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Testing the new AnnAGNPS simulation model on an intensively cultivated watershed within the Canadian climatic context

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Abstract

Physically-based simulation models are powerful tools to assess the origin and fate of non-point sources of contaminants generated by agricultural activities. They allow to locate vulnerable areas and questionable practices contributing to the impairment of the surface waters in rural areas. AnnAGNPS is a new continuous model being developed at the National Sedimentation Laboratory (USDA-ARS); it is the direct successor of the event-based AGNPS model. AnnAGNPS simulates, at the watershed scale, the load in N, P and SS exported by the surface waters in response to weather, physical characteristics of the watershed, and agricultural practices such as crop types, fertilisation rates and scheduling, manure spreading, and other field operations. The model has been applied to a small intensively cultivated Quebec watershed that is also supporting intensive livestock breeding (dairy cows and hogs). This well-documented experimental watershed was continuously monitored for meteorology, river discharge and water quality parameters, even during the winter. Using the data of 1998 and 1999, simulated export values were compared with measurements showing a good agreement in the general pattern of the exported loading spells which are triggered by the field operations and by precipitation events. During the winter and during the spring snowmelt, sizeable discrepancies appeared both for the simulated discharges and for the mass loading.

1 Introduction

In industrialised countries, intensive farming is inducing both the erosion of soil and the degradation of the quality of surface and ground waters draining agricultural watersheds. This problem is especially acute in areas of industrial

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livestock breeding where over-fertilisation by excess manure spreading contaminates water resources; this is a situation considered as a ticking time bomb. In this context, physically-based simulation models are needed to assess the evolution in stocks and fluxes within agricultural watersheds, to locate vulnerable areas that contribute to the bulk of the loading and to analyse the responsible prevalent management practices. In a subsequent step, such models can also be exploited to simulate the improved watershed response to the possible implementation of better management practices (BMP).

To approach this problem, AGNPS (AGricultural Non-Point Source pollution model), an event-based simulation model based on the Universal Soil Loss Equation (USLE) and the Curve Number (CN) technique, was devised by Young et al. [1] at the Agricultural Research Service of the United State Department of Agriculture. The AGNPS model has been widely distributed and used. More recently, a new version of the model called AnnAGNPS has been developed [2] at the National Sedimentation Laboratory in Oxford, Mississippi, to allow for the continuous simulation of sediment and nutrient exports to surface waters as a response to meteorological events, field operations, and crop growth.

Even though the new annualised model is still at the development stage, it has been tested on a small experimental and intensively cultivated watershed, the Boyer River, located near Quebec City. The objective was to evaluate the suitability of AnnAGNPS to predict runoff, sediment yields as well as nitrogen and phosphorus loading under Canadian climatic and agronomic conditions.

2 AnnAGNPS

The model is composed of three parts: data preparation, simulation processing, and source accounting output. Climate data, watershed physical parameters, and land management information are required for the simulation processing. Flownet, which consists of TopAGNPS and AGFlow, generates the watershed physical parameters, including watershed and cells delineation, land slope, and stream reaches data, using the D8 drainage algorithm. This algorithm called TOPAZ (Topographic ParameteriZation) was developed by Garbrecht and Martz [3]; it considers windows of 3 x 3 elevation cells and the eight neighbours: the steepest gradient indicates a discrete flow direction of the cell that is encoded to generate the hydrographic network and the watershed subdivisions. The simulation processing is based on the SCS Runoff Curve Number equation to simulate runoff; on the Revised Universal Soil Loss Equation (RUSLE) for the movement of sediment; on Bagnold equation for sediment routing; and on the SCS TR-55 procedures for the calculation of the time of concentration for a cell [4]. Furthermore, daily adjustments are made on several parameters to account for crop evolution, field operations, winter conditions, etc. AnnAGNPS has the ability to track the source and relative contribution of contaminants down through the channel network to the outlet of the watershed [5].

Yuan and Bingner [6] evaluated the performance of AnnAGNPS to simulate runoff and sediment yield on a watershed of the Mississippi Delta over a three-year period. They concluded that the model provides a reasonable estimate of

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long-term monthly and annual runoff and sediment yield without calibration. No other application of the AnnAGNPS model was found in the literature.

3 Methods

3.1 Description of the research watershed

The Boyer-Nord River, a small tributary of the Boyer River, with an area of 29.8 km^2, drains the experimental agricultural watershed studied here. Its watershed is located approximately 40 km east of Quebec City, on the southern bank of the St-Lawrence River (Figure 1).

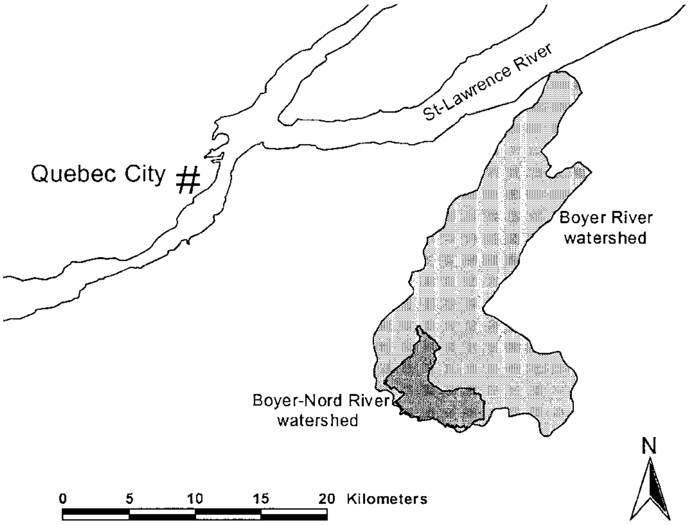

Figure 1: Geographical localisation of the Boyer-Nord watershed.

It has been intensively studied by ecologists because its previous large smelt (*Osmerus Morax*) population has actually almost disappeared. Siltation and eutrophication are often cited to have negatively affected their spawning site; this contamination is closely related to the intensification of agricultural practices and the industrialisation of livestock breeding techniques, which affect water usage.

The climate of the region is classified as temperate-cold with an average yearly temperature of 3.6°C and a mean annual precipitation of 1140 mm, including a water-equivalent of 280 mm falling as snow. Soils are mostly Loam (25% of the watershed) and sandy Loam (59%). The topography is rather flat with slopes of less than 2% on 70% of the watershed and half of the area supports an underground artificial drainage system designed to quicken the evacuation of excess water during snowmelt. The AnnAGNPS cells and reaches created by the Flownet generator were obtained from a 20-m digital elevation model (DEM) derived from 1:20000 numerical topographic maps (Figure 2).

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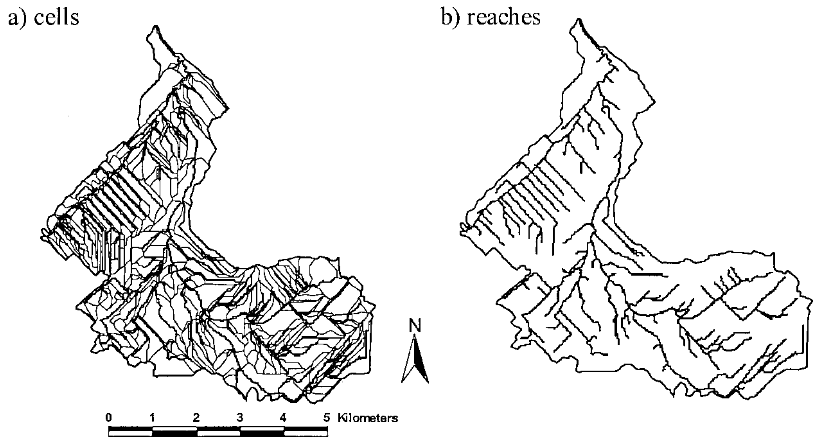

Figure 2: AnnAGNPS cells and channel reaches for the Boyer-Nord River watershed.

Half of the watershed is intensively cultivated and the other half is covered with forest; pasture (33%), corn (8%), and cereals (6%) are the most important crops. Animal breeding is quite intensive, reaching 3 AU-ha^{-1} and consisting mostly of hog breeding (57%) and of dairy cows (22%). As a result, soils are over-fertilised (manure and mineral fertilisers) with excess residual nitrogen amounting up to 27 kg N-ha^{-1} for the whole basin, including forested areas.

3.2 Input parameters for the AnnAGNPS model

The detailed description of the input data required for the execution of AnnAGNPS is presented in a portable document format (pdf) file that can be downloaded from the AGNPS web site. Although the version of the input editor used with AGNPS was slightly modified to comply with the most recent version of the model, the description of the input parameters of the input editor v.1 presented by Yuan and Bingner [6] and Bosch et al. [7] remains accurate.

The input editor v.2 counts over 40 input pages (or frames) totalling approximately 600 fields to enter the various input parameters defining daily climatic conditions, the watershed physical parameters, and land management information. The climate data consist of daily values for maximum and minimum temperature, precipitation, dew point temperature, sky cover, and wind speed and direction. The input editor allows for importing climatic data directly from formatted files. The watershed physical parameters, including watershed delineation, land slope data, cell boundaries, and reach data that were generated by TopAGNPS and AGFlow, can also be imported directly into the input editor. The remaining of the input parameters, however, must be entered manually in the fields of the input pages. The watershed land management parameters are composed of crop, soil, land use, field and field operations, chemicals and

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fertilisers applications, runoff Curve Number data. Furthermore, RUSLE factors are selected and entered in the input editor according to the watershed characteristics.

Several of the input pages need to be filled out several times in order to define parameters for each cell, channel reach, crop, soil, field operation, fertiliser application, etc. Nonetheless, default values are provided for a majority of parameters and several fields can therefore be left blank. However, the parameters should be representative of the physical watershed and thus, the default values might not be appropriate.

The input parameters defined for the Boyer-Nord watershed are shown in Table 1. The shaded area highlights the input pages that were left blank indicating which features were absent on the watershed or which characteristics were not considered. A total of over 1660 input pages were filled out.

Table 1: Input parameters inventory for the Boyer-Nord River watershed

Input page identifier			amount of input pages /data unit	amount of units	total of input pages
AnnAGNPS Identifier & Watershed Data			1	1	1
Cell Data			1 /cell	464 cells	464
Daily Climate Data			1 /day	730 days	730
Contour Data					
Crop Data	Crop Growth Parameters		2 /crop	10 crops	20
Feedlot Data	*Feedlot Data*	*Feedlot Cell Data*			
	Feedlot Management Data				
Fertilizer Data	Fertilizer Application Data		1 /application	32 applications	32
	Fertilizer Reference Data		1 /reference	12 references	12
Field Data	Field Data		1 /farm field	17 farm fields	17
	Field Management Data		1 /operation group	17 groups	17
Field Pond Data					
Global Output Specification			can vary according to the output desired		
Gully Data					
Impoundment Data					
Irrigation Application Data					
Landuse Reference Data			1 /landuse	3 landuses	3
Operations Data	Operations Data	*Pesticide Data*	1 /operation	78 operations	78
	Operations Reference Data		1 /reference	13 references	13
Pesticide Data	*Pesticide Application Data*				
	Pesticide Reference Data				
Point Source Data					
Reach Data	Reach Data		1 /reach	191 reaches	191
	Reach Geometry Data		1 /reach geometry set	1 set	1
	Reach Nutrient Half-life Data				
	Reach Output Specification		can vary according to the output desired		
Runoff Curve Number (CN)			1 /CN set	6 CN sets	6
Simulation Period Data	Simulation Period Data	EI Number Distribution	1 /simulation period + 1 /distribution	1 simulation period	2
	Cropland Global Initialization				
	Non-cropland Global Initialization				
	Pesticide Simulation Data				
Soil Data	Soil Layer Data		1 /soil + 1 /soil layer	17 soils and 55 soil layers	72
Source Accounting Output Specification			can vary according to the output desired		
Strip Crop Data					
Verification Data	User Output Options				
	Read Input Verification				
	Data Prep				
	Simulation Verification				

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Input parameters' selection is a critical part of applying the model because the parameters define the characteristics of the virtual watershed and the simulation conditions. Furthermore, the accuracy of the simulation relies mostly on the compliance of the simulation conditions to the physical environment and thus, on the exactitude of the input parameters.

Although default values for several input parameters are provided as part of the AnnAGNPS input editor, it is encouraged to define input parameters for local conditions. Reference data files are also provided as downloadable pdf and spreadsheet files; they supply listing of input parameters with regard to animal waste, crop, equipment and operations effects, non-crop land use, nutrient source, runoff cover conditions, runoff Curve Number data, and USLE LS factors. In addition, the Agriculture Handbook no. 703 and the Technical Release 55, both published by the United States Department of Agriculture (USDA), are other information sources recommended by the authors of the model.

However, reference data developed for the United States are not always readily applicable to the Canadian environment due to differing climatic conditions, soils, crops, and land management practices. Consequently, our main difficulty in using the AnnAGNPS model lied mostly in defining input parameters that represented the Boyer-Nord watershed and eastern Quebec climatic conditions as accurately as possible since Canadian standards equivalent to those published by the USDA are lacking.

The type of crop cultivated on each parcel and field was obtained by overlaying land registry maps with a reclassified satellite image (Landsat TM, bands 4 and 5). In addition, each of the 66 farmers was individually interviewed to confirm the culture grown on each of his fields and to inquire about operations scheduling on each parcel; emphasis was put on the monitoring of manure and mineral fertilisers scheduling and application rates. Furthermore, local experts in various fields, such as soil and plant sciences, were consulted in order to select most of the input parameters.

3.3 Field data collection

The experimental watershed is equipped with a continuous meteorological station monitoring the precipitation, using tipping buckets and cumulative rain gauges, and registering the temperature. A gauging station located at the outlet of the watershed has been installed at a critical V-shaped artificial cross section of the river in order to register continuously the water levels with an area velocity flow meter (American Sigma model 950) and to compute the water discharge. An interconnected refrigerated flow-proportional automatic sampler (American Sigma model 900) was used to collect water samples to be analysed for suspended solids and total nitrogen and phosphorus. That apparatus was located inside a heated shed in order to be operative during the winter and was visited once a week to bring the collected samples to the laboratory. This experimental setting allowed for evaluation of the actual mass discharges of sediment and nutrient exported by the river and consequently, for comparison with the simulation values produced by the model.

4 Simulation results and discussion

Monthly sediment and nutrient loads predicted with AnnAGNPS are compared to those observed at the gauging station over the simulation period, from January 1998 to December 1999 (Figures 3 and 4).

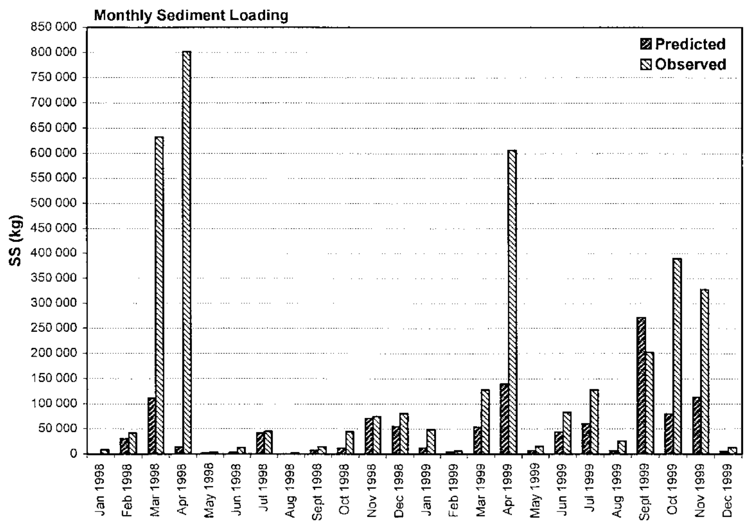

Figure 3: Comparison of monthly sediment load observed by sampling and predicted with AnnAGNPS.

The AnnAGNPS model underestimated grossly monthly sediment and total Nitrogen (adsorbed and soluble) loading while it overestimated monthly total Phosphorus (adsorbed and soluble) loading. The largest discrepancies occurred for March and April of both years and for November and December of 1999.

Each cell contribution in sediment and nutrient to the watershed streams network is recorded over the entire simulation period; then, annual averages are computed for any selected stream reach. Each cell's annual average contribution in sediment and total Nitrogen to the watershed outlet has been grouped into classes in order to illustrate the spatial concentration of the production (Table 2). Forty-five percent of the total sediment load at the watershed outlet originated from 7 cells that cover only 5% of the watershed surface area (Table 2a). Eighty-one percent of the watershed surface, constituted of 384 cells, produced no more than 40% of the total N yielded at the outlet while less that 10% of the watershed surface contributed to 33% of the total N yield. This shows that pollution related to erosion could be minimised on the Boyer-Nord watershed by concentrating remedial efforts on less that 10% of the watershed surface area, which corresponds to less than 270 ha.

The AnnAGNPS model also records pollutant loads upstream and downstream of each reach composing the watershed stream network.

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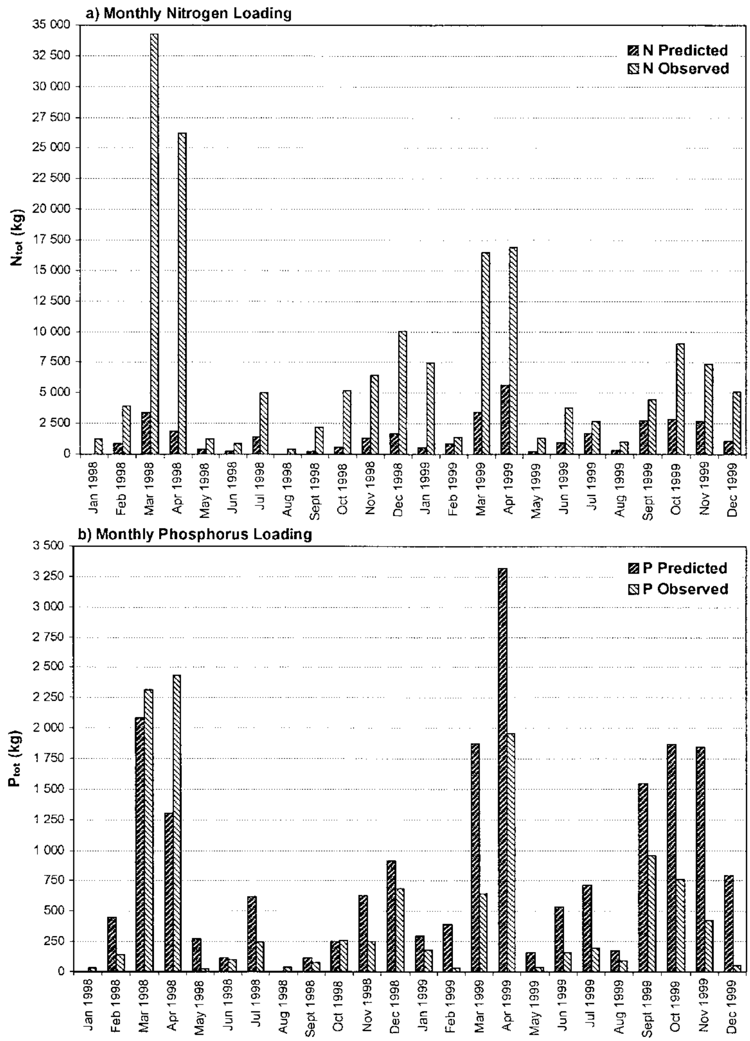

Figure 4: Comparison of monthly nutrient load observed by sampling and predicted with AnnAGNPS: a) monthly total Nitrogen load; b) monthly total Phosphorus load.

Thus, sediment and nutrient concentrations can be obtained to provide data for comparison with water quality standards.

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Table 2: Annual average cells contributions (SS_{tot}, N_{tot}) to the watershed outlet.

a)	SS_{tot} Load (kg/yr)			
	0 to 100	100 to 5000	5000 to 50000	50000 to 170000
No. of cells	312	91	54	7
% total of cells	67	20	12	2
Drained area (ha)	1 494	651	377	134
% of watershed area	56	25	14	5
Load (kg/yr)	6 046	123 127	840 612	800 024
% total load	< 0.5	7	47	45
b)	SS_{tot} Yield (kg/ha-yr)			
	0 to 100	100 to 1000	1000 to 10000	10000 to 20000
No. of cells	336	51	61	16
% total of cells	72	11	13	3
Drained area (ha)	1 883	369	369	35
% of watershed area	71	14	14	1
Yield (kg/ha/yr)	2 205	17 961	196 061	223 803
% total yield	< 1	4	45	51
c)	N_{tot} Load (kg/yr)			
	0 to 100	100 to 500	500 to 1000	1000 to 3050
No. of cells	421	38	3	2
% total of cells	91	8	1	< 0.5
Drained area (ha)	1 989	543	55	68
% of watershed area	75	20	2	3
N load (kg/yr)	7 481	7 780	1 834	2 670
% total N load	38	39	9	14
d)	N_{tot} Yield (kg/ha-yr)			
	0 to 10	10 to 20	20 to 30	30 to 45
No. of cells	384	37	13	30
% total of cells	83	8	3	6
Drained area (ha)	2 141	216	56	242
% of watershed area	81	8	2	9
N yield (kg/yr)	1 221	490	327	996
% total N yield	40	16	11	33

5 Conclusion

AnnAGNPS is a new continuous simulation model that predicts the effects of agricultural activities on surface water quality by linking land use to runoff exports. Although the model is still at the developing stage and the predictions were not quantitatively in agreement with field measurements, its application provided us with a valuable insight on the origin and the transportation mechanisms of the exported pollutants in relation with the agricultural practices adopted on the field. Furthermore, despite the fact that the model is not intended for short-term predictions, AnnAGNPS can still be used qualitatively to locate high pollutant production zones.

Nonetheless, its winter and snowmelt routines will need to be improved to represent the impact of frozen soils on the different fluxes. In addition, the application of AnnAGNPS in Quebec turned out to be difficult and time-consuming, due to the gathering of numerous information required as input parameters, leading us to conclude that a sensibility study should be considered to

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determine the parameters' importance on pollutant loading processes involved in the model.

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