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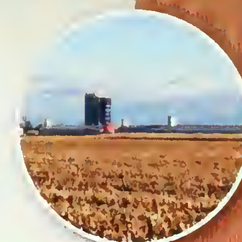

Watershed Evaluation of Beneficial Management Practices (WEBs)

Technical Summary #3

Hydrological and Integrated Modelling Components

Four-year review (2004/5 - 2007/8)

Ducks Unlimited Canada
Conserving Canada's Wetlands

Canada

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Agriculture and Agri-Food Canada 2010

Introduction

The Watershed Evaluation of Beneficial Management Practices (WEBs) is a national project led by Agriculture and Agri-Food Canada (AAFC), with Ducks Unlimited Canada as a major funding partner. WEBs was initiated in 2004 to measure the environmental and economic performance of selected agricultural beneficial management practices (BMPs) at a watershed scale. Research is carried out at seven micro-watershed sites across Canada (Figure 1).

Figure 1: Location of WEBs watersheds across Canada

For the purposes of this study, BMPs are science-based farming activities designed to help minimize potential environmental impacts, such as sediment and nutrient runoff into water bodies.

WEBs has applied a suite of BMPs at each site and has begun studying their environmental and economic impact at the small-watershed (300–2500 hectare) level. The selection of BMPs for testing in WEBs has been specifically tailored to the unique conditions of each watershed (Table 1). As a result, each site employs a suite of BMPs which may not directly correspond to practices in other WEBs watersheds.

Table 1: WEBs BMPs Applied by Watershed

	WEBs BMPs	Salmon River	Lower Little Bow River	South Tobacco Creek/ Steppler	South Nation	Bras d'Henri and Fourchette	Black Brook	Thomas Brook
Riparian	Cattle exclusion fencing (and off-stream watering)	✓	✓		✓			✓
	Off-stream watering without fencing		✓					
	Grazed versus mechanical harvesting			✓				
In-field	Manure management		✓			✓		✓
	Zero versus conventional tillage			✓				
	Crop rotation					✓		
	Perennial cover		✓	✓				
	Reduced herbicide use					✓		
Runoff	Diversion terraces and grassed waterways						✓	
	Storm water diversion (farmyard runoff)							✓
	Holding pond (cattle containment runoff)			✓				
	Small reservoirs			✓				
	Buffer strips		✓				✓	
	Suite of surface runoff control measures					✓		
Drainage	**Controlled tile drainage**				✓			

WEBs is not designed as a test of BMP effect across differing watershed conditions*

* **It is important to note that comparing the effect of individual BMP's across multiple watersheds and/or the assessment of any one BMP under a wide range of different watershed conditions is beyond the scope of WEBs.**

Each of the seven WEBs watershed sites across Canada includes the following components:

- *Biophysical evaluations* measure the impact of individual BMPs or a suite of BMPs on water quality and other environmental factors at a watershed scale.
- *On-farm economic assessments* determine the costs and benefits of implementing BMPs.
- *Hydrologic modelling* contributes to a better understanding of background and watershed interactions and facilitates the extrapolation of findings to other locations.
- At two of the project sites, *integrated modelling* combines hydrologic, economic and producer behavioural aspects into a multi-faceted decision tool to facilitate long-term planning.

WEBs is focused on water quality, a likely predictor of other environmental impacts such as soil quality, air quality and biodiversity. In many cases, additional environmental parameters such as soil or riparian health are being examined.

The history of conditions and trends at each of the seven WEBs sites is generally well understood, due to past activities and data collection by local watershed associations or multi-agency teams. It is anticipated that these sites will continue as long-term benchmark locations for watershed health.

This technical summary compiles the hydrologic modelling findings of the project's first four years (2004/5 - 2007/8) from six of the seven WEBs project watersheds. It also includes summaries from the two pilot integrated economic-hydrologic modelling pilot sites at South Tobacco Creek (Manitoba) and Bras d'Henri (Quebec). A compilation of findings from the biophysical research conducted under WEBs is available in a separate companion document entitled: "Watershed Evaluation of Beneficial Management Practices (WEBs), Technical Summary #1: Biophysical Component – Four-year review (2004/5 - 2007/8)". A compilation of findings from the economic research, including a farm [producer] behaviour component and metadata report, is available in a further companion document entitled "Watershed Evaluation of Beneficial Management Practices (WEBs), Technical Summary #2: Economics Component – Four-year review (2004/5 - 2007/8)". These documents are available in both print and PDF format in both official languages.

A condensed report "Watershed Evaluation of Beneficial Management Practices (WEBs): Towards Enhanced Agricultural Landscape Planning – Four-year review (2004/5 - 2007/8)", providing an overview of the WEBs project and summarizing the findings from all three of these Technical Summaries, is available in print and PDF format.

For further information on WEBs, please refer to our website at www.agr.gc.ca/webs or email us at webs@agr.gc.ca

Table of Contents

Hydrologic and Integrated Modelling for the Evaluation of Beneficial Management Practices in Six Watersheds in Canada

Figures

Tables

Hydrologic and Integrated Modelling for the Evaluation of Beneficial Management Practices in Six Watersheds in Canada

A Report on Progress in Watershed Modelling and Evaluating BMPs for the Watershed Evaluation of Beneficial Management Practices (WEBs I)

Prepared by: Brian T. Abrahamson
February 2009

Executive Summary

Initial results were generally good to very good across the six watersheds studied, particularly at the outlet of the watershed, and initial efforts to model the impacts of BMPs were encouraging. Further work is required to provide more consistent results to model sub-basins within the watershed and to use the models to evaluate BMPs. There are a few common problems such as inadequate data, insufficient length of record and a current lack of modelling capacity to model watershed processes at the local scale. This last might be remedied by better data.

The BMPs tested indicated trends which are consistent with expectations; however, because of problems with the model calibration, the absolute values are subject to question. Additional data are required for verification. Confidence in the BMP evaluations will increase as the quality of the watershed models increase.

Salmon River – The results of the SWAT model calibrations in the Salmon River watershed are varied. The hydrology at the outlet was good, however results at in-stream points varied from good to poor. The reason for this inconsistency needs to be explained. There were no data available to calibrate the model for sediment loading. As a result, sediment was modelled as a function of calibrated flows and using theoretical values from the model. The model was subsequently run to predict water quality (nitrogen and phosphorus), with very good or at least reasonable results at the outlet and varied results at the upstream stations. Further work is required to explain the inconsistencies. As well the water quality should be re-evaluated once a better calibration is achieved for sediment loading.

BMP assessments were limited to a sensitivity analysis undertaken to determine the impact of applications of inorganic fertilizer and manure on nitrogen loadings at the watershed outlet. The maximum amounts of fertilizer that could be applied in the watershed without exceeding the British Columbia water quality guidelines at the outlet, was estimated using the model and this method was suggested as a BMP. This assumes that the economic benefits increase as the application of fertilizer increases.

Lower Little Bow River – The Lower Little Bow River Watershed is located on a reach of the Little Bow River. Modelling of the watershed is at the very preliminary stage. While results are promising it should be kept in mind that only two years of record were used, which is not sufficient to take into account the seasonal and annual variation that might be expected on the watershed. Efforts were concentrated on determining the outflow from the watershed and on testing the operation of the model for irrigation. Runoff from the watershed was estimated on a monthly basis as the difference between the inflow and outflow to the watershed.

The second problem was to incorporate the effects of irrigation on the watershed. The watershed receives irrigation water from two sources: internally from the Little Bow River and externally from the Lethbridge Northern Irrigation District (LNID). The amount of water supply from each source was not available during the recent modelling exercises nor was it known to which parcels of land each type of irrigation water was applied. Additional information should be available on the irrigation water for use in WEBs II.

South Tobacco Creek – The South Tobacco Creek watershed has been modeled or studied for some 15 to 20 years. Several sub-watersheds have been instrumented, namely the Twin Watershed study and the Steppler Watershed. Modelling results for the calibration and validation phases at the watershed outlet near Miami were very good. The modellers were not able to get as good results in the experimental watersheds although they did show promise. For example, outflows from both sides of the Twin Watershed study matched observed flows with a Nash Sutcliffe coefficient of about 0.5. Values for the Steppler watershed where lower, however both indicated that there is a fair degree of correlation between predicted and observed values.

BMPs were modelled using data collected from the experimental watershed to develop specific modules regarding such components as the performance of small dams, the effluent from cattle yards, or the impact of using retention ponds to contain waste from cattle yards. When these BMPs were applied elsewhere in the watershed, the overall benefit to the South Tobacco Creek watershed was fairly well defined. Additional work is required to refine the sub-watershed models. The authors have attributed the calibration problem at least in part to the inability of the SWAT model to properly handle snowmelt runoff and infiltration events. Resolution of the input data may also have to be improved.

South Nation – Modelling of the South Nation Watershed is just getting underway.

Bras d'Henri/Beaurivage – The Bras d'Henri/Beaurivage watersheds are part of the Chaudière River Basin which has been modeled extensively over the last 15 years. The recent WEBs study is a refinement of previous studies, in that the hydrologic response units (HRUs) used for the WEBs study are smaller, improving the resolution of the model. As well the finer scale corresponds more closely to the average farm size within the watershed and therefore facilitates transfer of data and information from the environmental models to those economic models which can utilize data at a farm scale.

For the most part, the hydrologic calibrations of the Bras d'Henri and the larger Beaurivage watershed were well done, with good evaluation results. Sediment and water quality on the other hand were more difficult to evaluate. The authors had to plot the sediment and water quality outputs at a logarithmic scale in order to visually relate the predicted to observed values. It is therefore very difficult to use this information to reliably evaluate the impacts of the selected BMPs, even though the results of the BMPs evaluation look reasonable. Additional work is therefore required to improve the calibration of the basic model. It is quite likely that the inability to get a good calibration is at least partly attributable to the lack of representative data.

Black Brook – Modelling results for the hydrology, sediment and water quality components for the Black Brook Watershed were generally very good. The model was calibrated using data prior to the implementation of flow diversion terraces and grassed buffer waterways in 1995. The model was then validated using post BMP data. Routines were developed to evaluate these BMPs, providing input to the model that would approximate the BMPs. Once this was done the model was able to reproduce the observed data quite well. Some additional work is required to improve the function of the event-based grass buffer model.

Thomas Brook - The calibration for the Thomas Brook Watershed was done for a very short period of record (less than two years), so results should be considered as preliminary. A longer period of record is required for calibration and validation. There were also some problems with lack of representative data, in particular precipitation, and concerns were raised about the adequacy of the model to simulate watershed processes for such a small watershed.

Several BMPs were evaluated and the results were consistent with expectations. Work on the second phase of WEBs should include improving the calibration of the hydrology, sediment transport and water quality components of the model, after which another assessment of the BMPs could be undertaken.

Introduction

Seven (7) watersheds are being studied across Canada as part of the Watershed Evaluation of Beneficial Management Practices (WEBs). The study includes field programs, development of models to evaluate Beneficial Management Practices (BMPs), and economic modelling to determine the costs and benefits of implementing BMPs. This report summarizes the results of studies to model the impacts of implementing BMPs in *six* watersheds and the integration of the hydrologic/environmental models with the economic models on two of these watersheds.

All are located in agricultural regions of Canada. Table 2 contains a brief description of each watershed. The six watersheds discussed in this report are: Thomas Brook, Black Brook, Bras d'Henri/Beaurivage, South Tobacco Creek, Lower Little Bow River and Salmon River. The approximate location of these watersheds is shown in Figure 2. Integrated modelling was investigated on the South Tobacco Creek and Bras d'Henri/ Beaurivage watersheds. A groundwater modelling study of a seventh WEBs watershed, South Nation in Ontario, was not included in this review.

Figure 2: Location of WEBs watersheds

Table 2: Comparison of WEBs watersheds

Watershed	Physical Characteristics		Land Use			
	Area (Km^2)	Description	Cultivated agriculture %	Pasture/ forage %	Natural (forest, shrub, grass)	Other
Black Brook	1.3		62	6	24	8
Bras d'Henri/ Beaurivage	167/ 742	Nested sub-watershed	19	26	51	4
Lower Little Bow River	34.0	Segment of the Lower Little Bow River	31	45	25	
Thomas Brook	0.76	The smallest watershed	n/a	n/a	n/a	n/a
Salmon River	1500	Mountain watershed	8.3		91	0.7
South Tobacco Creek	74.6	Three distinct areas – upland, escarpment and plains	59	12	25.4	3.6

The **Black Brook** Watershed is located in northwest New Brunswick neat Grand Falls. The watershed is a tributary to the Little River. The watershed area is 1302 ha. The main issues in the watershed are erosion and water quality much of which comes from sediment-borne nutrients.

The **Bras d'Henri /Beaurivage** Watersheds - The Bras d'Henri is a sub-watershed of the Beaurivage Watershed. The areas are 167 km^2 and 742 km^2 respectively. The watersheds are located in the Chaudière River Basin which has been studied extensively over the last 15 years. The Chaudière Basin has one of the highest densities of livestock production in Quebec. The current study builds upon the previous studies.

The **Lower Little Bow River** Watershed is tributary to a reach of the Little Bow River about 40 kilometres north of Lethbridge, Alberta. The watershed comprises 34 km^2. The dominant land use is agriculture of which 47% is irrigated. Cereals (barley) and perennial forages are the main crops. The watershed is an incremental watershed in that it is located on a reach of the Little Bow River and almost 90 percent of the water that flows out of the watershed originates upstream of the watershed.

Irrigation is a dominant component of the water balance. The irrigation areas north of the river and in the valley bottom are supplied from the Little Bow River while areas south of the river are supplied from sources outside of the basin as part of the Lethbridge Northern Irrigation District.

The **Thomas Brook** Watershed, comprising some 760 hectares, is located north of the town of Berwick in Nova Scotia's Annapolis Valley. Thomas Brook is a tributary of the Cornwallis River. "Land uses include intensive agriculture and rural residential development. In addition to tree fruit, berry crops, and vegetables, other cropping includes corn, soybeans, and grains."[1]

The **Salmon River** Watershed is a mountain watershed located in south-central British Columbia in the Fraser River Basin. The watershed covers some 1500 km^2 from the headwaters to the outlet near Salmon Arm where it drains into Shushwap Lake. Forestry is the dominant land use covering 91 per cent of the watershed. Agriculture occupies 8.3 per cent of the watershed. Intensive land use including agriculture with its increased fertilizer and manure applications has resulted in a negative impact on water quality that has become a concern for the communities along the Salmon River as well as downstream.

The **South Tobacco Creek** Watershed is located on the Manitoba Escarpment near the town of Miami about 150 km south-west of Winnipeg. The watershed, comprising an area of 74.6 km^2, is a tributary to the Morris River which flows into the Red River and then into Lake Winnipeg. About 71 per cent of the area is cultivated. About 58 per cent of the cultivated area is in annual crops (mainly wheat and canola), and the remainder is in forage and pasture.

[1] http://www.nsfa-fane.ca/files/images/file/WEBS.pdf

Research Methods

The watershed modelling studies share two common objectives[1]:

1) to simulate the watershed hydrology and water quality under existing conditions using a distributed watershed model, and
2) to use the calibrated model to evaluate the effectiveness of watershed BMPs in reducing the impact of agricultural practices on the quality of surface water runoff from the watershed.

Two of the studies had a third objective which was to provide a method to integrate the environmental models (GIBSI, SWAT) with socio-economic models, namely the on-farm economic models and the farm behavioural models being developed under separate studies for the Bras d'Henri/Beaurivage and the South Tobacco Creek watersheds.

Water quality as discussed in this report generally refers to sediment and nutrient loading (nitrogen and phosphorus); however, there are two exceptions. Coliform and pesticide transport under various BMPs were modelled for the Bras d'Henri/Beaurivage Watershed using routines available within GIBSI, and a bacteria model was developed and tested using data from three livestock farms along the Salmon River.

The USDA's[2] Soil and Water Assessment Tool (SWAT) was the primary watershed model for five of the watersheds: Black Brook, Thomas Brook, South Tobacco Creek, Lower Little Bow River and Salmon River. The GIBSI[3] model was used on the Bras d'Henri/Beaurivage Watershed. The models perform continuous simulations of the hydrology, sediment and water quality on a daily time step. "Weather, Soil properties, topography, vegetation and land management practices are the main inputs." (Wanhong Yang, 2008) The process for watershed modelling is shown in Figure 3.

Additional modelling capacity was sometimes required to generate inputs to the SWAT model, or to analyze processes which the SWAT model was not able to handle in a satisfactory manner such as the impacts of structural BMPs. These include modelling the impacts of small dams, holding ponds to contain the runoff from cattle pens, and flow diversion terraces as well as landscape changes such as grass buffer strips. Difficulties were also encountered in modelling the runoff and water quality during snowmelt, and modelling short duration runoff events. When additional capacity was required the modellers would first attempt to utilize or adapt an existing model. When this did not work a new model or modelling routine was developed. The supporting models are discussed further in the following paragraphs.

The existing capacity of the GIBSI system was sufficient to meet most of the current modelling needs for the Bras d'Henri/ Beaurivage Watershed. GIBSI had been used previously to model flow and water quality for various locations in the Chaudière Watershed.

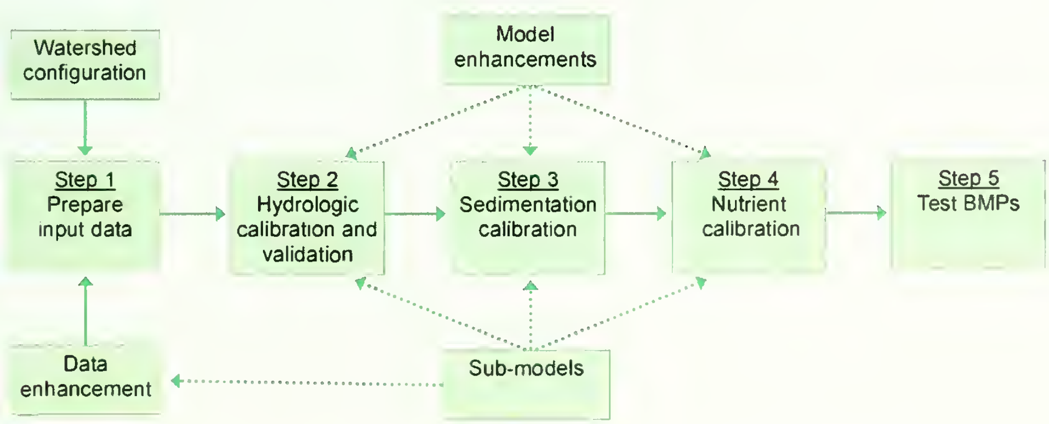

Figure 3: Schematic of WEBs modelling process

[1] This is a generalization to capture the essence of the individual study objectives which may have slightly different wordings.
[2] SWAT was developed by the U S Department of Agriculture, Natural Resources Conservation Service

[3] Gestion Integrée par Bassin-Versant à l'aide d'un Système Informatisé.

Watershed modelling

Data and watershed configuration - After establishing the modelling objectives, the first step is to prepare the input data. This includes selecting the time period for modelling, converting existing records to formats that can be used by the model, selecting representative precipitation data, filling in missing data, and defining the watershed configuration using a digital elevation model. Precipitation is normally input on a daily basis although sub-daily values can be used.

GIS is used to define drainage boundaries, drainage patterns and delineate the geographical units for the hydrologic analysis. For the SWAT model the watershed is divided into sub-watersheds, reaches and “hydrologic response units” (HRUs). Instead of an HRU, GIBSI uses a “relatively homogeneous hydrologic unit” (RHHU). Both represent areas of similar hydrologic performance and are selected based on land use, soil type and topography (slope).

Calibration and validation of the watershed model - The next step is to calibrate and validate the model to predict the surface runoff, and sediment and nutrient exports at the outlet from the watershed and intermediate points. The standard sequence for calibrating a watershed model[1] follows the outline given in the SWAT User's Manual which models hydrology, sediment and water quality in that order (Steps 2, 3 and 4 in Figure 3). The validated model can then be used to evaluate BMPs (Step 5, Figure 3)

A known set of records is selected for calibrating and validating the model. The SWAT User's Manual recommends dividing the record into three parts as shown in Figure 4. The first part is used as a warm-up stage to reduce the impact of any errors in estimating the initial conditions. (This was only used for the South Tobacco Creek Watershed).The remaining two periods are used for calibration and validation respectively.

Hydrology - The watershed hydrology is calibrated first. The SWAT User's Manual recommends separating the baseflow from the surface runoff and calibrating each component of runoff separately although this is not always required.

The main inputs are precipitation, temperature, and the flow parameters that define the hydrologic processes such as the amount and rate of runoff, snowmelt, infiltration, and discharge to groundwater.

The model is calibrated by adjusting the flow parameters until the predicted outflows from the watershed closely match the observed outflow in terms of magnitude, volume and timing. The calibrated model is then validated by running it for a second period using the precipitation for that period. Some model parameters may have to be adjusted at this stage to account for the effects of changes in the watershed such as development of water storage, implementation of BMPS that effect flow, or changes in land use. An example of this was the implementation of flow diversion terraces and grassed buffer waterways in the Black Brook Watershed which affected flows in the Black Brook Watershed during the validation period.

Sediment - The next step is to model the sediment processes using the model that has already been calibrated to simulate the hydrology. Adjustments are made to parameters that effect sedimentation namely erosion from the land surface and in the channel. Watershed erosion processes are very dependent upon the accuracy of the modelled flow. In turn the estimates of sediment significantly impact the transport of phosphorus from the watershed.

Water quality - The third step is to model water quality usually nitrogen and phosphorous in their various forms. Pesticides (atrazine) and fecal coliforms were also modelled for the Bras d'Henri/Beaurivage Watershed. A bacteria model was developed for the Salmon River Watershed.

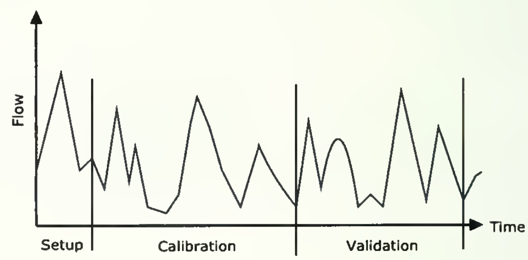

Figure 4: Steps to develop a watershed model

[1] A similar process was followed for both the SWAT and GIBSI base models.

Evaluating the modelling results - A variety of graphical and statistical methods was used to evaluate the quality of modelling results. Graphical methods, such as plotted hydrographs provided a visual check on the goodness of fit while plots of frequency distributions show whether or not the predicted results fit within the statistical distribution of the recorded data. The most commonly used statistical measures were the coefficient of determination (R^2) and the Nash-Sutcliffe Efficiency coefficient (NSE). Other measures used include percent bias (PBIAS) and Root Mean Square Error (RMSE). A more thorough discussion of evaluation criteria is presented in Section 4.

Evaluating BMPs

In the final step the calibrated and validated model is used to evaluate the impacts of BMPs on the quality of surface water at the watershed outlet and in some instance at intermediate points. BMPs include changes in land use management practices such as reduced application of fertilizers and pesticides, substitution of ammonia based fertilizers with manure, reducing tillage, converting annual crops to perennial forages, and planting of riparian buffer strips as well as the implementation of structural measures such as flow diversion terraces, and runoff detention ponds. Both the SWAT and GIBSI models have internal capacity to consider many of these changes in particular the non-structural changes in land use. For example the impact of forage conversion can be modelled by switching the land use from cereals to forage.

Additional models or model enhancements

Some additional models or routines were developed to prepare input data to the model or evaluate BMPs. For example an event based model was developed to assess the impact of grass buffer strips in the Black Brook Watershed. For that same watershed an Artificial Neural Network Model was developed to estimate soil drainage parameters using coarse resolution data that were very close to those that could be obtained through the use of finer resolution data. The models used in each watershed are shown in Table 3 and discussed further in the following paragraphs.

Table 3: Summary of models[1] or model enhancements used in WEBs I watershed studies

Watershed/Primary Model	Models/modules/enhancements	Function
Black Brook/SWAT	Flow Diversion Terrace Model	Estimate P-factors
	Event Based Grass Buffer Model	Model hydrologic impact of grass buffer strips.
	ANN model for soil drainage characteristics and soil organic carbon	Estimate soil parameters from coarse soil data
Lower Little Bow River/SWAT	Auto-calibration routine	Selection of hydrologic parameters
Salmon River/SWAT	Bacteria model	Model transport of fecal coliforms and *e coli* from livestock operations
	Hydrology module (part of bacteria model)	Estimating runoff from a rain event
South Tobacco Creek/SWAT	Small storage modules	Runoff detention from feedlots
	Auto-calibration	Calibration of parameters
	REMM equivalent	
Thomas Brook/SWAT	n/a	n/a
Bras d'Henri /Beaurivage/GIBSI	PHYSITEL GIS	Watershed delineation and drainage patterns
	TransPath	Coupling with GIBSI to model transport of pathogens (fecal coliforms) from pasture to stream

[1] These models were either used directly in SWAT or provided input to SWAT with the exception of the bacteria model developed for the Salmon River Watershed.

Integration with economic models

Data exchange between the environmental and economic models requires that they have similar temporal and spatial scales. Temporal scales are not a problem as data from the environmental models can be aggregated to produce the annual data required by the economic model. Spatial integration is more difficult to achieve as the environmental models work at the scale of a "hydrologic unit" such as a watershed or reach all of which follow natural boundaries while economic models work at the farm level defined by man-made surveyed farm boundaries, or political boundaries such as a township, crop district or province. The modellers for the Bras d'Henri/Beaurivage and the South Tobacco Creek watersheds have each proposed a method to overcome the spatial scale problem.

Bras d'Henri/Beaurivage - Spatial integration was accomplished by adjusting the size of the basic spatial unit for the GIBSI modelling system, the Relatively Homogeneous Hydrologic Unit (RHHU), to approximate the size of farms in the region, 50 to 105 ha. Farm scale data could then be produced at each RHHU by the environmental model, aggregated as required, and transferred to the economic model[1].

South Tobacco Creek - A software interface was developed to facilitate the exchange of information between the hydrologic and economic (on-farm-economics and farm behaviour) models for the South Tobacco Creek Watershed. The interface uses an ArcGIS based routine using look-up tables to convert hydrologic data at the scale of the Hydrologic Response Unit (HRU) to the land or farm scales used by the socio-economic models. Conversely the routine will also scale data used or produced by the economic models to the HRUs used by the hydrologic model.

The interface can be used to develop and test Beneficial Management Practice (BMP) scenarios, identified in the Farm Behaviour Model[2] for example, by entering the information required to change management practices in each affected land parcel. The interface will convert the information so that the benefits of the scenario can be evaluated with the hydrologic model.

[1] Socio-economic studies for the Bras d'Henri/Beaurivage Watershed are being done by teams at the Université Laval and McGill University.

[2] Socio-economic studies for the South Tobacco Creek watershed are being done by a modelling team at the University of Alberta.

The interface is only partially complete as the modules for the economic and farm behavioural modules have not yet been developed. If completed as planned the interface will provide a valuable tool for both researchers and conservation managers. The graphical input screens with drop down menus can potentially make this a user friendly interface.

Special modelling considerations by watershed

Black Brook - Flow diversion terraces and grassed buffer strip BMPs were implemented in the Black Brook Watershed beginning in 1995 which coincided with the beginning of the validation period 1995-2005. The model validation therefore, had to take into account the impact of these BMPS. Modelling routines, described in Table 3, were developed to provide information to model the impact of the BMPs.

Artificial Neural Network (ANN) models were developed for this study to predict soil texture, soil drainage class and soil organic carbon content for the watershed using information derived from widely available coarse resolution SLC[3] maps. The ANN outputs matched well with finer resolution maps available for the watershed. The ANN models could provide more accurate maps for extrapolating the study results to other watersheds.

Suitable models were not available for directly analyzing the impacts of BMPs, namely flow diversion terraces and grassed buffer strips at the watershed level. This study took the initial steps to bridge the gap by developing a flow diversion model and an event-based grassed buffer model. The flow diversion terrace model was developed to estimate a soil conservation factor (P-factor)[4] for different intervals of diversion terraces. The event-based grassed buffer model (GBSMOD) was developed to simulate flow and movement of sediment mass over grassed buffer strips as the REMM (Riparian Ecosystem Management Model) was considered to be unsuitable for simulating processes in grass waterways, and literature reviews did not reveal suitable alternatives.

[3] Soil Landscapes of Canada

[4] The P-factor is the ratio between soil erosion with and without soil conservation practices.

Bras d'Henri/ Beaurivage - The watersheds have been modelled previously as part of a larger study of the Chaudière Basin. The results of the current study can be compared with previous studies to provide an additional check on the quality of the model. One of the differences between the two studies is the use of smaller RHHUs in the current study which provide a more precise definition of watershed characteristics as well as a hydrologic response unit that closely approximates farm size.

The PHYSITEL GIS system was used to prepare the watershed delineation and drainage patterns for used in the model. The basic spatial unit for the hydrologic model is the Relatively Homogeneous Hydrologic Unit (RHHU) which range in area from 50 to 105 hectares, the approximate size of farms in the region. RHHUs were clustered (grouped) where there were insufficient data to assign unique attributes to each unit. RHHUs for the Bras d'Henri were clustered for modelling the hydrology with HYDROTEL.

Lower Little Bow River - The present study of the Lower Little Bow River Watershed focused on determining the incremental flow and incorporating irrigation from internal and external sources. Specific objectives were to "delineate the irrigation areas" and "incorporate irrigation practices in the hydrologic model and calibrate accordingly." (Rahbeh, 2008) The modelling objective is to predict the incremental contribution while accounting for irrigation.

As data were unavailable to accurately model irrigation practices the model was calibrated for three scenarios: 1) no irrigation, 2) unlimited irrigation and 3) fixed irrigation. An automatic calibration routine was developed to calibrate the hydrologic parameters for the SWAT model.

Estimating outflow from the watershed - As the watershed is an actual reach of the Little Bow River and flow measurements were available above and below the watershed, the runoff from the watershed (ΔQ) was estimated by subtracting the recorded flow at the upstream station from the downstream station for the period 2004-2006.

$$\Delta Q = Qout - Qin \quad \text{--------} \qquad (1)$$

Salmon River - Special considerations were as follows:

a) In the absence of sediment data the sediment loading was modelled with SWAT using calibrated flows and theoretical values (from the SWAT model documentation) for sediment parameters, relying upon the close relationship between flow and sediment transport to produce reasonable results.
b) A stand-alone watershed bacteria model was initiated and developed for the Salmon River Watershed to simulate the transfer of fecal coliform and *E. coli* bacteria from sources to the stream water accounting for hydrologic processes, climate effects and watershed management practices.
c) The study proposed and tested a process for using the model water quality outputs to develop BMPs that would maximizes economic returns while keeping the export of nutrients to surface water below established water quality guidelines.

In essence the procedure was used to determine the maximum applications of manure and inorganic fertilizers that could be used without exceeding water quality guidelines at the outlet of the watershed. This assumed that the economic returns were directly proportional to the amount of fertilizer applied.

South Tobacco Creek - There is a very extensive data base available for the study as a result of over 15 years of intensive study in the basin. Flow, sediment and water quality data were available at two locations in the lower reaches (one at the outlet) of South Tobacco Creek as well as at several locations in the upper reaches namely the Steppler watershed and from the Twin watersheds study.

The model calibration took into account existing BMPs: twenty-seven small dams and existing land-use management practices. The model was then validated for two periods each using the BMPs that were in existence at that time, the first using the same BMPs as for the calibration. The second validation added a holding pond and a grazing management area. This formed the base case for testing BMPs.

The South Tobacco Creek is the only one of the WEBs I watersheds to evaluate small dams and holding ponds. Considerable effort went into pre-processing of data and developing methods to simulate the impacts of BMPs including developing: storage-area-volume relationships for small dams, a table to locate point source loading from cattle yards, and a GIS interface between SWAT and the REMM model for modelling riparian buffers.

Thomas Brook - The SWAT model was used to calibrate the outflow, sediment, and nutrient (phosphorus and nitrogen) exports from the watershed for the period April 2005 to February 2006. Because of the short period of record daily data were used to compare predicted and observed outputs. The model was not validated.

Considerable effort went into selecting and preparing available data for use in SWAT. Data such as soil and land use had to be interpreted from existing formats to SWAT compatible formats. A continuous time series of sediment load had to be constructed using grab and composite samples, and streamflow. Sensitivity analysis was used to determine the most sensitive parameters.

Results by Watershed

Watershed models were calibrated for each of the six WEBs I watersheds, and the models were used to estimate the impact of Beneficial Management Practices (BMPs) on water quality in five of the watersheds: Black Brook, Bras d'Henri/Beaurivage, South Tobacco Creek, Salmon River, and Thomas Brook. The ability of the model to evaluate a BMP is dependent upon the quality of the model calibration. As well WEBs I investigated the integration of hydrologic and economic models for the Bras d'Henri/Beaurivage and South Tobacco Creek watersheds. The results of the model calibration and BMP testing are presented for each watershed in the following sections, as well as the results of the integrated modelling exercises.

Black Brook

The Black Brook watershed was studied for the period 1992-2005. Flow diversion terraces and grassed buffered waterways were implemented beginning in 1995. The record was therefore split into two periods; the first 1992-1994 and the second 1995-2005 representing pre-BMP and post-BMP conditions respectively. The watershed was then modelled under both conditions.

Model calibration (pre-BMP 1992-1994) - The model was initially calibrated for the period 1992 to 1994 which represented the state of the watershed before implementation of BMPs. Predicted monthly flows matched the observed flows with an R^2 of 0.91 and NSE of 0.88. The model slightly under-predicted sediment yield in early summer (June-July, 1992 and 1994) and over-predicted in late summer (October to January, all three years) resulting in an R^2 of 0.50 and a negative NSE.

Water quality results were mixed. Nitrate loadings were much higher than measured values and there were two high nitrate loading peaks each year that did not occur in the period of record. During the snow melt, the predicted peak loadings of NO_3-N were about one month later than observed peaks. Both R^2 and NSE were close to zero. Phosphorus predictions were much better although over-predicting the summer loads and that for October, similar to the results of the predictions of sediment yield. As with nitrates, there was a high peak value of P during the spring, associated with spring snow melting. The R^2 and NSE values were just over 0.80 which suggests a very good fit between modelled and observed values of phosphorous.

Re-calibration (post BMP 1995-2005) - The first simulation with the calibrated model was for 1995-2005, the period in which BMPs were assumed to be in place. The calibrated model over-predicted both flows and sediment loading. This was attributed to the absence of any consideration of BMPs. A second simulation was run with the model adjusted to account for the effect of flow diversion terraces. The model continued to over- predict flow and sediment. A third simulation was done using an increased infiltration rate to account for flow attenuation of the grass buffer strips. These changes produced a good match between observed and measured values of flow and sediment loading. Nutrients were not modelled.

Beneficial management practices - The study considered two BMPs which are currently practiced in the watershed: flow diversion terraces, and grassed buffer waterways. The general hypothesis of the study was that such BMPs could be extended over the potato growing regions.

Scenario analysis of flow diversion terraces - Analysis was undertaken to estimate the impacts of:

1) increasing the proportion of the watershed being protected by flow diversion terrace systems and
2) changing the distance between flow diversion terraces. The flow diversion terrace assessment model was used to estimate the soil conservation practice factor (P-factor). Tables were developed relating the P-factor to slope and to terrace intervals.

This information was used to develop a new set of HRUs based on slope as well as soil type and land use. The SWAT model was then run for several scenarios based on the percentage of the area protected by diversions and for differing intervals between diversions. The results indicate that sediment is reduced by up to 75% and phosphorus loading will decrease by 57% as the amount of area protected by the flow diversion terraces is increased to100%. Nitrogen loading, on the other hand increases by as much as 44% with the maximum area protected. The increase in nitrogen loading is consistent with literature on the subject.

As discussed earlier suitable models were not available to evaluate the impacts of grassed buffer strips. This necessitated the development of an event-based grassed buffer model. The model was tested on three storm events, modelling two of the three events successfully with $R^2 > 0.9$. R^2 for the third event was 0.42.

Bras d'Henri/Beaurivage

Model calibration - The Beaurivage Watershed has been modelled previously in studies of the Chaudière River Basin where the Bras d'Henri was included in the Beaurivage Watershed. In this study the Bras d'Henri was first modelled as a separate sub-basin and then modelled as part of the Beaurivage Watershed.

The study used the GIBSI modelling system which includes a GIS, a hydrologic model (HYDROTEL), and models for the overland and in-stream transport of sediment, nutrients, pesticides and pathogens. HYDROTEL satisfactorily modelled outflows from the Beaurivage and Bras d'Henri watersheds although there was a tendency to underestimate spring floods, and some flow events were missed likely due to lack of representative precipitation data. Also the model was not able to capture the effect of drains in the Bras d'Henri Watershed underestimating summer flows.

Modelling results were thoroughly evaluated using statistical and graphical techniques and were compared monthly, annually, and for the low flow season. This was the only study that examined the performance of the model specifically under summer low-flow conditions. The Nash-Sutcliffe coefficients for the flow calibration and validation were 0.79 and 0.75 for Beaurivage. Values for Bras d'Henri were lower with $E_{N\text{-}S}$ equal to 0.39 and 0.44 for calibration and validation respectively.

Logarithmic transforms were used to compare the results graphically. The trends in predicted values of sediment, nutrients, pesticides and pathogens agreed with measured values although there was considerable difference in magnitude and timing between modelled and observed values. The results were deemed satisfactory for use in evaluation of BMPS.

Beneficial management practices - Five BMPS were modelled: 1) riparian buffer strips at 1,3, and 5 metres; 2) reducing application of pesticides by 30 % (atrazine); 3) using manure spreading booms with trailing hoses; 4) converting fields from cereals and corn to hay and pasture; and 5) using no-till on corn fields. The reduction in in-stream loading at the outlet of Bras d'Henri and Beaurivage watersheds is shown in Table 4. BMPs were evaluated by changing the appropriate descriptors within the GIBSI modelling system. For example the effect of converting pasture to hay was done by changing the land-use of the RHHUs from pasture to forage and removing the cattle.

As stated earlier the absolute values of the reductions are dependent upon the accuracy of the model calibration. Nevertheless the results are consistent with other studies. Addition of buffer strips and converting pasture to hay were the most effective BMPS for reducing sediment and pesticide loading at the outlet of the Bras d'Henri Watershed, and sediment, phosphorus, nitrogen and pesticide loading at the outlet of the Bras d'Henri Watershed, and sediment, phosphorus, nitrogen and pesticide loading at the outlet of the Beaurivage Watershed. There were insufficient data to establish trends in the reduction going from the sub watershed (Bras d'Henri) to the larger watershed (Beaurivage).

Table 4: Results of the evaluation of BMPs in the Bras d' Henri/Beaurivage Watershed

Beneficial management practice (BMP)	Reduction in load at outlet of Bras d'Henri watershed (%)				Reduction in load at outlet of Beaurivage Watershed (%)			
	Sediment	Total P	Total N	Atrazine	Sediment	Total P	Total N	Atrazine
Buffer strips 1 m	10	29	58	40	10	29	56	42
Buffer strips 3 m	16	41	68	53	13	41	67	56
Buffer strips 5 m	19	49	72	62	15	49	71	64
Reduce atrazine 30%				37				39
Manure spreading - hoses			(+1)				1	
Convert corn and cereals to pasture and hay	26	72	47	100	16	60	30	100
No till	8	18	0	1	0	9	0	1

Integrated economic modelling - Data from the environmental model of the Bras d'Henri/ Beaurivage watershed have been provided to the economic modelling groups at the Université Laval and McGill University. The lack of a common physical scale has been the main obstacle to exchange of data between the economic and environmental models. The basic geographic unit for the socio-economic models is the farm while the basic unit for the watershed model is the RHHU which for this study has been sized to approximate the size of the farms in the watershed. This provides a common unit for transfer of data.

Lower Little Bow River

Model calibration - A SWAT model was calibrated to simulate outflow from the watershed for the period 2004-2005 under three scenarios, one without irrigation and the other two with irrigation. Calibration results for the three scenarios achieved very similar results. Nash-Sutcliffe efficiencies (NSE) ranged between 0.67 and 0.72, and R^2 values between 0.70 and 0.73.

Incorporating irrigation into the model - Irrigation can be a major influence on the water balance particularly for dry years. Approximately one-half of the watershed is irrigated. The irrigation water comes from two sources; the Lethbridge Northern Irrigation District (LNID) which is outside of the Little Bow River Basin, and the Little Bow River.

Initial calibrations were done for the three scenarios using data for 2004 and 2005. The first irrigation scenario assumed unlimited irrigation supply from the Lethbridge Irrigation District (LNID) which is outside of the watershed. The second scenario drew water from the main stream (Little Bow River) following a theoretical fixed irrigation schedule which provided water bimonthly between April 15 and August 15.

Even though there was a good match between model-predicted outflows and those derived from the recorded flows, none of the scenarios were fully representative of actual physical conditions in the watershed. Forty-seven (47%) per cent of the basin is irrigated which invalidates the non-irrigation scenario. Similarly the two irrigation scenarios, each drawing from a single source, do not reflect the reality of irrigation in the watershed. Irrigators draw water from two sources depending upon their location. Those in the southern part of the watershed irrigate from the LNID, and those in the north irrigate from the Little Bow River. The calibration will be re-done in WEBs II using additional information on the sources of irrigation water, as well as new information on timing of irrigation.

The sensitivity analysis conducted on the hydrologic parameters showed little variability in the parameters selected for each of the three scenarios. Because of this it is expected that re-calibration using the new irrigation data (amount and timing) should be successful.

Validation - In the next phase the model will be validated using data for 2006, which is a below average year for rainfall. Irrigation is expected to be the dominant driver of the hydrological cycle. With more accurate data on irrigation practices the model should provide useful results.

Beneficial management practices - The current study did not investigate BMPs for the watershed, however, investigations of two BMPs, manure management and converting annual cereal crops to green cover (alfalfa, grass), are planned for WEBs II. As well the results of this study suggest that managing irrigation to reduce nutrient (nitrate) leaching to groundwater could be investigated as a BMP.

Salmon River

Model calibration and evaluation - To quote from the report - "The SWAT model was calibrated and validated, spatially using stream flow and nutrient export data collected from five sites along the watershed from its headwaters at McInnis to its outlet at the Highway 1 Bridge, and temporally using monthly data from 1996 to 2006." (Zhu, Broersma, Meays, & Mazumder, 2008) The record was split for use in the calibration (1996-2000), and validation (2001-2006).

Following standard SWAT operating procedures the flow was calibrated first, followed by sediments and nutrients. The study concludes that the SWAT simulated monthly flows and nutrient exports match observed field data well. The NASH-Sutcliffe Efficiency coefficient was used to evaluate the model results. The NSE for flow calibrations ranged from 0.67 at the outlet near Salmon Arm to 0.46 further upstream at Falkland. Irrigation withdrawals were unaccounted for and could have influenced some of the flow observations during the summer.

There were no sediment data, however, sediment was estimated with the SWAT model using theoretical (SWAT default) values for sediment parameters and relying upon the close relationship between flow and sediment transport to produce reasonable results. The report states:

"The sediment is subject to runoff rate, so once the ratio of surface runoff to base flow is being simulated correctly, the sediment loading should be close to measured values." (Zhu, Broersma, Meays, & Mazumder, 2008)

Stream nutrient exports were calibrated by first verifying the initial concentrations of nutrients in the soils, the amount of fertilizer applications, and tillage operations; and then adjusting the parameters controlling nutrient leaching rates. The impact of current land-use on nutrient export was defined as the difference between the current level of nutrients and that which would have taken place under natural conditions. Estimates of nutrient exports under current and natural conditions were determined by running the model with current land use and then with the watershed covered by forest which was assumed to be the natural state. The total estimated export from the watershed to surface water is shown in Table 5.

Validation - The model was validated using the parameters for the calibrated model and meteorological, management and land-use data for 2001-2006. Modelled and observed flows matched quite well with NSE = 0.71 and 0.58 for HWY 1 Bridge and Falkland respectively.

Modelled water quality (N, P) agreed fairly well with recorded values. For example, NSE values for nitrogen (NO3-N ranged from NSE= 0.40 at Highway 1 to 0.62 at McInnes, the most upstream monitoring site. NSE for soluble residual phosphorus ranged from 0.23 near the outlet at Highway 1 to 0.51 upstream at Glenemma. Similarly the NSE for dissolved organic phosphorus ranged from 0.52 to 0.42.

Impact of current land use - The impact of current land use was estimated as the difference between loading for 1993 land use and a base case which assumed that all lands were covered by natural forest. Nutrient exports from the watershed under present and natural conditions are shown in Table 5.

Watershed bacteria model - A watershed bacteria model was initiated and developed to simulate the transfer of fecal coliform and *E. coli* bacteria from sources to the stream water accounting for hydrologic processes, climate effects and watershed management practices. A hydrology module was developed within the watershed bacteria model. From a visual inspection of modelled and observed daily flows for the Salmon River near Falkland, the hydrology module appeared to be able to simulate the daily flows quite well. This was not used to model BMPs.

Beneficial management practices - The impact of current land use was estimated by comparing the nutrient loadings for 1993 to the loadings for a base case with the watershed covered by forest. Results are shown in Table 5.

A process was outlined for developing BMPs that would maximize economic returns from implementing a BMP while keeping the export of nutrients to surface water below established water quality guidelines. The method assumes that economic benefits will increase with the application of the BMP and that the maximum application will be limited by the maximum allowable loading on the water quality.

Table 5: Estimated nutrient exports (tonnes/year) from the Salmon River Watershed

	Description of land use	NO_3	DON	SRP	DOP
Base case	Naturally forested	11	16	2	3
Current land use[1]	1993 land use	16	23	6	10

[1] Total exports determined by adding the increases documented in the report to the Base case.

The examples used were the application of manure to pasture, and nitrogen fertilizer (NH_4-NO_3) to forage in amounts that would keep the nitrate concentration in the water below the British Columbia Water Quality Guidelines of 10 mg per litre. A formula was derived for calculating the loading for the BMP which was defined as the difference between the maximum allowable load and sum of the current loading. From this it was estimated that maximum rate of NO_3-N fertilizer application is 210 kg ha^{-1} yr^{-1}, assuming that there is no manure applied. Similarly the maximum manure application is 40 t ha^{-1} yr^{-1}.

Sensitivity analysis - Using the validated model, a sensitivity analysis was undertaken to determine the potential impacts on surface water quality from applying NH_4NO_3 fertilizer to forage producing lands at the beginning of May, and applying manure to pasture during the grazing season. Application rates were 50, 100 and 150 kg ha^{-1} yr^{-1} for each BMP.

Nitrate exports increased significantly by 4.6 kg ha^{-1} yr^{-1} for each 100 kg of NH_4NO_3 fertilizer applied ($P<0.01$ and $R^2 = 0.84$). Manure applications did not significantly increase nutrient exports.

South Tobacco Creek

The South Tobacco Creek (STC) Watershed has been the focus of scientific studies for more than 15 years which has resulted in a valuable background data set of agronomic and environmental information for input to SWAT to model flow, and sediment and nutrient processes in the watershed. As well data are available from small sub-watersheds such as the 210-ha Steppler watershed which was designated as a WEBs experimental site in 2004 with the setup of nine monitoring stations.

Model calibration and validation - Calibration efforts were focused on improving model predictions at two monitoring stations on the South Tobacco Creek at Miami and HYW240. The calibration periods at Miami and HYW 240 were 1991-1998 and 1993-1998 respectively. The calibration included a warm-up period from 1986-1990 for Miami and 1993-1995 for HWY240 sites to minimize the impacts of uncertain initial conditions. This was not done for other WEBs watersheds.

SWAT successfully simulated streamflow, and sediment and nutrient loads at the watershed outlet. A sensitivity analysis was undertaken to determine key modelling parameters. An auto-calibration method was used to determine final values of the sensitive input parameters.

The results of the flow simulations show good agreement between modelled and observed flows for daily, monthly and annual time steps for both calibration and validation. The NSE ranged from 0.61 to 0.64 for daily flows, 0.74 to 0.76 for monthly flows, and 0.81 to 0.83 for annual flows for South Tobacco Creek at HW 240 and Miami respectively. Results for the smaller watersheds were not as good with the possible exception of the East and West Twin watersheds were NSEs were 0.51 and 0.47 respectively.

Water quality calibrations including sediment, nitrogen and phosphorus loading were focused on matching point predictions rather than continuous daily and monthly predictions because of the grab sampling frequency. Detailed descriptions of parameter setup for snowmelt, flow, and sediment and nutrient yields are presented in the project report.

Sediment - Because of the flat channel slope and the fine bed materials in the study watershed, the bed-load sediment transport can be neglected comparing to the total sediment load at the watershed outlet. Therefore, the model simulated sediment loading can be directly compared with the measured total suspended solids (TSS).

Sediment prediction at Miami station has a high correlation coefficient of 0.85, but for Twin West and Twin East, the correlation coefficients are reduced to 0.42 and 0.38 respectively due to the relatively poor predictions of flow and sediment concentrations at these two stations.

Evaluation - For flows the model performance was qualitatively evaluated with time series plots and quantitatively evaluated using two model performance statistics: bias[1] and the Nash–Sutcliffe Efficiency Coefficient (NSE). Monthly flow predictions were evaluated against recorded values using the correlation coefficient, the Root Mean Square Error (RMSE), and the coefficient of variation of the RMSE.

Beneficial management practices - Six BMPs were considered in this study all of which have been implemented to varying degrees in the South Tobacco Creek watershed. The BMPS are small dams, holding ponds, grazing management,

[1] Model bias can be expressed as the relative mean difference between predicted and observed streamflow for a sufficiently large simulation sample, reflecting the ability of reproducing water balance. (South Tobacco Cr. Report)

conservation tillage, forage conversion, and wetland restoration. In several cases pre-processing was required. The BMPs examined in the Steppler watershed include small dam, holding ponds, riparian grazing management, zero tillage and forage conversion.

Small dams - The STC watershed has 27 small dams constructed between 1985 and 1992 for the purpose of mitigating floods in the downstream reaches. These small dams also reduce sediment and nutrient loads. Considerable work was done to develop depth-area-volume-discharge curves for the small dams.

Holding ponds - SWAT was used to model water quality effects of all proposed holding ponds at the producer level and at the STC watershed outlet using data from the Steppler Watershed (2004-2006). Holding ponds store the waste from cattle yards preventing nutrients from entering the stream. Because the area contributing to the cattle yards is small the water effluent from cattle yards can be represented by point sources and simulated using the SWAT point source routine. Contaminants are held in the holding pond and excess water is pumped to neighbouring farmland for irrigation and treated as a manure application. Without holding ponds waste is discharged with runoff mainly during snowmelt season.

The locations of all point source inputs were identified in SWAT using a point source position table. The contributing area was subtracted from the SWAT subbasin input files to avoid double counting.

Grazing management - Grazing management practices simulated in this study include rotational grazing, off-stream watering and stream fencing. The grazing period is generally from mid-May to late September. SWAT does not have grazing management functions at the HRU level, e.g. rotational grazing management can not be implemented in one HRU. To solve this problem, rotational grazing was simulated at the subbasin level and then converted to the HRUs afterwards.

Conservation tillage - SWAT can simulate different tillage operations by selecting the required operation in the model input. Conservation tillage in the watershed includes single disking, chiselling, subsoiling, ridging and no-till.

Forage Conversion - Forage conversion is the change of cropland to perennial forage with reduced fertilizer supply and tillage intensity. This can be modelled by SWAT.

Wetland Restoration - Existing wetlands have already been accounted for in the selection of HRUs. Potential wetland restoration areas were identified using the Lidar DEM data to identify depressions in the landscape which may have been wetlands. Wetland restoration scenarios were developed as shown in Table 6.

Integrated environmental/economic modelling - A software interface has been developed that facilitates the exchange of information between the hydrologic and economic (on-farm economics and farm behaviour) models for the South Tobacco Creek Watershed using an ArcGIS based routine that has been developed to convert hydrologic data at the scale of the Hydrologic Response Unit (HRU) to the land or farm scales used by the socio-economic models. Conversely the routine will also scale data used or produced by the economic models to the HRUs used by the hydrologic model. The databases for each model remain as stand alone databases as each model was developed separately.

The interface can be used to develop and test Beneficial Management Practice (BMP) scenarios, identified in the Farm Behaviour Model for example, by entering the information required to change management practices in each affected land parcel. The interface will convert the information so that the benefits of the scenario can be evaluated with the hydrologic model. The interface is only partially complete as the modules for the economic and farm behavioural modules have not yet been developed. If completed as planned the interface will provide a valuable tool for both researchers and conservation managers. The graphical input screens with drop down menus can potentially make this a user friendly interface.

Thomas Brook

Model calibration and validation - The model was calibrated to predict daily flows, erosion and sediment transport, and water quality at the outlet to the watershed. Sensitivity analysis was used to determine the most sensitive parameters. The daily flow was modelled for the period April 2005 to February 2006 with an R^2 = 0.46. The model output for sediment and water quality was illustrated graphically but was not evaluated statistically. Lack of data such as on-site precipitation and temperature data, information on tile drainage, and accurate data on application of fertilizers were identified as deficiencies that needed to be addressed to improve model results.

The study concluded that the model was able to represent the hydrologic response of the watershed. The primary parameters that were

Table 6: Impacts of BMPs in South Tobacco Creek Watershed

BMP	Scenario	Percent reduction from BMP Application [a]			
		Flow	Sediment	Total nitrogen	Total phosphorus
Small dams	5-15 m3/sec	5.7	5.3	4.4	4.8
	1-5 m3/sec	2.1			
	0.5-1 m3/sec	0.5			
	<0.5 m3/sec	0.0			
Holding ponds	12 ponds	0.048	0.076	0.172	0.156
Grazing management		0.025	0.968	0.741	0.971
Conservation tillage	Convert conservation tillage to conventional tillage	1.82	(3.03)	(2.80)	(2.29)
	Convert conventional tillage to conservation tillage	(13.8)	9.5	9.2	11.1
Forage conversion	Convert cropland to forage	3.5	5.54	28.0	30.0
	Convert forage to winter wheat	(0.4)	(0.76)	(3.92)	(4.14)
Wetland restoration	All depressional storage	16.08	20.42	16.97	16.36
	1/2	8.49	11.42	9.27	9.05
	1/4	4.28	5.72	5.43	5.34
	1/8	2.69	4.40	4.28	4.14

Note [a]: Values shown in brackets represent an increase

calibrated were the groundwater parameters which affect the magnitude and timing of baseflow recession.

Beneficial Management Practices - Six (6) BMPS were evaluated and compared to a base case scenario over a five-year period. The BMPs focussed on practices which would mitigate soil erosion and reduce the export nutrients to surface runoff. The BMPs were:
1) removing pasturing of cows, 2) adding a 10 m filter strip for HRUs adjacent to water, 3) removing tillage practices from HRUs where corn was the dominant crop, 4) replacing inorganic fertilizer with manure, 5) strip cropping barley and corn, and 6) decreasing organic matter.

All BMPs were investigated by adjusting the parameters within the SWAT model. The BMPs had relatively no impact on flow. The transport of sediment (TSS) was reduced by the application of filter strips but remained relatively unchanged for the other BMPs.

The impact on water quality was varied. The Thomas Brook study was the only study to report nitrogen and phosphorus exports in forms other than total N and total P. Table 7 shows the relative impact on all water quality parameters reported; total suspended solids, mineral P, organic P, total P organic N, ammonium, total kjeldahl nitrogen, nitrates and total N. Table 8 shows percentage change in total P and N for each BMP.

Aggregated Results

SWAT was used to model all watersheds with the exception of the Bras d'Henri and Beaurivage watersheds which used the GIBSI system. The modelling sequence, however, remained the same for both systems (See Figure 3) following the sequence laid out in the SWAT User's Manual 2000. The calibrated models and support models developed during this study were used to evaluate the impact of selected BMPs on runoff, sedimentation and water quality.

Table 7: Predicted impacts of selected BMPS on water quality in the Thomas Brook Watershed

BMP	TSS	Mineral P	Organic P	Total P	Organic N	Ammonium	Total Kjeldahl Nitrogen	Nitrate	Total N
1. No pasturing	0	0	0	0	0	+1	0	0	+1
2. Filter strip (10m)	-1	+1	-1	-1	-1	+1	-1	-1	-1
3. Zero till corn	0	+1	+1	+1	+1	+1	+1	0	+1
4. Manure	0	0	0	0	0	+1	0	-1	0
5. Strip crop	0	0	-1	-1	-1	0	-1	0	-1
6. Less organic	0	0	0	-1	0	0	0	0	0
Legend:	+1 Increased loading,			-1 Decreased loading,		0 No change or insignificant change in loading			

Table 8: Reduction in sediment, total nitrogen, and total phosphorus loads in the Thomas Brook Watershed from BMPs

BMP	Reduction in loading (%)		
	Sediment	Total P	Total N
1. No pasturing	0.0	(0.2)	(1.7)
2. Filter strip (10m)	6.0	8.2	8.7
3. Zero till corn	0.6	(9.2)	(9.2)
4. Manure	0.0	(0.4)	(0.7)
5. Strip crop	0.6	3.6	(1.7)
6. Less organic	0.6	0.6	(-0.2)
Note: Values shown in brackets represent increased load.			

This section provides an overview of the modelling exercises illustrating progress on model development, and assessing the quality of the modelling. It is intended that the calibrated models will be eventually used to simulate watershed hydrology and water quality for other time periods, changes in land management practices and land use, watershed and BMP performance under climate variability and possibly for modelling unguaged watersheds[1]. A summary of BMPs is provided along with information on the effectiveness of the BMPs as determined by the models. This section also provides a summary of the efforts at integrating the hydrologic and economic models. A framework has been developed to measure progress in calibrating and developing the models, and in assessing BMPs. A method to assess the quality of the model outputs has been proposed which provides a science-base for comparing results across watersheds. Options for clarifying longer term goals for the WEBs modelling project can be found in Section 5.

Progress

As stated earlier in Section 2 the goals of WEBs I were to calibrate a watershed model, test the models efficacy in evaluating BMPs and develop methods for integrating the hydrologic and economic models. The participants in WEBs I have made substantial progress in evaluating BMPS, calibrating models to predict streamflow, sediment, and nutrient exports from the watersheds, and for two watersheds have investigated integrating the environmental and economic models with encouraging results. A summary of the study components completed is shown in Table 9.

In summary the SWAT model has been applied to five watersheds: Black Brook, Lower Little Bow River, Salmon River, South Tobacco Creek and Thomas Brook. The GIBSI model has been applied to the Bras d'Henri/Beaurivage Watershed. Hydrologic models have been calibrated for all six watersheds although some may need a bit more work. In three of the watersheds the models have

[1] This would require that the unique physical characteristics of the ungauged watershed be known such as precipitation, a digital elevation model, soil data and land use data. The ungauged watershed could be modelled by applying the SWAT model parameters from the calibrated watershed to a SWAT model contained the known physical characteristics.

Table 9: Summary of completed study components[1]

	Model calibration/validation			BMP Assessment	Integration
	Hydrology	Sediment	Nutrients		
Black Brook	Yes	Yes	Partial	Yes	No
Bras d'Henri/ Beaurivage	Yes	Yes	Yes	Yes	Yes
Lower Little Bow River	Partially complete	No	No	No	No
Salmon River	Yes	No	Partial	Yes	No
S. Tobacco Creek	Yes	Yes	Yes	Yes	Yes
Thomas Brook	Daily calibration	No	Yes	Yes	No

been calibrated to predict all three components, the watershed hydrology, and sediment and nutrient exports from the watersheds.

As well a variety of BMPs currently practiced or considered for implementation, have been evaluated using the calibrated models for each watershed with the exception of the Lower Little Bow River which will begin evaluating BMPs in WEBs II.

Additional work was done in order to evaluate BMPs in the South Tobacco Creek and the Black Brook watersheds. In the Black Brook Watershed models where developed for use in investigating the impacts of grass buffer waterways and flow diversion terraces. For the South Tobacco Creek Watershed the REMM model was integrated with the SWAT model in order to model the impact of buffer strips. As well extensive work was done to develop routines and data that can be used to model the effect of small dams and the impact of holding ponds for intensive livestock waste. BMPS in the Bras d'Henri/ Beaurivage, Thomas Brook, and Salmon River watersheds were modelled using the existing capacity of the GIBSI and SWAT models respectively. A bacteria model was partially developed however for the Salmon River however it was not used to test BMPs.

Quality of models and methods of evaluation

Information from the SWAT Users Manual 2002 and recently developed evaluation criteria developed by a team led by the USDA, Agricultural Research Service, provide useful guidelines for evaluating the quality of models. The SWAT User's Manual provides a check list for model testing and recommends statistical measures for model calibration and validation as shown in Figure 5 below. Some of these basic checks have been applied in WEBs I modelling such as the use of time series plots and flow duration curves. Seasonal calibrations (summer low flow) were done for the Bras d'Henri/ Beaurivage Watershed but not on any other watershed.

<u>**Check list for model testing**</u>

1. Water balance - is it all accounted for?
2. Time series
3. Annual total - stream flow and base flow
4. Monthly/seasonal totals
5. Frequency duration curve
6. Sediment and nutrients balance

<u>**Calibration/Validation Statistics**</u>

1. Mean and standard deviation of the simulated and measured data
2. Slope, intercept and regression coefficient/coefficient of determination (R^2)
3. Nash-Sutcliffe Efficiency coefficient

Figure 5: Check list for model testing [1]

More recently a research team led by the USDA's Agriculture Research Service (ARS) published guidelines for evaluating the results of model calibrations and validations. They recommend using plotted hydrographs and flow-duration curves comparing observed and predicted data as a first check on the quality of the model results. These plots provide a good visual look at the "goodness of fit". Obvious errors or bias in the model can be spotted.

Three statistical measures are recommended for assessing the quality of modelling work: the Nash-Sutcliffe Efficiency coefficient (NSE), the percent bias (PBIAS), and a relatively new statistic RSR.

[1] "Yes" indicates that both calibration and validation has been done, however, improvement might still be needed.

[2] Information from SWAT User's Manual Version 2000

RSR is defined as the ratio of the Root Mean Square Error index (RMSE) and the standard deviation of the observed sample. Suggested performance ratings are shown in Table 10.

The study recognizes that the correlation coefficient (r) and the coefficient of determination (R^2) which are included in the SWAT User's Manual Version 2002 are widely used to measure the quality of modelled outputs. However, R^2 has not been included in the recommended methods of evaluation. The reason for this, cited in their paper, is that R^2 is "over sensitive to high extreme values" and is "insensitive to additive or proportional differences" between predicted and observed data. It should be noted that NSE is also quite sensitive to extreme values. (Krause, D. P. Boyle, & F. Bäse, 2005).

These recommendations are based upon a survey of the results of watershed studies in the U. S. between 1996 and 2007. Despite this R2 does have value and as it is a widely recognized and understood statistical measure it should be retained as one of the measures for WEBs watershed studies.

Assessing model quality - The evaluation criteria shown in Table 10 are intended to be applied to each step of the calibration and validation process; hydrology, sediment and water quality. These have to be used with some judgement. The particular circumstances around the study of each watershed and the intended use of the model outputs can influence what is considered to be an acceptable result. The paper suggests that the highest standards apply when the consequences are high such as "congressional testimony, development of new laws and regulations, or the support of litigation." Lesser standards might apply for such things as technology assessment where litigation or regulation is not a concern. The standards could be reduced even further in cases of exploratory research.

Applications of the evaluation criteria for WEBs modelling - The end product of the WEBs modelling exercises will likely be to use the data to identify, design and support actions on the part of governments, conservation managers and landowners in selecting and implementing BMPs. This would require a fairly high level of modelling accuracy. The quantifications in Table 10 would provide a useful measure of the model quality.

While some of the current modelling for WEBs I would fall in the "Very Good" range based on NSE, most require additional work to develop additional statistics such as PBIAS and to investigate the seasonal and long-term performance of the model. Overall the modelling to date might be classed as a technological assessment, and in some cases exploratory. In the latter case any modelling exercise with NSE > 0 could be considered for further study if it is felt that there were legitimate opportunities to improve the modelling result. However, overall the results must be more thoroughly evaluated and in some instances improved before the model results can be considered acceptable for use in design, funding decisions and evaluation and/or selection of BMPS.

Table 10: Suggested performance ratings for mode evaluation statistics [1]

Performance Rating	RSR	NSE	PBIAS (%)		
			Streamflow	Sediment	N, P
Very good	0.00 ≤ RSR ≤0.50	0.75 < NSE ≤ 1.0	PBIAS < ± 10	PBIAS < ± 15	PBIAS < ± 25
Good	0.50 < RSR ≤ 0.60	0.65 < NSE ≤ 0.75	± 10 ≤ PBIAS < ± 15	± 15 ≤ PBIAS < ± 30	± 25 ≤ PBIAS < ± 40
Satisfactory	0.60 < RSR ≤ 0.70	0.50 < NSE ≤ 0.65	± 15 ≤ PBIAS < ± 25	± 30 ≤ PBIAS < ± 55	± 40 ≤ PBIAS < ± 70
Unsatisfactory	RSR > 0.70	NSE ≤ 0.50	PBIAS > ± 25	PBIAS > ± 55	PBIAS > ± 70

[1] Information from Model Evaluation Guidelines for Systematic Quantification of Accuracy in Watershed Simulations D. N. Moriasi et al, 2007 Transaction of the American Society of Agricultural and Biological Engineers Vol. 50(3) page 891 Table 4

Model evaluation statistics used in WEBs I

The watershed studies used a variety of measurement statistics which make it difficult to compare results. Evaluation criteria should be standardized to allow for comparison across watersheds.

Many different evaluation methods or efficiency criteria were used in the WEBs modelling studies as shown in Table 11 and a summary of the evaluation statistics (NSE and R2) for flow calibration and validation are given in Table 12. For example the researchers for the South Tobacco Creek hydrologic modelling study calculated the bias as a measure of efficiency in addition to the standard measures such as R^2 and NSE. In another instance the authors of the Bras d'Henri/Beaurivage study used logarithmic transforms to get a better visual look, and also plotted flow duration curves as per the SWAT check list.

In a study of various efficiency criteria including the coefficient of determination and the Nash-Sutcliffe Efficiency Coefficient Krause et al said this

"Overall, it can be stated that none of the efficiency criteria described and tested performed ideally. Each of the criteria has specific pros and cons which have to be taken into account during model calibration and evaluation. The most frequently used Nash-Sutcliffe efficiency and the coefficient of determination are very sensitive to peak flows, at the expense of better performance during low flow conditions."

Modelling beneficial management practices

A total of 17 BMPs were tested in five watersheds with the SWAT and GIBSI models. Table 13 shows the BMPS by watershed. Table 14 shows the information and methods used to evaluate BMPS in each watershed.

From an environmental perspective the BMPs are intended to reduce the adverse impacts of agriculture on the quality of water in the watershed. Most of the BMPs tested indicated a reduction in sediment and nutrient loading. These results may only represent a tendency as some of the models used to produce them are less than optimum. The BMPs should be re-evaluated when improved models are available.

Table 11: Methods used in WEBs I for evaluating watershed modelling results

Evaluation Methods	Black Brook	Bras d'Henri/ Beaurivage	Lower Little Bow River	Salmon River	South Tobacco Cr.	Thomas Brook
Time series plots	✓	✓	✓	✓	✓	✓
Water balance						
Annual Volumes or Mean		✓				
Root Mean Square Error (RMSE)					✓	
Slope/intercept		✓ (plots)				
Standard Deviation						
Coefficient of determination (R^2)	✓	✓	✓	✓	✓	✓
Nash-Sutcliffe Efficiency	✓	✓	✓	✓	✓	✓
Pearson coefficient (r)		✓				
Flow frequency curves		✓				
Bias					✓	

Table 12: Summary of evaluation statistics for flow modelling: Nash-Sutcliffe efficiency (NSE) and coefficient of determination (R^2)

Watershed/location	Statistic	Calibration			Validation		
		Daily	Monthly	Annual	Daily	Monthly	Annual
Black Brook /outlet	R^2		0.91				
Bras d'Henri /outlet	NSE	0.39			0.44		
Beaurivage /outlet	NSE	0.77			0.75		
	R^2	0.78					
Lower Little Bow River (watershed runoff)	NSE		0.72 – 0.67				
	R^2		0.73 – 0.70				
Salmon R. / Hwy 1 Bridge	NSE		0.67			0.71	
Salmon R. / Falkland	NSE		0.46			0.58	
South Tobacco Cr. / Miami	NSE	0.64	0.76	0.83	0.61 – 0.53	0.72 – 0.65	0.79 – 0.72
South Tobacco Cr./ HWY 240	NSE	0.61	0.74	0.81	0.64	0.75	0.84
South Tobacco Cr. / Steppler	NSE				0.21	0.25	0.24
Thomas Brook/outlet	R^2	0.46					

Table 13: Summary of Beneficial Management Practices evaluated in WEBs I

	WEBs BMPs	Salmon River	Lower Little Bow River	South Tobacco Creek/ Steppler	South Nation	Bras d'Henri and Fourchette	Black Brook	Thomas Brook
Riparian	Cattle exclusion fencing (and off-stream watering)	✓	✓		✓			✓
	Off-stream watering without fencing		✓					
	Grazed versus mechanical harvesting			✓				✓
In-field	Manure management		✓			✓		✓
	Zero versus conventional tillage			✓				
	Crop rotation					✓		
	Perennial cover		✓	✓				
	Reduced herbicide use					✓		
Runoff	Diversion terraces and grassed waterways						✓	
	– Storm water diversion (farmyard runoff)							✓
	Holding pond (cattle containment runoff)			✓				
	Small reservoirs			✓				
	Buffer strips		✓			✓	✓	
	Suite of surface runoff control measures					✓		
Drainage	Controlled tile drainage				✓			

WEBs is not designed as a test of BMP effect across differing watershed conditions*

Table 14: Summary of information and methods for evaluating the impact of BMPs on the export of sediment and nutrients from the WEBs I watersheds

Watershed	Source of Data for BMP	Recorded Data at the Watershed Outlet –Sediment, Total N, Total Phosphorus
Black Brook	Field data, model development	Yes
Bras d'Henri/ Beaurivage	Adjustment to model parameters	Yes (plus pesticide (atrazine) and fecal coliform data)
Lower Little Bow River	n/a	Yes
Salmon River	Adjustment to model parameters	No sediment data
South Tobacco Creek	Field data, model development, adjustment to model parameters	Yes
Thomas Brook	Adjustment to model parameters	Yes

Gaps and deficiencies

A summary of the gaps or deficiencies in data, modelling capacity and model calibration are presented in Table 15. Errors in calibrating and validating the models were attributed to the lack of representative precipitation in at least three of the watersheds; Bras d'Henri, Black Brook, and Thomas Brook. Lack of sediment data precluded the calibration of sediment against observed data for the Salmon River Watershed. Sediment was estimated based on flow and adjustment of model parameters. The Lower Little Bow River requires accurate information on the amount of water used for irrigation directly from the Little Bow River as well as the transfer of flows into the watershed from the Lethbridge Northern Irrigation District. Despite good initial calibration results the two-year period of record used to calibrate flow on the Lower Little Bow River Watershed is not sufficient to capture the potential effects of the range of wet and dry years that may be encountered. The lack of information on tile drainage hampered efforts to calibrate summer flows in the Bras d'Henri and Thomas Brook watersheds. Four of the studies reported problems with SWAT's capacity to model flow and water quality during winter and spring melt periods.

The SWAT model was not able to adequately model the effect of structural BMPs such as flow diversion terraces, and small storages requiring the development of independent models. Modelling of natural riparian areas and man-made grass buffers strips also needs improvement.

Table 15: Summary of modelling deficiencies in WEBs I modelling studies by problem (watershed)

<u>Missing or inadequate data</u>

- Meteorological data (Black Brook, Bras d'Henri, Thomas Brook)
- Sediment data (Salmon River)
- Water quality data (Thomas Brook)
- Agricultural (tile) drainage information (Bras d'Henri, Thomas Brook)
- Fertilizer and cropping data (Thomas Brook)
- Short period of record (Lower Little Bow, Thomas Brook)
- Irrigation data (Salmon River, Lower Little Bow)

<u>Lack of modelling capacity</u>

- Modelling capacity for BMPs (Salmon River, South Tobacco Creek, Black Brook)
- Flow diversion terraces (Black Brook)
- Buffer strips, filter strips (Black Brook)
- Modelling small watersheds (Bras d'Henri/Beaurivage, South Tobacco Creek)
- Riparian areas (Thomas Brook)
- Zero till routines, leaching of nutrients during zero-till (South Tobacco Creek, Bras d'Henri/Beaurivage)
- Channel erosion (Thomas Brook)
- Tile drainage (Bras d'Henri/Beaurivage, Thomas Brook)
- Modelling snowmelt runoff (Salmon River, Thomas Brook)
- Modelling of sedimentation and water quality (Black Brook, South Tobacco Creek)

<u>Modelling problems</u>

- Inability to model baseflow hydrology (Thomas Brook)
- Different model evaluation statistics and methods (All)

Discussion and Conclusions

Overall the modelling studies have demonstrated that the watershed models SWAT and GIBSI have good potential to simulate hydrologic and water quality and assess the impacts of BMPS in agricultural watersheds. Figure 6 shows the possible end-use of the watershed models which include using the models to simulate watershed process for a variety of land-use practices and future climatic conditions, and evaluating BMPs for implementation and design of watershed management programs. The model should also be transferrable to other like watersheds.

The current status of watershed modelling and BMP evaluation is shown in Table 16. Despite some very good evaluations (NSE > 0.75) the level of modelling is likely not at the stage required for developing policy and regulations, or making investment decisions. Some additional work is required as has been discussed earlier in this report.

For the most part the deficiencies in data and modelling capacity can be remedied. The paper by the USDA (Moriasi, Arnold, Van Liew, Bingner, Harmel, & Veith, 2007) suggests five reasons why the desired modelling results are not achieved: "1) conditions in the calibration period were significantly different from those in the validation period, 2) the model was inadequately or improperly calibrated, 3) measured data were inaccurate, 4) more detailed inputs are required, and/or 5) the model is unable to adequately represent the watershed processes of interest."

Some of these apply to the WEBs I modelling in particular 1) referring to changing conditions over time, and 4) referring to better data. Only one of the reasons faults the model, and even then the model may be improved by enhancements to the model such as the development of an improved snowmelt routine for colder Canadian climates. Most can be remedied with an expenditure of time and resources as discussed in the following paragraphs.

Data considerations

Data availability - Lack of data has been the most often quoted reason for a less than optimum calibration. Some of this may be remedied over time for those projects with an active monitoring system in place. The watersheds with the longer history such as South Tobacco Creek and Bras d'Henri/Beaurivage have the obvious advantage of a longer period of record which should produce more stable modelling scenarios. An additional expenditure in monitoring may be required.

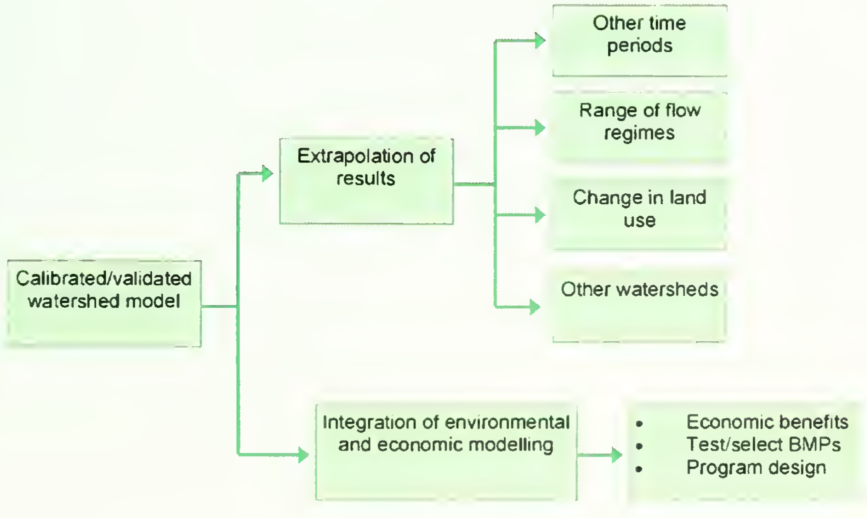

Figure 6: Schematic showing possible future uses of modelling results

Table 16: Status of watershed modelling and BMP evaluations

Watershed	Current status
Black Brook	• A good calibration of hydrology, sediment and nutrients for the period prior to BMPs. • Water quality needs to be evaluated post-BMP. • Effective modules developed to assess impacts of flow diversion terraces and grass buffer waterways. • Additional work is required on the event-based grass buffer model.
Bras d'Henri/ Beaurivage	• Overall the calibration statistics for hydrology were good although the model tended to underestimate spring flows and missed some discrete rainfall events in the Bras d'Henri Watershed. • Improvements are required to tile drainage routines. • Uses a range of graphical and statistical evaluation measures. • Sediment and water quality calibrations need to be improved. • BMPs should be re-run using updated calibration.
Lower Little Bow River	• Preliminary calibrations of flow under assumed irrigation scenarios have shown good results. Sediment and nutrients were not calibrated. • Defining the amount, timing and location of irrigation from the Little Bow River and the Lethbridge Northern Irrigation District is a critical step. • Model needs to be re-calibrated using correct irrigation configuration.
Salmon River	• Model has been calibrated to predict flows and nutrient loading at the outlet with good results. A sensitivity analysis of the impacts of applying inorganic fertilizers and manure was completed. • The results of flow and nutrient calibrations for upstream sites are mixed. Additional work needs to be done to explain the variations. • Sediment loading was modeled on a theoretical basis. • A bacteria model is being developed. Only the hydrology component was tested. Additional work is required to develop the model. • BMPs cannot be fully evaluated until the model has been satisfactorily calibrated for flow, sediment and water quality.
South Tobacco Creek Hydrology	• The flow, sediment load and water quality at the outlet of the watershed have been satisfactorily calibrated and validated. • Modelling results for the upstream sub-watersheds in particular the Steppler Research Watershed need to be improved. • Data from the Steppler Watershed were used to develop information to evaluate the effects of BMPs. • The assessment of BMPs appears to be good at the larger watershed scale but needs improvement at the local or sub-watershed scale.
Thomas Brook	• The model was calibrated for a short period of record (< two years) but not validated. Additional work required with more data. • Water quality calibrations need to be improved. • Need to correct data deficiencies. Not clear how impacts of residential areas on water quality have been handled. • BMP assessment should be considered preliminary and re-run after model has been fully calibrated.

Period of record - Model calibrations based on a short period of record as used in the Thomas Brook or the Lower Little Bow River studies can produce good results. However, with a short period of record it is not possible to cover all expected flow and climate ranges. It is very likely that parameters would have to be adjusted to accommodate future studies. If the monitoring program is on-going then over time the model should begin to produce more reliable results that are usually associated with a longer period of record.

Another option may be to move the study to another watershed with a longer period of record, calibrate the model, and then re-apply the model to the original watershed, validating the model against a known period of record. Then, provided that precipitation data are available, the model can be used to simulate a longer period.

Modelling considerations

Time steps - A review of the literature indicates that the accuracy of modelled results may vary with time step. It is generally accepted that monthly time steps produce better evaluations statistics than do daily flows. The SWAT model documentation suggests that annual flows produce better fits than those with shorter time steps. The South Tobacco Creek results tend to support this with NSE equal to 0.64, 0.76 and 0.83 respectively for daily, monthly and annual flow calibrations for the South Tobacco Creek at Miami. Another study suggests that the optimum time step is between one and three months or a season (Hartmann & Bardossy, 2005). The general consensus is to use monthly flows.

Modelling capacity (adequacy of modelling system) - Overall the SWAT and GIBSI modelling systems were able to provide satisfactory (at times good to very good) simulations of the watershed hydrology and sediment and nutrient transport. Also the models could accommodate the non-structural BMPs quite well. Despite this, additional work needs to be done to improve model performance. This may be done by making enhancement to SWAT or GIBSI, or developing coupled or stand-alone models to answer specific questions, or to analyze a particular scenario.

Some of the areas that require improvements as defined in WEBs I are to develop improved models or routines to simulate:

1) snowmelt,
2) tile drainage,
3) event based rainfall runoff,
4) flow, sediment and water quality over riparian buffer strips, and
5) tools for evaluating structural BMPs such as flow diversion terraces or runoff retention dams associated with feedlots.

Standards for evaluation - It is not possible to consistently evaluate the modelling activities for the WEBs watersheds without some standard against which the results can be measured. The different criteria used in each study also make comparison difficult.

Effect of watershed scale - There was not sufficient time nor information available in preparing this report to do a thorough examination of the influence of scale on the modelling results although there were several recommendations in the individual project reports that suggested that the SWAT model could not be used to model small watersheds. This appears to be borne out by the study results where, for example, the modelling results at the outlet of South Tobacco Creek Watershed were much better than those for the much smaller Steppler Watershed despite the establishment of nine monitoring stations in the Steppler Watershed in 2004. The expectations were that with this data could be used to model the hydrology and water quality of the sub-watershed including the impacts of BMPS.

One possible explanation of the success of the calibration of the larger watershed over that of the smaller watershed is that local variations or errors in input variables such as the amount and timing of precipitation events, the selection of land-use parameters and other variables are smoothed out in the larger watershed. There are many opportunities for compensating errors in the larger watershed. The scale of the HRU may be another source of error. Perhaps a finer resolution of HRU is required at the sub-watershed level matched by an equally fine resolution for the data. There have been some recent studies (Manoj Jha, 2004) (S. Govindaraju, 2006) which suggest that sediment and nutrient modelling results improve as the size of HRU is decreased to a threshold level. A full assessment of the impact of scale on the WEBs I watershed studies was beyond the scope of this report.

Extension of model results -
The transferability of model results should be considered from several points of view: spatial, temporal and situational. Models should be capable of simulating watershed processes for full range of climate variability, modelling a variety of structural and non-structural land management options, scaling up a model from a sub-watershed

to a watershed and simulating flows in unguaged watersheds. These require testing.

Land use changes have been investigated in WEBs I with the evaluation of BMPS; however, not all evaluations can be verified with data. One exception is the Black Brook where changes were made during the validation period to account for the impacts of flow diversion terraces and grass buffer strips implemented during the validation period resulting in a good calibration. Another is South Tobacco Creek where data collected from the Steppler Watershed to evaluate BMPs, and to develop routines to simulate BMPs (for example the impact of small dams), and data to evaluate BMPs.

The performance of the model under climate variability needs to be considered including modelling seasonal variability, and hot/cold/wet/and dry periods. (Hartmann & Bardossy, 2005) (Heathman & Larose). Rousseau et al tested the model on summer flows for the Bras d'Henri and Beaurivage watersheds.

Evaluating BMPs

The evaluation of BMPs is dependent upon the quality of the watershed model to simulate the physical and chemical processes within the watershed, and the capacity to describe how those beneficial management practices can alter those processes. Information to assess BMPs can be derived from field data and experiments, by adjusting the parameters within the model or both. Deficiencies in the modelling capacity can readily be identified by comparing modelled to observed values as was done in a number of these studies such as Black Brook. Others were able to model impacts using the internal capacity of the model. Acceptance of these latter assessments requires a good understanding of the processes in the model and confidence in the modelling capacity to correctly simulate the BMP.

It is important to note that the relationships and the range of adjustment available within a model, SWAT for example, were originally derived from field data so have some credibility. Coefficients developed from field experiments today will be considered as generic values in the future. The utility of existing coefficients and parameters usually come into question when something happens to the physical and chemical characteristics of the watershed which puts it outside of the normal range of experience. This occurs when a new BMP is implemented or when existing BMPs are subjected to a change such as periods of high or low flows. These can be tested by modelling the BMP under a wide range of conditions. Periodic monitoring may be required to verify the BMP performance, or field experiments can be developed to investigate the performance of the BMP.

Study linkages and opportunities for collaboration

There are several opportunities for collaboration. As a start the list of modelling deficiencies identifies a number of common problems that could be addressed collaboratively. Some opportunities are listed below:

- One obvious opportunity is the development of a snowmelt routine suitable for colder climates (Thomas Brook, Black Brook, South Tobacco Creek, and Salmon River).
- The development of tile drainage routine is another area. Routines could be developed that would suit both the SWAT and GIBSI modelling systems (Bras d'Henri, Thomas Brook).
- Further development and extension of integrated modelling. It is noted that there is already some collaboration between modellers in the Bras d'Henri/Beaurivage and Tobacco Creek modelling teams.
- There are opportunities to further develop models to measure the effectiveness of BMPs such as grassed buffers, or measure the effectiveness of natural riparian areas building upon the experience gained during WEBs I.

Conclusions and recommendations

WEBs I was a good start. The status of BMP evaluations and watershed modelling was shown earlier in Table 16. While results varied from project to project all projects showed promise. Some overall conclusions are listed below along with recommendations where appropriate.

1) Many of the WEBs modelling studies have exhibited good to very good results for predicting flows, and acceptable results for sediment and nutrient transport. The applicability of SWAT and GIBSI to model flows and nutrients in the watershed has been clearly demonstrated, however, additional work needs to be done to be able to use the results for program.

- *Models require testing over a range of seasonal and multi-year flow regimes to account for climate variability.*

2) It was difficult to assess the quality of the modelling studies of the watershed to compare studies across watersheds.

- *WEBs should adopt evaluation criteria based upon the work of Moriasi et al, 2007 as shown in Table 10.*

- *The appropriate statistics NSE, PBIAS, and RSR should be developed for the calibration and validation of each watershed.*

3) The results of modelling BMPs at the small watershed level such as the Steppler (research watershed) Watershed were not as good as expected. The evaluation statistics were better for the larger watershed than for the experimental watershed. Researchers have attributed the problem to the model and alternative models have been proposed. Part of the problem may also be attributed to errors in the data.

- *The investigations into the ways to improve the modelling of the Steppler Watershed should include an evaluation of both the model and the data.*

4) A number of deficiencies were identified relating to missing or lack of data, lack of capacity and problems within the selected models.

- *WEBs II activities should include filling in the gaps in WEBs I, and investigating the spatial and temporal application of the model.*

5) The length of record is an important consideration. Good modelling results based upon a short period of record will not or may not stand up in the longer term because they will not be able to account for variability in climate. This refers to the ability of the model to simulate flows during extended wet or dry periods.

- *A program of data collection should be implemented in order to establish a sufficient period of record and thereby establish confidence in the model results for extrapolation latterly in terms of other basins, and linearly in terms of into the future.*

Attention may have to be diverted to other aspects of the WEBs modelling in the interim as you await the collection of a suitable database. Another alternative would be to move the modelling to a watershed with similar characteristics but with a longer period of record.

6) A clear framework for decision making on future projects (i.e. those for WEBs II) is required.

- *Revisit the long term goals of this particular project. The schematic in Figure 6 of this report suggest what some of these long-term goals and objectives might be.*

- *Devise a work plan for achieving the goals and evaluate each project to see where it fits into the longer-term.*

7) There are opportunities for collaboration building upon the experience gained in WEBs I and from outside of WEBs.

- *Invite proposals for collaborative projects that address the deficiencies in current modelling capacity.*

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A Review of the Report on ArcGIS - Based Interface Development for the Integrated Economic - Hydrologic Modelling System

A review of the original document “ArcGIS-Based Interface Development for the Integrated Economic-Hydrologic Modelling System” prepared by Wanhong Yang[1], Jing Yang[1], Yongbo Liu[1], Chunping Ou[1], Peter Boxall[2], Marian Weber[3], Jim Yarotski[4], and Mohammad Khakbazan[4] - March 31, 2008

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Key Points

- The software interface has been developed that facilitates the exchange of information between the hydrologic and economic (on-farm-economics and farm behaviour) models for the South Tobacco Creek Watershed.

- The different scales used by the hydrologic and economic models are an impediment to model integration. This has been overcome through an ArcGIS based routine that has been developed to convert hydrologic data at the scale of the Hydrologic Response Unit (HRU) to the land or farm scales used by the socio-economic models. Conversely the routine will also scale data used or produced by the economic models to the HRUs used by the hydrologic model.

- The databases for each model remain as stand alone databases as each model was developed separately.

- The interface can be used to develop and test Beneficial Management Practice (BMP) scenarios, identified in the Farm Behaviour Model for example, by entering the information required to change management practices in each affected land parcel. The interface will convert the information so that the benefits of the scenario can be evaluated with the hydrologic model.

- The interface is only partially complete as the modules for the economic and farm behavioural modules have not yet been fully integrated into the system.

- If completed as planned the interface will provide a valuable tool for both researchers and conservation managers. The graphical input screens with drop down menus can potentially make this a user friendly interface

Introduction

The WEBs South Tobacco Creek Watershed is one of seven (7) watersheds being studied across Canada as part of the Watershed Evaluation of Beneficial Management Practices (BMPs). The South Tobacco Creek is one of two watersheds selected for research into the integration of economic and environmental modelling of BMPs. The study team has developed a prototype ArcGIS - based software interface that will facilitate the transfer of data between hydrologic models and socio-economic models for the South Tobacco Creek Watershed. The interface was developed by the University of Guelph; the same team led the development of the hydrologic model which is described in a separate report. Economic modelling and farm behavioural modelling is being led by a team from the University of Alberta.

The Problem

Economic and environmental models have different time and spatial scales. Economic models deal with decisions or activities implemented at the farm level on the basis of a year or over a period of years. The farm or the field is the basic spatial unit. Environmental models such as SWAT on the other hand operate on a daily time step and may provide information for a watershed or hydrologic response unit (HRU) in the watershed.

Time scales can be matched fairly easily. The SWAT daily simulations can be aggregated to produce monthly and yearly results. In the case of South Tobacco Creek the SWAT model is used to simulate outflow, sediment loading and nutrient loading from the watershed in daily time steps which can be expressed as annual impacts. These can then be considered by the economic models which characterize the economic impacts of implementing BMPs in terms of annual and multi-year costs and benefits.

Integrating data spatially is more difficult. Economic models characterize farm production at field or farm levels while environmental models are based on physical boundaries such as sub-basins. The challenge is to be able to transfer data from one spatial scale to another. As the study report says "... compromising of both time and spatial scales of the two sets of models is the foundation of model integration." A framework for integrated modelling taken from the original report is shown in Figure 7.

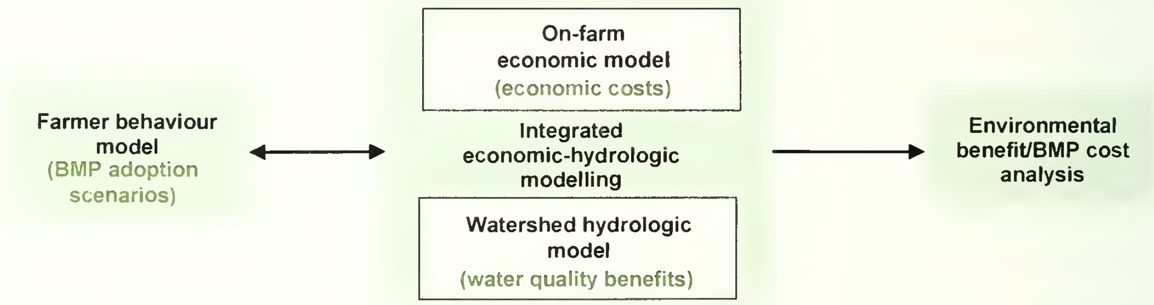

Figure 7: Framework for integrated economic-hydrologic modelling (Yang et al 2007)

The Solution

The study has overcome the spatial scale problem by developing an interface between the economic and environmental models as shown in Figure 8. The interface can transfer data based on the geo-spatial units used in the SWAT model such as the sub-basin, and the geo-spatial units (land) used in the Economic and Farm Behaviour models. Data for land parcels can then be aggregated to the farm level as required.

The transfer takes place between the two smallest units in each model, namely the HRU and the land parcel. As the HRU is usually much larger, encompassing more than one land unit, a method had to be devised to relate the two units. Transfer is facilitated by two look-up tables. The first establishes the relationship between the HRU and the Land Parcel defining the area and ID for the HRU to which the land belongs, and the percentage of the HRU occupied by the land. The second defines the relationship between land and farm and the percentage of the farm that the land parcel will occupy.

Crop management data – SWAT can handle one crop per HRU per year, however, the area encompassed by an HRU will likely have more than one crop. As well crop data are generally more readily available at the field scale. Conversion of data from a field to an HRU can be a cumbersome process particularly for a multi-year period of record. Therefore, a module was developed to facilitate transfer of crop management data from the field to an HRU. The module uses one of two methods depending upon the type of data. For management applications that can be defined on a unit of area such as fertilizer or pesticide applications the application for the HRU is the weighted average of all the land parcels contributing to the HRU. For other data such as crop selection or tillage practice, the interface will use the dominant practice.

Interface Modules

The interface is designed to include eight modules as shown in Figure 9 as taken from the main report. A full prototype has been developed for the Project, Information, Hydrologic Model, and Integrated Modelling modules. The Economic Model module is partially developed. The remaining modules will be developed in WEBs II. A brief description of the function of each module is given in Table 17.

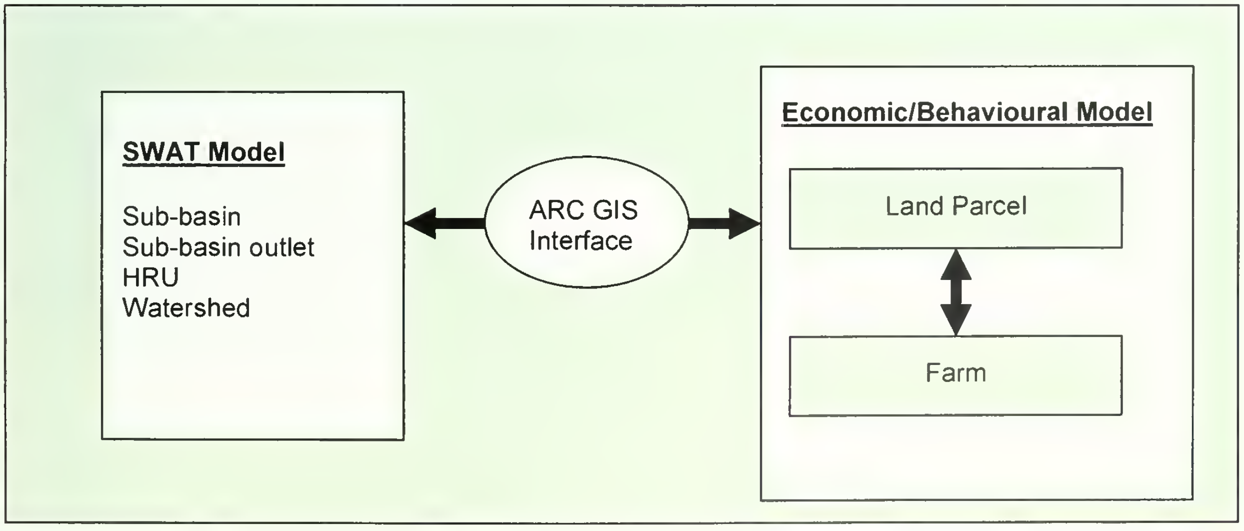

Figure 8: Framework for integrated economic-hydrologic modelling

Figure 9: Modules used in the ArcGis Based Integrated Modelling System

Table 17: Description of module functions/uses

Module	Functions/Uses	Status
Project	Set up new project or manage old project	Prototype
Information	Visualize basic data sets in the study watershed	Prototype
Hydrologic Model	Examine input data, develop BMP scenarios, watershed simulations and data output	Prototype
Economic Model	Economic data and costs, on-farm economic modelling	Partial prototype
Behavioural Model	Query behavioural data, farmer behaviour modelling, display farmer BMP adoption probabilities	To be developed
Integrated Modelling[1]	Integrate economic and hydrologic model to simulate current and future BMP scenarios	Prototype
Tools	Data management and maintenance	To be developed
Help	Information to use the system	To be developed

Developing scenarios - An important function of the Hydrologic Model module is the development and running of BMP scenarios. This function defines the BMP scenarios (management or land use changes) at a watershed scale, and provides for implementing a BMP or a group of BMPs at several sites within the watershed. Scenarios can be defined for either HRUs, or for the land and farm units used by the economic model. The function develops input files to the hydrologic and economic models for the scenario, runs the models with the updated files to determine the environmental and economic impacts, and displays the results in a time series or distributed on a map. Results can be displayed by land, reach or sub-basin. The scenario function allows the user to test and modify BMP scenarios for implementation and determine their economic ad environmental impacts.

Future scenarios can also be tested as demonstrated by the climate change scenario (2007-2018) that was run using data from the ClimGen model. As well existing conservation efforts can be evaluated by creating scenarios where conservation practices can be removed. For example the user can simulate the effect of removing small dams by activating the No Dams control.

Economic and farm behavioural modules - The interface provides a structure for the economic and farm behaviour models. The economic model interface is only partly developed, and the farm behavioural model interface will not be done until WEBs II.

[1] This will be completed in WEBs II when Economic Models will be more readily available.

Assessment of Interface

Overall the prototype interface appears to be a very useful tool. Its modular design allows for the integration problem to be approached from either the environmental or economic perspective with most of the work completed on the environmental modelling. Some work has been done on the economic modelling and a module will be developed for the farm behavioural model. It appears to anticipate the needs of users very well by providing a variety of tools to manage, analyze and display the data and model outputs. Some further testing is likely required. Some specific comments are given below:

1) The report says that the team has successfully used the interface to convert sixteen years of crop management data for input into SWAT. This was thought to have saved considerable time and effort. With the absence of other information it is assumed that the only measure of success used was the demonstrated capacity to convert the data from its original form to one that is compatible with SWAT. This in itself is very good, however, additional measures may be required as discussed in point 2.

2) An earlier review by Fred Martin[1] suggested that a sensitivity test be undertaken to determine whether or not the use of the dominant crop would significantly impact the modelling results and if so, then changes to the module would be needed. This warrants further investigation as the use of the dominant crop is a key component of the data transfer between the two models.

3) At this time, the interface is intended for the sophisticated user, namely researchers; however, there is good potential for it to be used by both modellers and conservation managers in the future. The modular setup, the built-in redundancies such as the ability to show distributed data from different modules, the inclusion of generic scenarios, the use of input screens, and the clarity of documentation all contribute to a user-friendly interface.

Next Steps

1) Integrate on-farm economic models and farm behavioural models into the integrated modelling system.

2) Improve the information system module to visualize more data for the study site;

3) Develop the "Tools" module to facilitate database management such as data updates;

4) Incorporate further development of existing hydrologic, on-farm economic and farm behavioural modelling in the South Tobacco creek watershed and possibly other Manitoba escarpment watersheds;

5) Integrate new models to address the complexity of watershed management and accessibility to users. For example, a fully distributed hydrologic model to examine BMP effects at more detailed spatial scales is proposed.

6) Develop optimization routines modules in the integrated modelling system for prioritizing BMP scenarios in the study watersheds.

[1] E-mail from Fred Martin to Valerie Stuart et al, May 21, 2008

A Review of the Report on Hydrologic and Integrated Modelling for the Bras d'Henri/Beaurivage Watershed

Original document: "Development of the GIBSI integrated modelling framework (economic-hydrologic) and the evaluation of beneficial management practices (BMPs) at the Bras d'Henri and Beaurivage Watersheds, Quebec - Final report presented to Agriculture and Agri-Food Canada and Ducks Unlimited Canada" - Alain N. Rousseau[1], Stéphane Savary[1], Sébastien Tremblay[1], Paul Thomassin[2], Laurie Baker[2], Sébastien Rivest[2], Bruno Larue[3], Pascal Ghazalian[3], Eric van Bochove[4]

Prepared by: Brian T. Abrahamson

February 2009

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Key Points

- The Bras d-Henri is a sub-watershed of the Beaurivage Watershed. The areas are 167 km^2 and 742 km^2 respectively.
- The Chaudière Basin in which these watersheds are located has been studied extensively over the last 15 years resulting in a substantive base of data and modelling experience for use in the current study.
- The study developed the geographic and data inputs, simulated hydrologic and water quality, and evaluated BMPS. Each step is extensively documented.
- The basic spatial unit for the hydrologic model, the Relatively Homogeneous Hydrologic Unit (RHHU), is sized to approximate the size of farms in the region thus facilitating the transfer of data between the hydrologic and economic models.
- The study used the GIBSI modelling system which includes a GIS, a hydrologic model (HYDROTEL), and models for the transport of sediment, nutrients, pesticides and pathogens. GIBSI's graphical interface aids data management and the development of BMP scenarios.
- HYDROTEL satisfactorily modelled outflows from the Beaurivage and Bras d'Henri watersheds although there was a tendency to underestimate spring runoff, and some flow events were missed likely due to lack of representative precipitation data. Also the model was not able to capture the effect of tile drains on summer flows in the Bras d'Henri Watershed.
- Modelling results were thoroughly evaluated using statistical and graphical techniques.
- The trends in predicted values of sediment, nutrients, pesticides and pathogens agreed with trends in observed values although absolute values varied considerably. Logarithmic transforms were used to compare the results. The results were deemed satisfactory for use in evaluation of BMPs.
- Five BMPs were modelled: 1) riparian buffer strips at 1,3, and 5 metres; 2) reducing application of pesticides by 30 % (atrazine); 3) using manure spreading booms with trailing hoses; 4) converting fields from cereals and corn to hay and pasture; and 5) using no-till on corn fields.
- The results of BMP from the agricultural RHHUs were provided to the economic modelling groups at the Université Laval and McGill University.
- The BMPs reduced the frequency of excursions above the water quality standards at the outlets of the Bras d'Henri and Beaurivage watersheds. About 12 % of the excursions in phosphorus were from point source effluent discharged into the stream.

Introduction

The WEBs Bras d'Henri/Beaurivage Watershed is one of seven (7) watersheds being studied across Canada as part of the Watershed Evaluation of Beneficial Management Practices (WEBs). The Bras d'Henri, located in the Chaudière Basin in southern Quebec, is a sub-watershed of the Beaurivage River. The area of the Beaurivage Watershed is 742 km^2. The Bras d-Henri sub-watershed has an area of 167 km^2 and supports one of the highest concentrations of animal production in Quebec. Just over 50 per cent of the Bras d'Henri Watershed is used for crops and pasture compared with approximately 36 percent in the Beaurivage Watershed. The Bras d'Henri/Beaurivage study is only one of two WEBs watershed studies in which integrated hydrological/economic modelling is being investigated.

The GIBSI[1] model is used to predict the quantity and quality of runoff, assess the impact of implementing BMPs, and provide a framework for integrated hydrologic-economic modelling of BMPs in the Bras d'Henri and Beaurivage watersheds.

Agro-economic models for the watershed are being developed separately at the Université Laval and McGill University. The GIBSI system can be coupled to the agro-economic models. The study relies heavily on the model parameters developed from previous studies of the Chaudière Watershed.

Data used or required to calibrate and validate the watershed model

The Bras d'Henri and Beaurivage watersheds are particularly well documented in terms of water quality and related data as they have been the subject of intensive study over the past decade or more. As well considerable literature has been published on watershed modelling on the Beaurivage watershed and in the Chaudière Basin.

The available data are summarized below.

Spatial data – Spatial data such as the watershed delineation, drainage network, locations of monitoring stations, and land use and soil data were all managed by the PHYSITEL GIS system. The watershed was divided into relatively homogeneous hydrologic units (RHHUs) of approximately 105 hectares each using a 20 metre resolution Digital Elevation Model (DEM) and a detailed delineation of the drainage network. The RHHUs are discrete areas of surface runoff that feed into a specific reach of the hydrometric network. The size of the RHHUs approximates the size of farms in the region. The Beaurivage watershed is represented by 675 RHHUs. The Bras d'Henri has 141 RHHUs.

Sizing the RHHUs to approximate the size of farms is a significant part of the integration of the hydrologic and economic models. Because the economic models operate at a farm scale both models will then be acting upon the same spatial scale thus facilitating transfer of information between the two models.

Current land-use information for the study was obtained from a land-use class map generated from Landsat images for the year 2003 coupled to a map obtained from la Financière Agricole du Québec for the year 2007.

Soil data were obtained from soil polygons for the watershed adapted to fit the RHHUs. This was accomplished by superimposing the RHHUs over the soil polygons and determining the physiochemical properties of the soil in the RHHU from the weighted average of the polygons.

Meteorological data - Records were available from seven (7) meteorological stations located around the perimeter of the Beaurivage Watershed. None of the stations were located within the Bras d'Henri watershed.

Hydrometric data - Stream flow data are available near the outlets of the two watersheds beginning in 1972 and, since 1999, at one location within the Bras d'Henri Watershed.

Water quality data - Water quality data has been available from the Bras d'Henri and Beaurivage Watersheds since 1982 near the outlet of the two watersheds, and more recently, 1999, for one station more centrally located within the Bras d'Henri watershed. The data include particulate and dissolved phosphorus, suspended matter, total nitrogen, nitrites and nitrates, nitrogen (NH_4-NO_3), turbidity, fecal coliforms and chlorophyll-a. Water quality data were not continuous.

Additional data were available from an auxiliary station near the outlet of the Beaurivage watershed: water quality since 1988 and streamflow since 1972. Streamflow and water quality stations were operated by the Quebec Department of Sustainable Development, Environment and Parks (MDDEP).

[1] Gestion Intégrée par Bassin-Versant à l'aide d'un Système Informatisé (or computerized integrated watershed management system)

Calibration, validation and evaluation

Modelling was undertaken using the GIBSI (Gestion Intégrée par Bassin-Versant à l'aide d'un Système Informatisé) system to predict daily flow from precipitation and watershed physiographic characteristics, sediment and nutrient (nitrogen, phosphorus) loadings and concentrations, the transport and fate of pesticides and the movement of pathogens (coliforms) from the field to the stream. A schematic of the GIBSI modelling system showing the modelling sequence is shown in Figure 10.

Hydrology - Flows were calibrated and validated near the outlets of Bras d'Henri and the Beaurivage River for the periods shown in Table 18 using the HYDROTEL model, one of the models that forms the GIBSI.

HYDROTEL is a distributed model and can therefore take into account the spatial variability of the physiographic characteristics of the watershed and assigns values to each RHHU provided that there is sufficient resolution of the data to define unique parameter values such as depths of soil layers and other calibration parameters of interest to each RHHU. However, when detailed physiographic information is not available, it is acceptable to provide identical calibration parameter values over a larger scale. In this study the RHHUs for the Bras d'Henri Watershed were clustered for the purposes of modelling the outflow from the Bras d'Henri Watershed and used in the calibration of flows for the Beaurivage Watershed. The study conducted a very extensive evaluation of the modelled outputs using the coefficient of determination (R^2), the Nash-Sutcliffe coefficients ($E_{N\text{-}S}$), and the Pearson correlation coefficient to compare simulated and observed flows. These are shown in Table 19 for various time periods. Several additional steps were taken to verify the performance of the model including comparing modelling results with those of a previous study of the Chaudière Watershed, conducting long term simulations (1979-2004), and evaluating the performance of the model in predicting summer flows (May-Oct) for that same period.

The modelling results were also compared graphically by plotting the cumulative frequency curves and recurrence curves of simulated and recorded flows. This provided a very good method of visually evaluating how the modeled results compared to existing results over a longer term which included a range of weather conditions.

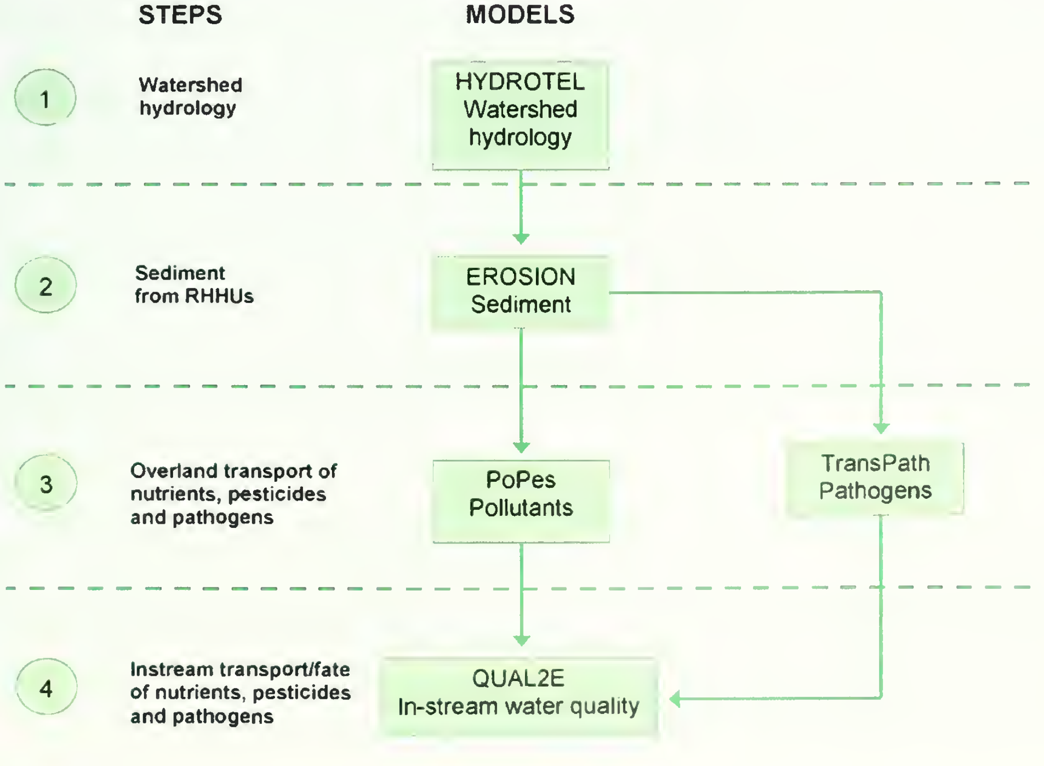

Figure 10: Schematic showing GIBSI models and modelling sequence

The study concluded that the modelled outputs were satisfactory for simulation of BMPs for both watersheds, however, it was recognized that the model tended to under estimate peak flows from spring runoff and discrete rainfall events for both watersheds although the simulations for Beaurivage were better than those for Bras d'Henri. Because flow rates during spring flood periods were consistently underestimated the evaluation of BMPs (Bras d'Henri) was limited to the summer months (May 1 to October 31).

Erosion and water quality - Erosion, nutrient, pesticide and pathogen exports from the agricultural land cover of each RHHUs were estimated using the Erosion, PoPes and TransPath models, and combined in the QUAL2E model to determine the in-stream transport and fate of pollutants. The outputs from the RHHUs were combined to provide an estimate the total loading at the edge of field referred to in the text as overland flow.

The overland flow from the agricultural RHHUs represents the contribution from farm sites, an essential component of the social economic studies which required farm scale data. As there were no edge of field data to verify the overland flow erosion and water quality modelling were evaluated using QUAL2E simulations and observed data near the outlets of the watersheds.

The modelling parameters for the erosion and water quality models were derived from those developed and verified in an earlier study of the Chaudière watershed. The results of modelling of overland exports and in-stream water quality for both watersheds are discussed together in the following paragraphs.

Erosion (sediment) - Estimating erosion is a critical step considering the role sediment transport plays in the movement of pollutants through the watershed. As well erosion is very dependent flow. Errors in flow modelling will be carried through to sediment modelling. Erosion exports from the fields and the in-stream sediment loading and concentrations at the outlets of the Bras d'Henri and Beaurivage watershed were modelled using the Erosion and QUAL2E models.

The report showed the results of sediment modelling at the outlet of Bras d'Henri for 1988 and 1989, and Beaurivage for 1989 and 1996. The results of sediment modelling are shown in Table 19. Results were mixed, with the 1989 simulations producing the best results for both watersheds.

Table 18: Evaluation Statistics for Streamflow Simulations for the Beaurivage and Bras d'Henri Watersheds

	Beaurivage	E_{N-S}	R^2	Bras d'Henri	E_{N-S}	R^2	r	Comments
Calibration	1984-1989	0.79		1995-1999	0.39			
Validation	1989-1994	0.75		1999-2004	0.44			
Combined	1984-1994	0.77	0.78	1995 -2004	0.42	0.48		
Long-term	1979-2004	0.77	0.77	1979-2004	0.47	0.53		Includes BMP 80-99 and period of w.q. data 88-04
Low flows	1979-2004	0.76	0.77	1979-2004	0.52	0.57		May 1 - Oct 31

Table 19: Evaluation of sediment modelling at the outlet of the Beaurivage and Bras d'Henri watersheds

Evaluation Criterion	Beaurivage				Bras d'Henri			
	1989		1996		1988		**1989**	
	Conc.	Load	Conc.	Load	Conc.	Load	Conc.	**Load**
R^2	0.22	0.94	0.84	0.61	0.02	0.00	0.27	**0.61**
Nash-Sutcliffe	-1.05	0.67	0.42	0.27	-0.25	-0.11	0.20	**0.45**
Pearson (r)	0.47	0.97	0.91	0.78	0.13	0.04	0.52	**0.78**
Total frequency[1]	**0.90**	**0.69**	**0.64**	**0.55**				

[1]The probability of being within the 10 % and 90% quantiles.

Predictions of sediment load were better than those for concentration. Note that sediments where modelled also on a long term period (1998-2004) and results were compared to measurements available for the same period. These results are presented with a statistical analysis.

Two other methods were used to estimate sediment loading: a ratio estimator which estimates sediment loading as a function of flow, and a statistical estimator. Both methods are documented in the literature. Estimated, simulated and observed sediment loads at the outlets of the Beaurivage and Bras d'Henri watersheds are compared using a logarithmic scale in Figures 11 and 12.

The study concludes that the results are considered acceptable "because it reflects the orders of magnitude of measured and estimated concentrations and reproduces the overall dynamics for the entire year relatively well."

Nutrients - Phosphorus (total, dissolved and organic P) and nitrogen (NO_2^-+NO_3^-) exports from agricultural lands were simulated using the pollution model (PoPes) and in-stream water quality at the outlets of the watersheds was simulated by the QUAL2E model.

Examples of daily output for modelled phosphorus and nitrogen were available for Bras d'Henri (1988 and 1989), and Beaurivage (1989 and 1990). Evaluation statistics were reported for Bras d'Henri, 1989, and Beaurivage, 1990, the years which produced the best results. The simulations for Bras d'Henri for 1988 and 1989 are shown in Figures 13 and 14. Modelling results for total P, dissolved P, organic P and total N loadings at the outlets of the Beaurivage and Bras d'Henri watersheds for selected years are shown in Table 20. The performance of the model for low flow (May-Oct) for the period 1988-2004) was also investigated.

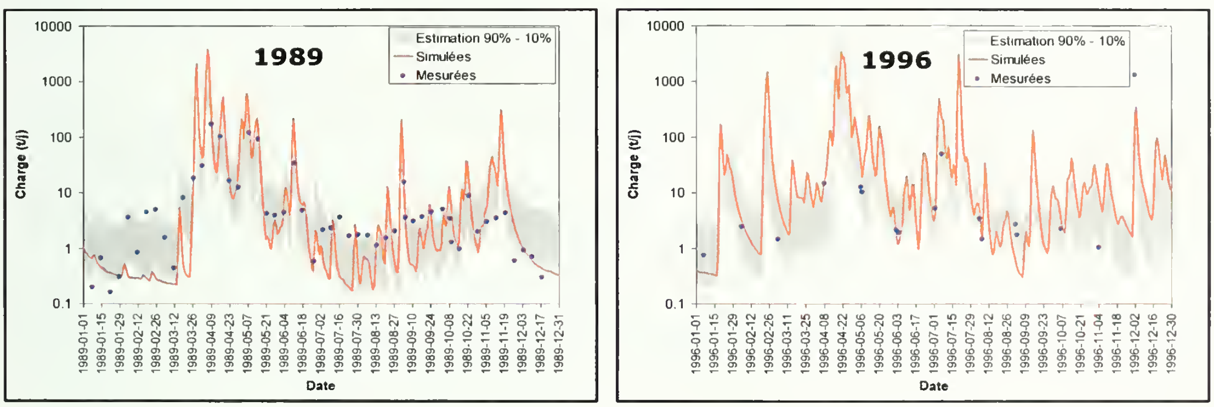

Figure 11: Simulated, estimated[1] and observed daily sediment loads (tonnes/day) at the outlet of the Beaurivage watershed for 1989 and 1996

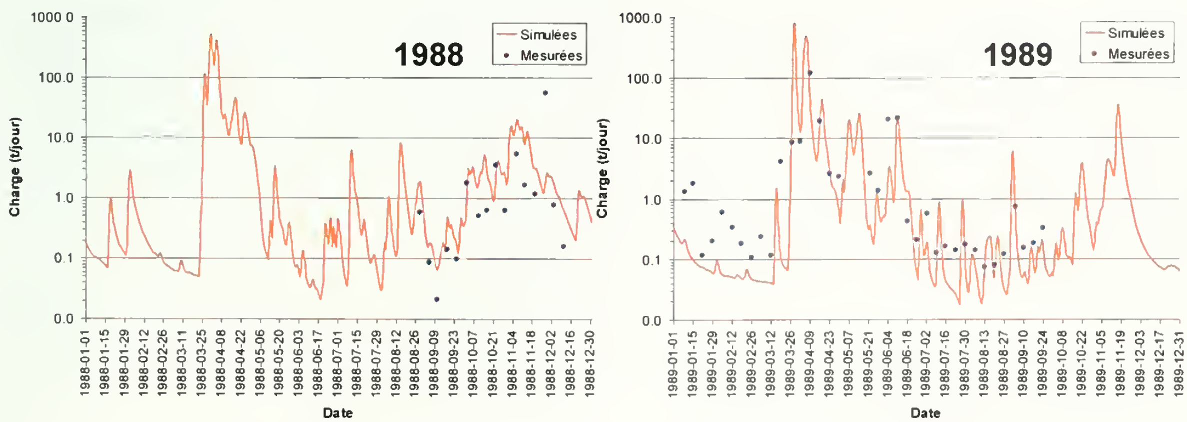

Figure 12: Simulated and observed daily sediment loads (tonnes/day) at the outlet of the Bras d'Henri Watershed for 1988 and 1989

[1] Estimated using analysis of frequency distribution

Table 20: Results of water quality modelling at the outlets of the Beurivage and Bras d'Henri watersheds for selected study periods

Water quality constituent	Beaurivage			Bras d'Henri			Comments
	Period	R^2	Pearson (r)	Period	R^2	Pearson (r)	
Total P	1990	0.58	0.76	1989	0.64	0.80	Loads
Total P	1988-2004	0.34	0.58	1988-2004	0.18	0.43	Loads (May- Oct)
Dissolved P	1990	0.36	0.60	1989	0.74	0.86	Loads
Dissolved P	1988-2004	0.24	0.49	1988-2004	0.16	0.40	Loads (May- Oct)
Organic P	1990	0.83	0.91	1989	-0.14	0.30	Loads
Organic P	1988-2004	0.31	0.55	1988-2004	0.09	0.30	Loads (May-Oct)
NO_3^- NO_2^-	1989	0.77	0.88	1988	0.28	0.53	Loads
NO_3^- NO_2^-	1990	0.89	0.95	1989	0.37	0.51	Loads
NO_3^- NO_2^-	1988-2004	0.58	0.76	1998-2004	0.26	0.51	Loads (May-Oct)

The May-Oct period was selected to minimize the influence of under-estimating flow and sediment during the spring floods. While information was also available for concentrations at each watershed outlet evaluation statistics were generally not available. Simulations of nutrient loadings compared more favourably with observed values than did simulated concentrations.

Figure 13 shows considerable variation between the simulated concentrations and loads of total dissolved phosphorus compared to measured values observed near the outlet of the Bras d'Henri Watershed. The report concludes that in general "the system reflects orders of magnitude, especially as regards its simulation of measured loads."

Figures 15 and 16 show that the nutrient transport model tends to over-estimate the nitrogen (NO_2^- + NO_3^-) concentrations and loads. The study concludes that simulated concentrations and loads display significant variations compared to measured values observed near the outlet of the Bras d'Henri River watershed, and like phosphorus it reflects the orders of magnitude of measured values, especially for summer low-flow periods.

The study suggests that the variations may be due in part to inaccuracies in the outputs of the flow and erosion models. As well the phosphorus and nitrogen loadings are highly dependent upon the amount and date of application of fertilizers which may not be reflected in the model input.

Pesticides - The overland transport and fate of pesticides was modelled using the PoPes model. Pesticide transport is dependent upon the amount of sediment from soil erosion by water and the surface and sub-surface movement of water under various agricultural land-use classes. Uncertainty in the modelled overland flow and sediment made it difficult to define absolute values; however, it was concluded that the "the orders of magnitude of simulated concentrations and loads are consistent with concentrations and loads measured in the vicinity of the outlet of the Beaurivage River watershed."

Pathogens (fecal coliforms) - The transport of fecal coliforms were modelled using the TransPath model which supports direct movement of fecal coliforms into streams from animal excrement. Modelling was conducted at a station near the centre of the Bras d'Henri Watershed for 2003 and 2004 using data collected as part of the WEBs project.

Figure 17 shows that the TransPath model overestimates fecal coliform concentrations during the agricultural activity period; however the report concludes that the "the model's performance is acceptable around high coliform concentrations (1000 CFU/100 ml)".

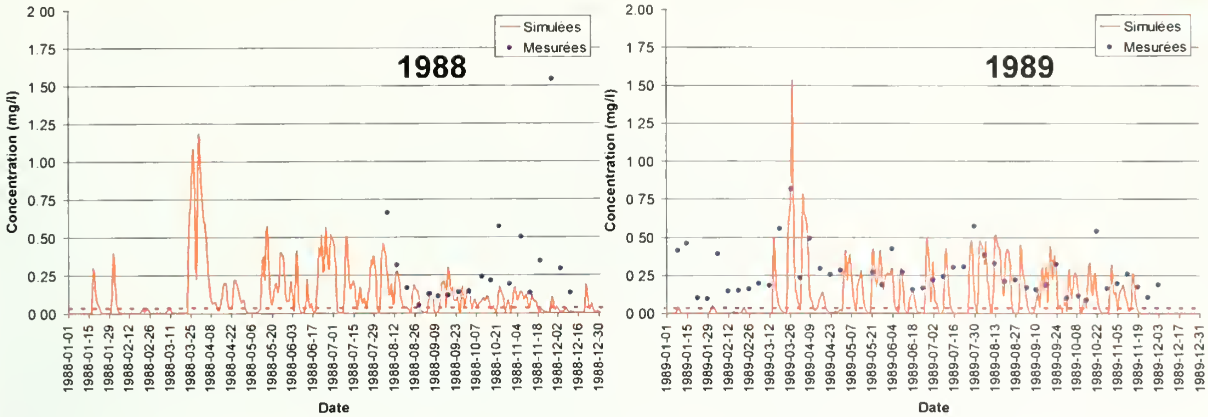

Figure 13: Comparison of simulated daily total phosphorus concentrations and observations[1] (mg/l) near the outlet of the Bras d'Henri Watershed for 1988 and 1989

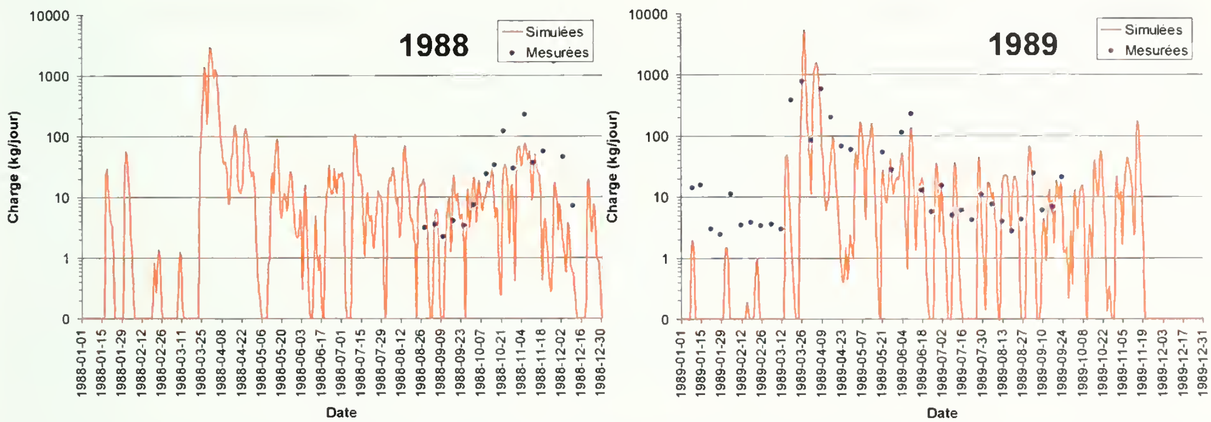

Figure 14: Comparison, on a logarithmic scale, of simulated daily total phosphorus loads and observations (kg/day) near the outlet of the Bras d'Henri Watershed for 1988 and 1989

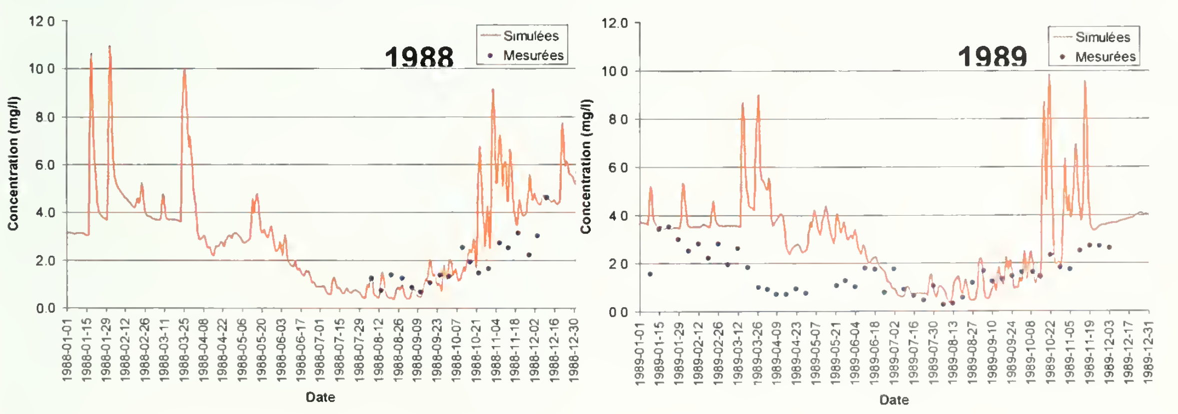

Figure 15: Comparison of simulated daily nitrogen (NO_2^-+NO_3^-) concentrations and observations[1] (mg/l) near the outlet of the Bras d'Henri Watershed for 1988 and 1989

[1] Observed concentrations are instantaneous values which provide a measure of the water quality at a specific point in time. Simulated concentrations are daily averages.

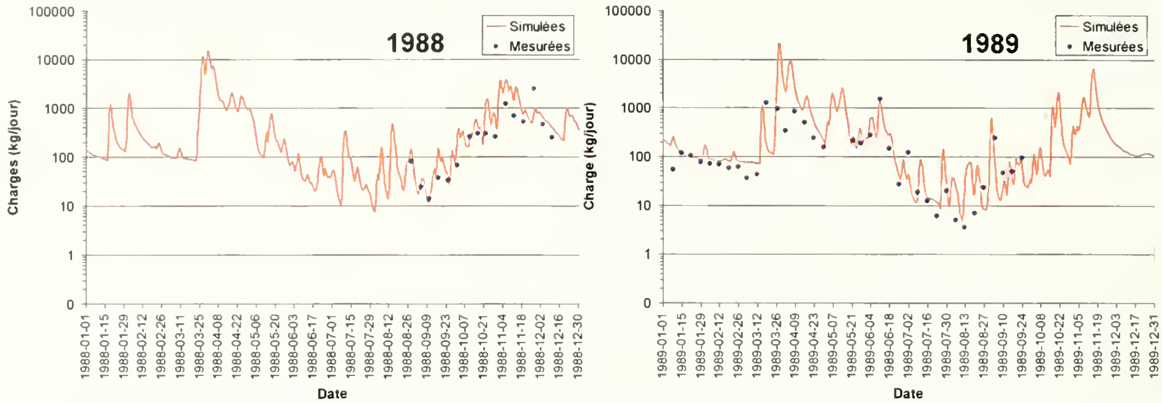

Figure 16: Comparison of simulated daily nitrogen (NO_2^-+NO_3^-) loads and observations (mg/l) near the outlet of the Bras d'Henri Watershed for 1988 and 1989

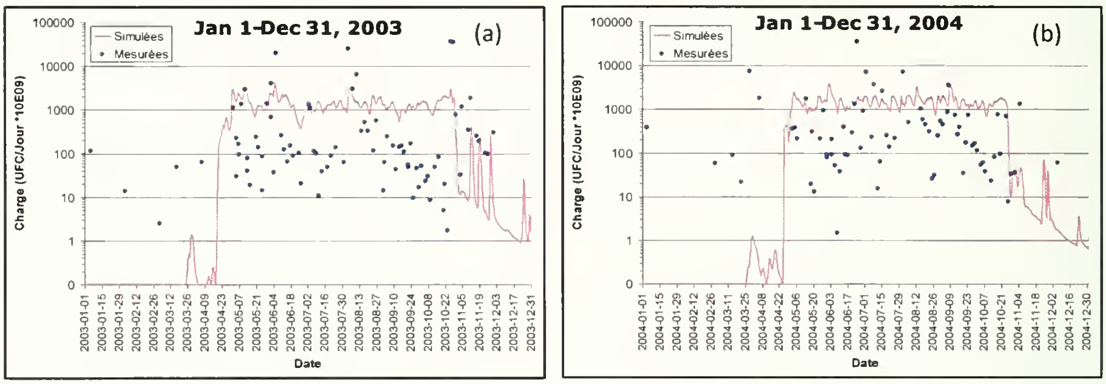

Figure 17: Comparison of simulated daily fecal coliform loads and measured values at station MDDEP 0234009 within the Bras d'Henri Watershed for 2003 (a) and 2004 (b)

BMPs (selection and assessment)

The study evaluated five BMPs; riparian buffer strips of 1, 3, and 5 m; reducing application of pesticides by 30% (atrazine on corn), using manure spreading booms with trailing hoses, converting fields from cereals and corn to hay and pasture and using no-till on corn fields. These can all be investigated by changing the model inputs. The impacts were evaluated for the period 1980 to 1999[1] using the calibrated models to simulate sediment and nutrient loads and concentrations at the outlets of the Bras d'Henri and Beaurivage watersheds as well as the overland loads from the majority of the agricultural RHHUs in the Bras d'Henri watershed. The percent change in loading was obtained by comparing the modelled results with a baseline scenario in which no BMPs were applied. Simulated concentrations at the watershed outlets were compared with water-quality criteria (provincial standards for example) defined for sediments, total phosphorus, nitrogen, atrazine, and fecal coliforms. The results are shown in Tables 21 and 22.

Application of Fertilizer - The study examined the nutrient balance in the Bras d'Henri watershed and determined that the available supply of nutrients though manure application exceeded crop requirements. Applying fertilizer in accordance with crop requirements would reduce overland and in-stream phosphorus loads. The study suggests that "In order to be more consistent with the application practices seen in the field, the current practice of fertilizer application according to requirements should constitute the reference scenario or a BMP".

[1] Stream-access scenarios related to fecal coliforms were modelled for the period 2000-2006.

Table 21: Percentage decrease in watershed exports of sediment, nutrients, and pesticides resulting from implementing BMPs[1]

	Overland flow				Outlet of Bras d'Henri Watershed				Outlet of Beaurivage Watershed			
	Sediment	Total P	Total N	Pesticides	Sediment	Total P	$NO_2^- NO_3^-$	Pesticides	Sediment	Total P	$NO_2^- NO_3^-$	Pesticides
Buffer strips 1 m	37	28	40	32	10	29	58	40	10	29	56	42
Buffer strips 3 m	51	41	52	44	16	41	68	53	13	41	67	56
Buffer strips 5 m	59	48	58	51	19	49	72	62	15	49	71	64
Reducing atrazine by 30 %				30				37				39
Manure spreading with trailing hoses			1				1				1	
Conversion to pasture/hay	65	72	47		26	72	17		16	60	30	
No-till (on corn)	20	19	12		8	18	0		0	9	2	

Table 22: Impact of BMP scenarios on the probabilities of exceeding water quality standards and reductions in total average loads at the outlet of the Beaurivage watershed [2]

	Probability of exceedance and (percentage reduction in in-stream load) (%)			
	Sediment	Total P	$NO_2^- NO_3^-$	Pesticides
Reference	27%	85%	0%	4.6%
Buffer strips 1m	23% (10%)	82% (29%)	0% (56%)	2.2% (42%)
Buffer strips 3m	22% (13%)	80% (41%)	0% (67%)	1.3% (56%)
Buffer strips 5m	21% (15%)	78% (49%)	0% (71%)	0.8% (64%)
Reducing atrazine by 30 %	-	-	-	2.6% (39%)
Manure spreading with trailing hoses	-	-	0% (+1.26%)	-
Conversion to pasture and hay	20% (16%)	74% (60%)	0% (30%)	0% (100%)
No-till	27% (0%)	85% (9%)	0% (0.07%)	4.5% (0.8%)

[1] BMP results showed little impact on coliform transport partly due to the low detection limits.

[2] From Table 5.16 "Development of the GIBSI integrated modelling framework (economic-hydrologic) and the Evaluation of Beneficial Management Practices (BMPs) at the Bras d'Henri and Beaurivage Watersheds, Quebec" – Rousseau et al 2008

Integrated modelling

The impact of BMPs was available for all agricultural RHHUs. Statistical analysis of mean daily load of sediments, phosphorus, nitrogen and pesticides showing the percentage change in edge of field exports from the agricultural RHHUs resulting from the application of BMPs were determined for the study period and transferred into the agro-economic models developed by the teams at Université Laval and McGill University.

Key findings with respect to the hydrologic/environmental modelling

The model results provided an improved understanding of the impact of BMPs on watershed water quality. Some of the key findings are listed below.

- The HYDROTEL model was able to simulate flows at the watershed scale but had some difficulty in reproducing some event based runoff. The model tended to underestimate spring flow. These inaccuracies were carried into the Erosion and PoPes model resulting in further inaccuracies in the output from those models.
- The model was able to evaluate the impacts of BMPs on overland transport of sediments and nutrients however results could not be verified directly due to lack of edge-of-field data. Validations were supported with in-stream loadings and concentrations.
- GIBSI can be successfully combined with specific agro-economic models. In this study data describing the percentage change in edge-of-field exports of sediment, nutrients and pesticides were transferred to the on-farm economic and farm behavioural models.
- Converting annual cropland to pasture and hay had the greatest impact on reducing phosphorus loads at the edge-of-field and at the outlet of the watersheds with 60% reduction from the base case scenario.
- The study indicated that an average of 25% of total phosphorus concentrations at the outlet of the Beaurivage watershed came from point sources such as effluents from publicly-owned waste water treatment plants. These point sources of phosphorus are responsible for an exceedance probability of 12% with respect to the water quality standard for total phosphorus.

Gaps or deficiencies in modelling/environmental

The report contains a very detailed discussion of each component of the study including data input, the GIBSI modelling system, the simulation of flows, sediment and water quality, and the evaluation of BMPs. Several problems were noted that should be addressed.

1) The HYDROTEL model consistently underestimated the spring runoff which limited the application of the calibrated model to the summer months May to October.
2) HYDROTEL also had difficulty simulating summer flows as it could not account for tile drainage. This made it difficult to model both flow and nutrient export which would move more rapidly through the drains.
3) There was no weather station within the Bras d'Henri watershed. This may have resulted in missing some peak flows and the impacts of those peaks.
4) Future work should include field-edge measurements to calibrate flow transport models. Evaluations were done using the QUAL2E model output at the watershed outlets.
5) The impacts of buffer strips were modelled using empirical relationships (abatement coefficients) to estimate reductions in overland and in-stream sediment, phosphorus, nitrogen and pesticide loads. Other physically based models might be combined with GIBSI to produce more realistic results.
6) GIBSI does not take into account the leaching of nutrients released by plant degradation in no-till scenario (in this study it was no-till corn).

Modules and enhancements to models

GIBSI was used as is with only minor modifications. Previous studies of the Chaudière Watershed have aided the selection of watershed parameters, and on-going research at the Institut National de la Recherche Scientifique, Centre Eau-Terre et Environnement has improved the overall modelling capacity. This experience has been applied to the present WEBs study of the Bras d'Henri/Beaurivage watersheds.

Adjusting the size of the RHHUs to approximate the size of farms/fields and the coupling of the TransPath model with the GIBSI system were two important innovations. The farm-size RHHUs facilitated interchange of information between the hydrologic and the integrated modelling groups. The TransPath model, as discussed earlier, allowed the study to look at the effect of pasturing animals in lands adjacent to the streams.

Next Steps

The following priorities are suggested for WEBs II:

1) Implement a fully distributed watershed model on the two micro-watersheds to investigate the impacts of farm practices on surface and groundwater. The CATHY model would be used to investigate the groundwater relationships.

2) Complete development of the proto-type integrated economic-hydrologic modelling system incorporating updated data on the valuation of environmental goods and services.

3) Complete analysis of environmental benefit/on-farm cost within the Bras d'Henri/Beaurivage watersheds.

Notes