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HYDROLOGIC MODELLING OF AN AGRICULTURAL DRAINED MICRO-WATERSHED: PERFORMANCE ANALYSIS OF COUPLED SURFACE WATER/GROUNDWATER MODELS

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ABSTRACT The objective of this study is to quantitatively assess the impact of subsurface drainage and soil properties on the hydrological behaviour of a headwater micro-watershed located in the Bras d'Henri watershed, Quebec (Canada). The studied 2.4-km² micro-watershed is characterized by intensive livestock production supported by forages and annual crops such as corn grain or soybeans. It is one of Agriculture and Agri-Food Canada's WEBs watersheds (Water Evaluation of Beneficial management practices). Hydrometeorological monitoring has shown that soil properties and subsurface drainage could negatively affect the expected behaviour of beneficial management practices at the watershed scale. Therefore there is a need to understand the influence of these properties on hydrology and one way to study this problem is to set up a physically-based hydrological modelling investigation. Specifically, this project focuses on evaluating the ability of two or three coupled hydrological models (surface flow/subsurface flow) to simulate flows at the micro-watershed outlet and water table depth fluctuations while quantifying the surface and subsurface contributions to flows. The models under consideration are: CATHY (Camporese *et al.*, 2010), DRAINMOD (Skaggs, 1978) and PESTDRAIN (Branger *et al.* 2009).

Keywords: Subsurface drainage, Physical modelling, Coupled hydrologic model, Cathy, Drainmod, Pestdrain

1 INTRODUCTION

In recent years, emphasis on environmental issues has helped to heighten the interest in modelling the storage and movement of water in soil. Soil water plays an important role in many agricultural management decisions, including optimizing the application rate and timing of fertilizers, pesticides, and irrigation water. Frequency and duration of soil saturation determine a soil's suitability for a variety of uses such as agricultural use.

Due to the humid climate of the Quebec City region, some of the agricultural fields of the Bras d'Henri micro-watershed have subsurface drainage systems to remove excess water from the soil profile in order to provide suitable growing conditions. Most of the excess water occurs during the spring and fall months. The main purposes of subsurface drainage systems are to remove that excess water from the soil surface, lower the water table for maximum plant growth, and increase workability. When drainage systems are installed in some places of the watershed, they firstly modify the transfer functions like runoff yield and groundwater flow yield and secondarily modify superficial storage and soil humidity (Vandenberg, 1985).

Conceptual and physically-based models that feature some forms of coupling between the governing equations of surface flow and subsurface flow are useful in the study of surface water and groundwater interactions. The main objective of the present study is to extend our understanding of the complex interactions between groundwater and surface water, with a special emphasis on the role of soil properties and drainage systems, by implementing a 3D hydrological model (CATHY) at the Bras d'Henri micro-watershed scale as well as two field-scale models (DRAINMOD and PESTDRAIN) to selected tile-drained fields.

2 REGION OF STUDY

This study is part of a Canadian wide research program called Watershed Evaluation of Beneficial Management Practices (WEBs) (Yang *et al.*, 2007), launched in 2004 and led by Agriculture and Agri-food Canada to measure the environmental and economic impacts of selected agricultural beneficial management practices (BMPs) at the watershed scale. One of the study sites is a headwater watershed, referred to as a micro-watershed, of 2.4 km² embedded in the Bras d'Henri River watershed located in the agro-climatic region of Chaudière-Appalaches, in southern Quebec (Figure 1). This site is characterized by an intensive crop production consisting mainly of forage, corn grain, and soybean.

Located in the Quebec Appalachians, the Bras d'Henri micro-watershed is characterized by a rolling relief ranging from 150 to 170 m above mean sea level. The surficial geologic materials were deposited during the presence of the Champlain Sea and consist of thin (< 10 m) littoral sediments (sand, sandy silt, coarse sand, and gravel) overlying clayey glacial diamictons (Gadd, 1974). These diamictons generally reach a thickness of 1.0 to 1.5 m, but they are not present throughout the micro-watershed. The surficial sediments overlay the regional bedrock that consists of fine-grained schist and mudstones (Slivitzky and St-Julien, 1987). The surficial soils in the micro-watershed are predominantly sandy to coarse loams that are well drained.

Twelve (12) piezometers (PZ-01D, PZ-01S, PZ-02, PZ-03, PZ-04, PZ-05, PZ-06, PZ-07D, PZ-07S, PZ-09, PZ-10, and PZ-11) were installed within the micro-watershed according to land uses, management practices and hydrogeological conditions (Figure 1). The locations of drains in the micro-watershed and selected tile-drained fields are presented in Figure 2.

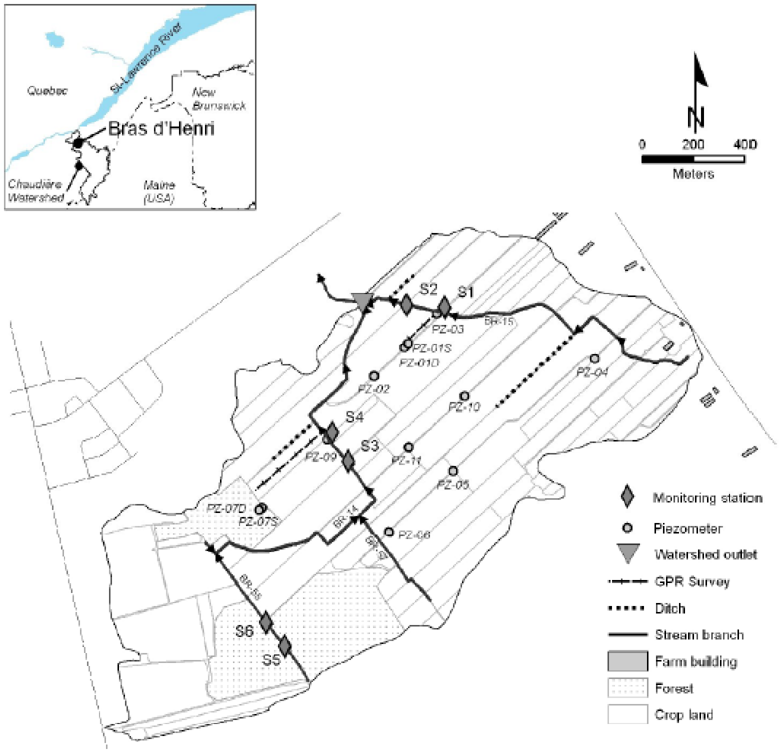

Figure 1 – Location of stream branches and piezometers in the agricultural Bras d'Henri micro-watershed

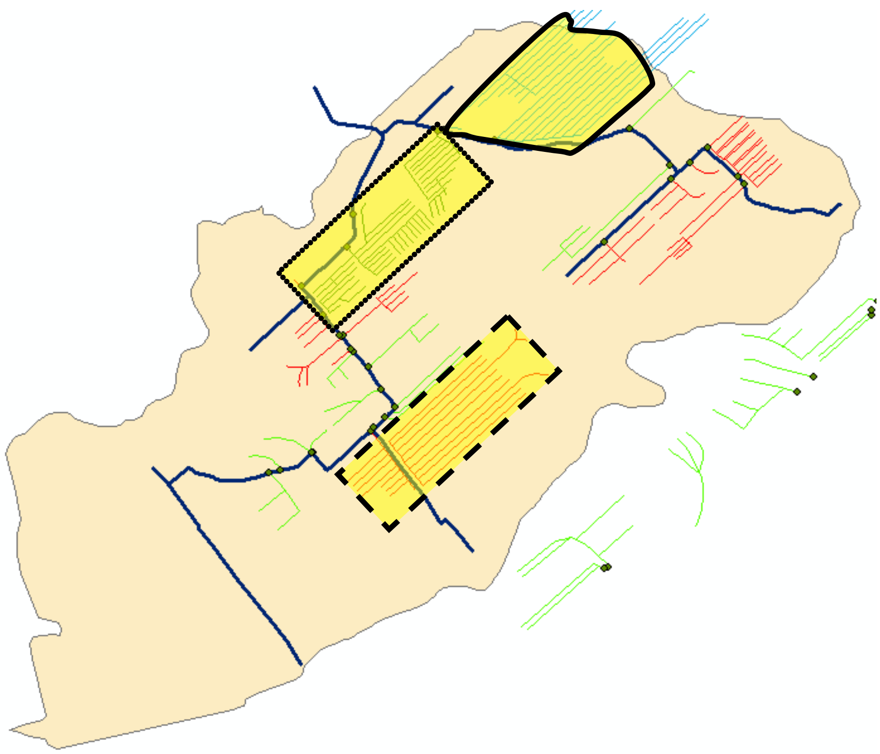

Figure 2 – Drain locations in the micro-watershed and three selected tile-drained fields (coloured in yellow). The blue, red, light green and dark green tile-drains are located, in the NF102, JP_Fortin, Dan_Fortin and NF106 fields, respectively.

3 DESCRIPTION OF THE HYDROLOGICAL MODELS

3.1 CATHY

3.1.1 Model description

The CATHY (CATchment HYdrology) model is a distributed and physically-based model which integrates land surface and subsurface flow processes (Camporese *et al*., 2010). The three-dimensional Richards equation represents variably-saturated flow in porous media and is solved numerically by Galerkin finite elements in space using tetrahedral elements and linear basis functions, and by a weighted finite difference scheme for integration in time. The van Genuchten, Brooks and Corey, or Huyakorn expressions are used to specify the $K_r(\psi)$ and $S_w(\psi)$ nonlinear characteristic relationships.

Topographic data are read from a DEM (digital elevation model) and analyzed with catchment characteristics (structural, terrain analysis, rivulet and channel network parameters) in a pre-processing stage which determines the surface drainage network (direction of flow) and sets up the surface discretization from which the subsurface grid is automatically generated. The distinction between grid cells belonging to a hillslope (flow concentrates in rills or rivulets) and stream channel systems can be made according to three different threshold-based options, based on criteria such as up-stream drainage area, local terrain slope and land surface curvature. DEM cells are sorted and processed in the order of descending elevation: water is then routed from higher cells to lower cells.

In addition to the DEM, aquifer parameters (hydraulic conductivity, porosity and specific storage coefficient), soil water retention characteristic relationships and atmospheric boundary conditions (rainfall and potential evaporation) are the main inputs to the model. The exchange flux or coupling term between the surface and subsurface is computed via a boundary condition switching procedure as the balance between atmospheric supply (rainfall) or demand (evaporation) and the amount of water that can actually infiltrate or exfiltrate the soil. The boundary condition for any given surface node can switch between specified head (Dirichlet condition) and specified flux (Neumann condition) depending on the saturation (or pressure) state of that node.

The CATHY model outputs include surface ponding depths, overland fluxes, subsurface pressure head and moisture content values, and groundwater velocities. Numerous other variables can be derived from these main outputs such as aquifer recharge, catchment saturation, and streamflow. Surface and subsurface contributions to runoff can be computed at any specified surface node within the catchment, and by default also at the catchment outlet, representing the total streamflow at the outlet.

3.1.2 Model implementation

For this study, surface and subsurface discretizations were derived from a 20-m DEM. According to bedrock depths given by piezometers, a flat base at 2.65 m parallel to and below the soil surface was used. A total of 12 layers was used for the vertical discretization, with the thinnest layers (0.15 m) located closest to the surface and drains in order to capture interactions between surface water and groundwater, including rainfall-runoff-infiltration partitioning, and the influence of drains to flow. In the drained fields, drains were located at 1.0 m depth and were represented in the model by the discretization nodes closest to the drains.

No-flow boundary conditions were assigned across the lateral boundaries and base of the catchment, while the surface was subjected to atmospheric forcing, with the input fluxes taken as the difference between daily precipitation and daily potential evapotranspiration. As a first approximation, the nodes representing drains were characterized as internal Dirichlet conditions with assigned pressure heads of zero.

3.2 PESTDRAIN

3.2.1 Model description

PESTDRAIN consists of three modules (Figure 3), which are coupled together using a modelling framework called LIQUID (Viallet *et al.*, 2006):

(i) SIDRA is physically-based and simulates water flow in the saturated zone;
(ii) SIRUP is capacity-based and simulates water flow in the unsaturated zone and the surface runoff;
(iii) SILASOL is transfer function-based and simulates pesticide transport in both saturated and unsaturated zones.

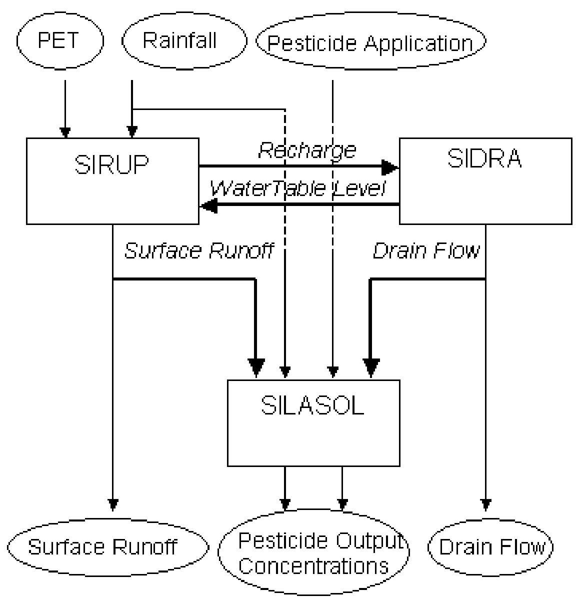

Figure 3 – Structure of the PESTDRAIN model: inputs, outputs and couplings between the three modules SIDRA, SIRUP, and SILASOL. PET is the potential evapotranspiration.

3.2.2 Drainage flow simulation: SIDRA

SIDRA (SImulation of DRAinage) was originally developed with the objective of explaining and predicting fast peak flow rates in France that occur in winter during rainfall events in shallow, silty clay soils (Zimmer *et al.*, 1995). It is based on the classical approach of the Boussinesq equation for the saturated zone. The Boussinesq equation is integrated analytically, assuming vertical equipotential lines (Dupuit-Forchheimer assumption) and a constant elliptic water table shape. It leads to the following equations:

$$\mu A_2(dH/dt) = \Phi(t) - J(H) \quad (1)$$

$$Q(t) = A_1 J(H) + (1 - A_1)\Phi(t) \quad (2)$$

$$J(H) = KH^2/L^2 \quad (3)$$

where $H(t)$ is the water table elevation midway between two parallel drains [L]; Q(t) the drain flow rate [$L.T^{-1}$]; and A_1 and A_2 are constant water table shape factors [-]. Assuming an elliptic water table, their theoretical values are 0.86 and 0.90, respectively. μ is the drainable porosity [-]; $\Phi(t)$ is the recharge rate [$L.T^{-1}$], and $J(H)$ is the Hooghoudt function (Hooghoudt, 1940), corresponding to the steady-state solution of the Boussinesq equation for a drain lying on an impervious substratum. L is the half drain spacing [L]. K is the soil equivalent, saturated, hydraulic conductivity [$L.T^{-1}$]. In the SIDRA module, Equations (1) and (2) are solved using the Euler algorithm. The first right-hand term of Equation (2) represents the water table contribution to drainage flow. The second term is independent from water table rise and corresponds to the contribution of recharge.

3.2.3 Surface runoff simulation : SIRUP

SIRUP (SImulation of RUnoff at the Plot scale) allows computation of surface runoff and recharge to the water table as functions of the rainfall, the potential evapotranspiration (PET), and the water table level (Kao *et al.*, 1998). SIRUP consists of three separate conceptual reservoirs, respectively accounting for (Figure 4):

- Storage of water in the superficial soil layer, and infiltration/runoff distribution depending on the water table depth (Reservoir 1 with 3 parameters);
- Storage of infiltrated water and moisture distribution in deeper soil layers, evapotranspiration, and recharge to water table (Reservoir 2 with 1 parameter);
- Lamination of surface runoff (Reservoir 3 with 1 parameter).

Reservoir 1 has a maximum water level R1 [L] and stores rainfall water. Water flows from reservoir 1 to reservoir 2 according to the emptying equation:

$$\varphi_1(t) = l_1(t)[T(d - H(t)) + M] \quad (4)$$

where φ_1 [$L.T^{-1}$] is the emptying flow, d [L] is the depth of the impervious layer, $l_1(t)$ [L] is the water level in Reservoir 1, and T [$L^{-1}T^{-1}$] and M [T^{-1}] are empirical parameters. Equation (4) accounts very simply for the influence of water table level on soil infiltration: a high water table level implies a reduced infiltration flow. When Reservoir 1 overflows, excess water flows to Reservoir 3 and is changed into surface runoff, according to:

$$\varphi_3(t) = l_3(t)B \quad (7)$$

where $\varphi_3(t)$ [$L.T^{-1}$] is the emptying flow of Reservoir 3, $l_3(t)$ [L] is the water level, and *B* [T^{-1}] is an empirical parameter. Reservoir 2, at last, receives infiltration flow from Reservoir 1 and is emptied by evapotranspiration only. It has a maximum water level *R2* [L]. The overflowing water constitutes the recharge to the water table $\Phi(t)$ (see Equations 1 and 2).

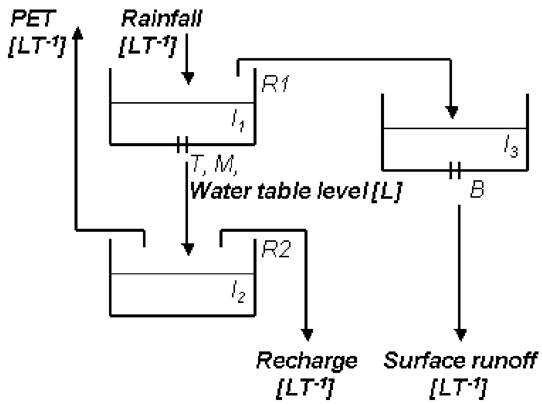

Figure 4 – Structure of the SIRUP module. l_1, l_2 and l_3 are the water levels in the reservoirs; *R1* and *R2* are the sizes of Reservoirs 1 and 2, respectively; *T*, *M*, and *B* are the parameters of the emptying laws of Reservoirs 1 and 3; *PET* is the potential evapotranspiration.

3.2.4 SILASOL (SImuLAtion of SOLute transport)

Solute transport simulation in the PESTDRAIN model uses a simple conceptualization based on transfer functions. The soil is conceptually divided in two compartments, as shown in Figure 5. Compartment 1 represents the soil located far from the drain, corresponding to low velocities and the contribution of the water table to solute transport. Compartment 2 represents the soil located close to the drain, corresponding to high velocities and the contribution of recharge. A characteristic solute transfer time and a contribution to the total drain concentration are attributed to each compartment. For more SILASOL description, see Branger (2007) and Branger *et al.* (2009).

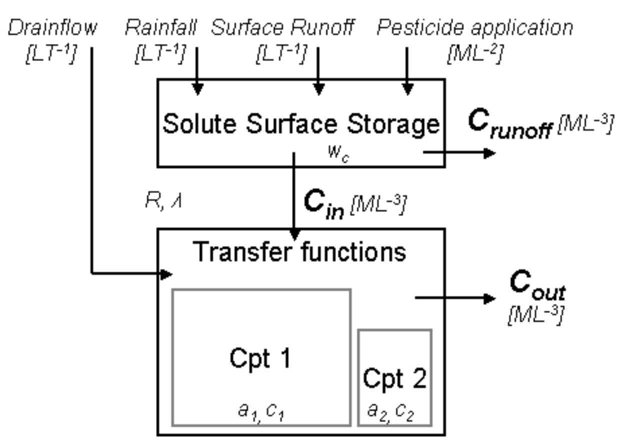

Figure 5 – Structure of the SILASOL module. Compartments Cpt1 and Cpt2 account for slow and fast solute transport to the tile drain, respectively. SILASOL requires five parameters: the pesticide adsorption retardation factor *R*, the pesticide decay coefficient

λ, the solute surface storage water capacity w_c, the compartments transfer function coefficients a_1 and a_2, and the compartments relative contributions c_1 and c_2.

3.3 DRAINMOD

3.3.1 Description

Widely used around the world for its reputation of being easy to use and having good accuracy, DRAINMOD (Skaggs, 1978) is based on water balances conducted both above and below the soil surface. The basic relationship in the model is a water balance for a section of soil of unit surface area, located midway between the drains and extending from the impermeable layer to the surface. The water balance for a time increment of Δt can be written as

$$\Delta V_a = D + ET + DS - F \quad (8)$$

where: ΔV_a is change in air volume (cm); D is lateral drainage from or subirrigation into the soil (cm), ET is evapotranspiration (cm); DS is deep seepage (cm); and F is infiltration entering the section in Δt (cm).

3.3.2 Subsurface Drainage Theory in DRAINMOD

DRAINMOD uses Hooghoudt's equation or Kirkham's equation to calculate drainage leaving a field, based on the shape of the water table. Hooghoudt assumed radial flow in the region near the drains and used the Dupuit-Forchheimer assumptions in the region away from the drains. The Dupuit-Forchheimer assumptions are: (i) all flow to the shallow sink is horizontal and (ii) the velocity along the streamlines is proportional to the slope of water table but independent of depth. Hooghoudt's steady-state solution to parallel tile systems was derived using the method of images and Darcy's law, where flow along any vertical cross-section of a drain (Figure 6), given a water table of elliptical shape and constant infiltration, is:

$$q = (8K_e d_e m + 4K_e m^2)/S^2 \quad (9)$$

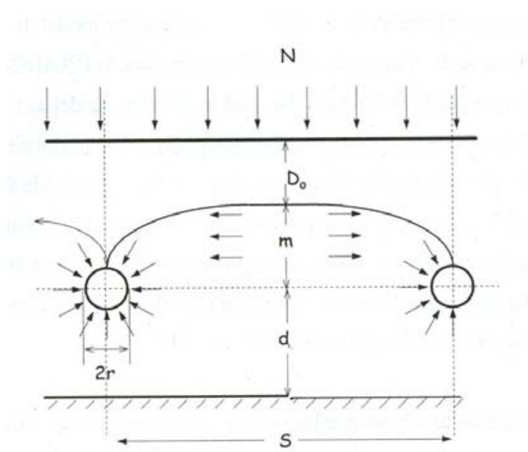

Figure 6 – Parallel tile flow to drains

where q is the flux ($cm.h^{-1}$), d_e is the equivalent depth of the impermeable layer below the drain (cm), m is the midpoint water table height above the drain (cm), K_e is the effective lateral hydraulic conductivity ($cm.h^{-1}$), and S is the distance between drains (cm), D_o is the depth of water table, r is the effective radius of the drain tube, and N is the rainfall rate or accretion.

There are several assumptions of Hooghoudt's equation that have to be considered for effective modeling. Assumptions include parallel and equally spaced tiles, homogeneous soil, constant accretion, vertical water flow from the ground surface to water table, constant depth to the subsurface impermeable layer, and no water pressure in drains. Many of these assumptions require conditions that are practically impossible in a natural setting and others do not apply to all subsurface drainage designs.

3.3.3 Input Parameters

The input parameters of DRAINMOD are mainly grouped into weather (precipitation, temperature, PET, *etc.*), soil hydraulic properties (water retention curve, saturated hydraulic conductivity, drainable porosity, *etc.*), drainage system (drain spacing, depth, *etc.*), crop and trafficability parameters. Precipitation and temperature are required to define the upper boundary of the tile landscape. DRAINMOD requires hourly precipitation and daily maximum and minimum temperatures as weather input for the simulation processes. For hydrological simulations, DRAINMOD also requires the relationships between water table depths *versus* volume drained, water table depth *versus* upward flux, and Green-Ampt parameters.

4 FRAMEWORK

The overall framework of this study is based on the accomplishment of the following tasks:

(i) Preliminary calibration of CATHY at the watershed scale;
(ii) Application of DRAINMOD and PESTDRAIN to selected tile-drained fields;
(iii) Implementation of tile-drain modelling in CATHY, application of the adapted model to the aforementioned fields and comparison of the resulting performance with those obtained with the field-scale models;
(iv) Implementation of a pesticide transport and fate model in CATHY, application of the adapted model to the aforementioned fields and comparison of the resulting performance with those obtained with the field-scale models;
(v) Using a fully adapted CATHY model, simulation of the impact of various pesticide management practices and tile drains on pesticide losses at the watershed scale and;
(vi) Examination of the impact of soil properties on the performance of pesticide BMPs.

5 WORK PROGRESS

At this point, preliminary simulations using CATHY and PESTDRAIN have been performed and in summer 2010 DRAINMOD will be implemented on the studied fields. This study will be completed over the course of the next two years.

REFERENCES

Branger F., Tournebize J., Carluer N., Kao C., Braud I., Vauclin M., 2009. A simplified modelling approach for pesticide transport in a tile-drained field: The PESTDRAIN model. *Agricultural Water Management*, 96: 415-428.

Branger F., 2007. *Utilisation d'une plate-forme de modélisation environnementale pour représenter le rôle d'aménagements hydro-agricoles sur les flux d'eau et de pesticides. Application au bassin versant de la Fontaine du Theil* (*Ile-et-Vilaine*). PhD thesis, Université Joseph Fourier, Grenoble.

Camporese, M., Paniconi, C., Putti, M., Orlandini, S., 2010. Surface-subsurface flow modelling with path-based runoff routing, boundary condition-based coupling, and assimilation of multisource observation data. *Water Resour. Res.*, 46, W02512, doi: 10.1029/2008WR007536.

Gadd, N.R., 1974. Surficial geology – Saint-Sylvestre. Map 1407A, scale 1:50000, Ottawa, Geological Survey of Canada.

Hooghoudt, S., 1940. Hooghoudt's theory of drainage. Tech. Rep., Institut voor Cultuurtechnik en Waterhuishouding, The Netherlands (in Dutch).

Kao, C., Nédélec, Y., Zimmer, D., 1998. Surface runoff mechanisms and modelling in subsurface drained fields. In: Brown, L. (Ed), 7th Annual Drainage Symposium "Drainage in the 21st century: Food Production and Environment", ASAE, Orlando, USA, Vol. 7, pp. 258-266.

Slivitzky, A., St-Julien, P., 1987. Compilation géologique de la région de l'Estrie-Beauce (MM 85-04). Québec : Ministère de l'Énergie et des Ressources.

Skaggs R.W., 1978. A water management model for shallow water table soils. Technical report No. 134 of the Water Resources Research Institute of the University of North Carolina, NC State University, Raleigh, NC, USA.

Vandenberg, A., 1985. Modèle physique d'infiltration verticale, d'écoulement des drains et de ruissellement de surface. Rapport n° 25 de l'Institut national de recherches en hydrologie, Ottawa, Canada, 60 p.

Viallet, P., Debionne, S., Braud, I., Dehotin, J. Haverkamp, R., Saâdi, Z., Anquetin, S., Branger, F., Varado, N., 2006. Towards multi-scale integrated hydrological model using the LIQUID framework. In: Liong, S., Phoon, K., Babovic, V. (Eds), 7th Hydroinformatics Int. Conf., Nice, France, Vol. 1, pp 542-549.

Yang, W., Rousseau, A.N., Boxall, P., 2007. An integrated economic-hydrologic modeling framework for the water shed evaluation of beneficial management practises. *Journal of Soil and Water Conservation*, 62: 423-432.

Zimmer, D., Lorre, E., Lesaffre, B., 1995. Parameter sensitivity and field evaluation of SIDRA model. *Irrig. Drain. Syst.* 9, 279-296.