INTEGRATION OF A TOPOGRAPHIC INDEX IN THE HYDROLOGY COMPONENT OF THE INDICATOR OF RISK OF WATER CONTAMINATION BY PHOSPHORUS

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Integration of a Topographic Index in the Hydrology Component of the Indicator of Risk of Water Contamination by Phosphorus

Report to

Agriculture and Agri-Food Canada (AAFC)

Indicators of Risk of Water Contamination (IROWC)
National Agro-environmental Health Analysis and reporting Program
(NAHARP)

Prepared by :

Alain N. Rousseau Ph.D., ing.
Renaud Quilbé D.Sc.
Benoît Lacasse M.Sc.
Jean-Pierre Villeneuve D.Sc.

Centre Eau Terre et Environnement
Institut National de la Recherche Scientifique (INRS-ETE)
2800, rue Einstein, Case postale 7 500, SAINTE-FOY (Québec), G1V 4C7

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1 INTRODUCTION

To assess the risk or vulnerability of water contamination and identify critical parameters and management practices, Agriculture and Agri-Food Canada (AAFC) initiated, under the 1993 Agri-Environmental Indicator Project, the development of two Agri-Environmental Water Quality Indicators (AEWQIs) related to the potential loss of soil phosphorus (P) and nitrogen (N). In 2001, under the National Agri-Environmental Health Analysis and Reporting Program (NAHARP), work was continued on the N and P Indicators of Risk of Water Contamination (IROWC) and development of a pesticides indicator and a pathogens indicator was undertaken. According to AAFC, the applications of IROWCs and their ensuing relations to economic and environmental models will improve and facilitate the decision making process needed to assess environmental policies in agriculture before they are put in place (Cessna and Junkins, 2003).

One of the databases used to derive IROWCs is the Census of Agriculture which covers all agricultural regions of Canada. Agricultural production system characteristics such as cropland information, livestock numbers, soil properties, weather data, N and P fertilization practices are some of the data included in the Census. The other key database is the Canadian Soil Land Information System (CanSIS). This geographic database contains attributes of all the distinct Soil Landscapes of Canada (SLC), that is, specific soil types and their corresponding characteristics (*e.g.*, landform, slope, water table, permafrost, lakes). In the CanSIS database, SLCs are mapped using polygons, where a polygon is made up of the soil and land attributes of either: (i) one soil landscape with or without inclusions (that is, nonsoil features such as outcrops), (ii) two soil landscapes (the dominant and subdominant soil landscapes), or (iii) two soil landscapes and inclusions (Agriculture Canada, 1992).

IROWCs may be calculated at the soil landscapes polygon level by linking, for example, the CanSIS database with the Census database. After either scaling up or down, these indicators may be aggregated at a regional or watershed scale. Values of IROWCs can be obtained from a weighted sum of intermediate values computed from specific algorithms or models related to soil chemical balance, water balance, potential soil loss, soil water flows, *etc.* Currently, some of the algorithms or models are firmly set while others are not. However, as reported at the 2004 IROWCs Hydrology Technical Workshop (Sainte-Foy, Quebec, February 18 and 19), the possibility of a common hydrology component for the four IROWCs should be investigated. Towards this, the Sainte-Foy Soils and Crops Research and Development Centre of AAFC mandated us to contribute to the development of the *Hydrology Component* of IROWC within the context of *IROWC_P*.

1.1 IMPORTANCE OF THE HYDROLOGY COMPONENT

Transport of pollutants from cropland to surface waters depends on: (i) quantity and availability of soil agricultural chemicals, (ii) cropping practices and (iii) rainfall-runoff processes. For *P*, studies have shown that runoff from soils with high degrees of *P* saturation can contribute up to 40 % of the total river load, while another 40 % may come from soils with moderate degrees of *P* saturation but with high degrees of hydrological connectivity (*i.e.*, proximity) to the river network (Schoumans and Breeuwsma, 1997; Sharpley *et al.*, 1999). Several studies have also shown that runoff from a relatively small portion of a watershed (*e.g.*, 10 % of the area), that located along the drainage/river network, may account for all of the dissolved *P* load into a river (Gburek *et al.*, 2000).

These findings show why hydrological processes need to be accounted for in the development of IROWCs. However, the relationship between rainfall and runoff is complex and influenced by many parameters such as geology, topography, soil characteristics and land use. Thus, hydrological processes governing runoff production have to be distinguished depending on these characteristics. The three hydrological processes governing runoff are: precipitation/infiltration excess runoff (also referred to as Hortonian runoff), saturation excess runoff, and exfiltration runoff (see Appendix A).

1.2 ACCOUNTING FOR HYDROLOGICAL PROCESSES

Runoff processes at the agricultural landscape level may be characterized in different ways by means of state variables, provided either by direct measurement, mathematical simulation using deterministic hydrologic models, or representative indicators.

Direct measurement of water and pollutant balances provides a means of identifying the runoff processes responsible for water contamination at various scales, that is, from the point scale through the plot and hillslope scales (Quinn, 2002). However, findings at these scales are difficult to scale up at the watershed level because of the increasing spatial and temporal complexities of the runoff processes and interactions between landscape, soil, and human activities.

Deterministic models are useful tools to simulate complex and multi-factorial processes on the basis of current scientific knowledge. In the case of environmental risk assessment, some integrated models, such as SWAT (Neitsch *et al.*, 2000) or GIBSI (Mailhot *et al.*, 1997; Rousseau *et al.*, 2000, 2002; Villeneuve *et al.*, 1998), provide a means of evaluating the effects of agricultural management scenarios on water quantity and quality at the watershed scale, for instance. However, such models require extensive input data (*i.e.*, variables and parameters related to soils characteristics, topography, river network, land use, cropping practices, and meteorological variables, *etc.*) that make their use complex.

As an alternative, indicators represent a compromise when compared to data derived from deterministic models. The purpose of indicators is to simplify a complex system so as to make the reality accessible to users in the form of diagnostic or decision support tools/indices (Girardin *et al.*, 1999). Indicators must be easily quantifiable and quickly reveal changes of states. Values taken by an indicator are not usable in an absolute sense, but are of interest with respect to a spatial or temporal frame of reference.

1.3 THE PROPOSED APPROACH: A TOPOGRAPHIC INDEX

For areas with gentle slope and shallow soils on an impermeable rock or impervious soil layer, topography plays a key role in surface runoff production, especially under temperate and humid climate conditions where saturation excess runoff dominates (see Appendix A). For these areas, and under these specific conditions, Beven (2001) reports that the surface runoff process can be predicted with an index of hydrological similarity based on topographic considerations [ex : the Kirkby index, base of the TOPMODEL hydrological model of Beven *et al.* (1995)].

Following this concept, all topographic units or spatial elements of a watershed with an identical index value develop, in principle, the same conditions for saturation, surface and subsurface flow/runoff. In the context of a soil rich in nutrients, pesticides or pathogens, and suitable to the production of saturation excess runoff, the knowledge of topographic index values can be used to illustrate the spatial distribution of watershed areas with a risk of pollutant loss from soil to surface waters, that is the "hydrologically" connected areas. For *N* and *P*, Quinn (2002) refers to the terms critical source areas (CSAs) and variable source areas (VSAs) to describe water contamination by surface source areas and subsurface source areas, respectively. VSAs are generally topographically controlled while CSAs are controlled through management practices.

The goal of this study is to assess the feasibility of integrating a topographic index (*TI*) of hydrological similarity in the *Hydrology Component* of *IROWC_P*. Specifically, the scope of this report is to present:

(i) the rationale behind the use of *TI*; that is definition, conditions of application and determination;

(ii) the availability of data and algorithms required to apply and determine *TI* values at the national level; and

(iii) the potential integration of *TI* in the *Hydrology Component* of IROWC.

Note that an initial assessment of the feasibility of integrating *TI* in the aforementioned *Hydrology Component* was presented at the 2004 IROWCs Hydrology Technical Workshop (see Appendix C).

2 THE TOPOGRAPHIC INDEX (TI)

Hydrological processes are dynamically and heterogeneously distributed in space and time. Furthermore, interactions between landscape, soil and rainstorm dynamics make the runoff phenomenon difficult to predict and model (Beven, 2001). However, the topographic control of surface and subsurface flows may be suitable to a macroscale conceptualization of the rainfall-runoff process (Beven, 2001). For the case of a shallow soil relative to a hillslope scale, this gravitational pattern can lead to a water table that is nearly parallel to the topography over much of the hillslope length. This is particularly true if there is a constant recharge rate over the hillslope and if the surface slope is equal to the local downslope hydraulic gradient. Under these conditions, water is expected to flow downhill from steep to shallow slope, and into areas of slope convergence.

In any watershed, there may be many areas that behave in a "hydrologically" similar fashion, with similar water balance and runoff generation characteristics, whether by surface or subsurface flow. If it were possible to classify areas or points within a watershed in terms of their hydrological similarity, then a hydrological model could be developed based on hydrogeomorphological aspects of runoff formation, without the requirement of considering all individual areas independently (Beven, 2001). The TOPMODEL of Beven *et al.* (1995) is based on this premise; that is the distributed predictions of watershed responses are made based on a simple theory of hydrological similarity of points within the watershed.

Although this report refers to TOPMODEL (Beven *et al.*, 1995), it is not the intent here to further elaborate on this hydrological model since the primary focus is on the *TI* concept. Nonetheless, when the report introduces elements of discussion pertaining to TOPMODEL, it does so to enrich the presentation without loss of continuity and as a means of illustrating how the *TI* concept has been used in a hydrological modeling context.

2.1 HYDROLOGICAL SIMILARITY: THE TI CONCEPT

The hydrologic similarity concept is based on two assumptions:

(i) the dynamics of the saturated zone may be viewed as successive steady-states of the saturated zone on an area a_i draining to a point i on a hillslope; and

(ii) the hydraulic gradient of the saturated zone can be approximated by the local surface topographic slope measured with respect to plan angle $\tan(\beta)$.

In terms of hydrological modeling, these assumptions lead to a simple relationship between watershed storage (or storage deficit below saturation) in which the main factor is the Kirkby topographic index (Kirkby 1975; Beven 2001) also referred to as *TI*:

$$TI_i = \ln\left(\frac{a_i}{\tan(\beta_i)}\right) \tag{2.1}$$

TI_i represents the propensity of a point i in a watershed to develop saturated conditions and, hence, contribute to saturation excess runoff. High values will be caused by either long slope or upslope contour convergence and low slope angles, and the corresponding areas will tend to saturate first. Thus, these points delineate potential surface or subsurface contributing areas to watershed runoff (*i.e.*, VSAs).

Figures 2.2 and 2.3 depict the spatial and statistical distributions of *TI* values on a studied watershed, where, without loss of continuity, the index i was dropped. As pointed out by D'Odorico and Rigon (2003), it is possible to estimate the probability distribution of *TI* and for any value of a quantile, Q, to map the corresponding VSAs having a *TI* value of $v(Q)$.

$$P\left[TI \geq v(Q)\right] = Q \tag{2.2}$$

From a hydrogeomorphological point of view, this mapping allows for the identification of the "hydrologically" connected parts of the watershed given a fixed value of the quantile.

As mentioned earlier, the *TI* approach was developed into a complete rainfall-runoff model, TOPMODEL (Beven and Kirkby, 1979; Beven *et al.*, 1995), and generalized to allow for differences in soil characteristics within a watershed. Within this context, the use of the Kirby index is based on a third assumption:

(iii) the distribution of the downslope transmissivity with depth can be represented by an exponential function of storage deficit or depth to the water table:

$$T = T_0 e^{-D/m} \tag{2.3}$$

Where T_0 is the horizontal transmissivity when the soil is saturated (expressed in $[L^2T^{-1}]$), and D is a local storage deficit below saturation expressed as a water depth [L] and m is a model parameter which control the rate of decline of transmissivity in soil profile (expressed in [L]).

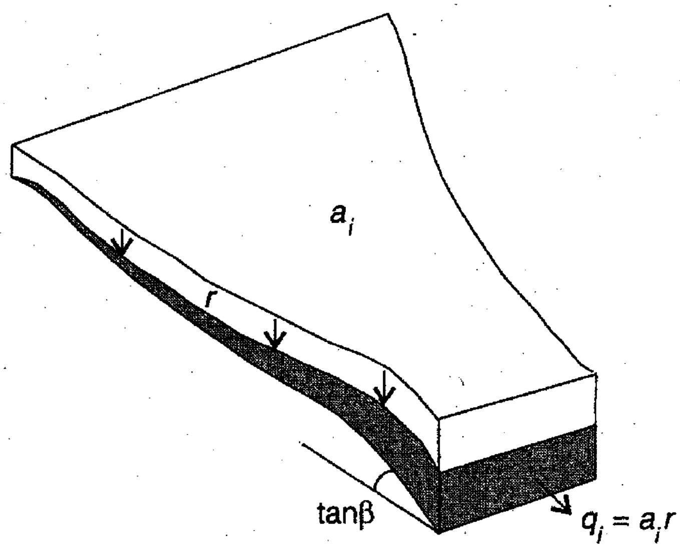

Figure 2.1 Illustration of the upslope area per unit contour length draining through a point i, a_i [L], within a watershed. Where r is the recharge rate [LT^{-1}] over the upslope and q_i is the subsurface flow per unit contour length [L^2T^{-1}] (Beven, 2001).

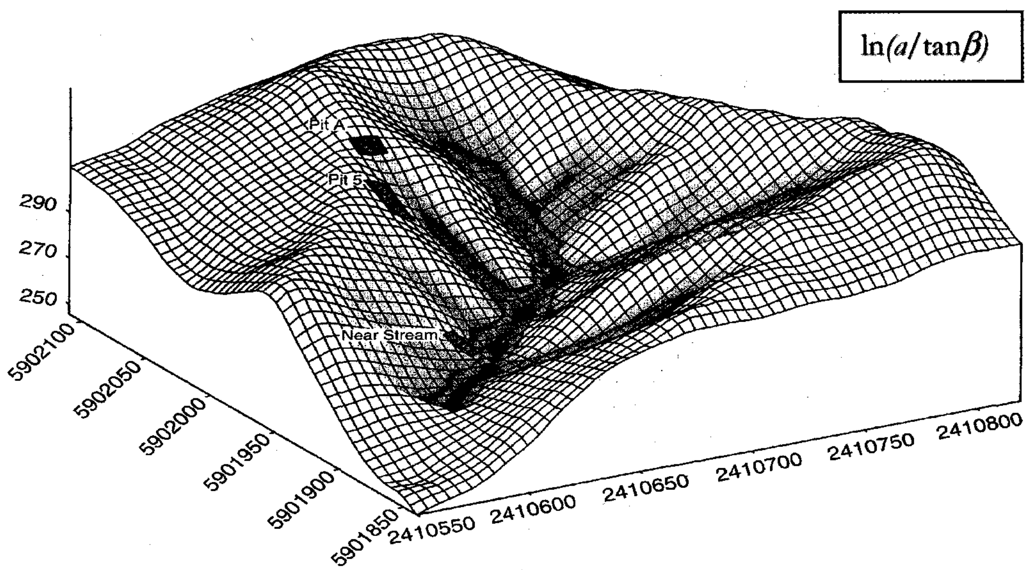

Figure 2.2 Spatial distribution of *TI* in a 3.8-ha watershed (Beven, 2001). High values of *TI* in valley bottoms and hillslope hollows imply that, in principle, these areas will saturate first.

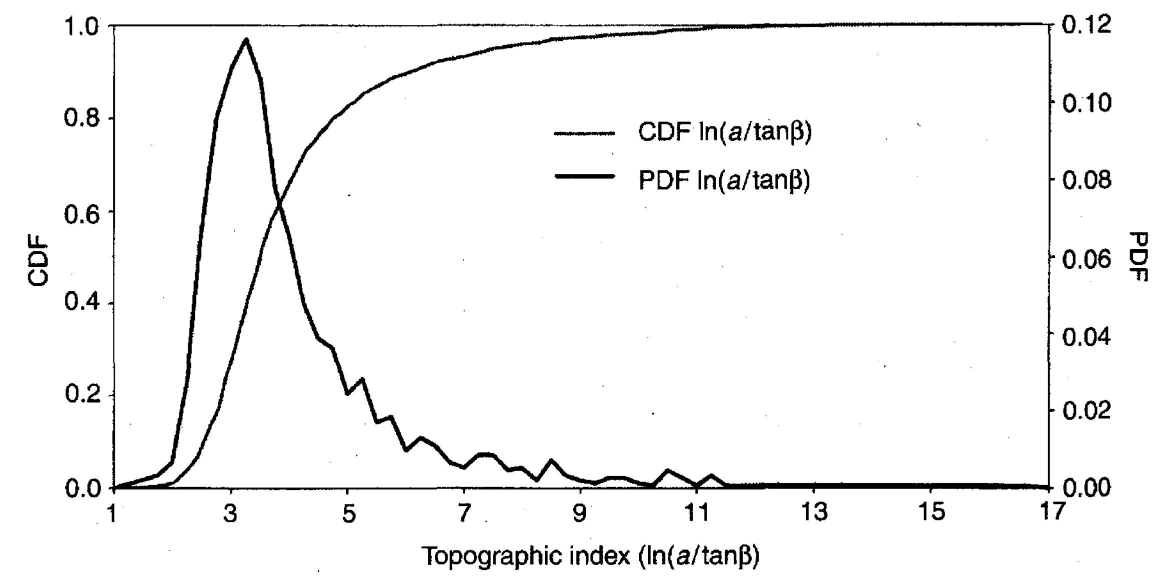

Figure 2.3 Cumulative distribution function (CDF) and probability density function (PDF) in a 3.8-ha watershed (Beven, 2001).

2.2 APPLICATION CONDITIONS AND LIMITATIONS

In the context of various TOPMODEL applications, Beven *et al.* (1995) and Beven (2001) reviewed the evidence for the success of the *TI* concept in predicting patterns of saturation (*i.e.*, soil moisture and water table depths) in different field/modeling studies. Sometimes the saturation patterns appear adequate, sometimes they do not. These inconstancies can be best explained by examining the way the *TI* concept simplifies the dynamics of a watershed and by underlining the fact that the underlying assumptions may occasionally be too strict. Note that Beven (1997) has published a complete critique of TOPMODEL.

The first assumption, which views the dynamics of the saturated zone as successive steady-states, implies that there are a constant recharge rate and a downslope flow everywhere over the hillslope which is clearly not the case where hillslopes are seasonally dry. Indeed under these conditions (*e.g.*, Beven, 1997, 2001; Blazkova *et al.*, 2002): (i) the effective upslope contributing areas do not extend to the hillslope divide or boundary, and (ii) the saturated zone may become localized and isolated so the effective *TI* value reduces, only to re-expand during wetting as the contributing areas spread. From a modeling point of view, this behavior leads to a difficulty in estimating subsurface flow discharge during wetting-up periods. Discharge rates can be spatially and dynamically non-uniform since they temporally change during a storm event or dry spell so steady state conditions are never actually met. Beven and Freer (2001) established that under such conditions, the development of a perched water table would limit the validity of any index-based approach. Hence, in watersheds where there is a long dry season and a long wetting up period, the dynamics or lack of steady-state saturated flow conditions will, on one hand, restrict the use of TOPMODEL, and on the other hand, highlight the fact that the dynamics of the contributing areas are governing the hydrological behavior of the watershed.

There are also concerns about the second assumption where the premise is that the water table is nearly parallel to surface topography for relatively thin soils over an impermeable soil layer on moderate slopes. Under this condition, the hydraulic gradient is assumed to be equal to the slope angle. However, this behavior will be violated as soils get deeper or if there is a strong spatial or temporal change in the recharge rate (Beven and Freer, 2001). Many local effects on groundwater may also lead to variations of the second assumption pattern as well (*e.g.*, existence of substantial preferential flows).

Given the above observations, TOPMODEL should not be expected to perform well on all watersheds. However, the model will likely perform well when applied on watersheds where all the underlying conditions are met, particularly those related to the first two assumptions, that is, those of a topographic control of the water table depth and a quasi-parallel water table with respect to hillslope topography. From a landscape point of view, these watersheds are likely to have relatively shallow, homogeneous, soils where surface and subsurface flows are governed by contributing areas exhibiting saturation excess runoff. On the other hand, on watersheds where precipitation/infiltration excess runoff processes are thought to be important, it is unlikely that the assumption of a topographically controlled water table holds. These restrictions or constraints do not invalidate the *TI* concept but rather highlight the circumstances or conditions under which TOPMODEL should be applied and the need to extend the concept to other conditions (see Ambroise *et al.*, 1996a,b).

2.3 COMPUTATION OF TI

As mentioned by Beven *et al.* (1995) and Beven (2001), in the early stage of development of TOPMODEL, computation of *TI* relied upon manual analysis (based on map and air photo information) of local slope angles, upslope contributing areas and cumulative areas. Nevertheless, Beven and Kirkby (1979) proposed a computerized technique to derive the *TI* distribution function based on the division of the watershed into small "local" slope elements on the basis of dominant flow paths identified with field observations. Flow paths were inferred from lines of greatest slopes and computation of *TI* was performed for the downslope edge of each element. This technique was particularly useful to delineate the effects of manmade infrastructures, such as field drains and roads, in controlling effective upslope contributing areas.

Digital Terrain Analysis (DTA) programs, based on raster elevation data, are now available to derive the required topographic information by TOPMODEL. Applications of these programs to watershed studies have been described by Quinn *et al.* (1991) and Quinn and Beven (1993). The availability and description of these programs are introduced in Chapter 3. The functional nature of *TI* depends on the quality of the representation of hydrologically significant topographic features by DTA methods.

To derive *TI*, a scale of resolution for the watershed DTM must first be selected. The DTM must have a fine enough resolution to properly reflect the effect of topography on surface and subsurface pathways (D'Odorico and Rigon, 2003). Coarse resolution DTMs may fail to represent some convergent slope features and some apparent sources or sinks for water contaminants. However, too fine a resolution may introduce perturbation to flow directions and slope angles that may not be reflected in the smoother water table surface (Quinn, 2002). The appropriate resolution depends on the scale of the hillslope features, but 50 m or better data is normally suggested (Beven, 2001).

2.4 SUMMARY

From an indicator point of view, the *TI* concept should be used to predict the propensity of a point in a watershed to develop saturated conditions and, hence, contribute to saturation excess runoff. For a soil rich in potential water contaminants and likely to be the site of saturation excess runoff, knowledge of *TI* values will clearly illustrate the spatial distribution of watershed areas with a high risk of pollutant loss to surface waters.

It is noteworthy that most Canadian prairies watersheds do not have shallow soil systems, with moderate slope angle, and a long wet season. In fact, most of the prairies have relatively deep soils and are exposed to a long dry season where perhaps infiltration excess runoff might dominate the runoff production process during the summer. This said, we believe the *TI* approach can be used with confidence as an indicator of saturation excess runoff where it applies, that is, in eastern Canada and on the Canadian west coast where the upslope contributing area generally extends to the hillslope divide during fall, winter and spring. For summer and for the Canadian prairies, the use of *TI* as an indicator of water contamination by agricultural nutrients should be used with care as it is more likely that the Hortonian runoff process dominates. Nevertheless, we firmly believe that it will be useful to determine *TI* values for those watersheds and conditions.

3 AVAILABILITY OF DATA AND ALGORITHMS

To determine *TI* values at the scale of Canadian agricultural areas, the following data and algorithms are required:

(i) digital elevation data with a fine grid resolution (50 m or better, if possible) and

(ii) software or algorithms to calculate the $\ln(a/\tan\beta)$ spatial distribution based on the digital elevation data

3.1 AVAILABILITY OF DIGITAL ELEVATION DATA AT THE CANADIAN SCALE

Canadian Digital Elevation Data (CDED) are produced jointly by the Centre for Topographical Information (CTI) and the Canadian Forest Service, Ontario Region (CFS). These data are free of charge and readily available on the GeoBase website (http://www.geobase.ca/geobase/Geobase).

CDED consist of an ordered array of ground elevations at regularly spaced intervals. They are derived from the National Topographic Data Base (NTDB) digital files at the 1:50 000 and 1:250 000 scales, based on the divisions of the National Topographic System (NTS). All CDED files are produced using ANUDEM (Australian National University Digital Elevation Models) software, after scanning NTS map sheets. An important distinguishing feature of the ANUDEM approach is the fact that it includes the identification and correction of mislabelled contour data and provides a properly flowing connected streamline hydrology.

The number of points per profile and the number of profiles per cell are constant for all the files (1201 x 1201). Each cell holds 1 442 401 elevation points. The North American Datum of 1983 (NAD83) is used as the reference system. Elevations are orthometric and expressed in reference to the Mean Sea Level (Canadian Vertical Geodetic Datum).

The grid spacing of the CDED is based on geographic coordinates. Cell coverage varies according to three geographic areas: below the 68th parallel, between the 68th and the 80th parallel, and beyond the 80th parallel (Centre for Topographic Information, 2000). As agricultural regions are located in the first area, this report focuses on this area and ignores the other two.

For 1:50 000 CDED, the cell coverage is 15' x 15' with a grid spacing of 0.75" x 0.75", which corresponds to approximately **23 m (N-S) x 16-11 m (E-W, depending upon latitude)**. For 1:250 000 CDED, the cell coverage is 1° x 1° with a grid spacing of 3" x 3", which corresponds to approximately **93 m (N-S) x 65-35 m (E-W, depending upon latitude)**. Note that Digital Elevation Model (DEM) at coarser scales have been produced by the Landscape Analysis and Applications Section (LAAS) at the Canadian Forest Service, based on a resampling of the 1:250 000 DEM.

3.1.1 Territory Coverage

The 1:250 000 CDED provides complete seamless coverage of the entire country (see Figure 3.1). Most of the 1:50 000 CDEDs are currently in production (no publication date is available from GeoBase). They will only provide a partial coverage of the country, mainly in inhabited areas and where economic activity is significant. At present, only British Columbia, Southern Saskatchewan and a large part of the Maritime Provinces are covered (see Figure 3.1).

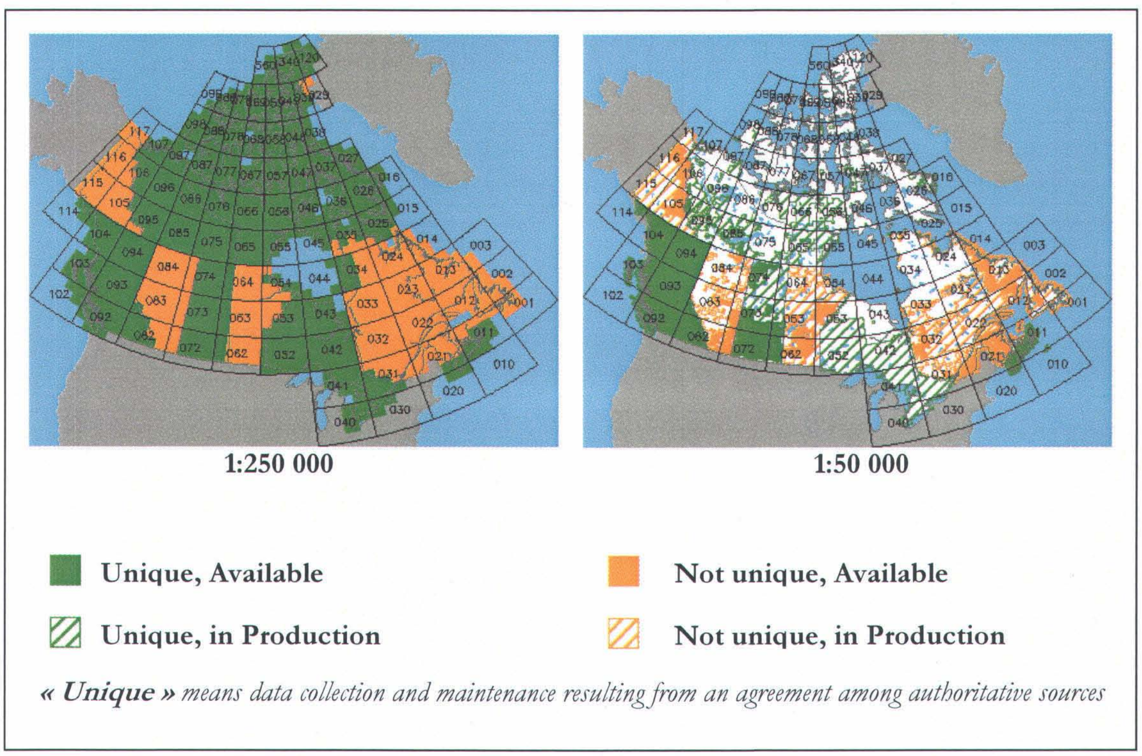

Figure 3.1 Canadian areas covered by 1:250 000 and 1:50 000 CDED (GeoBase®)

As previously indicated, the suggested grid resolution for determination of *TI* is 50 m or better, finer resolution being better. Therefore, 1:50 000 CDED will be used where available, and 1:250 000 CDED will be used elsewhere (see Figure 3.1).

3.1.2 File Format

The file format is very similar to the ASCII version of DTED of the United States Geological Survey (USGS). Therefore, the data are compatible with all translators designed for the USGS DTED.

3.2 AVAILABILITY OF ALGORITHMS

Several programs are readily available, free of charge, on TOPMODEL website (http://www.es.lancs.ac.uk/hfdg/beven2000/Beven2000.html): TOPMODEL, TFM, GLUE and DTM-ANALYSIS.

The program of interest here is the DTM-ANALYSIS program, which contains three options (see Appendix B for a description of the software). The *TI* Distribution Calculation option enables the derivation of a distribution of $\ln(a/\tan\beta)$ values from a regular raster grid of elevations for any watershed or subwatershed. The calculation algorithm is based on the multiple direction flow algorithm of Quinn *et al.* (1995). The output is a histogram of the distribution of the $\ln(a/\tan\beta)$ values, and a map file of $\ln(a/\tan\beta)$ values. However, the simple use of this algorithm with an elevation data grid may lead to high *TI* values for pits and sinks which are not connected to river network. To avoid these misleading results, the Automatic Sink Removal option allows for the modification of the elevation data and removal of sinks by using successive averaging of surrounding elevations to resolve pits. Additionally, this feature handles the case of small river channels for which the elevation grid cannot resolve the continuous flow pathway. The *TI* Distribution Calculation also requires that only elevations of points within the watershed are supplied, all other values in the matrix being set to greater than a value of 9999.0 (m). The Catchment Identification option provides for values above a specified pixel value to be removed from the watershed using a hill climbing algorithm. This option is important in the current context since the elevation data that will be used do not have watershed boundaries *a priori*.

As previously mentioned, it is recommended that the elevation data should be at a 50 m resolution or better. It should be noted that the derived $\ln(a/\tan\beta)$ distribution will be dependent on the resolution of the elevation data used and on the particular rules for distributing upslope areas and dealing with river channels that are smaller than the grid size. Different distributions may result in different effective parameter values for a given watershed.

3.2.1 Input File Format

Only one file is required to run the program. This is a file of elevations in metres, listed in order from the bottom left hand (south west) corner of the map, row by row working northwards. The first line of the file must contain an 80 character title; the second line the number of columns, the number of rows and the grid spacing in m. It is assumed that all points falling outside of the watershed have already been identified and given an elevation > 9999. The input elevation file should thus have the following form:

1. Title ; Descriptive title for watershed or elevation grid
2. NX, NY, DX ; Number of columns, number of rows, grid size (m)
3. ((E(I,J),I=1,NX),J=1,NY) ; Elevation values ordered row by row

3.2.2 Output Files

Two files are produced by the DTM-ANALYSIS program, formatted to be directly used in TOPMODEL program:

(i) An ASCII file with the distribution of the $\ln(a/\tan\beta)$ values. Values are classified into 50 classes, and the file gives the frequency and the cumulative frequency corresponding to each class. These data enable to do statistical analyses.

(ii) An ASCII file with $\ln(a/\tan\beta)$ values, following the same structure as input file with elevation data :

1. Title ; Descriptive title for watershed or elevation grid
2. NX, NY, DX ; Number of columns, number of rows, grid size (m)
3. ((T(I,J),I=1,NX),J=1,NY) ; Topographic index values ordered row by row

This file can be used to visualize spatial distribution of topographic index values with any Geographic Information System (GIS) software, after transformation of the ASCII file into a raster file format by the mean of importation tools.

3.2.3 File Format Compatibility

The file format of CDED cannot be directly used as input file for DTM-ANALYSIS program. A simple adaptation algorithm will be required to convert the CDED files to a compatible format. Another problem is the grid cell dimension: in the CDED, the cell length and width are not equal, while a square cell size is required in DTM-ANALYSIS program. To resolve this issue, a simple geomatic procedure (*i.e.* a Lambert conic projection) will be used.

3.3 SUMMARY

This Chapter introduced the relevant data and algorithm/program/software needed to compute *TI* values at the scale of Canadian agricultural areas. Namely, the required DTMs can be obtained, free of charge, from CDED at either a 1:50 000 or 1:250 000 scale. While the required DTM-ANALYSIS program can be downloaded from the TOPMODEL website.

4 INTEGRATION OF TI IN THE HYDROLOGY COMPONENT OF IROWC

In this Chapter, the integration of *TI* is analysed and proposed in terms of *IROWC_P*. Also, as mentioned in the first chapter, we explore means of integrating the representation of the *TI* concept at the SLC polygon, that is, the elementary unit of the IROWC computational domain.

4.1 PROPOSED METHOD

The calculation of *IROWC_P* was initially defined as follows:

$$IROWC\_P = P\_Balance + P\_Status + P\_Transport \tag{4.1}$$

This formulation corresponds to the Phosphorus Index (*PI*) introduced by (Lemunyon and Gilbert, 1993). The *P_Transport Component* (or *Hydrology Component*) consists of the addition of two terms: *P_Runoff* and *P_Erosion*. The *P_Runoff* term is a runoff index calculated using the SCS-Curve Number method (USDA, 1972). The *P_Erosion* term is an erosion index calculated with the RUSLE model (Pringle *et al.*, 1995). Moreover, all components are weighted by a rating value, different for each studied area, and a weighting factor that has to be adjusted for each indicator.

4.1.1 Integration of TI in the Hydrology Component

First of all, we propose to combine the *Soil Component* (*P_Balance* + *P_Status*) and the *Hydrology Component* since they are independent and limiting factors for pollutant loss from soils to surface waters as follows:

$$IROWC\_P = (P\_Balance + P\_Status) \times P\_Hydrology \tag{4.2}$$

With this formulation, an area with a high *P* content but without any hydrological connectivity would have an *IROWC_P* value of 0.

4.1.2 Hydrology Component Formulation

Several other components are in the process of being added to those already in place: *Water Balance*, *Surface Drainage*, *Subsurface Drainage*, and *TI*. These components should be considered in an additive way since most of them are somewhat dependent or intrinsically related.

An important issue is to avoid any overlap between the different terms, and this is especially worth investigating in the case of the *TI* term, the *P_Runoff* term, and the *Water Balance* term since they are all meant to deal with runoff processes. The SCS-CN method used to calculate the *P_Runoff* term is rooted in a conceptual model based on the water balance equation and represents a hydrological abstraction of the Hortonian or excess infiltration runoff process (see Chapter 1 and Appendix A) during a rainstorm event. The runoff volume depends on rainfall intensity, initial soil moisture conditions, and land use. On the other hand, *TI* is an indicator of the propensity of a watershed area for saturation excess runoff, and thus has nothing to do with Hortonian runoff. Therefore, these two terms are meant for different processes, at different spatial and temporal scales, and can be used in a complementary way within the *Hydrology Component*. Another difference is that *TI* accounts for neither precipitation nor water balance, while the SCS-CN method does. That is why it is also important to introduce a *Water Balance* term, calculated on a daily time-step; that allows for the estimation of the annual volume of water available for saturation excess runoff and/or infiltration. Note that there is a potential overlap between the *P_Runoff* term and the *Water_Balance* term; an issue that will need to be addressed.

The proposed formulation of the *Hydrology Component* is as follows:

$$Hydrology = P\_Runoff + P\_Erosion + Water\_Balance + TI + Surface\_Drainage + Subsurface\_Drainage \quad (4.3)$$

The objective of the *Hydrology Component* formulation is to reproduce the main processes that are involved in contaminant transport from soils to surface waters and the water table. In this formulation, the two first terms (*P-Runoff* and *P-Erosion)* represent storm event processes producing excess infiltration runoff (*i.e.*, Hortonian runoff). The terms *Water Balance* and *TI* account for the propensity of producing runoff and saturation excess runoff, respectively. The two last terms (*Surface Drainage* and *Subsurface Drainage*) represent the artificial hydrological connectivity to surface waters and the water table. Note that *TI* indirectly accounts for the natural (akin to floodplains) hydrological connectivity to surface waters and the water table.

Obviously, all these terms do not have the same relative importance with respect to each pollutant considered in the development of IROWCs. The weighting values that are attributed to each term, will take different values for different IROWCs, and, thus, the selection of the most important factors and processes with that respect. Finally, other terms could be added to improve the overall representation of the hydrological processes responsible for water contamination (*i.e.*, macropore or preferential flow), but that is beyond the scope of this study.

4.2 SEASONAL PARTITIONING

One way to avoid any overlap and to take advantage of the complements of the different terms of the *Hydrological Component* would be to consider a seasonal partitioning in the calculation of *IROWC_P*. For example, under Canadian conditions, a large part of the annual *P* load in surface waters occurs during the spring season. Since a large part of the *P* transport process is governed by saturation excess runoff due to snowmelt, the terms *Water Balance* and *TI* become the most important driving factors for delineating the areas with a high risk of water contamination during this period. A similar assumption can be made for the fall season since the contributing areas are mainly those defined by *TI*.

Meanwhile, during summer, the principal hydrological processes responsible for *P* transport from soils to surface waters are likely to be induced by precipitation excess runoff. Therefore, for a better assessment of the *P* contributing areas, the *P_Erosion* and *P_Runoff* terms should be considered as the dominant terms of the *Hydrology Component* during this period.

This seasonal partitioning could be achieved by assigning a different weighting value for each season, and by calculating the terms that depend on climatic factors (*Water Balance*, *P_Runoff* and *P_Erosion*) on a seasonal time step, instead of determining an annual average value.

4.3 TI VALUE AT SLC POLYGON LEVEL: COMPATIBILITY ISSUES

The elements of the spatial compatibility issues are related to the following observations:

(i) The elevation data that is required to calculate *TI* are available at a scale of 1:50 000 or 1:250 000 with grid cells containing 1201 x 1201 elevation points (or pixels). This corresponds to a coverage of 27,6 km (S-N) x 19,2 km (E-W) for the 1:50 000 CDED, and 111,6 km (S-N) x 82,8 km (E-W) for 1:250 000 CDED, for low latitude regions.

(ii) The DTM-ANALYSIS program can be used to define watershed delimitations based on elevation data and calculate *TI* values for each pixel of a watershed.

(iii) The determination of a single value of *TI* at the scale of each SLC polygon (a scale of 1:1 000 000. The size of a SLC polygon may vary in a wide range (100 km^2 to 10 000 km^2).

There are three information layers that need to be considered: polygons, watersheds, and elevation data grid cells. The use of a GIS software will enable the superimposition of these layers and the management of the data. As these three spatial scales are independent, it is necessary to determine *TI* values for each pixel contained within a polygon in order to determine a single value for the whole polygon. So we need to determine the *TI* values for all the watersheds that have a connection with a SLC polygon. To do so, all watersheds have to be identified by the DTM- ANALYSIS program, and which requires running the program, not on each grid cell separately, but on an aggregated grid cell containing all the elevation data of the watersheds that are connected to the SLC polygon.

Therefore, we first have to define a range of size for the watersheds on which *TI* will be determined separately. As we will mainly use 1:250 000 CDED (see Section 3.1), and as the covered area for a single CDED is around 9 000 km^2, it seems more appropriate to consider large watersheds. The following procedure will have to be applied for each watershed (see Figure 4.1): the first step is to identify the grid cells of CDED that contain a part of the watershed. This can easily be done with a GIS. The second step requires the aggregation of the elevation data of each CDED grid cell to a single grid cell covering the whole watershed. This task can also be performed with a GIS, but only if all the CDEDs are at the same scale (1:50 000 or 1:250 000). The third step consists in running the DTM-ANALYSIS program to identify the watershed delimitations with the Catchment Identification option, to remove sinks and pits with the Automatic Sink Removal option and then run the *TI* Distribution Calculation algorithm. This will generate a *TI* value for each pixel contained in the watershed.

Once all the watersheds that are contained in - or connected to - the polygon of interest (in the case of a small polygon, it may also be contained in a single watershed), a simple GIS procedure will allow for the generation of a map file with a *TI* value for each pixel contained in the polygon. Finally, the last step consists of choosing a statistical value that will represent the whole polygon in the *Hydrology Component*: the mean, the median, the mode? As the typical distribution of *TI* values is strongly asymmetric with numerous low values and few high values, it is important to choose a statistical indicator that represents all the values and especially the extreme values. Therefore, the mean value is the more appropriate statistical moment. However, to consider high risk water contamination conditions, it is also possible to calculate other quartile values. Note that the size of the watersheds used for *TI* calculation may be reduced for regions covered by 1:50 000 CDED and for small SLC polygons (100 km²).

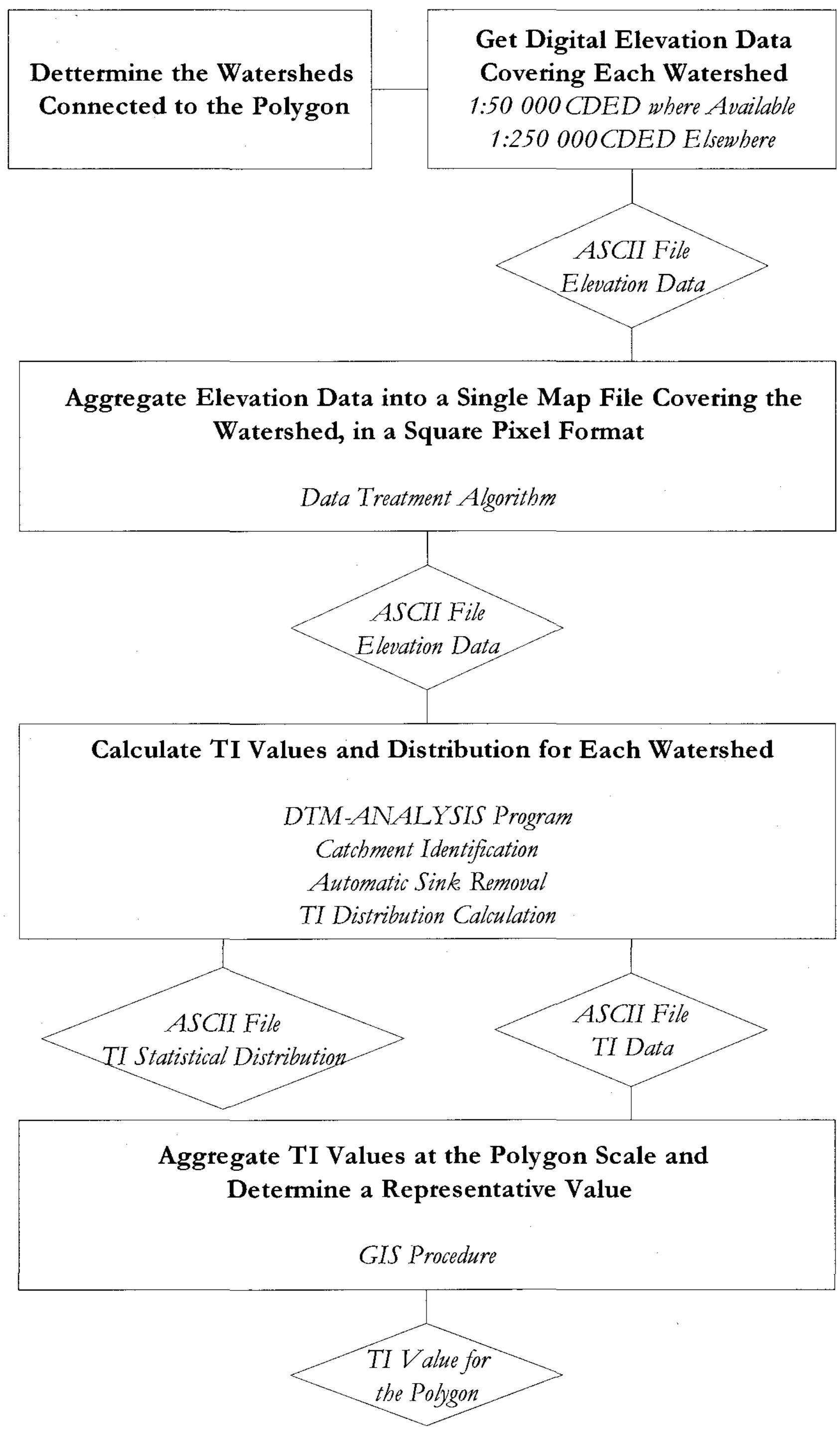

Figure 4.1 Summary of the procedure to calculate a representative *TI* value for a SLC polygon.

4.4 SUMMARY

This chapter discussed the potential integration of *TI* in the *Hydrology Component* of IROWCs. We proposed to consider *TI* as an additive factor together with (in the case of *P*) : *P-Runoff*, *P-Erosion*, *Surface Drainage*, *Subsurface Drainage*, and *Water Balance* terms. The result shall be multiplied by the numerical value of the *Soil Component* (*P_Balance* + *P_Status*) to obtain *IROWC_P*. Also, we proposed to take into account a seasonal partitioning in the *Hydrology Component* in order to improve the differentiation between saturation excess runoff (spring, fall) from infiltration excess runoff (summer). Finally, a protocol was put forward for the up- or down-scaling of *TI* at the SLC polygon level, by first aggregating elevation data (CDED) into a single file for each watershed connected to the polygon, running the DTM-ANALYSIS program on this data file, and then use a GIS procedure to get a spatial distribution of *TI* values at the polygon level, which allows for inferring a single representative value.

5 CONCLUSION

The topographic index (*TI*) of hydrological similarity of Kirby (Kirby, 1975; Beven, 2001) has been used to represent the propensity of any point *i* in a watershed to develop saturated conditions and, hence, contribute to saturation excess runoff. High values of *TI*, defined by the natural logarithm of the ratio of the upslope draining area at that point over the local slope, are representative of either long slope or upslope contour convergence and low slope angles. These corresponding areas will tend to saturate first. For a soil rich in nutrients, pesticides or pathogens, and suitable to the production of saturation excess runoff, the knowledge of *TI* values can be used to illustrate the spatial distribution of watershed areas with a risk of water contamination (*i.e.*, VSAs). The goal of this study was to assess the feasibility of integrating a *TI* term within the *Hydrology Component* of *IROWC_P*. With this respect and more specifically in terms of the three objectives introduced in Section 1.3, this report concludes that:

(i) Application of the *TI* concept is most relevant in watersheds where there is a topographic control on water table depth and a quasi-parallel water table with respect to hillslope topography, that is, where surface and subsurface flows are governed by contributing areas exhibiting saturation excess runoff. We believe that the *TI* concept can be used with confidence as an indicator of saturation excess runoff in eastern Canada and on the Canadian west coast where the upslope contributing area most likely extends to the hillslope divide during fall, winter and spring. For summer and for the Canadian prairies, the use of *TI* as an indicator of water contamination by agricultural runoff should be used as a first approximation since it is likely that the Hortonian runoff process might be more dominant.

(ii) Relevant data (*i.e.*, DTMs) and algortithms/program (*i.e.*, DTM-ANALYSIS program) needed to compute *TI* values are available, free of charge, at either a 1:50 000 or 1:250 000 scale from the GeoBase and TOPMODEL websites, respectively.

(iii) For the potential integration of *TI* in the *Hydrology Component* of IROWC, we propose to multiply together the resulting values of the *Soil Component* (*P_Balance* + *P_Status*) and the *Hydrology Component* since they are independent and limiting factors for pollutant loss from soils to surface waters. Furthermore, the following terms should all be considered and added together in the *Hydrology Component*: *P-Runoff, P-Erosion, Surface Drainage, Subsurface Drainage, Water Balance* and *TI*. The two first terms account for storm event processes producing excess infiltration runoff

> (*i.e.*, Hortonian runoff). The two middle terms represent the artificial hydrological connectivity to surface waters and the water table. The last two terms account for the propensity of producing runoff and saturation excess runoff, respectively. If we were to compute *TI* values at the SLC polygon level, there are three information layers that need to be considered: polygons, watersheds, and elevation data grid cells. The use of a GIS software will enable superimposition of these layers and management of the data. As these three spatial scales are independent, it will be necessary to determine *TI* values for each pixel contained within a polygon in order to determine a single value for the whole polygon. Thus, we will need to determine *TI* values for all watersheds that have a connection with a SLC polygon.

Finally, we can reasonably write that the choice of an indicator for a given problem is a matter of a subjective choice given constraints of understanding of the processes involved, available data, and parameter identifiability. The choice of introducing an index of hydrological similarity in the *Hydrology Component* certainly falls under this paradigm. Because they are well defined limitations on both the geographical and seasonal validity of the *TI* concept under Canadian agricultural landscape conditions, we believe that the concept will provide a genuine framework for highlighting the distributed runoff response of a watershed, and hence, the potential contributing areas of water contamination.

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APPENDIX A. RUNOFF GENERATION PROCESSES

Surface runoff and subsurface flow represent the principal sources of stream flow and lake recharge. As far as surface runoff goes, the most frequent concepts used to explain the contributions to streamflow are: (i) precipitation/infiltration excess runoff (also know as Hortonian runoff), (ii) saturation excess runoff, and (iii) exfiltration runoff. Figure A.1 illustrates all three types of surface runoff.

Hortonian runoff occurs when rainfall intensity exceeds the soil infiltration capacity. For this case, saturation of the top boundary layer of the soil surface saturates and, once surface depressions are all filled in, hillslope runoff takes place and contributes to the rising limb of the storm flow hydrograph. At the bottom boundary layer of the saturated soil surface, the water table is recharged by gravity and eventually contributes to the river base flow during dry periods. Note that Hortonian runoff may be limited to small areas of a watershed. The exceeding water may subsequently contribute to subsurface flow after infiltration downslope.

Saturation excess runoff takes place when rain falls directly on saturated zones. The exceeding water contributes either to subsurface flow (akin to piston flow) or surface runoff along the hillslope. In the case of piston flow, old water is forced out of the soil matrix into the river. These contributing areas are generally located along the river network (*i.e.,* floodplains), in valley bottoms or upslopes where soils are generally shallow. These contributing areas directly supply the storm runoff hydrograph via surface and subsurface storm flows. Figure A.2 introduces spatial and temporal distributions of a watershed response over the course of a precipitation event producing saturation excess runoff.

Exfiltration runoff tends to occur along the hillslope when the water table seeps out (see Figure A.1).

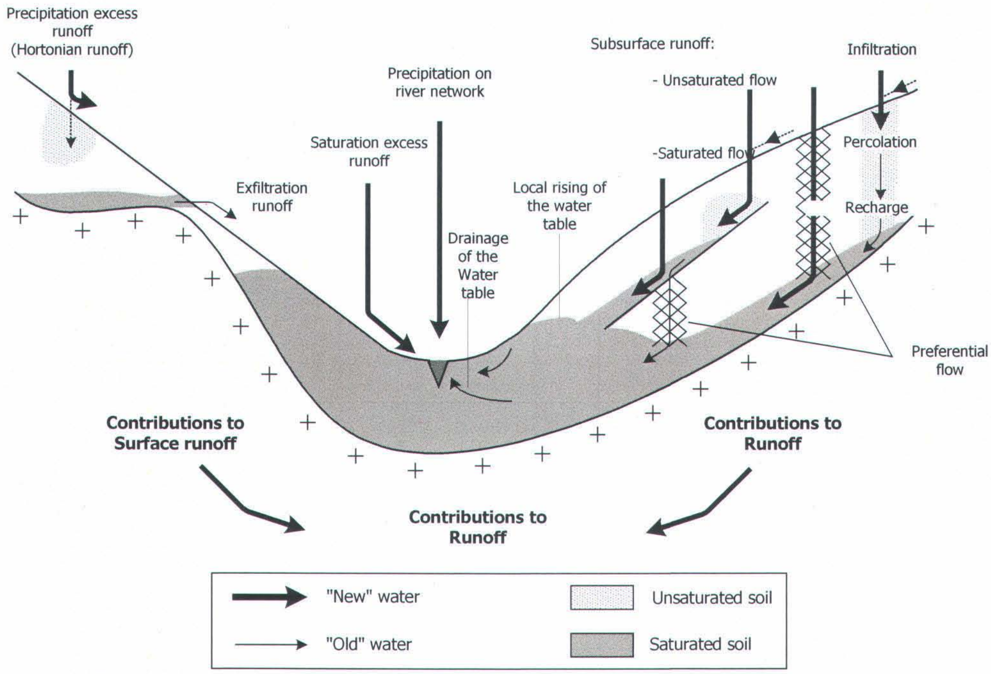


Figure A.1 Runoff generation processes (Ambroise, 1998).

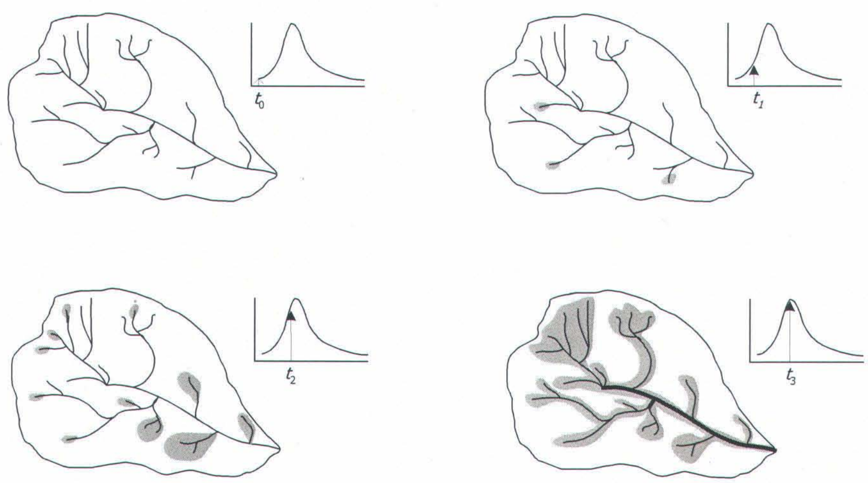


Figure A.2 Spatial and temporal distributions of a watershed response (Chow *et al.*, 1988)

APPENDIX B. USE OF THE DTM-ANALYSIS PROGRAM

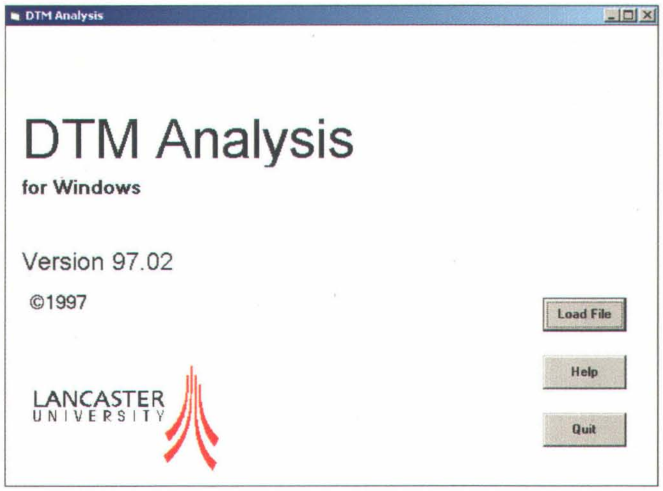


Figure B.1 DTM-Analysis program window.

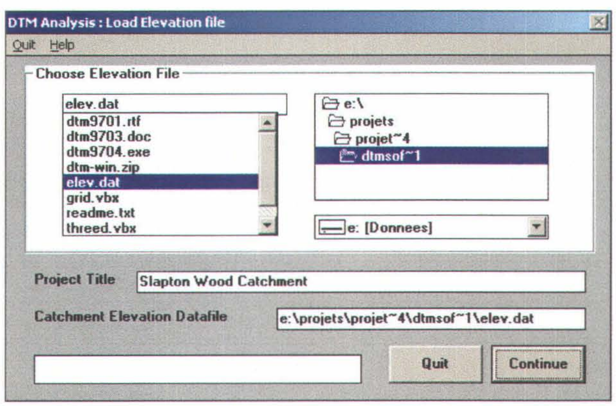


Figure B.2 The first step is to load the elevation data file (demonstration watershed : Slapton Wood Catchment, Devon, UK)

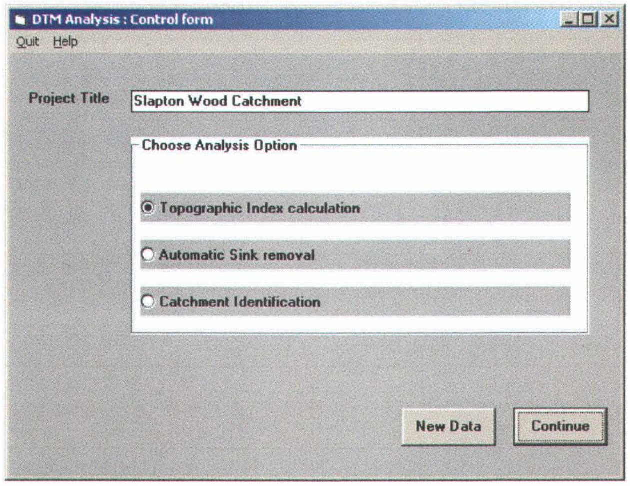


Figure B.3 Once the elevation data file is loaded, the user has to choose between the three options.

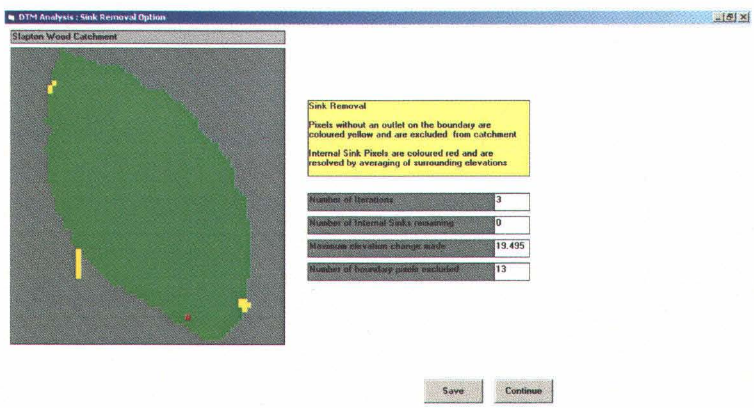


Figure B.4 Sink Removal Analysis Window.

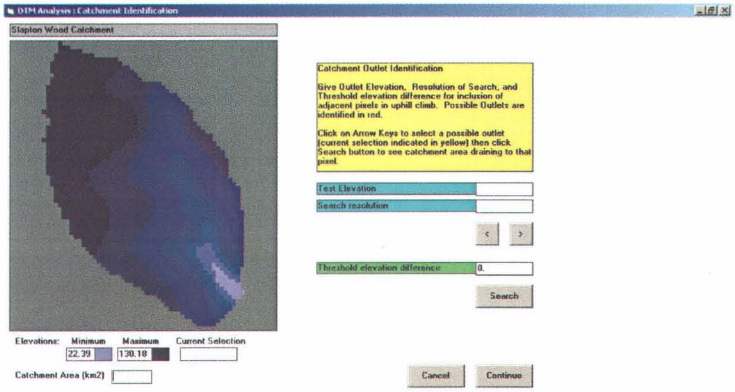


Figure B.5 Catchment Identification Window.

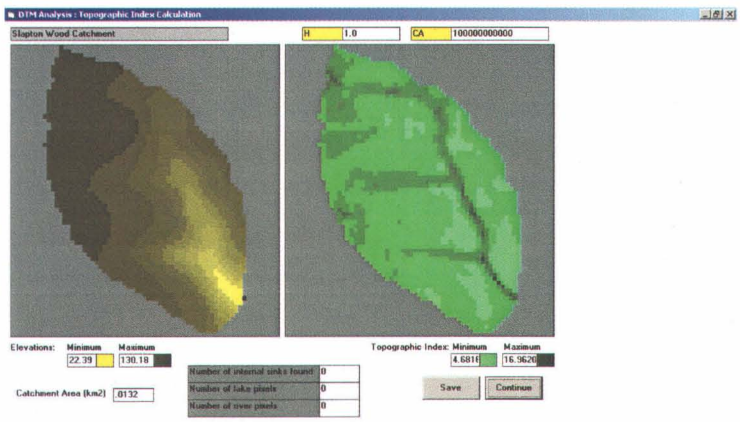


Figure B.6 TI Calculation window, with the elevation map (left) and the *TI* values map (right)

APPENDIX C. PRESENTATION OF ROUSSEAU ET AL. MADE AT THE 2004 IROWCS HYDROLOGY TECHNICAL WORKSHOP HELD IN SAINTE-FOY, QUEBEC (FEBRUARY 18 AND 19)

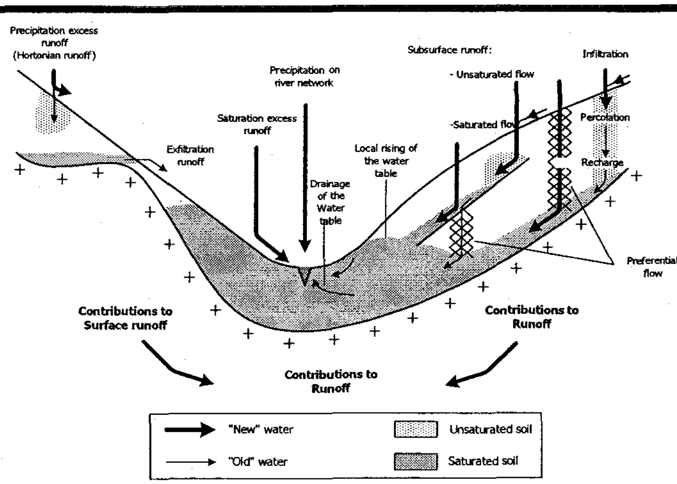
The Topographic Index

A.N. Rousseau, R. Quilbé, B. Lacasse
& J.-P. Villeneuve
Centre Eau, Terre et Environnement
Institut National de la Recherche Scientifique
Université du Québec

National Agri-Environmental Health Analysis and Reporting Program (NAHARP)
2004 IROWCs-Hydrology Technical Workshop
February 18-19, 2004, Québec

18-19/02/2004 INRS-ETE 1

Infiltration & Runoff Processes[1]



[1] Ambroise, B. (1998). *Revue des Sciences de l'Eau*, **11**(4) : 471-495.

18-19/02/2004 INRS-ETE 2

Contributing Areas of P Loss

- Particulate P Loss ≈ Hortonian Runoff (Summer)
  - *High Intensity Rainfall, Steep Slope, Storm Flow*
- Non-Point Pollution of Dissolved P Loss ≈ Saturation Excess Runoff (*i.e.*, Spring Snowmelt)
  - *Gentle Slope, High Water Table, Low Flow*
- Contributing Areas of Dissolved P Loss ≈ Ripairian Zones & Valley Bottoms[1] (Spring & Fall)

Areas of Saturation Excess Runoff ≈ Contributing Areas of Dissolved P Loss to Water Courses

[1] Sharpley *et al.* (1999). *Agric. Water Manag.*, **41**: 77-89

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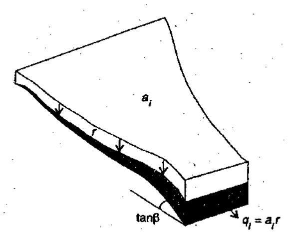
The Topographic Index (TI)

- Kirkby (1975)[1], Basis of the Rainfall-Runoff Empirical Model **TOPMODEL**
- TI ≈ " Propensity of Any Point in a Catchment to Develop Saturated Soil Conditions & Hence to Contribute to Saturation Excess Runoff "

$$\boxed{TI = ln\left(\frac{a}{tan(\beta)}\right)}$$



[1] Kirby, M. (1975). In Peel, R., M. Chisholm, P. Haggett, *Processes in Physical and Human Geography*. Heineman, London, pp.69-90.

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Use of TI

- Hypotheses[1]
  1. *Saturated Zone Dynamics ≈ Successive Steady State Representations*
  2. *Hydraulic Gradient of the Saturated Zone ≈ Local Surface Topographic Slope*
  3. *Distribution of Downslope Transmissivity with Depth ≈ Exponential Function of Storage Deficit or Depth to Water Table*
- Application Conditions :
  - *Humid Temperate Conditions*
  - *Shallow Homogeneous Soils*

[1] Beven, K. J. (2001). *Rainfall-Runoff Modelling: the Primer.* John Wiley & Sons, New York

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Determination of TI

- Analysis of Watershed Topography
  - Digital Terrain Model (DEM) & DE Analysis Program[1,2]
- Result
  - A Watershed Distribution Function of $\ln(a/\tan\beta)$

[1] Quinn, P.F., K. Beven et R. Lamb. (1995). *Hydrological Processses*, **9**: 161-182.
[2] Quinn, P.F., K. Beven, P. Chevallier et O. Planchon. (1991). *Hydrological Processses* **5**: 59-79.

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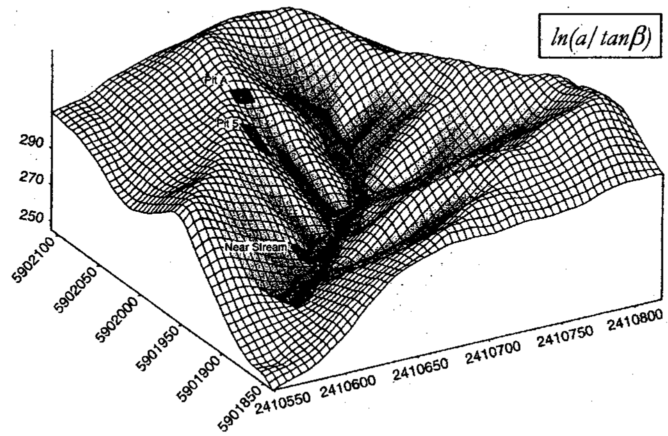
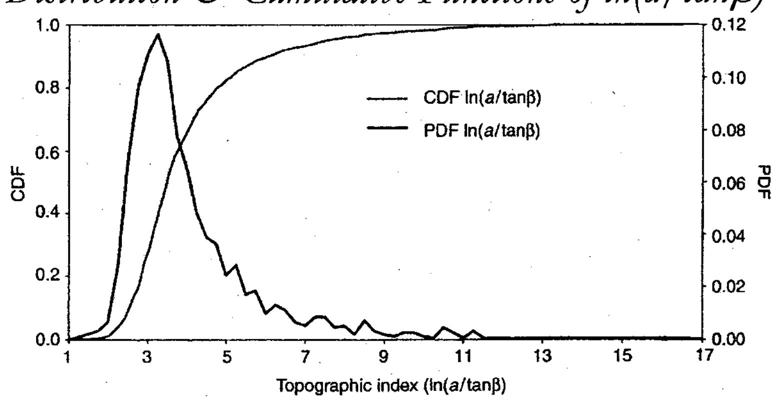
Example of Application[1]



[1] Beven, K. J. (2001). *Rainfall-Runoff Modelling: the Primer.* John Wiley & Sons, New York

Example of Application[1]

Distribution & Cumulative Functions of ln(a/ tanβ)



[1] Beven, K. J. (2001). *Rainfall-Runoff Modelling: the Primer.* John Wiley & Sons, New York

Integration of TI in IROWC

IROWC's Hydrological Component

P-Transport = P-Erosion + P-Runoff

P-Hydrology =

Water Balance Factor + Topographic Index + Surface drainage + Subsurface drainage

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Questions & Issues

- Avoid any Overlap or Duplication Between Hydrological Components
  - *P-Runoff, P-Erosion, Water Balance Factor & TI*
- Seasonal Partioning of Hydrological Component
  - *Winter-Spring & Fall : Water Balance & TI*
  - *Summer : P-Runoff & P-Erosion*
- Scale
  - *What is the Minimum Resolution for Watershed DEM ?*
  - *How Do We Aggregate TI Values from a Watershed DEM Scale to a SLC Polygon Scale ?*

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Future Work

- **Integration of TI with IROWC's Hydrological Component**
  - Data Requirements & Availability (namely DEM)
  - Availability of Geomatic Algorithms
  - Compatibility with Spatial Scales of IROWC-P Subcomponents
  - Suitability of the Approach in the Canadian Prairies

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