Options on How to Set Phosphorus Limits in Runoff to Protect Water Quality of Receiving Water Bodies

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ABSTRACT

This study identifies three practical options to set phosphorus limits in overland runoff so as to protect the water quality of receiving water bodies. In order of increasing relevance, these options are adoption of the Alberta surface water quality guideline of 0.05 mg L^{-1}, derivation of regional limits, and derivation of site-specific limits.

Stream phosphorus data from 52 small streams mostly influenced by agricultural non-point sources were used to illustrate how regional limits could be derived. Stream data were grouped according to broad ecological areas in Alberta (boreal forest, parkland, and grassland), and agricultural intensity in the watershed (low, medium, and high). Depending on the ecological area and the current level of agricultural intensity, total dissolved phosphorus limits ranged from 0.02 to 0.56 mg L^{-1} and export from 0.001 to 0.090 kg ha^{-1}.

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Stream data for agricultural streams in Alberta originate primarily from water quality sampling programs conducted under the Canada-Alberta Environmentally Sustainable Agriculture Agreement and its successor the Alberta Environmentally Sustainable Agriculture Program. Several individuals, including David Trew, Al Sosiak (Alberta Environment), and Sandra Cooke (Grand River Conservation Authority, Ontario) also contributed data from separate research projects.

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INTRODUCTION

The purpose for development of soil phosphorus limits is to minimize the amount of phosphorus that leaves agricultural watersheds and enters surface waters (i.e., acceptable risk). The ultimate goal is to minimize eutrophication. Limits to phosphorus losses due to human activities on the landscape need to take into account factors that influence natural losses of phosphorus. These factors include the type and nature of soils; the landscape, including local topography; and the climate, particularly as it relates to the amount of runoff from the watershed.

This report describes and discusses options that may help define phosphorus limits in overland runoff so that the water quality of receiving water bodies is protected. This information may provide some guidance for selecting runoff quality objectives used to calculate proposed soil phosphorus limits as described by Jedrych et al. (2006).

CONCEPTUAL APPROACH

Options for Water Quality Limits

Three options were considered to set limits for dissolved phosphorus concentrations in runoff water entering surface waters: (1) application of the Alberta surface water quality guideline (Alberta Environment 1999), (2) development of site-specific or water-body-specific objectives, and (3) adoption of interim regional limits. The following are details about these three options.

Alberta surface water quality guidelines. The Alberta Surface Water Quality Guidelines specify a limit of 0.05 mg L^{-1} total phosphorus (TP) for the protection of surface waters (Alberta Environment 1999). This is an established provincial limit, which is a general reference value that offers a uniform level of protection. This limit applies regardless of spatial or temporal differences that typify the range of different water bodies in the province. In some cases, this limit may be too stringent and unattainable because background levels may be higher. In other cases, it may not be protective enough because it exceeds background levels.

Site-specific objectives. Site-specific or water-body-specific objectives for phosphorus is the preferable, but most complex option. To set site-specific or water-body-specific phosphorus objectives requires a good understanding of the limnology and hydrology of the water body. Point sources and non-point sources in the watershed need to be identified and quantified. Water quality objectives are a societal decision. Therefore, stakeholders who have a vested interest in the watershed and the water body need to be involved, and this includes downstream users. Objectives need to be defined in such a way that they recognize the water quality requirements for various uses as well as the limitations due to natural background conditions and the current level of development of the watershed. Once a phosphorus objective is defined, limits are allocated to point and non-point sources so the objective can be met. Mitigative measures need to be implemented if limits are already exceeded. Site-specific objectives are attainable and offer the appropriate level of protection for that water body. The development of a watershed management plan for phosphorus is an implicit requirement in the successful implementation of a site-specific or water-body-specific phosphorus objective. It was far beyond the scope and time frame of this study to develop objectives and management plans for each water body in the province.

Interim regional limits. The adoption of interim regional phosphorus limits is a compromise between the use of a uniform water quality limit and the development of site-specific objectives for all water bodies in the province. Regional limits can take into account sources of natural variability, as well as the current level of development. Consequently, regional limits are attainable. They are qualified as interim because the ultimate goal is to replace them with site-specific or water-body-specific objectives. Interim regional limits may not offer the appropriate level of protection for all individual water bodies within the region; only site-specific objectives will achieve that goal.

The option of development of interim regional limits was described above. Conceptually, these limits apply to runoff water upon entry into surface waters. Proposed limits are not intended as a substitute for the Alberta Surface Water Quality Guidelines.

Selecting Water Bodies Directly Influenced by Agricultural Runoff

Phosphorus levels are documented for a wide range of water bodies in Alberta. In contrast, the database that documents phosphorus in runoff from agricultural fields is relatively small. To relate phosphorus levels in agricultural runoff with phosphorus levels in surface waters, water bodies that would most directly be influenced by agricultural non-point source runoff were selected in the surface water quality database. Specifically, these are small agricultural streams in the headwaters of larger streams and rivers or streams that drain directly to lakes. Most of these small streams are intermittent in nature and are typically fed by runoff water from their watershed. These stream phosphorus data were used to set limits for phosphorus in the runoff that feeds them.

An extensive water quality database has been assembled for such agricultural streams in recent years in Alberta, as part of studies conducted under the Canada-Alberta Environmentally Sustainable Agriculture (CAESA) Agreement, the Alberta Environmentally Sustainable Agriculture (AESA) Program, or as part of lake management and research studies (Trew et al. 1987; Sosiak and Trew 1996; Cooke and Prepas 1998). These studies have highlighted a number of important factors that influence broad-scale patterns of phosphorus transport in Alberta, and the need to be accounted for and standardized when attempting to set allowable export loads from agricultural land.

Standardizing the Data Set

To set upper limits to contributions from land-based activities, it is important to standardize for other influences. Agricultural streams in Alberta are influenced by different climatic zones and they vary greatly in their hydrological characteristics. They are also managed at different levels of agricultural intensity. Hydrological characteristics such as stream flow and runoff patterns greatly influence phosphorus transport or flux in watersheds. Mass transport can be expressed in terms of mass loads, export coefficients, and flow-weighted mean concentrations (FWMC). Flow-weighted mean concentrations are the preferred expression because they standardize for differences in flow regime among streams. Mass load and export coefficients are less desirable in such comparisons because they tend to be highly influenced by stream discharge.

At a watershed scale, total dissolved phosphorus (TDP) tends to be a better indicator of agricultural runoff than TP, which can be strongly influenced by stream discharge.

Climate, soils, and landscapes can influence the flux of phosphorus from land to water. Ecoregions are fairly uniform with respect to climate, soils, and landscapes. Watersheds within an ecoregion can be expected to behave more uniformly with respect to phosphorus flux rates than watersheds among ecoregions.

The relationship between stream phosphorus level and agricultural intensity of the watershed is apparent in the Alberta stream data set (CAESA 1998). The data set showed that on average, streams in watersheds with high agriculture intensity had about four times the phosphorus concentration compared to streams in watersheds with low agriculture intensity. Streams draining watersheds with similar agricultural intensity are expected to behave more uniformly with respect to phosphorus flux rates than streams that differ broadly in agricultural intensity. Each watershed was rated for agriculture intensity based on 1991 and 1996 agricultural census data.

Defining Acceptable Total Dissolved Phosphorus Flow-weighted Mean Concentration

Streams within the same ecoregion that drain land of similar agricultural intensity will exhibit some variability in TDP FWMC because of local variation in land-use practices and climatic conditions. The range of variability in TDP FWMC can be captured by multiple years of data for many streams. To maintain water quality conditions, a minimum requirement would be to maintain the median of the distribution of stream phosphorus concentrations at a steady value. The median is the mid-point of the distribution (i.e., 50% of the numbers will be higher and 50% will be lower than the median). Therefore, for a given ecological region and agricultural intensity, the 50^{th} percentile TDP FWMC becomes the target number.

Defining Acceptable Export Coefficients

The annual unit runoff was calculated from the total volume of water that contributes to stream flow divided by the active portion of the drainage area. The annual unit runoff can vary from year to year, mainly because of variability in precipitation. In a long-term data set, the 50^{th} percentile represents a general, typical measure of unit runoff for a given geographical area. For a given ecoregion and level of agricultural intensity, the product of 50^{th} percentile TDP FWMC and the 50^{th} percentile unit runoff yield represents a median TDP export coefficient for that region and represents the maximum allowable export target.

METHODS

Assumptions

The following assumptions were made in assessing the data.

- For each stream group, the data used to generate median TDP FWMC are representative.
- The 50th percentile is the best measure to use as a reference for no further deterioration (i.e., technically, in 50% of the cases the situation could improve, while in 50% the situation could deteriorate). However, it is recognized that median stability does not necessarily ensure range stability.
- Total dissolved phosphorus will continue to be the best marker for agricultural losses of phosphorus (i.e., continued emphasis on erosion control is needed).
- All land within a watershed is assumed to contribute equally (export coefficients are averages for the watershed).
- All phosphorus transported by the stream is assumed to be derived from terrestrial origin.
- Flow-weighted mean concentrations and export coefficients apply to the entire flow period (i.e., annual), they are not event based.

Data Source

Phosphorus transport has been quantified for many agricultural streams in Alberta since the late 1970s. Most of the data on dissolved phosphorus are from the 1990s. Most of the stream data used here were derived from water quality monitoring carried out under the CAESA or AESA programs that were available in 2000 when this assessment was carried out. Additional stream data were extracted from Trew et al. (1987), Sosiak and Trew (1996), and Cooke and Prepas (1998). Stream names and years of data are shown in Table 1. Ecological region and agricultural intensity class to which streams were assigned are also shown in Table 1.

Annual FWMC reported by Sosiak and Trew (1996), Anderson et al. (1998), Cooke and Prepas (1998), Anderson (2000), Donahue (2000), and values calculated for AESA streams monitored in 2000, are derived either from

- one location on each stream, at or near a flow-gauging station maintained by Environment Canada, Alberta Environment, or a researcher,
- up to 20 grab samples collected per year on a flow-weighted basis (higher sampling frequency during periods of runoff and high flow),
- standardized calculations using the International Joint Commission (IJC) method (Environmental Laboratories 1995) or an equivalent method.

Annual unit runoff on the Canadian prairies has been compiled and summarized by Bell (1994). The 50th percentile isopleth map was used to select a value for the annual unit runoff, which could be used for illustration of the calculations and would be applicable to the broadly defined, ecological region. Annual unit runoff depth can exhibit substantial differences within some regions and recognition of these differences could help refine the calculation of export coefficients.

Table 1. List of sites and years for which phosphorus data were used in defining phosphorus limits for runoff entering surface waters.

	Agric. intensity [z]	Station code	Stream	Years of data
Boreal Forest Area				
Peace lowland, boreal transition	M	07GE003	Grande Prairie Creek	99-2000
Peace lowland, boreal transition	M	07GE002	Kleskun Drain	99-2000
Western Alberta upland	L	07BB013	Paddle River near Anselmo	96-97,99-2000
Dry Mixedwood (Northwest)	H	07BC007	Wabash Creek	99-2000
Dry Mixedwood (Grande Prairie-Peace R.)	L	07FD011	Hines Creek	99-2000
Dry Mixedwood (Northwest)	L	07AH909	Goose	95-96
Dry Mixedwood (Northwest)	L	07AH004	Christimass	96-97
Western Alberta upland	L	07BB007	Little Paddle	96-97
Western Alberta upland	L	07AH004	Sakwatamau	96-97
Mixed boreal upland, Slave R. & Wabasca lowland	M		Baptiste (1977,78), stream B	77-78
Mixed boreal upland, Slave R. & Wabasca lowland	M		Baptiste (1977,78), stream M	77-78
Mixed boreal upland, Slave R. & Wabasca lowland	M		Baptiste (1994), stream A1 (=A in 1977, 78)	77-78,94-95
Mixed boreal upland, Slave R. & Wabasca lowland	M		Baptiste (1994), stream A2 (=N in 1977, 78 above)	77-78,94-95
Mixed boreal upland, Slave R. & Wabasca lowland	L		Baptiste (1977,78), stream K	77-78
Mixed boreal upland, Slave R. & Wabasca lowland	L		Baptiste (1977,78), stream L	77-78
Mixed boreal upland, Slave R. & Wabasca lowland	L		Baptiste (1994), stream F1 (=E above)	94-95
Mixed boreal upland, Slave R. & Wabasca lowland	L		Baptiste (1994) , stream F2 (=E above)	94-95
Peace lowland, boreal transition	L	07CA0051	Flat	96
Peace lowland, boreal transition	H	05DF006	Strawberry Creek near mouth	96-99
Peace lowland, boreal transition	H	05EA0171	Atim	96
Western Alberta upland	L	05DE009	Rose Creek neat Alder Flats	96-2000
Peace lowland, boreal transition	M	05CC010	Blindman Creek near Bluffton	96-2000
Peace lowland, boreal transition	M	05DE011	Tomahawk Creek near Tomahawk	96-98,2000
Peace lowland, boreal transition	M	05CC011	Lloyd Creek near Bluffton	96-97
Peace lowland, boreal transition	M	05CC012	Block Creek near Leedale	96-97
Parkland Area				
Aspen parkland	H	05CE012	Ray Creek near Innisfail	96-2000
Aspen parkland	H	05CD914	Haynes at M1	96-2000
Aspen parkland	H	05CD007	Haynes Creek near Haynes	96-2000
Aspen parkland	H	05CE020	Threehills Creek below Ray Creek	96-2000
Aspen parkland	H	05EE007	Stretton Creek near Marwayne	96-2000
Aspen parkland	H	05FE004	Buffalo Creek near Highway 43	96-97,99-2000
Aspen parkland	H	05EB018	Amisk Creek near Shonts	96
Aspen parkland	H		Pine Lake stream (1989) 1	89,92
Aspen parkland	M		Pine Lake stream (1989) 2	89,92
Aspen parkland	H		Pine Lake stream (1989) 3	89,92
Aspen parkland	H		Pine Lake stream (1989) 4	89,92
Aspen parkland	M		Pine Lake stream (1989) 5	89,92
Aspen parkland	H		Pine Lake stream (1989) 6	89,92
Aspen parkland	L		Pine Lake stream (1989) 7	89,92
Grassland Area				
Fescue grassland	M	05AB007	Trout Creek near Granum	96-97,99-2000
Fescue grassland	M	05AB031	Meadow Creek near mouth	96-97,99-2000
Northern continental divide	M	05AB046	Willow Creek at Highway 811	98
Mixed grassland	H-irr	05AJ004	Drain S-6 near Bow Island	99-2000
Mixed grassland	H-irr	05BN006	New West Coulee	99-2000
Moist mixed grassland	H-irr	05AD039	Battersea Drain	98-2000
Moist mixed grassland	H-irr	05AC023	Little Bow River	98
Moist mixed grassland	H-irr	05AG003	Expanse Coulee	98
Fescue grassland	L	05AD037	Prairie Blood Coulee near Lethbridge	96,99-2000
Aspen parkland	H	05CE013	Renwick Creek near Threehills	96-2000
Moist mixed grassland	M	05BM016	West Arrowwood Creek near Arrowwood	96-97
Moist mixed grassland	M	05BM020	West Arrowwood Creek near Ensign	96-97
Moist mixed grassland	M-irr	05BM010	Crowfoot Creek near Cluny	96-2000

[z] Agricultural intensity: L = low; M = medium; H = high; irr = irrigated.

The National Ecological Framework of Canada (Marshall and Schut 1999) defines ecozones, ecoprovinces, ecoregions, and ecodistricts as four scales of ecological classification. Stream TDP

FWMC data are not adequately dense to group by ecodistricts. Alberta has 25 ecoregions within its borders. For the purpose of this study, the TDP FWMC data were grouped into four ecological areas, based on the boundaries of the ecoregions: Alpine Area (two ecoregions), Grassland Area (four ecoregions), Parkland Area (one ecoregion), and Boreal Forest Area (18 ecoregions). Agricultural activity is not located in the Alpine Area, so this area was not considered in the classification process.

RESULTS AND DISCUSSION

Critical percentiles for TDP FWMC are shown in Fig. 1 for each agricultural intensity group within each ecological area. The annual export coefficient derived from the product of the 50th percentile FWMC and the annual unit runoff volume selected for that ecological area are shown in Fig. 2.

Figure 1 shows that overall, the range in TDP FWMC between the 10th to 90th percentile is relatively narrow, and the range in TDP FWMC is expanded mainly by the maximum values, which represent less than 10% of the watersheds. This fairly tight distribution suggests that the choice of the median as a phosphorus objective is an attainable goal.

Within an ecological area, higher TDP FWMC tend to be associated with higher agricultural intensity. However, streams in intensively farmed areas in the Boreal Forest Area had a lower median TDP FWMC than streams in areas of moderate farming intensity. This deviating pattern is likely due to the small number of data points for the high intensity stream group. Until this group can be described with more accuracy, data from streams in areas of high and moderate agricultural intensity have been merged.

In the Grassland Area, data for streams in dryland and irrigated areas have been separated. The data set for irrigated areas is small and TDP FWMC values are influenced by the quality of the source water. For example, Crowfoot Creek (i.e., data for the moderate intensity group) receives water from the Bow River below Calgary. Its TDP FWMC values are much higher than those for the high intensity streams, which receive water from foothill or mountain streams. Because source water quality has such a high importance on TDP FWMC, the relationship between TDP and agricultural intensity is weaker than for dryland streams. One additional complication with irrigated watersheds is the difficulty in defining an appropriate unit runoff volume for these streams. At this time, TDP FWMC for streams in irrigated areas are not suitable as target limits. Until these complications can be resolved, the use of TDP FWMC derived for intensively farmed dryland in the Grassland Area have been applied to irrigated areas.

The process that was used defines, in general terms, maximum acceptable phosphorus losses per unit area from agricultural watersheds. Maximum losses were derived from water quality data and apply to entire agricultural watersheds in broadly defined, ecological areas. There was no distinction among contributions from point sources, non-point sources, or specific land-based activities. Maximum losses defined were used as conservative references for acceptable phosphorus losses from agricultural land.

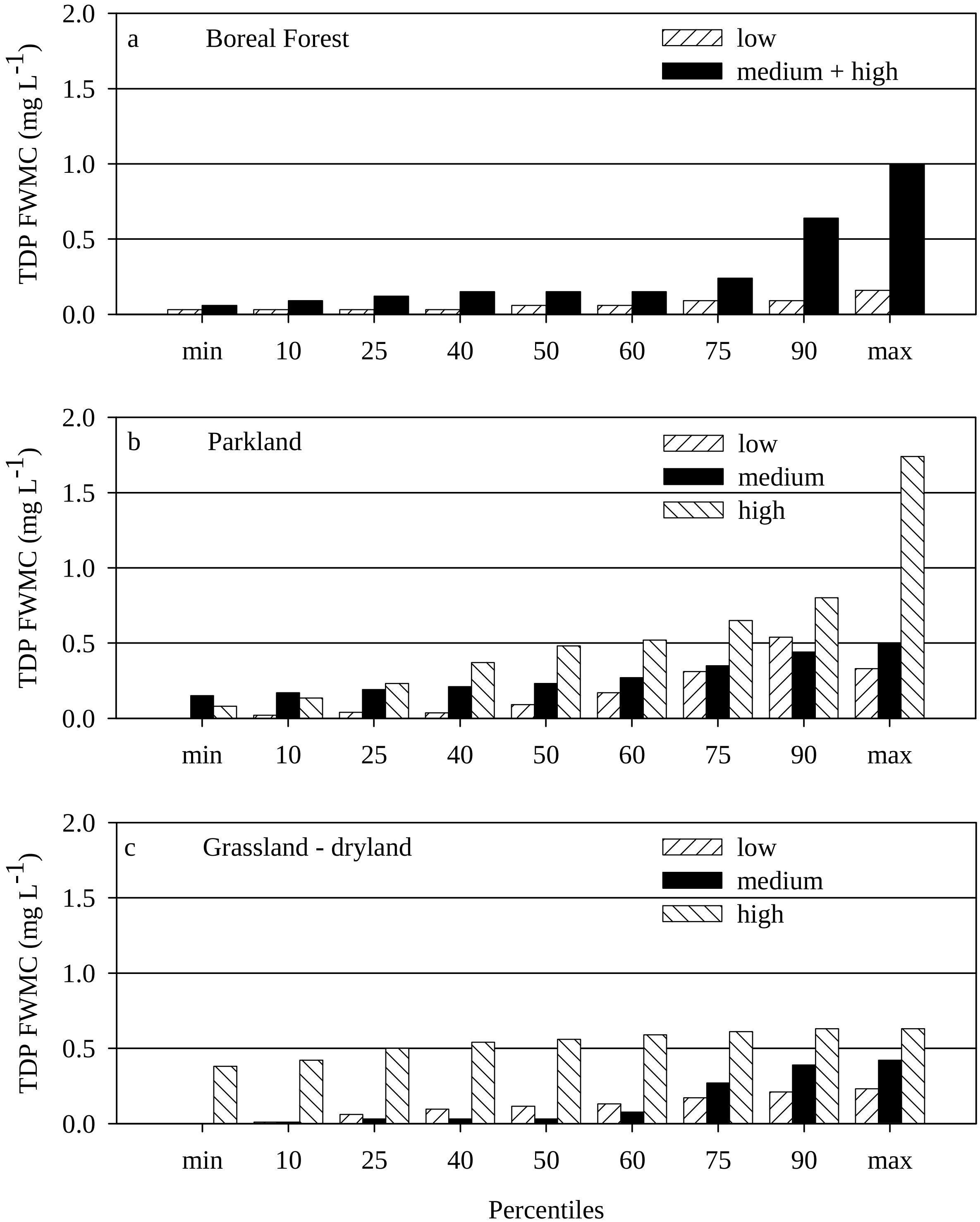
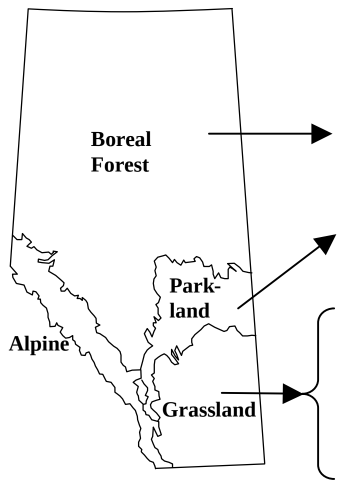


Fig. 1. Percentile distribution of total dissolved phosphorus (TDP) flow-weighted mean concentration (FWMC) for low, medium, and high agricultural intensity within the (a) Boreal Forest, (b) Parkland, and (c) Grassland Areas.



Agricultural intensity	Number of stream years (number of streams)	Runoff depth 50th percentile (mm)	TDP-FWMC 50th percentile (mg L^{-1})	Annual TDP export coefficient 50th percentile (kg ha^{-1} yr^{-1})
High + Medium	31 (13)	50	0.180	0.090
Low	28 (11)	50	0.050	0.025
High	33 (14)	15	0.463	0.069
Medium	4 (2)	15	0.234	0.035
Low	4 (2)	15	0.099	0.015
High	4 (1)	5	0.560	0.028
Medium	11 (7)	5	0.046	0.002
Low	2 (1)	5	0.115	0.006
High irrigated [z]	8 (6)	5	0.023	0.001
Medium irrigated [z]	5 (1)	5	0.134	0.007

[z] Indicates areas where additional data or information is needed to refine numbers.

Fig. 2. Total dissolved phosphorus (TDP) flow-weighted mean concentration (FWMC) and export coefficients by ecological area.

These broadly-defined, maximum losses need to be reviewed and adjusted to ensure they meet specific conservation and management objectives for sensitive water bodies such as lakes or streams, which are important for recreation, fisheries, or drinking water supplies.

FUTURE WORK

Link with the Soil Phosphorus and Runoff Phosphorus Relationship

The process described here defines maximum acceptable contributions from the entire watershed to the stream, but it does not necessarily relate directly to actual losses from fields. Results from the watershed field study (Little et al. 2006) can be used to predict phosphorus losses based on soil test phosphorus. However, the predicted losses from edge of field or site may not necessarily determine the phosphorus load that enters a stream. This is because of the complicated nature of the processes that occur between the edge of a specific site or soil polygon and the stream. The relationship between field losses and maximum acceptable contributions to the watershed needs to be evaluated. Such a relationship could be evaluated based on detailed watershed modeling.

Another approach would be to explore empirical relationships. Total dissolved phosphorus FWMC values have been defined for more than 60 different watersheds. Available soil phosphorus data for these watersheds should be compiled and summarized. The relationship between soil phosphorus data and FWMC could be described (e.g., regression analysis) and used to generate retention coefficients. These retention coefficients would help refine predictions of phosphorus field losses that actually enter surface waters. Alternatively, regression analysis could be used to predict acceptable phosphorus levels in soils within watersheds.

Phosphorus balances could also be derived for all watersheds in the province based on phosphorus applied (as fertilizer or manure) and phosphorus removed (based on phosphorus content of harvested biomass – crops and livestock). Data can be derived from 1996 census data. Residual phosphorus would be an indication of over-application. Relationships between the amount of phosphorus over-applied and FWMC could again be used to generate a retention coefficient, or to determine if there is a threshold between theoretical over-application and TDP FWMC.

More Detailed Spatial Representation of Estimates

Calculation of maximum acceptable TDP export has been illustrated for broadly defined ecological regions. These calculations could be applied to a much smaller land base such as ecodistricts. Ecodistricts can be ranked according to agricultural intensity and assigned an appropriate TDP FWMC based on numbers presented in Fig. 2. The median annual unit runoff depth for each ecodistrict can then be used to obtain a more refined value of maximum TDP export.

Effectiveness of Beneficial Management Practices

Although work on beneficial management practices (BMPs) is outside the scope of this study, it seems critical to highlight the need for reliable data on the effectiveness of BMPs to reduce phosphorus losses from farm land. Such documentation is needed at the watershed scale as well as the field scale.

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