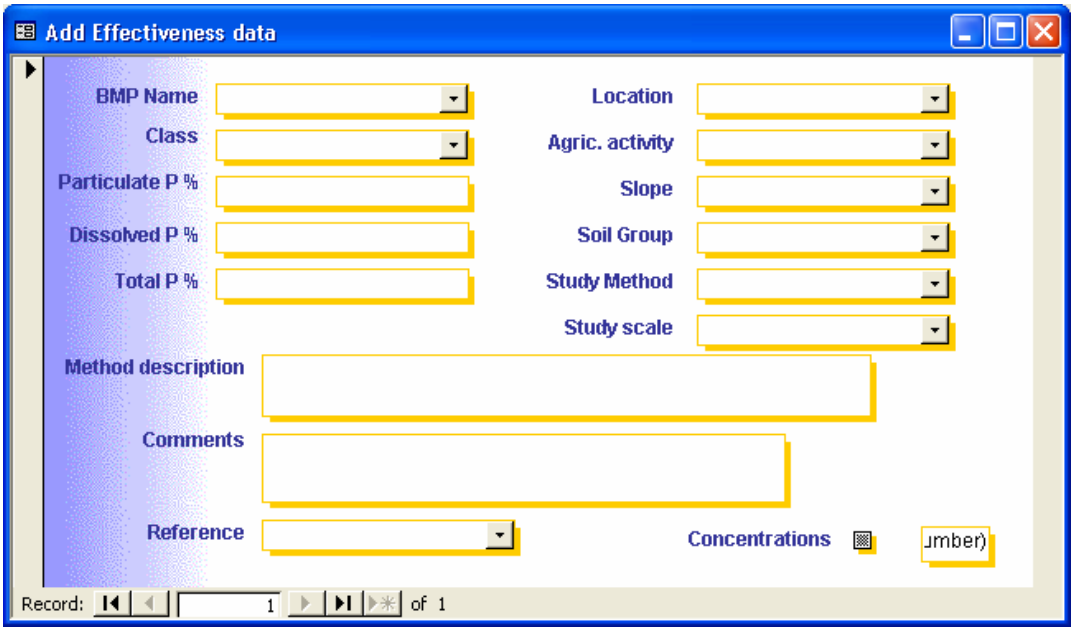

Figure 12: Data entry form allowing effectiveness data to be added to the database.

Data entered is read directly into the table EffAnalysis with the exception of concentration data, which is read into a different table. The **Edit effectiveness data** option allows editing of existing and newly entered effectiveness information.

Considerations for article selection and data collection are discussed in detail in the associated article (Gitau et al., 2005).

Other capabilities

1. To view BMP descriptions (Figure 13), click on *BMP description* in the main interface.

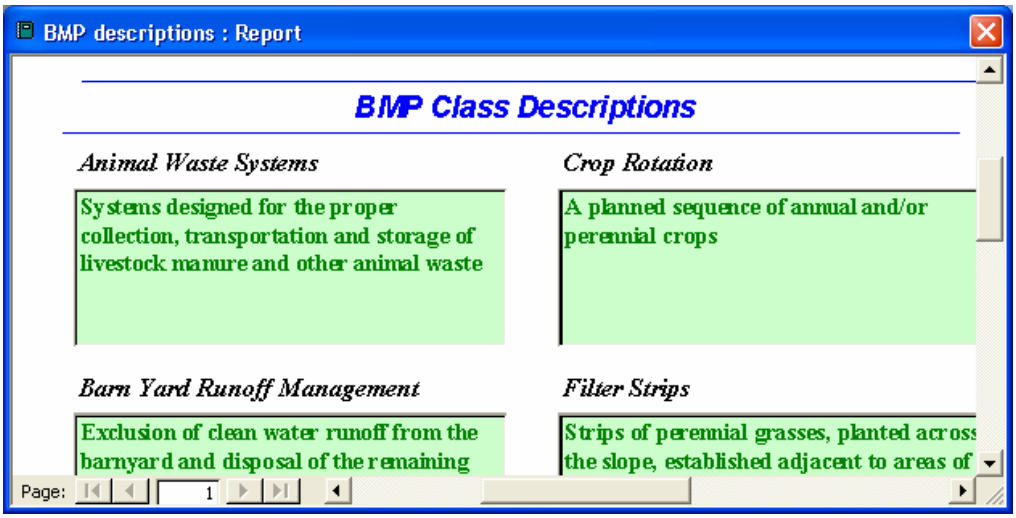

Figure 13: BMP descriptions.

2. To browse references (Figure 14), click on the *Browse references* link in the main interface.

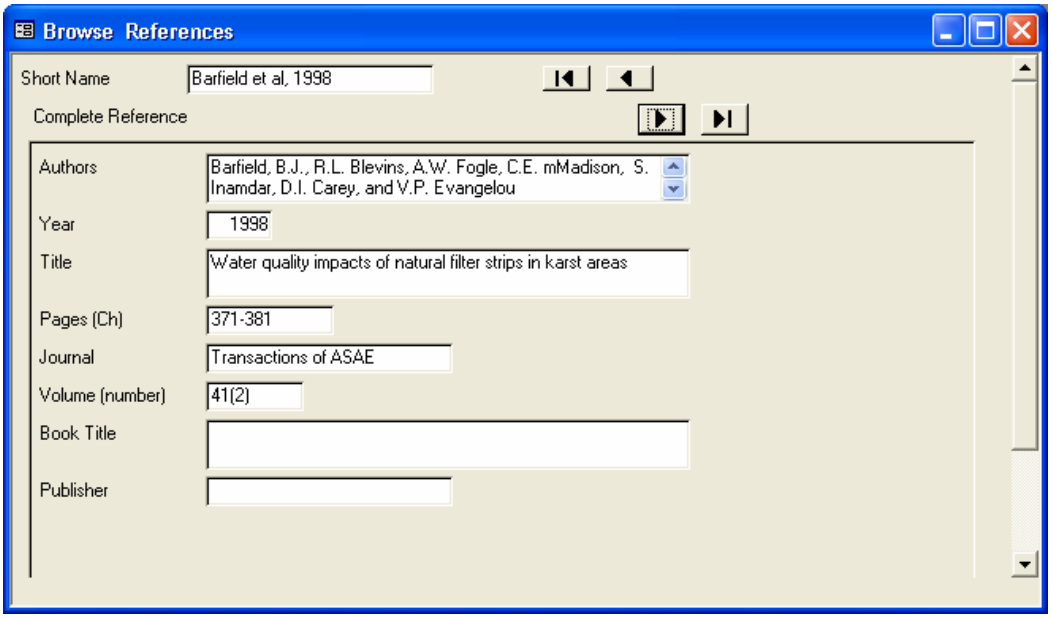

Figure 14: Browsing existing references.

A tool for estimating best management practice effectiveness for phosphorus pollution control

M.W. Gitau, W.J. Gburek, and A.R. Jarrett

ABSTRACT: A best management practice (BMP) tool was developed as a part of an effort to address the phosphorus (P) pollution and associated eutrophication problem affecting the Cannonsville Reservoir, part of the New York City water supply system. P reaching the reservoir is thought to emanate from runoff from the surrounding farms, mainly as a result of manure spread on these farms. Efforts to address the problem have involved implementation of BMPs on the watersheds; however, the effectiveness of these practices is not known. This study establishes a means of estimating BMP effectiveness, based on data available in the literature, and develops a tool that allows users to obtain BMP effectiveness estimates for their respective site soil and slope conditions. The tool offers stand-alone capabilities and has the potential to be linked to a GIS. An example is presented to illustrate tool application for effectiveness-based BMP selection, with a focus on a farm within the New York City watersheds.

Keywords: Best management practice (BMP) effectiveness, BMP tool, cumulation, analyses

There is a continuing concern regarding impairment of surface waters as a result of pollutants emanating from agricultural land uses. A major focus has been surface water pollution resulting from excessive P loadings (Sharpley and Beegle, 2001), a major impact of which is the eutrophication of these waters (Harper, 1992; Logan, 1993; Sharpley, 1995; Sharpley et al., 1999). The eutrophication problem affects close to 50 percent of the lakes and reservoirs that have been assessed in the United States (EPA, 1998). Human and wildlife concerns associated with eutrophication include repulsive taste and odor in drinking water, impairment of waters for recreation and industry, and toxicity to humans, fish and livestock (Sharpley, 1995).

The enormity of the P problem is widely acknowledged; the recent past has seen an emphasis on efforts to reduce P pollution, with due recognition being given to the importance of reducing P at its source (Logan, 1993; Sharpley et al., 1999; Heathwaite and Sharpley, 1999). Consequently, there are a number of best management practices (BMPs) that are being routinely applied to agricultural land use in an attempt to reduce P losses to surface waters. Yet to be answered definitively though, is the critical question of how effective these practices are in reducing P losses, with effectiveness being defined as the percentage by which P loss is reduced. With the increasing use of BMPs this question becomes even more critical, as does the need to determine BMP effectiveness prior to implementation.

Many studies have been carried out with the aim of determining the effectiveness of the various P control measures. Results from previous studies have, however, varied widely. Osei et al. (2000), for example, report values as low as 14 percent and as high as 91 percent from different experiments as the effectiveness of nutrient management plans in reducing total P. Perry et al. (1999) report an effectiveness as low as 1.5 percent for riparian forest buffers, while Lee et al. (2000) report this effectiveness as being 93 percent. Several authors have provided reasons as to why data from various BMP studies are likely to exhibit such great variability. Often, site specificity of BMP effects has been a focus (Baker and Johnson, 1983; EPA, 1993; Deere and Company, 1995), with differences in effectiveness being attributed to factors such as slope, soils, and geographic location, among others (Baker and Johnson, 1983).

Consequently, the effectiveness data, when considered individually, can only be reliably used for the particular site from which the data were obtained. When considered collectively, however, these data comprise BMP effectiveness values representative of a wide range of site conditions, and include site characteristics and other information (such as study location) necessary to qualify the data. In this regard, it is hypothesized that data from previous BMP studies can be accumulated in such a way as to provide insights as to the variability in the data, and subsequently, to provide a simple means of obtaining reliable, site-specific estimates of BMP effectiveness.

This paper reports on the cumulation and analyses of BMP data from various studies, and the subsequent development of a BMP tool which uses the underlying data in making BMP effectiveness estimates. It also presents an example showing how the tool can be applied in selecting BMPs, with a focus on a farm located within the New York City water supply watersheds.

Cumulation and analyses of data from previous studies. To obtain BMP effectiveness estimates in the manner hypothesized, it is necessary to have in place a mechanism for accumulating existing data. A logical way is to assemble these data into a database from which information can be derived in a raw or analyzed form, and through which there are capabilities for the development of analytical tools. In its most simple form, analyses of the data would involve finding an average of the results from all studies considered (Hunter et al., 1982; Light and Pillimer, 1984; Hunt, 1997); for example, the average reported effectiveness for filter strips in dissolved P control. Taking an average, however, masks the variability in the data; it oversimplifies the estimation of BMP effectiveness while also

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excluding the effects of factors that affect BMP effectiveness. Light and Pillimer (1984) and Hunt (1997) suggested the need to look deeper at the data, at factors that could affect the results. Thus, in addition to collecting BMP effectiveness values, it is important to include as much associated information as is possible, such as site characteristics and methods used.

The most involved part of a cumulation of research findings is the process of article selection, which constitutes the initial portion of the data collection process. Key considerations include the kinds of articles that should be included, whether to use only published material, rejection of articles on the basis of the methodology, the amount of data necessary for analyses, and, once all the data has been assembled, the handling of data showing up as outliers within the combined dataset.

Expectedly, the articles included must be relevant to the current study (Light and Smith, 1971; Hunt, 1997) and must provide information necessary for the achievement of the study goals. Thus, for BMP effectiveness estimation, the articles must have BMP information that either gives values of BMP effectiveness or allows their determination from the data provided; They should preferably contain original material, so as to provide study details, and so as not to have been subject to re-interpretation.

Published studies are generally deemed as having more reliable data than do unpublished ones (studies that have been or are being carried out, but for some reason, associated articles have not yet been accepted for publication). Thus, the tendency is to want to include only published studies. This may, however, result in a bias (Light and Smith, 1971; Hunter et al., 1982; Light and Pillemer, 1984; Bland, 2000) as studies are often preferentially published based on the significance of differences obtained. These authors recommend the identification and inclusion of both published and unpublished information.

Related to published and unpublished information is the adequacy of the study methods used. It can be argued that there can be flaws in the methodologies, which would lead to the studies not being published (Hunter et al., 1982). Generally, researchers may have differing views on what constitutes a "good" study, and, as pointed out by Hunter et al. (1982), flaws can be identified in almost any article, this being dependent on the reviewer. Rejection of articles based on perceived inadequacy in the methods may introduce an element of subjectivity in the cumulation effort (Light and Smith, 1971). It also often leads to a greatly decreased data size (Hunter et al., 1982), thus greatly impacting subsequent analyses.

The handling of outliers is always a controversial issue; should outliers (considering all assembled data) and therefore articles containing these data be included or should they be left out, and if so, what would be the basis for leaving them out?

The considerations for data collection outlined in this section summarize the considerations that were made in the cumulation process for this study. A discussion on articles included, based on these considerations, is presented in the materials and methods section.

Methods and Materials

This study involved the collection of BMP effectiveness data documented in the literature, assembly of the data into a database, analyses of the data, and subsequent development of a BMP tool based on these data. This section reports on the methods used in this study.

Data collection. For the various BMPs reported in the literature, data were collected on particulate P (PP), dissolved P (DP), and total P (TP) effectiveness, study location, soils, slopes, and agricultural activities, as well as on the study methods and study scale. These data were assembled into a database developed in Microsoft Access. Data were also collected on nitrogen, sediment, and runoff BMP effectiveness. As P was the focus of this study, and because analyses and capabilities described for P apply to the other pollutants, these pollutants will not be discussed further in this paper. Effectiveness information was obtained from text, tables, or graphs depending on how it was presented in the literature. Both quantitative and qualitative information was collected, although the current analyses have only involved quantitative information.

A broad range of articles was examined. These were subjected to the considerations discussed in the previous section. Articles selected were primarily those that had original data and included details on study and site characteristics. These were almost always the original articles, though occasionally secondary materials were used if the original ones could not be located. With the secondary material, site and study characteristics were not always reported. Associated data were nevertheless documented, but were only used in the computation of overall descriptive statistics.

Data reported in the studies had to be consistent with the goals of this study, which was to quantify the effects of BMPs relative to the pre-BMP case. Targeted articles then had to have their control being a pre-BMP case, and not another BMP. Some studies evaluated a number of BMPs at a time (for example, Prato and Wu, 1991; Sugiharto et al., 1994). Published results were, thus, more indicative of combined effects of the BMPs, making it difficult to extract values representing individual BMPs. Such studies were excluded from the database. Thus far, the database only contains data from published material (journal articles, books, government publications, etc.), as these are generally more easily accessible than unpublished material. With regard to outliers, that is as pertains to assembled data, these are often associated with extreme site or study characteristics, thus their exclusion might result in the exclusion of these extremes. Outliers were thus not eliminated from this study.

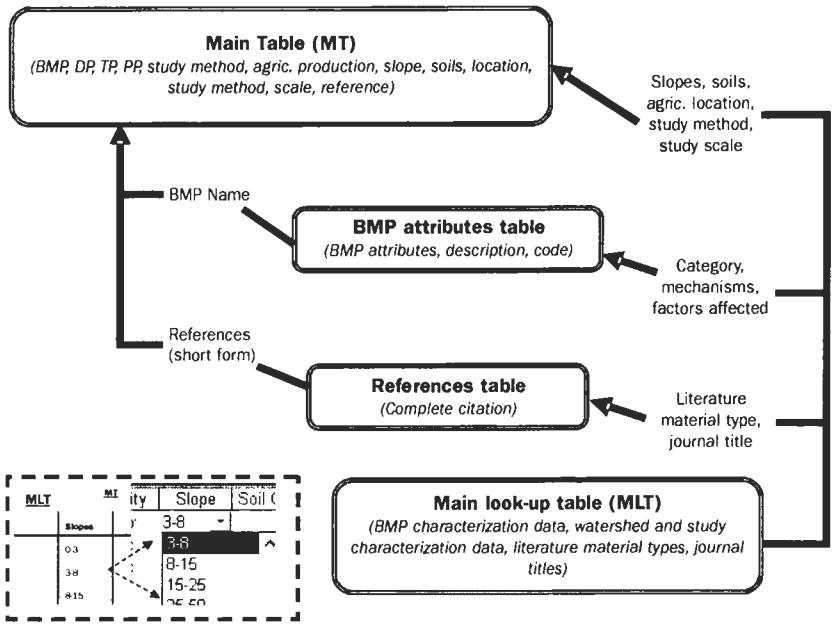
Database description. The database consists of three types of interlinked tables (Figure 1).

The main table holds all information related to effectiveness, including effectiveness data and corresponding site and study characteristics information.

The secondary tables are the "BMP attributes table" and the "References table." These tables hold information that occurs in more than one record within the main table, such as the BMP name and citation (represented by the short form of the citation, for example, "Hamlett and Epp, 1994"). These tables also hold supporting information that is not read into the main table but that is necessary to provide further information about the specific entry. For example, within the reference table, the short name field is read into the main table. Other information pertinent to the citation remains within the references table and is obtainable through queries on associated records. Finally, the main look-up table functions in a manner similar to the secondary tables, except that it contains only entries that are used as look-ups, including BMP names, slope classes, soil groups and a journals list, among others. Entries in this table are read into the other tables using drop-down lists (see inset Figure 1).

The database currently contains 32 BMPs grouped into three broad categories: barnyard

Figure 1
Database schematic showing component tables, contents and links. Inset: Look-up values such as slope reside in the main look-up table (MLT) and are read into the main table (MT) through drop-down lists linked to the main look-up table.



management, erosion control, and nutrient management. Of these, 21 BMPs had sufficient data for further analyses. These 21 BMPs have been grouped into eight classes (Table 1), namely animal waste systems (AWS), barnyard runoff management (BYRM), conservation tillage (CONST), contour strip crop (CSC), crop rotations (CR), filter strips (FS), nutrient management plans (NMPs), and riparian forest buffers (RFBs), with grouping being based on similarities in BMP operation mechanisms. For example, practices included in barnyard runoff management are such as roof runoff diversion and upslope runoff diversion, as both serve to exclude runoff from the barnyard area. Other BMPs have been grouped in a similar manner.

Data analyses. For the eight classes of BMPs there are 148 associated entries that have quantitative information on their effectiveness in reducing P loss. Descriptive statistics (average, maximum, minimum, and standard deviations) were computed for dissolved P, total P and particulate P effectiveness, and the corresponding distributions plotted. An assessment was then made, using ANOVA, to establish the effects of the primary factors thought to influence BMP effectiveness. Based on the literature, factors identified were slopes, soils, location, and study scale. These were also the most commonly reported within study site descriptions.

In this study, site slopes were represented using slope classes corresponding to limits for the various soil map units, as documented in the National Soils Data Access Facility (*http://soils.usda.gov/*) soils database. Site soils were represented using the hydrologic soil group (indicator of soil runoff potential) as defined by the U.S. Department of Agriculture's Natural Resources Conservation Service (1996). Site locations were represented geographically as being in the North East, South East, South West, Mid West, or Pacific West, based on site locations within the United States as reported in the articles. Study scale was represented by grouping reported study site areas into four classes, < 1 ha (≈ 2.5 ac), 1 - 100 ha (2.5 - 250 ac), 100 - 10,000 ha (250 - 25, 000 ac), and

Table 1. Classifications of best management practices (BMP) as used in the database.

BMP class	BMP class description
Animal waste systems, AWS	Systems designed for the proper collection, transportation and storage of livestock manure and other animal waste.
Barnyard runoff management, BYRM	Exclusion of clean water runoff from the barnyard and disposal of the remaining barnyard runoff in a way that minimizes its pollution potential.
Conservation tillage, CONST	Any tillage and planting system that leaves a minimum of 30% of the soil surface covered with plant residue after the tillage or planting operation (i.e. reduced-till, no-till etc.).
Contour strip crop, CSC	Alternating strips of a row crop with a small grain or forage, planted on the contour (Contour strip cropping) or across the slope (Field strip cropping).
Crop rotation, CR	A planned sequence of annual and/or perennial crops.
Filter strips, FS (as filters for barnyard runoff)	Strips of perennial grasses, planted across the slope, established adjacent to areas of high pollutant potential and managed for pollutant removal by overland flow.
Nutrient management plan, NMP	Managing the rate, timing, and placement of fertilizers, manures and other nutrient sources to encourage maximum nutrient recycling and minimize nutrient runoff and leaching.
Riparian forest buffers, RFB	Areas of trees, shrubs and grasses located adjacent to ponds, lakes, and streams that filter out pollutants from runoff, as well as providing shade for fish and wildlife.

> 10, 000 ha (25,000 ac), with grouping being based on natural breaks in the assembled data.

Factors found to have a significant effect based on the analyses were used in the development of a tool that could be used to estimate BMP effectiveness, based on user-specified values of the said factors.

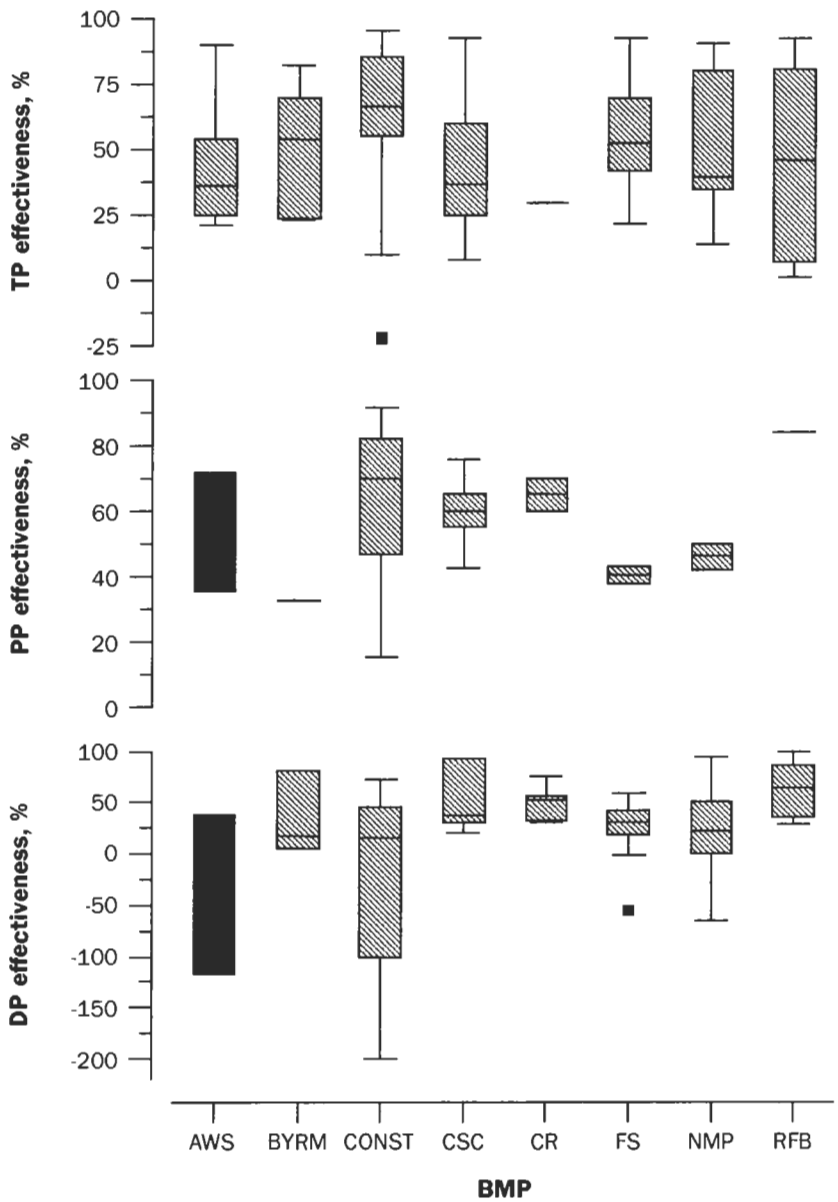
Results and Discussion

Data analyses. Table 2 presents descriptive statistics for all BMP data analyzed while Figure 2 shows box plots of the BMP effectiveness data associated with the various BMPs. From Table 2, all BMPs have the potential to reduce total P and particulate P losses, based on the average effectiveness of the practices as calculated from the data. Based on these averages, particulate P could potentially be reduced by a maximum of about 80 percent (riparian forest buffers) and total P by a maximum of 60 percent (conservation tillage). Notably, however, both conservation tillage and animal waste systems could potentially cause increases in dissolved P losses, depicted by negative effectiveness values in the table. With conservation tillage, this is attributable to increased surface concentrations of soluble pollutants due to lack of soil inversion associated with the practice (Romkens et al., 1973; Baker and Laflen, 1983; Dillaha, 1990) while for animal waste systems, excess runoff from the facility could contain dissolved pollutants, thus aggravating the problem. The variability in BMP effectiveness data can be seen from both Table 2 and Figure 2. This variability is thought to be associated with some or all of the aforementioned factors that could potentially affect BMP effectiveness.

Table 3 shows the results of an ANOVA of the BMP effectiveness data with regard to slope, soil, location and study scale effects. From Table 3, slope had a significant effect on both total P and particulate P BMP effectiveness at the 95 percent level of significance, while soil effects were significant for particulate P effectiveness at the same level of significance. Soil effects were also significant for total P when considered at the 90 percent level of significance. Location effects were significant for both total P and particulate P BMP effectiveness at the 95 percent level of significance, while study scale showed no significant effect on BMP effectiveness for all the three forms of P, when considered at both the 95 percent and the 90 percent levels of significance.

Figure 2

Box plots showing variability in total phosphorus (TP), particulate phosphorus (PP), and dissolved phosphorus (DP) effectiveness data relative to various best management practices.



AWS: animal waste systems; BYRM: barnyard runoff management; CONST: conservation tillage; CSC: Contour strip crop; CR: crop rotation; FS: filter strips; NMP: nutrient management plan; RFB: riparian forest buffers; ■ Outliers. For DP, values less than -200 have been excluded from the plots to enable the display of the other plots.

From the analyses, slopes, soils and location were key factors affecting BMP effectiveness. Given the size of analyzable data, however, only two factors could be included in the tool at any one time. For this study, a choice was made to include site slopes and soils, as these would allow wider tool application. These are also key factors suggested in the literature as impacting on BMP effectiveness (Troeh et al.,

Table 2. Descriptive statistics of best management practices (BMP) effectiveness data as documented in the literature.

BMP class	Variable	Average %	Std. Dev. %	Min. %	Max. %	Number	Reference number
Animal waste systems, AWS	DP§	-13*	71	-117	40	4	3, 21
	TP#	42	24	21	90	7	3, 5, 16, 20, 21
	PP†	59	21	35	72	3	3
Barnyard runoff management, BYRM	DP	30	35	5	81	4	4, 28
	TP	53	23	23	82	7	4, 22, 28
	PP	33	—	33	33	1	21
Conservation tillage, CONST	DP	-167	262	-889	73	18	1, 2, 11, 13, 15, 17, 27, 29, 32
	TP	62	29	-22	95	21	2, 5, 11, 14, 15, 17, 20, 21, 22, 32
	PP	63	20	15	92	17	1, 11, 13, 15, 29, 32
Contour strip crop, CSC	DP	45	28	20	93	5	11, 13
	TP	44	25	8	93	22	14, 21, 22
	PP	60	11	43	76	6	6, 11, 13
Crop rotation, CR	DP	50	17	30	75	6	5, 6, 13, 22
	TP	30	—	30	30	1	21
	PP	65	4	60	70	4	13, 22
Filter strips, FS	DP	26	25	-56	59	18	8, 9, 10, 21, 30
	TP	56	18	22	93	23	6, 8, 10, 11, 14, 19, 22, 24, 30
	PP	41	4	38	43	2	10
Nutrient management plan, NMP	DP	26	41	-66	94	14	23, 31, 33
	TP	47	24	14	91	9	4, 22, 23, 31
	PP	46	4	42	50	3	31
Riparian forest buffers, RFB	DP	62	26	28	99	8	7, 9, 12, 18, 26
	TP	43	36	2	93	9	12, 18, 21, 25
	PP	84	—	84	84	1	26

* **Negative values signify increases in P losses**

§ **Dissolved phosphorus**

\# **Total phosphorus**

† **Particulate phosphorus**

#	Reference (short form)
1	Baker and Laflen, 1983
2	Berg et al., 1988
3	Brannan et al., 2000
4	Brown et al., 1989
5	Chesapeake Bay Program, 1987
6	Clark et al., 1985
7	Corley et al., 1999
8	Daniels and Gilliam, 1996
9	Doyle et al., 1977
10	Eghball et al., 2000
11	EPA, 1993
12	Franco et al., 1996
13	Haith, 1979
14	Hamlett and Epp, 1994
15	Hansen et al., 2000
16	Hession et al., 1989
17	Laflen and Tabatabai, 1984
18	Lee et al., 2000
19	Magette et al., 1989
20	Mostaghimi et al., 1989
21	Novotny and Olem, 1994
22	NYSDEC, 1991
23	Osei et al., 2000
24	Parsons et al., 2001
25	Perry et al., 1999
26	Peterjohn and Correll, 1984
27	Phillips et al., 1993
28	Robillard et al., 1983
29	Romkens et al., 1973
30	Schmitt et al., 1999
31	Schuman et al., 1973
32	Sharpley et al., 1991
33	Walter et al., 2001

Table 3. Analyses of the statistical significance of slope and soil effects on best management practice (BMP) effectiveness at the 95 percent level of significance.

		Factor effects on effectiveness for:		
Factor	**Statistics**	**TP#**	**DP§**	**PP†**
Slope	No. of entries	56	45	15
	p-value	0.0153	0.54	0.0071
	Significance	S‡	NS**	S
Soil	No. of entries	56	45	15
	p-value	0.0909	0.6619	0.0026
	Significance	NS	NS	S
Location	No. of entries	77	64	21
	p-value	0.0285	0.1917	0.041
	Significance	S	NS	S
Scale	No. of entries	71	52	12
	p-value	0.3373	0.6648	0.1685
	Significance	NS	NS	NS

§Dissolved phosphorus
#Total phosphorus
†Particulate phosphorus
‡Significant
****Not Significant**

1980; NCAES, 1982a, 1982b; Baker and Johnson, 1983; Clark et al., 1985; Dillaha, 1990).

The BMP tool. Based on the factor effect analyses site slopes and soils were selected as the factors to be used in the BMP tool. Data were grouped by both hydrologic soil groups and slopes, and descriptive statistics computed for the combined data. Descriptive statistics were also computed for dissolved P, particulate P, and total P data grouped by hydrologic soil group and by slope classes individually.

Data from the combined soil and slope analyses were used to design a BMP effectiveness estimator driven by user-specified hydrologic soil groups and slope classes. This estimator forms the core of the BMP effectiveness tool. Data from the other analyses formed the basis for other tool capabilities, such as provision of summary data. In all cases, expressions for the computation of the descriptive statistics reside in the database as structured query language (SQL) statements based upon Microsoft Access built-in statistical functions. These statements are executed at run time, based on data available at the time of execution; thus, estimates obtained are current and reflective of all data existing in the database at the time of execution.

The BMP tool developed consists of a main interface (Figure 3a) and three other basic interfaces—the estimates dialog box, the summary data interface, and the update data interface—all of which are accessible from the main interface. The main interface is the primary tool screen. It allows users to access the other three interfaces. Additionally, it allows access to other information, such as BMP class descriptions (Figure 3b) and existing citations. It also provides access to summary notes on the tool and the underlying database.

The estimates dialog box forms the core of the BMP tool. It enables the user to obtain effectiveness estimates for BMPs within selected categories for specified site soils and slopes. By specifying soil and slope, as well as the category of BMP to be assessed, a user is able to obtain BMP effectiveness estimates for dissolved P, particulate P, and total P, based on combined slope and soil effects (Figure 3c). Blanks, such as with contour strip cropping and riparian buffers in Figure 3c, imply that sufficient data are currently not available to allow effectiveness estimates to be made based on both soil and slope. In such cases, estimates can be made by averaging individually obtained slope-based estimates and soil-based estimates for the BMP in question. An overall average for the BMP (regardless of soil and slope) could also be utilized as an estimate if neither category of data were available.

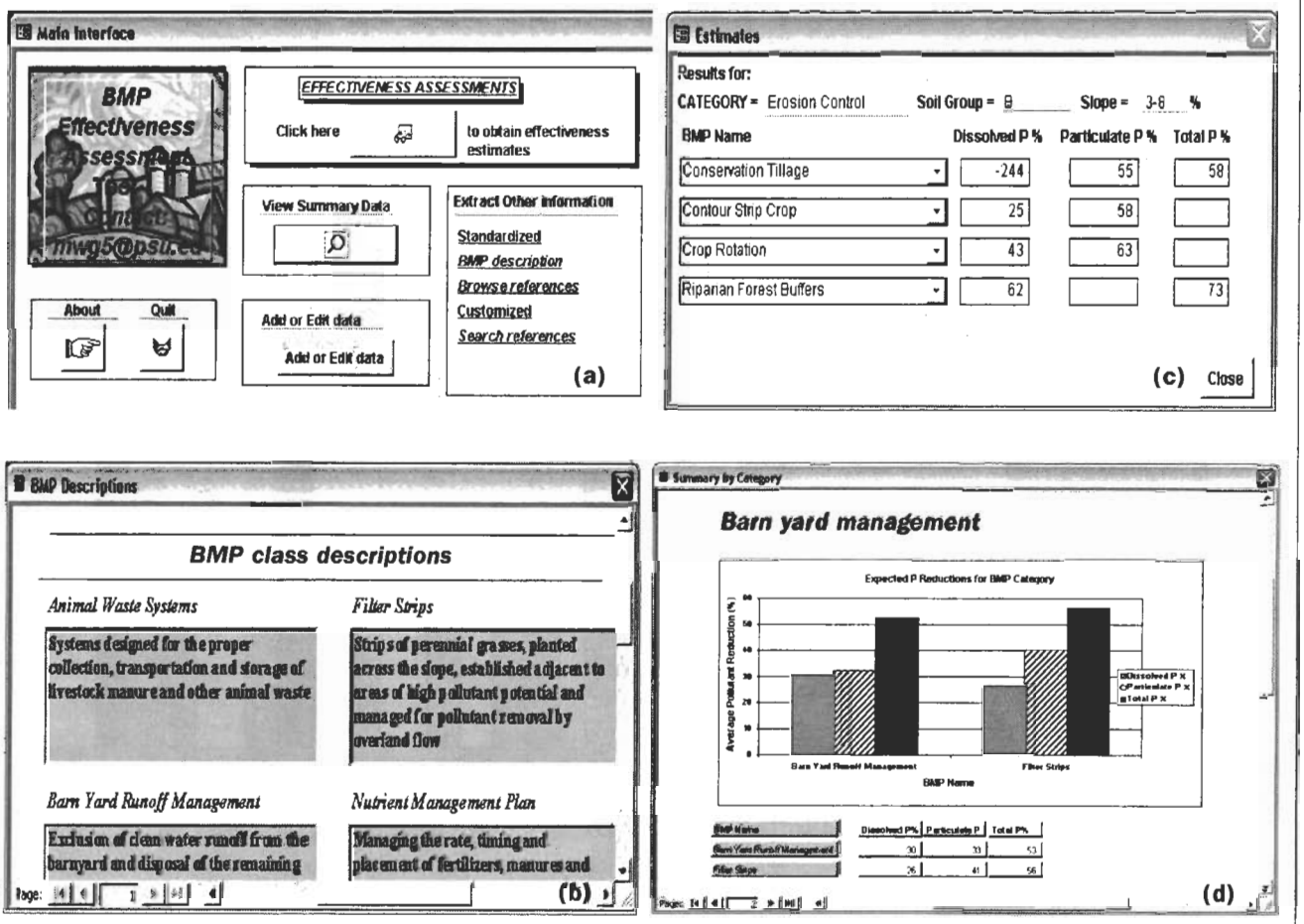
The summary data interface allows access to summary statistics of the BMP effectiveness data. Descriptive statistics can be obtained for dissolved P, particulate P, and total P, either individually or summarized by BMP category (Figure 3d). Slope and soil effects on BMP effectiveness can also be viewed in graphical format within the tool. This interface also provides user access to complete citations of publications from which data were obtained. The updates interface allows effectiveness information and associated citations to be added and edited within the database. Other updates that can be made include additions and edits to journal and BMP lists, and the BMP classes.

Example application. A farm within the New York City watersheds has undergone a site environmental review (WAC, 2001), and individual fields have been categorized based on their risk with regard to P pollution (Figure 4 inset). The site environmental review process involves analyses and inventory of water, soil, air, plant, and animal resources on the farm, and subsequent determination of the potential water quality impacts of the farm, in relation to watershed water quality goals. The three fields categorized as high risk are all cropland fields. These are on hydrologic soil group C with a 3 to 8 percent slope. Farm planners feel that BMPs must be implemented on this farm to prevent P losses. The key question here is: *Which BMP(s) should be implemented and how effective is it/are they likely to be in reducing P pollution?*

Using the BMP tool and selecting the appropriate soil hydrologic group and slope class, as well as the desired BMP category, estimates of effectiveness for various BMPs can be obtained (Figures 4a and b). In this case, since the fields are cropland, interest would be in either erosion control or nutrient management categories of BMPs.

From Figure 4a and b, crop rotations and nutrient management plans appear most favorable for P control, based on their effectiveness. Conservation tillage offers benefits with regard to particulate P effectiveness. However, its effectiveness is much diminished when it comes to dissolved P. Thus, in this case, crop rotations and nutrient management plans would be the BMPs of choice. If for some reason, either of the BMPs cannot be implemented, contour strip cropping would be the alternative, albeit a less effective one. Estimates can be obtained in a similar manner for fields/sites with different soil and slope characteristics. These estimates can then be used to guide BMP selection, with the BMP(s) that have the highest effectiveness

Figure 3
Main interface (a) and best management practice (BMP) tool capabilities i.e. BMP class descriptions (b); effectiveness estimates (c), and access to summary data (d).



values being the BMPs of choice and other less effective BMPs serving as alternatives.

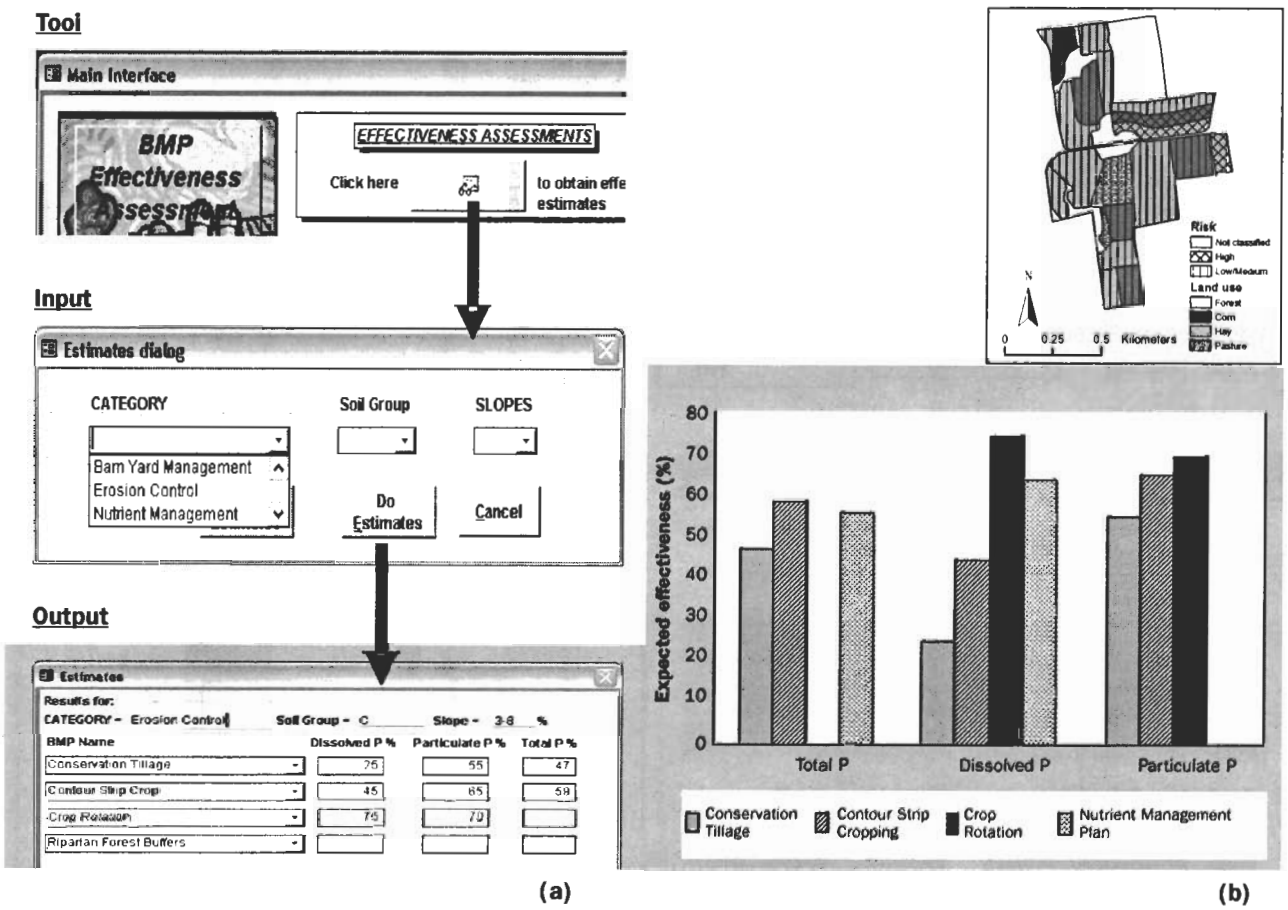
Discussion. The need to determine the effectiveness of BMPs for P loss control prior to BMP implementation has been discussed, as has the need for a means of determining or estimating BMP effectiveness that is more practical and more widely applicable than through the use of individual field studies. Also, the existence of a wide range of BMP effectiveness data and associated site and study information, and the potential for the collective analyses and use of these data in making BMP effectiveness estimates has been demonstrated. The current study has focused on accumulation and analyses of these data, with a view to providing a means of obtaining BMP effectiveness estimates. This has been accomplished through the determination of key factors affecting BMP effectiveness and the subsequent development of a BMP tool. The tool provides a simple means of estimating BMP effectiveness that can either be used as a stand-alone application, or be linked to a geographic information system (GIS). A link between the tool and a GIS would allow for automation of tool inputs, allowing more efficient tool application for a wide variety of site and management conditions.

With regard to the BMPs, most of the BMPs in use for P control were originally intended for soil conservation. Thus, they reduce pollutant loads by reducing runoff volumes and encouraging infiltration, and/or by reducing soil loss. These may not work as expected in frozen soil conditions where practically no infiltration occurs. Consequently, caution should be applied in using these values under winter or early spring conditions. Practices such as NMPs, which work on reducing P concentrations at the soil surface, would still be effective during these time periods, provided background P levels are not so high as to render the BMPs ineffective.

The issue of time is also important, as BMP effects may not be felt immediately, and further, may start to diminish after a given time period. The tool does not currently provide time-based estimates of BMP effectiveness. However, the data analyzed originated from studies carried out for a variety of time periods, from a series of events to over 60 years. Estimates obtained using the tool may thus be considered to represent average BMP effects over time.

Tool results do not currently contain raw data on the effect of combinations of BMPs. Combined effects may be approximated by assuming sequential passage of pollutant from

Figure 4
Example best management practice (BMP) tool application: tool input and output (a); comparison of multiple tool output (b). Inset: Farmland use and classification with regard to phosphorus (P) pollution.



one BMP to another, with each BMP contributing to reducing the remaining pollutant load. This might lead to a slight overestimation of combined BMP effects; however, it does serve to provide information on the relative effectiveness of BMP combinations.

Finally, it is interesting to note how a look at data can offer insights into the effects of BMPs on various pollutant forms. Conservation tillage, for example, has often been used for P pollution control since it is effective in reducing sediment losses, and by extension, in reducing sediment-bound P. Based on tool output, the practice is indeed suitable for reducing sediment P; however, it can potentially cause increases of up to 200 percent in dissolved P losses (soil group B, 3 to 8 percent slopes). According to Romkens et al. (1973), Baker and Laflen (1983), and Dillaha (1990), such increases are attributable to reduced soil disturbance associated with conservation tillage, and thus an increased availability of soluble nutrients at the soil surface. Additionally, expected reductions in runoff, due to the practice, may not be in significant amounts to counter the increases in soil surface P concentrations (Baker and Laflen, 1983; Dillaha, 1990). The expansion of this tool to offer the same functionality for nitrogen (N) as for P would provide similar insights into BMP effects on N for a BMP targeted at P-pollution control.

Summary and Conclusion

An accumulation and analyses of data from existing studies has been carried out and used as a basis for the development of a BMP tool. The tool allows BMP effectiveness estimates to be made based on site soil and slope conditions, while also providing access to a summarized form of existing BMP data. The tool offers a simple and more practical means of obtaining BMP effectiveness estimates than does setting up experimentation on all sites being considered for BMP implementation. Additionally, it provides estimates for alternative BMPs thus allowing for effectiveness-based BMP selection. This tool has been developed with the New York City water supply watersheds in mind; however, it is based on data derived from a variety of conditions beyond this region. It is, therefore, widely applicable. The tool also sets a stage for similar analyses for nitrogen, as tool capabilities developed for P can be extended to nitrogen data.

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