

Calculation of Soil Phosphorus Limits for Agricultural Land in Alberta

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Alberta Soil Phosphorus Limits Project

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ABSTRACT

A method was developed to calculate soil phosphorus limits for agricultural land in Alberta. The proposed method involves calculation of total phosphorus (TP) export coefficients based on hypothetical TP runoff water quality limits (TPRWQLs) of 0.5 or 1.0 mg L⁻¹ and on calculated flow volumes at the watershed scale. Flow volumes were estimated for each watershed using 40 yr of Water Survey of Canada data measured at 144 hydrometric stations. Within each watershed, the medians of estimated flow volumes were partitioned among soil polygons according to the runoff potential simulated by the Water Erosion Prediction Project model. The allowable phosphorus concentrations were then calculated for the surface runoff from each soil polygon and for the estimated watershed TP export coefficient. These phosphorus concentrations were then substituted into the soil-test phosphorus (STP) and runoff TP flow-weighted mean concentration (FWMC) relationships measured in Alberta for two soil depths (0 to 2.5 cm and 0 to 15 cm), and then STP limits were calculated. Two major assumptions were applied in the development of the method. First, it was assumed that there was no base flow; therefore, surface flow volume was equal to the total flow volume from a watershed. Second, it was assumed that each unit area within a watershed contributed equally to the total phosphorus load. The water quality limits were applied to the total runoff volume in the watershed prior to runoff entering the stream.

The proposed method was applied to six watersheds and seven microwatersheds in Alberta. The STP limits calculated at the watershed and microwatershed scales were variable among soil and hillslope polygons. The variability was directly related to the runoff potential among polygons, the selected TPRWQL, and the STP-TP FWMC relationship used. There was little difference between STP limits calculated using the 0- to 2.5-cm STP-TP FWMC relationship compared to STP limits calculated using the 0- to 15-cm STP-TP FWMC relationship. As runoff potential from polygons within a watershed or microwatershed decreased, the allowable TP in the runoff increased, which in turn resulted in higher STP limits. The TPRWQL value of 0.5 mg L⁻¹ resulted in STP limits of 60 mg kg⁻¹ or less in the top 15 cm of soil for most of the land within the selected watersheds and microwatersheds. However, when a TPRWQL value of 1.0 mg L⁻¹ was used, the majority of the area had STP limits from 30 to 120 mg kg⁻¹.

The proposed method uses a quantitative approach for determining soil phosphorus limits, based on data collected under Alberta conditions, and can be used to assign soil phosphorus limits to agricultural land in Alberta. The method can be refined by further investigation of watershed-scale water quality limits for Alberta, by application of digital elevation model data in runoff modeling, and by calculating the contribution of base flow to the total flow volume.

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Tim Martin developed and helped implement a computer program that automatically generated the Water Erosion Prediction Project (WEPP) model input files for all the AGRASID soil polygons in Alberta. In addition, the program automated labour-intensive WEPP simulations at the soil-polygon scale and helped tabulate the simulation results into the final report. Wiebe Buruma was also very helpful in preparation of tables and figures for this report.

TABLE OF CONTENTS

Abstract	iii
Acknowledgements	iv
Table of contents	v
List of figures	vi
List of tables	vii
List of appendices	viii
Introduction	1
The approach used to calculate soil phosphorus limits	3
Scales of application	3
Watershed scale	3
Soil-polygon scale	3
Microwatershed scale.....	3
Hillslope scale	4
Soil phosphorus and phosphorus in runoff water	4
Hydrological modelling	6
Estimating runoff depth at the PFRA watershed scale	8
Water quality limits	10
Procedure for calculating soil phosphorus limits.....	13
Application of calculation procedure	17
Approach	17
Results and discussion	18
Summary and conclusions	26
References.....	28
Appendices	32

LIST OF FIGURES

Fig. 1.	Landscape scales used for soil-test phosphorus limit calculations	4
Fig. 2.	Comparison of predicted soil-test phosphorus (STP) using Equations 1, 2, and 3...	5
Fig. 3.	Comparison between WEPP-predicted runoff values using AGRASID defined 100% and 20% hillslope length scenarios	7
Fig. 4.	Annual unit runoff map with overlaid annual runoff depth values derived from 144 hydrometric stations.....	9
Fig. 5.	Comparison between the hydrometric station observed and map-estimated runoff depth values	11
Fig. 6.	Location of selected microwatersheds and watersheds used to demonstrate the calculation of soil phosphorus limits.....	17
Fig. 7.	Distribution of calculated soil-test phosphorus (STP) limits at the watershed level using Equation 3 (0- to 15-cm soil layer) and total phosphorus runoff water quality limits (TPRWQLs) of (a) 0.5 and (b) 1.0 mg L ⁻¹	21
Fig. 8.	Distribution of calculated soil-test phosphorus (STP) limits at the microwatershed level using Equation 3 (0- to 15-cm soil layer) and total phosphorus runoff water quality limits (TPRWQLs) of (a) 0.5 and (b) 1.0 mg L ⁻¹	23
Fig. 9.	Distribution of calculated soil-test phosphorus (STP) limits for agricultural soils in Alberta using Equation 3 (0- to 15-cm soil layer) and total phosphorus runoff water quality limits (TPRWQLs) of (a) 0.5 and (b) 1.0 mg L ⁻¹	24

LIST OF TABLES

Table 1.	Summary of calculated TP_i and STP_i limits at the selected PFRA watersheds	19
Table 2.	Summary of calculated TP_{ii} and STP_{ii} limits at the selected microwatersheds	22
Table 3.	Distribution of calculated soil-test phosphorus (STP) limits for all AGRASID soil polygons in the agricultural zone of Alberta using different total phosphorus runoff water quality limits (TPRWQLs) and STP models	25
Table 4.	Comparison between microwatershed measured and soil polygon calculated soil-test phosphorus (STP) values	25

LIST OF APPENDICES

Appendix 1.	Estimated allowed total phosphorus (TP) concentrations, soil-test phosphorus (STP 0-2.5 cm and STP 0-15 cm) limits, and TP loads within selected watersheds using a TP runoff water quality limit (TPRWQL) of 0.5 mg L ⁻¹	32
Appendix 2.	Estimated allowed total phosphorus (TP) concentrations, soil-test phosphorus (STP 0-2.5 cm and STP 0-15 cm) limits, and TP loads within selected watersheds using a TP runoff water quality limit (TPRWQL) of 1.0 mg L ⁻¹	53
Appendix 3.	Estimated allowed total phosphorus (TP) concentrations, soil-test phosphorus (STP 0-2.5 cm and STP 0-15 cm) limits, and TP loads within selected microwatersheds using a TP runoff water quality limit (TPRWQL) of 0.5 mg L ⁻¹	74
Appendix 4.	Estimated allowed total phosphorus (TP) concentrations, soil-test phosphorus (STP 0-2.5 cm and STP 0-15 cm) limits, and TP loads within selected microwatersheds using a TP runoff water quality limit (TPRWQL) of 1.0 mg L ⁻¹	81

INTRODUCTION

Phosphorus losses from agricultural land to surface water are a concern in Alberta. A province-wide study from 1993 to 1998 showed that as agricultural intensity in watersheds increased the amount of phosphorus in the watershed streams also increased (Anderson et al. 1998). In 1999, the Alberta Soil Phosphorus Limits Project was started to develop soil phosphorus limits for agricultural land in Alberta for the protection of surface water quality.

Some jurisdictions in the United States have proposed a soil limits or threshold approach to managing soil-test phosphorus (STP) levels in agricultural soils. However, this approach has been criticized on the grounds that STP levels are highly variable within farm fields and thus are difficult to measure and to regulate. As well, thresholds do not consider transport processes that move phosphorus from soil to receiving water bodies (Feagley and Lory 2005). However, Sharpley et al. (1996) outlined an approach that integrates STP source factors with estimates of transport factors in the form of potential runoff and erosion losses based on local climatic, topographic, and agronomic factors. The approach lists three steps to identify environmentally sound phosphorus thresholds in soil: (1) determine the extraction coefficient, or slope of the relationship between phosphorus in soil and in runoff; (2) use water erosion models to identify runoff potential to calculate phosphorus loads; and (3) apply a water quality limit to identify maximum allowable concentrations of phosphorus in surface water.

Many researchers have shown that STP in the soil surface (e.g., 0 to 5 cm) is linearly related ($r^2 = 0.58$ to 0.98) to the concentration of dissolved reactive phosphorus (DRP) in runoff water (Sharpley et al. 2002; Schroeder et al. 2004; Vadas et al. 2005). Researchers often use rainfall simulators to determine the phosphorus extraction coefficient, which is the slope of the linear relationship between STP and DRP. This value has been shown to vary according to management and soil factors (Sharpley et al. 1996). Soil factors include forms of soil phosphorus, organic matter content, and phosphorus sorption capacity (Sharpley 1983). Researchers, such as Pote et al. (1999), McDowell et al. (2001), McDowell and Sharpley (2002), and Torbert et al. (2002), have reported extraction coefficients ranging from 0.0002 to 0.0011 for STP and DRP measured under simulated rainfall in grassed fields. Wright et al. (2003) reported higher values for cultivated soils. Despite these differences, Vadas et al. (2005) reported that a single extraction coefficient adequately described runoff DRP in simulated runoff from 30 soils.

Only a few studies have documented the relationship between STP and total phosphorus (TP) in runoff (Sharpley et al. 1992, 2001, 2003; Andraski and Bundy 2003; Schroeder et al. 2004; Kleinman et al. 2004). Although Andraski and Bundy (2003) and Kleinman et al. (2004) reported that TP is not as well related to STP as is DRP for controlled plot scales under rainfall simulation, Schroeder et al. (2004) found good relationships between STP and TP. The results of Wright et al. (2003) indicate that the relationship between STP and TP improves at field scales relative to plot scales. The results of the field-scale Microwatershed Study conducted between 2002 and 2005 in Alberta support the direct linear relationship between STP and TP concentrations in runoff (Little et al. 2006). Other Alberta studies have documented the relationship between phosphorus in soil and phosphorus in runoff water based on laboratory rainfall simulations (Wright et al. 2006), field rainfall simulations (Wright et al. 2003; Ontkian et al. 2006), monitoring runoff from small watersheds (Wright et al. 2003), and studying soil

phosphorus sorption characteristics (Whalen and Chang 2002; Wright et al. 2003; Casson et al. 2006).

Extrapolating field and laboratory measurements made in controlled conditions to larger areas is difficult and is complicated by processes that act differently at larger scales compared to plot scales. For example, Gburek and Sharpley (1998) outlined the concept of a critical or variable source area where only small portions of a watershed contribute runoff. As such, the validity of extrapolation of plot results to field scales must be questioned since variables and generalizations are site and soil specific (Young and Mutchler 1976; Mannaerts 1992). The few research results that compare phosphorus transport from simulated rainfall plots with those from larger areas under natural rainfall are conflicting (Vervoort et al. 1998; Sharpley et al. 1999; Sharpley and Tunney 2000). Calhoun et al. (2002) used unit area export values to characterize phosphorus losses from plot (0.04 ha), field (0.8 to 3.2 ha), and watershed (1.6 million ha) scales in northeastern United States, and found only vague relationships between phosphorus losses at the river mouth and upstream soil conditions at the large watershed scale. Although similarities in TP export were found between scales within the same watershed, there were instances where TP export was greater at the field scale relative to the plot and watershed scales. They, and others (Sharpley et al. 2002), concluded that site-specific factors such as soil texture, landscape, and climate conditions are important factors in impacting phosphorus export from watersheds.

Hydrologic models have been used to extrapolate measured relationships to other locations. Nash et al. (2002) stated that simulation models provided the best opportunity to generalize results from empirical studies to the wider landscape, particularly if they simulate soil, water, and chemical processes. Gburek and Sharpley (1998) pointed out that extrapolation of soil phosphorus and runoff phosphorus relationships developed for plot scales becomes problematic when we recognize that spatially variable phosphorus sources, sinks, and transport processes are linked by the watershed-scale flow system. They suggested that a strategy to address soil phosphorus impacts on water quality must integrate the effects at the field scale where management practices are implemented, and at the watershed scale where the results of the strategy are evaluated. Kirkby et al. (1996) and Sharpley et al. (2002) described a variety of models that address transport processes at various scales.

The objective of this report was to propose a method for calculation of site-specific soil phosphorus limits for agricultural land in Alberta using the general approach described by Sharpley et al. (1996) and the field-scale relationships and information obtained from various studies carried out within the Alberta Soil Phosphorus Limits Project.

THE APPROACH USED TO CALCULATE SOIL PHOSPHORUS LIMITS

Scales of Application

Information from four landscape scales was used to calculate soil phosphorus limits. These landscape scales included, in order of decreasing size, watershed, soil polygon, microwatershed, and hillslope (Fig. 1).

Watershed scale. The watershed scale relates to the Prairie Farm Rehabilitation Administration's (PFRA) Watershed Project (Cherneski and Ackerman 1998). There are approximately 865 PFRA gross watersheds in Alberta. It is expected that water quality limits would be applied at this scale.

Soil-polygon scale. The soil-polygon scale relates to the Agricultural Region of Alberta Soil Inventory Database (AGRASID) (MacMillan and Pettapiece 2000). This scale represents the most detailed level of soil information that is available in Alberta for the area of interest. Each PFRA watershed may contain a few to hundreds of soil polygons depending on the size of the watershed. In each soil polygon, a unique allocation of one or more soils is distributed across the slope positions of the landform. A single soil polygon is associated with 1 of 53 landform models for which slope steepness and slope length are defined. In reality, each area identified by an AGRASID soil polygon may contain a large number of unique field-scale hillslopes, and the single landform model is an idealized simplification of these. The AGRASID database covers only the agricultural area of Alberta, with 28,370 soil polygons ranging in size from approximately 260 to 9,300 ha. It is at this scale that soil phosphorus limits were calculated.

It should be noted that the soil-polygon boundaries in the agricultural region of Alberta do not follow watershed or sub-watershed boundaries, which are associated with landscape topography. To delineate the sub-watershed scale boundaries within each soil polygon, digital elevation model (DEM) data would be required as input into the landform topography simulations. Modeling surface flow at this scale was considered to be extremely difficult and beyond the scope of this report.

Microwatershed scale. The microwatershed scale relates to the drainage areas of the seven cultivated field-scale study sites used in the Microwatershed Study (Little et al. 2006). The drainage areas of the cultivated microwatersheds ranged from 26 to 248 ha, with the largest site of 248 ha containing four similarly managed fields. Drainage from the microwatersheds matched surface runoff from first-order streams that were ephemeral and dominated by terrestrial vegetation. In contrast, watersheds are drainage basins of second- to fifth-order streams (Strahler 1952). Microwatershed-sized areas leading to first-order streams are the key areas in which to monitor surface runoff and pollutants because they deliver the greatest volume of runoff within stream networks (United States Department of Agriculture 2000) and they are the size of areas typically managed in farm operations. Thus, microwatersheds have the greatest potential to deliver contaminants to streams. The microwatershed scale also offers the potential to relate runoff quantity and quality to land use practices. For these calculations, the microwatershed annual unit runoff was estimated based on the soil-polygon unit runoff map and hydrological modelling to distribute runoff depth among hillslope polygons within the microwatersheds.

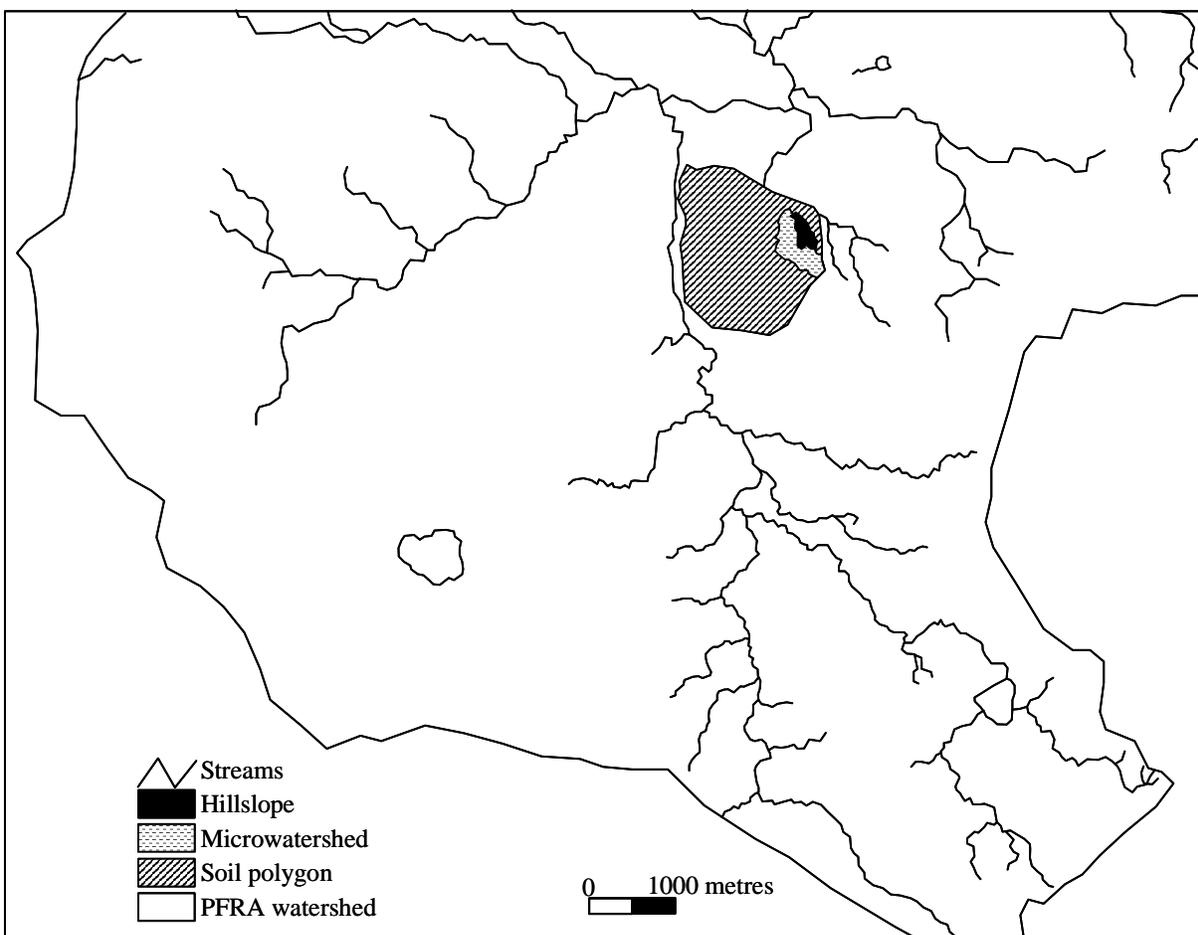


Fig. 1. Landscape scales used for soil-test phosphorus limit calculations.

Hillslope scale. The hillslope polygon scale relates to landscape polygons within a microwatershed and is based on partitioning of areas with similar slope steepness and slope lengths.

Soil Phosphorus and Phosphorus in Runoff Water

Field-scale relationships between STP and TP flow-weighted mean concentration (FWMC) in runoff were used to calculate soil phosphorus limits. The relationships were developed using 3 yr of field data obtained from eight field-scale microwatersheds (2 to 248 ha) located throughout Alberta (Little et al. 2006). The relationships included STP versus TP FWMC and STP versus DRP FWMC, using STP values from three soil depths: 0 to 2.5 cm, 0 to 5 cm, and 0 to 15 cm. In the study, the STP values ranged from 3 to 530 mg kg⁻¹. In this report, only the three STP-versus-TP FWMC equations were examined. Similar to other relationships reported in the literature (e.g., Vadas et al. 2005), the equations reported by Little et al. (2006) were expressed

as STP (independent variable) versus TP FWMC (dependent variable). These equations were rearranged to solve for STP, as shown in Equations 1 to 3.

$$\text{STP}_{0-2.5} = (\text{TP FWMC} - 0.039) \div 0.013 \quad r^2 = 0.87 \quad (1)$$

$$\text{STP}_{0-5} = (\text{TP FWMC} - 0.046) \div 0.013 \quad r^2 = 0.87 \quad (2)$$

$$\text{STP}_{0-15} = (\text{TP FWMC} + 0.160) \div 0.014 \quad r^2 = 0.88 \quad (3)$$

Where:

STP = soil-test phosphorus measured by the modified Kelowna extraction method (mg kg^{-1}). The subscripts (0-2.5, 0-5, and 0-15) refer to the STP sampling depth of 0 to 2.5 cm, 0 to 5 cm, and 0 to 15 cm, respectively.

TP FWMC = total phosphorus flow-weighted mean concentration in runoff water (mg L^{-1}).

The performance of these equations was examined by comparing the predicted STP values (Fig. 2). Equations 1 and 2 predicted STP almost identically. The similarity of STP prediction is not a surprise since both equations have similar extraction coefficients. The application of Equation 3 resulted in slightly lower STP values, and this agreed with field observations, which

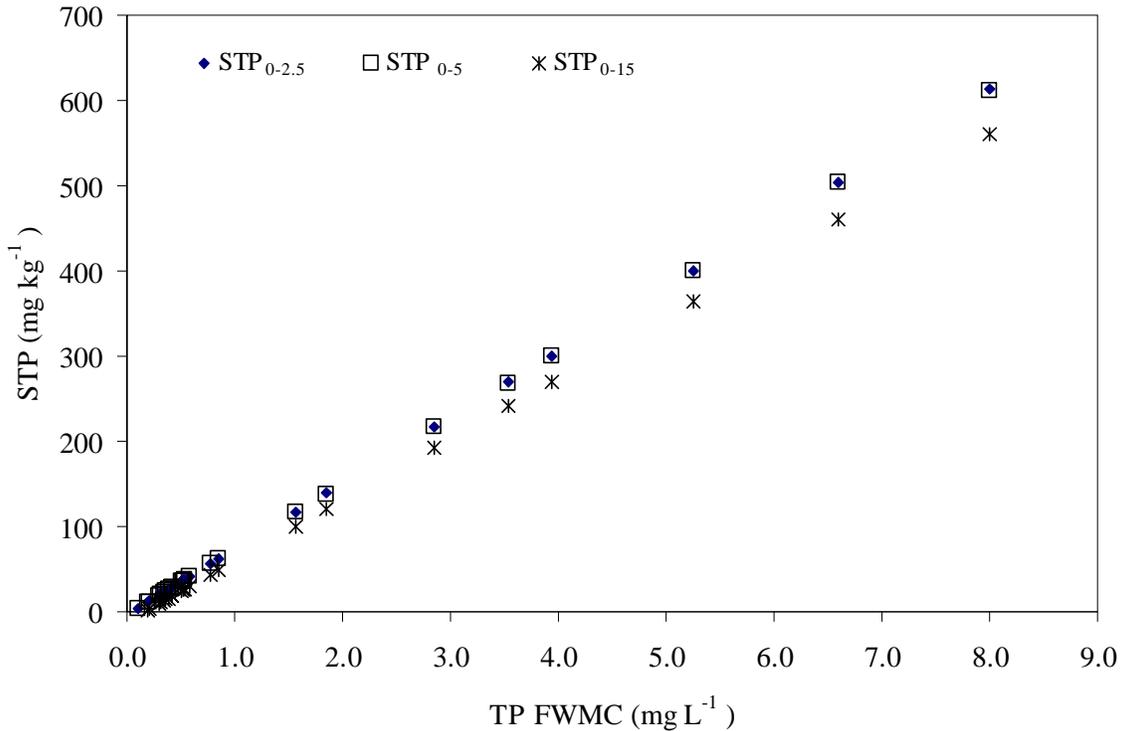


Fig. 2. Comparison of predicted soil-test phosphorus (STP) using Equations 1, 2, and 3.

showed that the top 0- to 15-cm layer had lower STP values than the top 0- to 2.5-cm layer in the same sampling location. Based on these results, Equations 1 and 3 were used to demonstrate the procedure for calculating STP limits.

The field-scale relationships between STP and TP developed in the Microwatershed Study were developed using 3 yr of data, 90% of which were generated by spring snowmelt and the remainder by summer rainfall and irrigation events. The relatively minor contribution of summer runoff events to the phosphorus exported by overland flow compared to spring runoff is typical of cold climates in the western Canadian prairies. Nicholaichuk (1967) estimated that 80% of the runoff from two small watersheds in Saskatchewan was generated by spring snowmelt. In Alberta, total yearly runoff from small agricultural watersheds tend to be dominated by snowmelt (Gill et al. 1998). Wuite and Chanasyk (2003) reported that springmelt accounted for 86% of the annual discharge volume in the Haynes Creek basin near Lacombe, Alberta, during a 24-yr period (1978 to 2001).

Hydrological Modelling

The Water Erosion Prediction Project (WEPP) model was used to estimate the runoff potential (factor) in this study since extensive work has been done to evaluate and calibrate WEPP for Alberta conditions (Jedrych et al. 1995; Wright and Vanderwel 1998 unpublished). The WEPP model represents a new erosion prediction technology based on fundamentals of stochastic weather generation, infiltration theory, hydrology, soil physics, plant science, hydraulics, and erosion mechanics (Flanagan and Livingston 1995). The model requires the input of four datasets, which characterize site-specific soil, hillslope, climate, and land use conditions. It can be run in a hillslope or a watershed application. In this project, the hillslope application was used at the AGRASID scale and the watershed application at the microwatershed scale.

The hillslope application was selected at the AGRASID scale because its database defines each soil polygon with 1 of 53 landform models (hillslopes). In the AGRASID database, the hillslope length ranges from 135 to 1000 m. These values appear to be too large for the WEPP application (Dennis Flanagan, Agricultural Engineer, USDA-ARS, pers. comm.). Simulation tests showed that WEPP simulated zero runoff values for 489 out of 26,819 soil polygons. A second simulation test was conducted using hillslope lengths that were reduced by five times (27- to 200-m range). Comparison of predicted runoff depths using these two simulation tests showed a strong relationship ($r^2 = 0.97$), and on average, the predicted runoff depths were 9% higher when the reduced slope length values were used (Fig. 3). In addition, the number of polygons with predicted zero values was reduced from 489 to 23. Considering this strong relationship and the fact that the STP calculation method (described below) does not accept zero runoff values, the reduced slope-length values were assumed to be more appropriate for the AGRASID-scale WEPP simulations. The WEPP model simulations were conducted for 26,819 soil polygons within the agricultural region of Alberta. A computer program was written to automatically generate WEPP landform input files, which described hillslope steepness, length, width, and aspect. Within the AGRASID database, there were 1551 soil polygons that did not have any soil and hillslope information because they were classified as flood plains, lakes, wetlands, or urban zones. Therefore, these polygons were excluded from WEPP simulations.

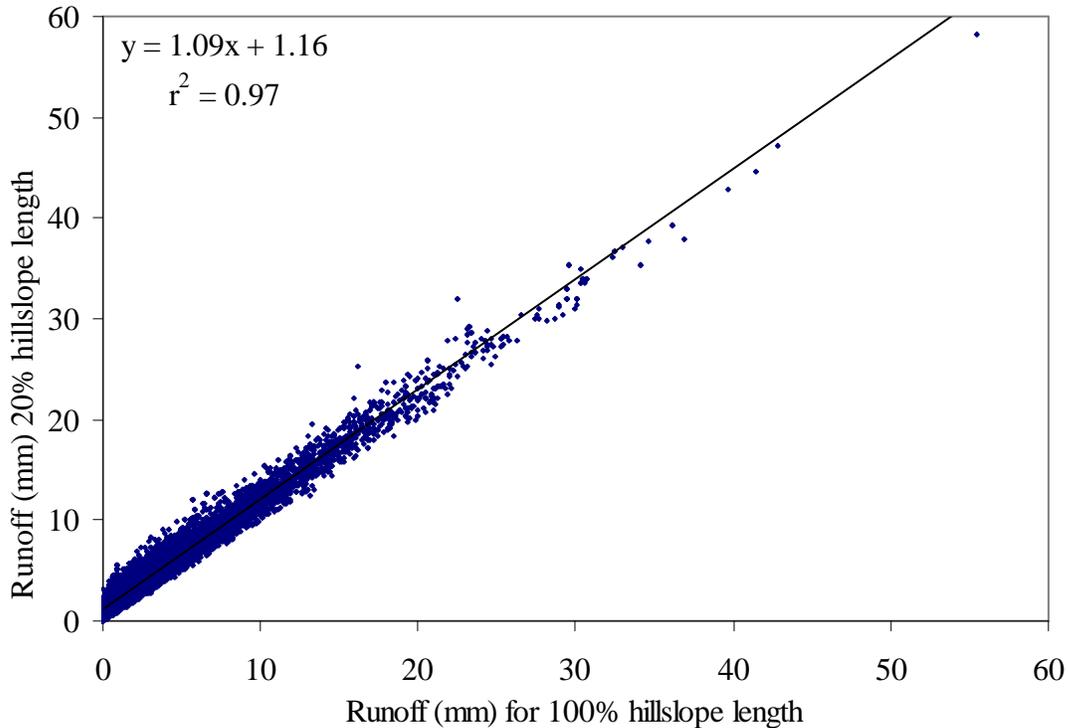


Fig. 3. Comparison between WEPP-predicted runoff values using AGRASID defined 100% and 20% hillslope length scenarios.

The WEPP-watershed simulations were also conducted at the field scale for the seven cultivated microwatershed sites (GPC, WAB, PON, THC, REN, CFT, and LLB) of the Microwatershed Study (Little et al. 2006) using detailed soil and digital elevation model (DEM) data. The DEM data were analyzed using the geo-spatial interface for the WEPP model called GeoWEPP (Renschler et al. 2002). GeoWEPP delineated the drainage area of each microwatershed and associated hillslope polygons, and automated the preparation of topographical input parameters for WEPP soil and slope input files.

The same weather and land use input data input were used at the AGRASID soil-polygon and microwatershed scales for the WEPP simulations. The weather data consisted of 43 yr of daily values of precipitation, temperature, solar radiation, wind speed, wind direction, and dew point temperature for the 894 Soil Landscapes of Canada (SLC) polygons in Alberta (Shields et al. 1991), as developed for the Alberta Environmentally Sustainable Agriculture (AESAs) Soil Quality Program (Shen et al. 2000). The AESA climate dataset does not contain storm characteristic variables. Therefore, simulated values for storm duration, storm intensity, and time-to-peak were calculated, based on statistical distributions from available hourly climate data. Hourly data from 22 stations were used to generate statistical distributions of storm characteristics by four seasons and three provincial regions. Continuous barley production under conventional tillage was chosen to normalize land-use effects on predicted runoff.

Generally, the highest runoff depths were predicted in polygons that had fine soil textures and were on steep slopes in the western part of Alberta. The predicted runoff depths were used to calculate runoff factors (RF) for all soil polygons within a specific PFRA watershed and for all hillslope polygons within the microwatershed sites. The RF is the WEPP-predicted average annual runoff depth for the whole watershed (or microwatershed) divided by the WEPP-predicted average annual runoff depth for individual soil (or hillslope) polygons. Using the WEPP model simulations to calculate RF values provided a means to determine the relative contribution of runoff from each soil polygon to the whole watershed and the relative contribution of each hillslope polygon to the whole microwatershed. The RF values were then used to partition the measured watershed average runoff depth, derived from Water Survey of Canada hydrometric station data, among the soil polygons within each watershed, and to partition the estimated microwatershed average runoff depth among the hillslope polygons within each microwatershed.

In this project, model validation was not conducted due to the lack of available data. However, it should be noted that WEPP model predictions included four possible sources of error: (1) the AGRASID database may not accurately describe soil physical, spatial, and landform properties; (2) the SLC polygon scale climate data may not represent the actual soil-polygon scale weather; (3) the land-use input data may not have uniform effect (i.e., only continuous barley on conventional tillage) on the estimated runoff throughout the agricultural area; and (4) the WEPP model had limitations. While it is very difficult to validate model performance using the existing data, it is believed that the model adequately simulated the runoff potential within each watershed. The WEPP simulations can be refined in the future with the application of more detailed topographic data and more sophisticated models. Researchers from Alberta Environment are currently conducting a 3-yr study to develop hydrological tools to estimate runoff for ungauged watersheds in Alberta (Michael Seneka, Hydrologist, Alberta Environment, personal communications).

Estimating Runoff Depth at the PFRA Watershed Scale

Bell and Martin (1994) developed a runoff depth map for Alberta. Their report was based on 40 yr of flow data (1950 to 1989) derived from 165 selected hydrometric stations. The study included estimated median annual unit runoff for 10%, 25%, 50%, 70%, 75%, 80%, and 90% probabilities of exceedance. These runoff values were calculated using PFRA defined watershed effective drainage areas. Godwin and Martin (1975) defined the effective drainage area as “that portion of a drainage basin which might be expected to entirely contribute runoff to the main stream during a flood with a return period of two years”. In the calculation of runoff values, a significant number of stations were selected that had fewer than 40 yr of flow data. The runoff values for these stations were estimated using linear regressions that were developed for stations in the same hydrological regions.

A subset of 144 of the 165 hydrometric stations was selected to develop a runoff map for the agricultural region of Alberta (Fig. 4). The subset included stations that did not receive runoff contributions from glacial melt or from irrigated land. For this report, the unit runoff values of 50% probability of exceedance (Bell and Martin 1994) were chosen to represent median annual

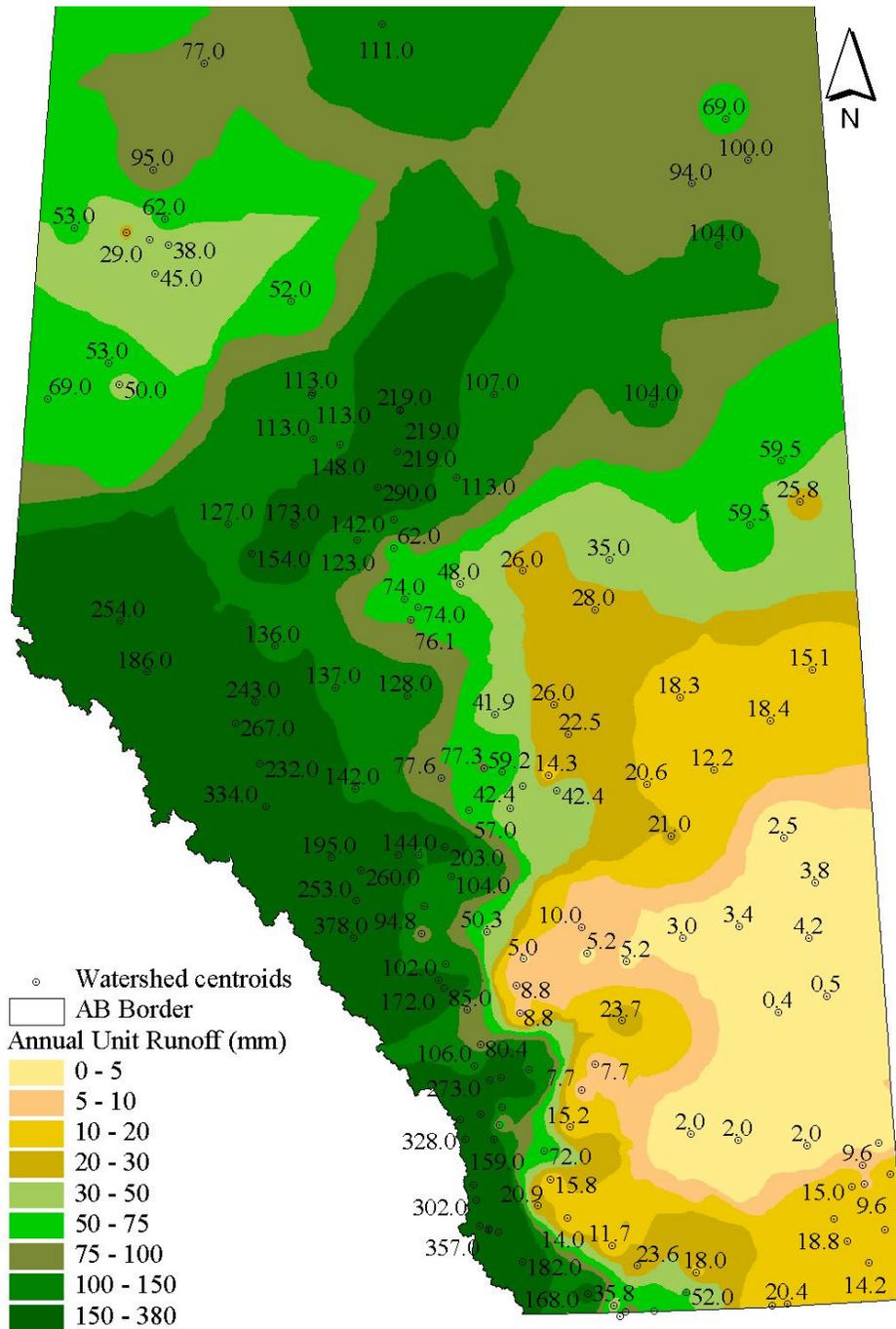


Fig. 4. Annual unit runoff map with overlaid annual runoff depth values derived from 144 hydrometric stations.

flow conditions within each watershed. The 50% probability value gives an approximately 50% chance that the estimated runoff depth will occur in any given year or, approximately once every 2 yr. In addition to the subset of 144 stations, the runoff map included five more points estimated from Fig. 12 in the report by Bell and Martin (1994). This was necessary to fill the large gap among station points in the southeastern region of Alberta.

The unit runoff map was prepared using ArcView software and its extensions. Initially, the subset of runoff depth values from 144 stations was assigned to the centroids of corresponding watersheds. The additional runoff depth values were then estimated for the remaining watersheds using the runoff values from four nearest neighbour stations, the 800-m grid-resolution coverage, and the Inverse Distance Weighted option. This procedure resulted in production of an 800-m grid-resolution runoff depth map. This map was subsequently smoothed out by calculating mean grid values within 5000-m neighbourhood radii to reduce local variability in runoff values of adjacent watersheds. The newly produced runoff map was later overlaid with the PFRA watershed boundary map, and the median runoff value was calculated for all watersheds. The final version of the map showed annual median runoff depth values calculated for the PFRA watersheds in the agricultural region of Alberta (Fig. 4.)

The accuracy of the unit runoff map was examined by conducting regression analyses between the map-estimated values and the hydrometric station observed runoff depth values. In this process, 144 station data points were compared with map-estimated runoff values. There was a very strong relationship ($r^2 = 0.99$) between these two sets of data (Fig. 5). However, this strong relationship applied only to the area near selected stations. The distribution of the stations was not uniform throughout the province, and as the distance increased between them, the accuracy of estimated runoff values in these areas decreased. This was particularly true in the southeastern part of the province. The runoff map in these areas can be improved with application of more recent hydrometric data and hydrological models.

Water Quality Limits

The appropriate selection of a watershed-scale TP runoff water quality limit (TPRWQL) for agricultural land is critical in controlling phosphorus delivery to streams. However, identification of a TPRWQL is problematic, particularly since TP levels at watershed scales may not be appropriate at field scales due to dilution by base flow (groundwater discharged to streams). Although Alberta does not have targeted water quality limits for watersheds, 0.05 mg L⁻¹ TP is considered to be the guideline for the protection of freshwater aquatic life in higher order rivers and streams (Alberta Environment 1999). Stream monitoring of phosphorus during the past three decades shows that phosphorus concentrations can vary considerably. However, even streams within watersheds with low intensities of agricultural development have phosphorus concentrations above the 0.05 mg L⁻¹ guideline (Anderson et al. 1998; Anderson 2006). As such, selecting 0.05 mg L⁻¹ TP as a water quality limit for agricultural land in the province may be unrealistic (Anderson 2006). The AESA Water Quality Monitoring Program data in 2002 showed that TP flow-weighted mean concentrations (TP FWMCs) were 0.25 mg L⁻¹ in low intensity agricultural watersheds, 0.40 mg L⁻¹ in moderate intensity agricultural watersheds, 0.92 mg L⁻¹ in high intensity agricultural watersheds, and 0.65 mg L⁻¹ in streams that

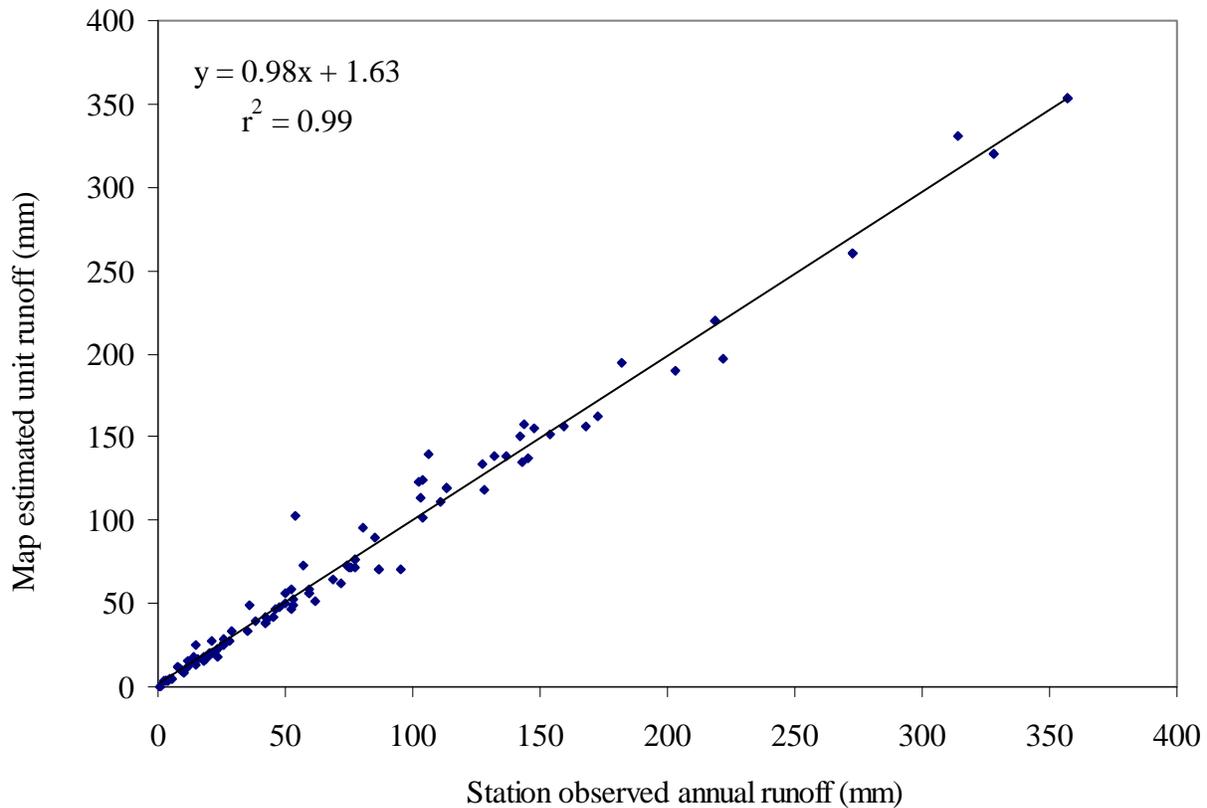


Fig. 5. Comparison between the hydrometric station observed and map-estimated runoff depth values.

received irrigation return flow (Depoe 2004). Little et al. (2006) reported TP FWMCs ranging from 0.10 to 0.52 mg L⁻¹ in a native-grassland microwatershed, from 0.20 to 1.57 mg L⁻¹ in non-manured agricultural microwatersheds, and from 1.84 to 8.00 mg L⁻¹ in manured agricultural microwatersheds. Based on the 2002 AESA stream monitoring data and on the Microwatershed Study, hypothetical watershed-scale TPRWQLs of 0.5 and 1.0 mg L⁻¹ were selected for agricultural land as target concentrations to calculate a first approximation of STP limits.

The total flow from a watershed is the result of surface flow, or runoff, and base flow contributions, less evaporation, groundwater recharge, and other withdrawals. The phosphorus concentration in water at the outflow of a watershed will depend on contributions from runoff, base flow, point sources (agricultural and non-agricultural), and in-stream processes. The contribution of base flow is not well known, and the quantitative assessment of base flow and in-stream processes was beyond the scope of the Soil Phosphorus Limits Project. Therefore, the hypothetical TPRWQL values to calculate phosphorus limits were applied to the total runoff volume within a watershed prior to runoff entering the stream. This approach removed us from trying to suggest a TPRWQL for watershed discharge. Plus, we did not have to account for base flow and in-stream processes, as well as other sources of phosphorus to the stream. However, we acknowledge that a result of using this approach is that the final TP concentration leaving the watershed is unknown. Because of the uncertainty with base flow, it was not taken into account,

and we made the assumption that the total discharge from a watershed was derived solely from surface runoff, as described in the next section.

For the proposed STP limits, the selected TPRWQL was applied in stages. First, the TPRWQL was assigned to PFRA watershed area, and then it was estimated for soil-polygons, microwatershed, and hillslope areas in each watershed. A condition of the method is that all polygons within a watershed are allowed to export the same amount of TP on a per unit area basis (e.g., kg ha^{-1}). To meet this target, the soil-polygon TPRWQL was adjusted according to its runoff potential. Generally, higher TPRWQLs were allowed from polygons with lower runoff potentials, and lower TPRWQLs were allowed from polygons with higher runoff potentials. The microwatershed-scale TPRWQL was assumed to be equal to the soil-polygon TPRWQL in which the microwatershed was located. However, the highest TPRWQL that would be allowed in runoff from an individual hillslope polygon within the microwatershed was adjusted again according to its runoff potential. The STP calculations at the microwatershed and hillslope scales allowed identification of site-specific critical source areas that may have a large impact on runoff discharge and export of phosphorus, as described by Gburek and Sharpley (1998).

PROCEDURE FOR CALCULATING SOIL PHOSPHORUS LIMITS

The STP limit calculation method involves assigning a watershed-scale TPRWQL for the agricultural land and then determining site-specific TP concentration limits within the watershed through hydrological modelling. Site specificity is at the AGRASID soil polygon, microwatershed, and hillslope polygon scales (Fig. 1). Based on WEPP-predicted relative runoff potentials, polygon-specific TP concentrations were determined such that higher runoff phosphorus concentrations were allowed from fields with lower runoff potential and lower runoff phosphorus concentrations were allowed from fields with higher runoff potential. This distribution of TP concentration limits within the watershed should result in the TP FWMC in the total runoff volume in the watershed meeting the selected water quality limit.

Numerous models (SWAT, EPIC, AnnAGNPS) can estimate phosphorus export from a given watershed area as a function of the water volume and the concentration of phosphorus in the water (Sharpley et al. 2002; Borah and Bera 2004). A generalized relationship that computes the export of TP on a per unit area basis from a watershed is

$$L_{ex} = (Q \times TP / 1000) / A \quad (4)$$

Where:

L_{ex} = annual TP export coefficient (kg m^{-2})

Q = watershed annual average discharge (m^3)

TP = concentration of TP in runoff (mg L^{-1})

A = watershed drainage area (m^2)

Discharge volume is calculated as

$$Q = (D/1000) \times A \quad (5)$$

Where:

D = runoff depth from the watershed (mm)

The runoff depth (D) in Equation 5 was estimated for the agricultural zone of Alberta using the procedure outlined previously in this report. The hydrometric data include daily total discharge volume (Q), which is a composite of surface flow, or true runoff (Q_s) and base flow (Q_b). The relative proportion of Q_s to Q_b varies among watersheds; however, in the majority of Alberta streams, the Q_s component accounts for a larger portion of the total discharge flow (Q) on an annual basis (Michael Seneka, Hydrologist, Alberta Environment, personal communications). Since, the contribution of Q_b to the total phosphorus load is uncertain, it was assumed for Equation 5 that all of the discharge flow volume (Q) was derived from surface flow (Q_s).

The TP term in Equation 4 refers to the TP FWMC in the total runoff volume and can be used as a runoff water quality limit (TPRWQL). The total load (L) of TP exported in runoff to the stream is the sum of TP loads exported from all soil polygons (l_i) within the watershed. The L_{ex}