Indicator of risk of water contamination by phosphorus from Canadian agricultural land

Water Science & Technology Vol 53 No 2 pp 303–310 © IWA Publishing 2006

E. van Bochove*, G. Thériault*, F. Dechmi*, A.N. Rousseau, R. Quilbé**, M.-L. Leclerc* and N. Goussard****

*Agriculture and Agri-Food Canada, Soils and Crops Research and Development Centre, 2560 Hochelaga Boulevard, Sainte-Foy, Quebec, G1V 2J3, Canada (E-mail: *vanbochovee@agr.gc.ca; theriaultg@agr.gc.ca; dechmif@agr.gc.ca; leclercml@agr.gc.ca; goussardn@agr.gc.ca*)

**Institut national de la recherche scientifique, Eau, Terre et Environnement, 490 de la Couronne, Québec, G1K 9A9, Canada (E-mail: *alain_rousseau@ete.inrs.ca; Renaud_QUILBE@ete.inrs.ca)*

Abstract The indicator of risk of water contamination by phosphorus (IROWC_P) is designed to estimate where the risk of water P contamination by agriculture is high, and how this risk is changing over time based on the five-year period of data Census frequency. Firstly developed for the province of Quebec (2000), this paper presents an improved version of IROWC_P (intended to be released in 2008), which will be extended to all watersheds and Soil Landscape of Canada (SLC) polygons (scale 1:1, 000, 000) with more than 5% of agriculture. There are three objectives: (i) create a soil phosphorus saturation database for dominant and subdominant soil series of SLC polygons – the soil P saturation values are estimated by the ratio of soil test P to soil P sorption capacity; (ii) calculate an annual P balance considering crop residue P, manure P, and inorganic fertilizer P – agricultural and manure management practices will also be considered; and (iii) develop a transport-hydrology component including P transport estimation by runoff mechanisms (water balance factor, topographic index) and soil erosion, and the area connectivity to water (artificial drainage, soil macropores, and surface water bodies).

Keywords Agriculture; hydrology; indicator; phosphorus; soil; water contamination

Introduction

Nutrient management in agricultural production is of critical importance from the standpoint of environmental protection and agro-ecosystem sustainability. Excessive amounts of P in surface fresh water contribute to eutrophication of rivers and lakes. The contamination of water is of greatest concern in areas where soil tests show high P levels, ability of soils to retain P is low, susceptibility to runoff is high, macropore flow is high, soil erosion is high, and where connectivity to surface water and artificial drainage is dense.

Phosphorus, a major nutrient used in agricultural activities, is getting more and more attention in Canada. In the provinces of Quebec and Ontario, phosphorus is currently part of nutrient management plans developed for farming operations in order to reduce the risk of contamination of adjacent surface water bodies. Moreover, other provinces are considering the possibility to come up with similar management plans.

It is important to demonstrate to the Canadian public and to the Canadian economic partners that a national indicator of risk of water contamination by P is being developed on current scientific knowledge and that it could be efficiently used for governmental policies. The relevance to develop a national indicator of risk of water contamination by P for Canada is to identify critical areas across the country where more prospecting is required to protect surface water. Once identified, these areas would be investigated carefully at the operational management watershed scale. Stakeholders could then enforce

doi: 10.2166/wst.2006.064

management plans and beneficial management practices at the farm level in critical areas following the concept of strict regulations for voluntary adoption. Rather than assuming that inappropriate farm management is responsible for water quality problems, the underlying causes of the symptoms (regional and global economic pressures and constraints) must be also addressed (Sharpley *et al.*, 2001).

An indicator of risk of water contamination by phosphorus (IROWC_P) was developed during the Agri-Environmental Indicator Project (McRae *et al.*, 2000) at the Soil Landscapes of Canada (SLC) polygon scale on the basis of a phosphorus index (PI) developed by Lemunyon and Gilbert (1993) and USDA-NRCS (1994). The first version of IROWC_P (Bolinder *et al.*, 2000) was applied only for Quebec because reliable site information was available from provincial soil surveys (Tabi *et al.*, 1990), particularly the degree of soil P saturation (DSPS) and soil test P (STP). Although some soil surveys across the country included P data, no soil P-status databases were available for other Canadian provinces. Therefore, as a primary requirement to estimate risk of water contamination by P, a national DSPS database for agricultural soils will be created. The modified IROWC_P will also include a transport–hydrology component that will improve estimation of the risk of P transport to water by soil erosion, infiltration and surface runoff to water by accounting for the connectivity of agricultural land to drainage areas at a daily interval. The scope of this paper is to present the current state of development of a national indicator of risk of water contamination by P intended to cover all Canadian agricultural land.

Methodology

IROWC_P formulation and data sources

The national IROWC_P modified version will be built on the first version of IROWC_P (Bolinder *et al.*, 2000) and adapted to Canadian soil and climate characteristics. The modified IROWC_P will be calculated at both SLC polygon and watershed levels using existing Census of Agriculture, farm environmental management surveys, hydrology, and climate databases.

Agriculture and Agri-Food Canada (AAFC) in collaboration with Statistics Canada – Agriculture Division have developed an "area-weighting" process for re-allocating Census of Agriculture data from census polygon based geographies to other "target" polygon-based geographies such as Soil Landscapes of Canada and Drainage Area (Watershed) spatial frameworks (Canadian Soil Information System, 2004). The SLCs are based on existing soil survey maps which have been recompiled at a 1:1 million scale. Each area (or polygon) on the map is described by a standard set of attributes. The full array of attributes that describes a distinct type of soil and its associated landscape, such as surface form, slope, water table depth, permafrost and lakes, is called a soil landscape. SLC polygons may contain one or more distinct soil landscape components and may also contain small but highly contrasting inclusion components. The location of these components within the polygon is not defined. SLCs were originally conceived as a standardized database consisting of major attributes relevant to plant growth, land management, and soil degradation. These data have since turned out to be a useful framework to support other databases.

The modified IROWC_P includes the soil P-status component (*PS*), the annual P-balance component (*PB*) and the P transport-hydrology component (*PT_H*). The different IROWC_P subcomponents will be weighted to estimate their relative importance for P transfer to water and rated by their corresponding P class values. Finally, the three component values will be combined following equation 1 to estimate the risk of water contamination by P. IROWC_P values will be associated to five vulnerability classes (very low, low, medium, high and very high) to obtain a corresponding magnitude of risk for each polygon.

$$\text{IROWC\_P} = (PS + PB)PT\_H \quad (1)$$

Phosphorus status component

The degree of soil P saturation (DSPS) characterizes the actual P status of the soil and its long-term capacity to retain P. The DSPS is defined as the ratio of the soil-test P (STP) (Sims, 1993) to the inherent soil characteristic, the P sorption capacity (PSC) (Bache and Williams, 1971; Syers *et al.*, 1973). In the first version of IROWC_P, the PSC was estimated by the Mehlich-3 extractable Al and consequently the DSPS was calculated as the ratio of Mehlich-3 extractable P to Mehlich-3 extractable Al (Beauchemin and Simard, 1999; Khiari *et al.*, 2000). This modified version of IROWC_P will calculate a DSPS from two newly created databases: a STP and a PSC database, both at the SLC polygon and watershed levels.

Creation of the STP database. In Canada, the majority of soil and plant analyses are performed by private laboratories. Their STP databases are generally referenced on the basis of a producer, a producer association or a fertilizer dealer address level. Two current pathways of STP analysis exist between farms and soil laboratories (Figure 1). The development of the modified IROWC_P will need collaboration between the federal government and the agriculture industry through a third party to permit access to the existing STP databases. Therefore, an agreement between AAFC and a national fertilizer institute will be proposed to obtain a five-year period STP data aggregated at the SLC polygon and watershed levels.

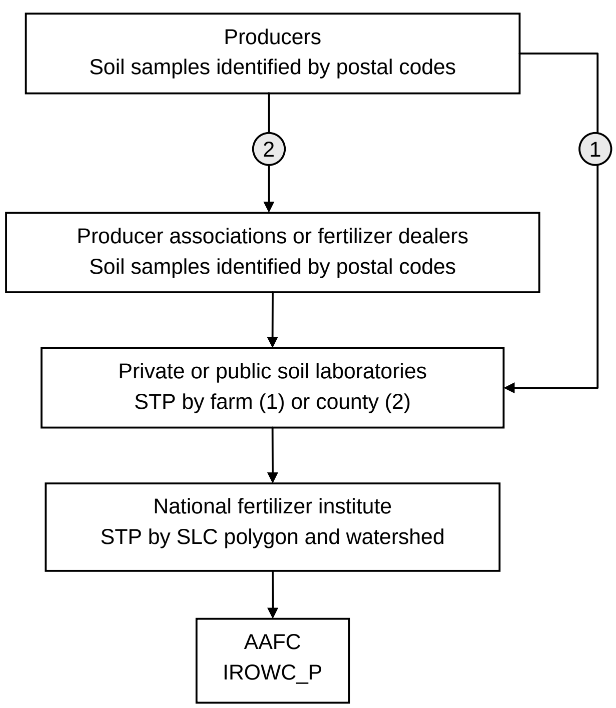

Figure 1 Flow chart of STP data aggregation at the SLC polygon and watershed levels; 1 and 2 are current pathways of soil sample and data transmission

Creation of a PSC database. To create the PSC database, a survey of the dominant soil series (A, B horizons) characterizing the agricultural SLC polygons in each province will be conducted. This survey is necessary as no agricultural soil PSC database is currently available in Canada. The soils will be analysed for their PSC and other related soil properties (pH, texture, OM, Ca, Fe and Al contents). Multivariate analysis will be performed (Leclerc *et al.*, 2001) to create soil groups presenting similar characteristics. These groups will then be used to classify each agricultural SLC polygon (dominant soil series) into a class of PSC (very low to very high). Thereafter, the first subdominant soil series of each polygon will be allocated to a PSC class using the related soil properties information available from existing soil surveys and SLC databases (Figure 2).

Phosphorus balance component

The modified IROWC_P will use the same P-balance component as in the first version of IROWC_P (Bolinder *et al.*, 2000). The current three subcomponents of P-balance are:

Mineral Fertilizer Phosphorus. This subcomponent is currently estimated from crop fertilizer P recommendation rates using information on the status of current STP levels. These estimations will be weighed against values derived from provincial summaries (total dollars spent on fertilizers and lime; the quantity of nutrient sold) and the following attribute of Census of Agriculture: “dollars spent on fertilizer and lime” at the SLC polygon level. As previously described, a STP value will be estimated for each agricultural SLC polygon and watershed. The Census of Agriculture will be the source of information for the area of production of the main crops.

Manure Phosphorus. This subcomponent is currently estimated from the Census of Agriculture database information. Data on the number of animals within different categories, manure production coefficients and manure P coefficients for each animal category will be used to calculate an estimation of the phosphorus coming from manure for a given SLC polygon. Several changes in management practices (animal feeding,

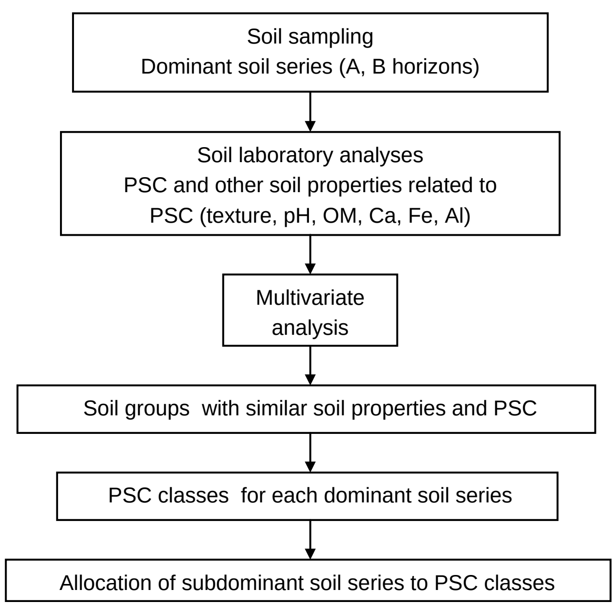

Figure 2 Different steps to allocate dominant and subdominant soil series of each SLC polygon to PSC classes

water utilization, etc.) have occurred in the past few years and have caused noteworthy changes in quantities of nutrients excreted and applied to agricultural soils. Consequently, the basic coefficients used in the calculations are under revision.

Crop residue Phosphorus. This subcomponent is currently estimated from the Census of Agriculture database and Provincial Census information: phosphorus uptake and phosphorus harvest coefficients. Only the major annual crops and hay categories for each province are considered. This subcomponent estimates values of exported phosphorus out of the SLC polygon or watershed at harvest, and also estimates values of crop residue phosphorus remaining on the agricultural soil after harvest.

Phosphorus transport–hydrology component

Under Canadian conditions, snowmelt runoff, rainfall runoff (Hortonian and saturation excess runoff), and subsurface flow represent the dominant hydrologic processes governing P transfer to surface water. The importance of each process is variable in time and space and depends on various factors such as drainage conditions, meteorological conditions, cropping and tillage practices, soil characteristics and topography (Figure 3).

In the revised IROWC_P, the risk of contamination is estimated on the basis of the transport–hydrology component *(PT_H)*, the particulate and dissolved sources of P (*PP* and *DP*) as well as other factors accounting for hydrological connectivity between sources and water bodies (Figure 4).

At the SLC polygon level, *PT_H* may be viewed as a function of erosion (*E*), surface runoff (*R*), infiltration (*I*), topography (*TI*), preferential flow (*PF*), tile drainage (*TD*), and surface drainage density (*SD*):

$$PT\_H = f(E, R, I, TI, PF, TD, SD) \quad (2)$$

Although we do not know a priori the form of the function introduced in (2), as a first approximation, we propose, on an annual basis, the following arrangement:

$$PT\_H = (SD)(E) + (TI + SD)(R) + (TD + PF)(I) \quad (3)$$

The risk of *PP* contamination increases with the product of *SD* and *E*; meanwhile, the risk of *DP* contamination increases with the product of the two water balance surplus factors

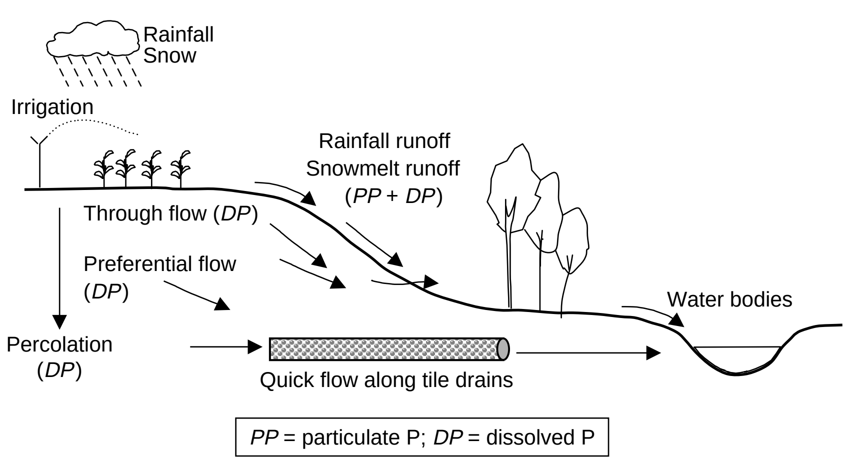

Figure 3 Phosphorus transport pathways

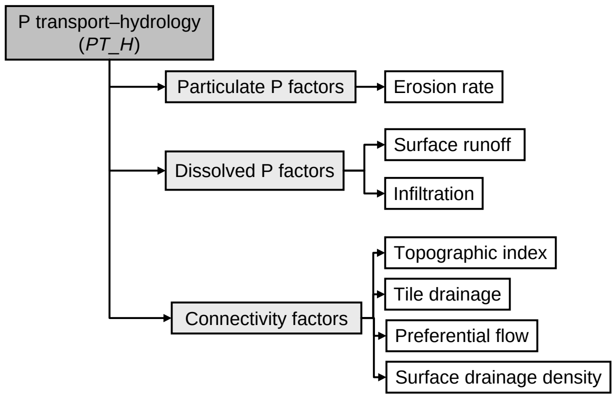

Figure 4 Phosphorus transport–hydrology factors

(*R* and *I*) and the hydrological connectivity factors governing surface runoff ($TI + SD$) and subsurface runoff ($TD + PF$) respectively without generating sediment loss.

Soil erosion rate, *E*, will be calculated using the Revised Universal Soil Loss Equation for Application in Canada (RUSLEFAC, 1997). This model predicts the amount of sediment loss (given in tons of soil loss per hectare and per year) in overland flow and accounts for winter and non-winter conditions in different Canadian regions (Prairie region, Eastern Canada and British Columbia). The methodology to use the RUSELFAC equation at the SLC polygon level is actually under investigation to be improved and included in the Risk of water erosion indicator (van Vliet, 2004).

A soil water balance approach is used to quantify excess soil water that runs off cropland as surface and/or subsurface flow using the Versatile Soil Moisture Budget model modified by Akinremi *et al.* (1996). This model uses the SCS-CN method (USDA-SCS, 1972) to partition *R* and *I*. The soil water balance calculation will be performed on a daily time step, thus providing upon summation an annual water balance. A seasonal partitioning of *R* will be considered to account separately for snowmelt runoff and rainfall runoff. Climatic variations between years will be considered as well.

The hydrological connectivity between P sources and water bodies is modelled using: (i) the topographic index, *TI*, of Kirby (1975) which accounts for the propensity of watershed area for saturation excess runoff; (ii) tile drainage, *TD*, and preferential flow, *PF*, because significant quantities of P could be exported from saturated-P soils intensively drained and through soil macropores (Sharpley *et al.*, 1994; Hansen *et al.*, 2002); and (iii) surface drainage density, *SD*, which accounts for ditches, brooks, rivers, ponds, lakes and wetlands. All these factors will be weighted with research and development work as well as already available national databases.

Discussion

The feasibility to create a national STP database depends on the data availability from the soil laboratories and the establishment of regional rating value tables. Canada has a variety of acidic and calcareous agricultural soils. Therefore, different STP methods of analysis are adapted to intrinsic characteristics: Mehlich 3, Olsen, Kelowna. Accordingly, the STP rating values will be discussed within Provincial P-expert commitees and adapted to the regional conditions and function of the crop P requirements.

In the calculation process of mineral fertilizer P inputs, the only nationwide available data giving some indirect information on the quantity of fertilizers applied on agricultural soils is the Census of Agriculture attribute “dollars spent on fertilizer and lime”. Using this data in the ratio method with data coming from provincial summaries may lead to serious deficiencies. For example, a distortion by the nutrient costs encountered by specialty production can lead to an unreasonably large quantity of fertilizers used in more common productions. Also, the same proportion of nutrients is being allocated to the polygon regardless of the crop mix. As previously mentioned, several changes in management practices (animal feeding, water utilization, application techniques, etc.) have occurred in the past few years and caused noteworthy changes in quantities of nutrients excreted and applied to agricultural soils. The basic coefficients are dynamic and one should make sure that they reflect the reality as much as possible.

The development of the P transport–hydrology component should improve estimation of risk of water contamination by accounting for the main P transport processes, climate, and the connectivity of agricultural land to water bodies. Also its formulation defines separately erosion, runoff and infiltration, which control the P transport, in order to weigh their relative impacts as a function of the different agro-climatic regions. Furthermore, these transport processes are modulated by relevant factors that define the hydrological connectivity to surface and ground waters. The transport–hydrology component is also developed with the objective to estimate the risk of water contamination by other contaminants from agricultural activities such as nitrogen, pesticides and pathogens. The four indicators of risk of water contamination (IROWCs) are simultaneously developed under the National Agri-Environmental Health Analysis and Reporting Program (NAHARP) with the objective to use the same water budget model, the same national hydrology databases and the same soil erosion model.

Conclusions

The first version of IROWC_P for Quebec will be updated with 2001 Census data and SLC v3.0 by the end of 2004. The modified IROWC_P will be completed in 2008 and will be validated at the watershed level with local or regional water quality data in some catchment areas across Canada.

Acknowledgements

We thank our colleagues of IROWC-N, C. Drury, R. De Jong, B.J. Yang, and T. Huffman, IROWC-pathogens, E. Topp, and IROWC-pesticides, A.J. Cessna, A. Farenhorst, and R. McQueen for their comments and collaboration on the development of the transport–hydrology component. We acknowledge the staff from the National Agri-Environmental Health Analysis and Reporting Program of Agriculture and Agri-Food Canada: A. Lefèbvre and W. Eilers.

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