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# Water Balance Components in the Canadian Mixed Wood Ecozone

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## ABSTRACT

**Partitioning of precipitation into canopy interception, surface runoff, soil water storage, evapotranspiration and drainage, is essential for agricultural water management planning and design purposes. The objective of this study was to assess the spatial and temporal variability of the water balance components in the intensively farmed area of the Mixed Wood ecozone of Canada. The SWATRE simulation model was modified to account for the overwinter redistribution of water in the soil profile, and surface runoff calculations were incorporated. The model was run continuously from 1961 to 1990 to estimate annual and seasonal changes in canopy interception, surface runoff, soil water content, evapotranspiration, and drainage. Simulations were made for three crop rotations (corn-soybean-winter wheat; continuous corn and pasture) at 13 locations, using selected local soils under conventional and conservation tillage practices. Spatial and temporal variability of the climatic conditions was fairly high, and, coupled with variable local soil hydraulic properties, resulted in highly variable simulated surface runoff, soil water storage, evapotranspiration and drainage. Over 70% of the surface runoff and drainage occurred during the non-growing season. There was less surface runoff and less drainage from continuous pasture as compared to the annual crops. Compared to regular tillage, conservation tillage increased interception by about 50%, reduced surface runoff and evapotranspiration, but had little effect on drainage.**

## INTRODUCTION

The Mixed Wood Ecozone of Canada covers the lower Great Lakes-St. Lawrence River valley. Its gentle topography, fertile soils, warm growing season and abundant rainfall have made it an intensively farmed area. However, the weather is highly unstable because the region lies along one of the major storm tracks in North America, and hence the components of the water balance are highly variable in both space and time.

From an agricultural point of view, the partitioning of precipitation into canopy interception, surface runoff, soil water storage, evapotranspiration and drainage is often less than ideal. Soils are frequently either 'too dry' or 'too wet'. Dry spells of varying severity occur nearly every summer in southern Ontario and Quebec, curtailing crop water uptake and thus yields. On the other hand, excess water is commonly experienced in spring and fall, and it causes reductions in water and nutrient uptake due to poor aeration. Runoff and drainage of excess water is also an environmental concern in that it can cause agrochemical contamination of surface- and ground waters.

The magnitude of soil water deficits and surpluses during the growing season in Ontario was computed for a perennial forage crop by De Jong and Bootsma (1997). Their work should be extended to include local soil conditions and annual crop management practices. The information is needed for policy and/or management decisions, especially related to water quality issues, irrigation practices and the design of tile drainage systems.

The objective of this study was to evaluate the spatial and seasonal variability of water balance components in the Mixed Wood Ecozone (scale 1:7.5 million) of Canada. We used a modified version of the SWATRE simulation model (Feddes et al. 1978) to estimate the water balance components of three crop management systems at 13 locations within the ecozone. The SWATRE model was chosen because it has been subjected to numerous validation exercises worldwide (Feyen, 1987; De Jong and Kabat, 1990; Faria et al., 1994; Bastiaanssen et al., 1996). Moreover, based on a variety of error statistics, this model performed satisfactorily for various soil and crop combinations in Ontario and Quebec (Clemente et al., 1994; Veenhof and McBride, 1994; Mahidian and Gallichand, 1966).

## MATERIALS AND METHODS

### The SWATRE model

SWATRE is a transient, one-dimensional soil water flow model which uses soil physical properties, crop characteristics and weather data to estimate the soil water balance on a daily basis. The model is based on Richards' equation expressed as:

$$C(h)\frac{\partial h}{\partial t}=\frac{\partial}{\partial z}[K(h)(\frac{\partial h}{\partial z}-1)] - S(z,t)$$

where h is pressure head (L), t is time (T), C(h)=dθ/dh is the differential water capacity ($L^{-1}$), with θ being the volumetric water content ($L^3\ L^{-3}$), K(h) is the hydraulic conductivity-pressure head relationship ($L\ T^{-1}$), S(z,t) is a sink term for water uptake by plant roots ($T^{-1}$) and z is depth below the soil surface (L). The sink term S(h) in Eq.(1) is defined by:

$$S(z,t) = R_{df}(z,t)\ \alpha(h)\ S_{max}$$

where $R_{df}$ is a root distribution function (dimensionless), α(h) is a dimensionless function of pressure head (Clemente et al., 1994, Fig. 1) and $S_{max} = T_p/z_r$, with $T_p$ the potential transpiration rate ($L\ T^{-1}$) and $z_r$ the rooting depth (L). Unlike most models, SWATRE takes into consideration that

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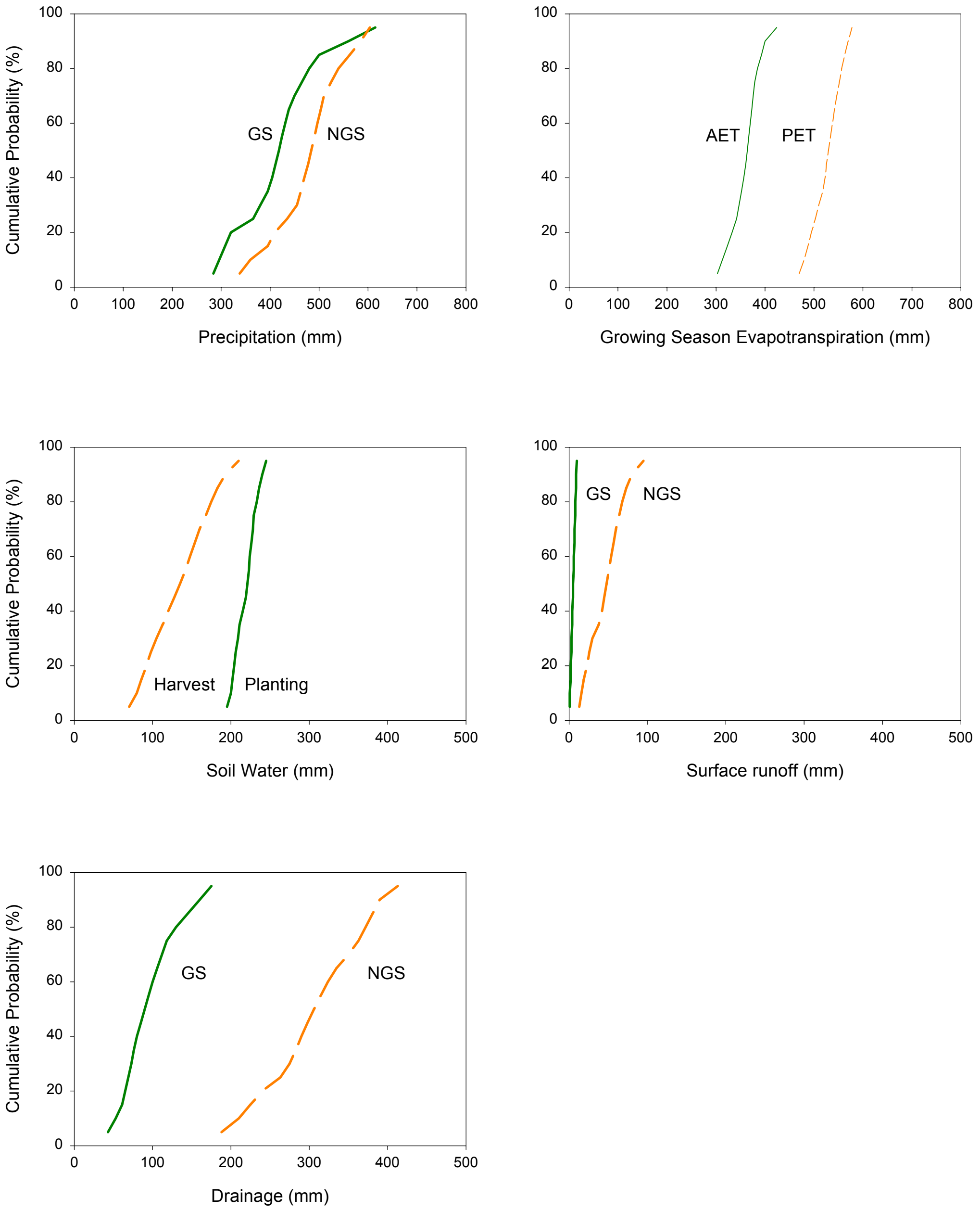

Fig. 1. The temporal variability in water balance components of continuous corn at Ste Clotilde (GS - Growing Season data; NGS - non-growing season data).

**Table 1. Rooting characteristics and water uptake parameters in the sink term**

| Crop | Maximum rooting depth | Root extinction coefficient, b | Pressure head limits of sink term† $h_3^1$ | $h_3^2$ |
|---|---|---|---|---|
| | **cm** | **$cm^{-1}$** | **kPa** | |
| Corn | 90 | 0.083 | -50 | -100 |
| Soybeans | 80 | 0.066 | -80 | -120 |
| Winter wheat | 100 | 0.063 | -50 | -100 |
| Pasture (grass) | 50 | 0.092 | -50 | -80 |

† $h_3^1$ at $T_p = 5$ mm $d^{-1}$; $h_3^2$ at $T_p = 1$ mm $d^{-1}$

transpiration is reduced under both extremes, i.e. when soil water conditions are too dry or too wet. Under non-optimal conditions root water uptake is reduced by the pressure head-dependent $\alpha$ function. Water uptake at $h \geq h_1$ (oxygen deficiency, -1 kPa) and $h \leq h_4$ (wilting point, -1500 kPa) is zero. Between $h_1$ and $h_2$ (-3 kPa) and between $h_3$ and $h_4$ a linear variation in $\alpha$ is assumed. The value of $h_3$ varies between $h_3^1$ and $h_3^2$ with the evaporative demand of the atmosphere; its values are reported for each crop in Table 1.

The relative root distribution, $R_{df}$, which distributes the potential transpiration across the rooting depth, was calculated from an exponential root distribution function:

$$R_{df} = Y_0 \int_{Z_1}^{Z_2} exp(-bz) \; / \; Y_0 \int_{0}^{Z_r} exp(-bz)$$

where $Y_0$ is the root density at the soil surface (L $L^{-3}$), $z_1$ and $z_2$ are respectively the upper and lower depth of the soil layer under consideration, and b is an extinction coefficient ($L^{-1}$) which varied among different crop types (Table 1).

## Surface runoff

The SWATRE program was modified to account for surface runoff by using a modification of the curve number (CN) methodology as described by Williams (1995). This technique was selected because (i) it has been successfully used for many years in the US and Canada; (ii) the required inputs are generally available; and (iii) it relates runoff to soil type, land use and management practices. In the current application it was assumed that the CN of the annual crops was 75 or 80, depending on whether the soil was coarse- or fine textured. For pasture we assumed CNs of 64 and 65 respectively for coarse and fine textured soils.

## Multiple year simulation

The 'single-season' SWATRE model was changed to run over a number of consecutive years to estimate seasonal changes in soil water content, evapotranspiration, leaching, runoff and canopy interception. The modifications included development of multiple year weather and crop management input files and various program changes to account for over-winter redistribution of water in the soil profile. It was assumed that during the 'winter' (defined as when the weekly mean air temperature is less than 0ºC), the soil surface is frozen and there is no water flux across the atmosphere/soil interface. Consequently, the existing water in the profile slowly redistributed during the winter via gravity drainage. Precipitation during the winter was assumed to occur as snow, which accumulated with the assumption that 30% was lost due to blowoff, evaporation and sublimation. The remaining 70% was available for infiltration and runoff during the first 7 days of 'spring' (defined as when the weekly mean air temperatures is and remains above 0°C).

## Crop management

The SWATRE model was run for 30 years with three cropping systems: (i) corn-soybean-winter wheat (each phase present in every year); (ii) continuous corn; and (iii) pasture. Annual planting dates of corn and soybean were based on criteria developed by Bootsma and Brown (1995). Emergence of corn took place when 50 soil Growing Degree Days (GDD) above 10ºC were accumulated since planting (Hayhoe et al., 1996). Soil growing degree days were estimated from air temperatures using the method described by Dwyer et al. (1990). Soybeans emerged when 70 GDD above 7ºC (based on air temperatures) were accumulated since planting (Supit et al. 1994).

Phenological research on corn at Harrow (Tan and Fulton, 1980) and Ottawa (Dwyer and Stewart, 1986) has shown that 'full cover' occurs on average 72 days after planting, i.e. at approximately 45% of the average Crop Heat Unit (CHU) rating of 3500 at Harrow and approximately 60% of the average CHU rating of 2300 at Ottawa. A linear relationship between '% CHU to full cover' (PERC) and 'average available CHU to maturity (AVCHU)' was constructed:

$$PERC = 88.75 - 0.0125 \; AVCHU$$

Since AVCHUs were available for various climate stations (Bootsma and Brown 1995), we calculated the 'full cover' date based on eq. (4) and the actual annual accumulated CHUs since planting. Senescence of corn began when 85% of the AVCHUs were accumulated. For the soybean 'full cover' date we followed the same approach as for corn. Soybean senescence began when 80% of the AVCHUs were accumulated.

Corn harvest dates were based on the first occurrence of <-2 $^{0}$C or when the average daily mean air temperature was 12 $^{0}$C, whichever date came first. The soybean growing season ended when the minimum air temperature dropped to <0 $^{0}$C or when the long-term average mean daily air temperature was 15 $^{0}$C, whichever date was earlier (Bootsma and Brown, 1995).

Soil cover, used to partition potential evapotranspiration (PET) into its components potential transpiration and evaporation, increased sigmoidally from 0% at emergence to 95% at 'full cover', remained at 95% until senescence began and then decreased linearly to 55% (corn) or 30% (soybean) at the time of harvest (Doorenbos and Pruitt 1977). The rooting depth increased linearly from 0 cm at the planting date to a maximum value (Table 1) at the date of 'full cover'. The rooting depth remained constant between 'full cover' and harvest.

Winter wheat was planted either 5 days after the soybean harvest, or at the 'average' optimum seeding date (Bootsma et al., 1993), whichever came later during the year. Winter wheat emerged after 125 GDD were accumulated since planting (De Wijngaert, 1986). Between emergence and the onset of 'winter' (see above), crop cover increased as a function of crop development rate (Supit et al., 1994). The rooting depth increased linearly (starting at the planting date) at a rate of 1.2 cm $day^{-1}$ to a maximum of 30 cm prior to the beginning of 'winter'. There was no root growth nor phenological development during the winter. The start of winter wheat re-growth in spring was based on work done by Sly (1982). Soil cover with winter wheat increased sigmoidally from its value reached in the previous fall to 95% at 'full cover', remained constant until senescence began, and then dropped linearly to 25% at harvest (Doorenbos and Pruitt, 1977). The rooting depth of winter wheat increased linearly from its previous fall value to 100 cm at 'full cover' and stayed constant thereafter.

The starting date of the pasture growing season was the same as the start of winter wheat re-growth in spring. 'Full cover' occurred when 110 GGD (above 5°C) were accumulated since the start of the season (Selerio and Brown 1979). There was no senescence of the grass since it was assumed to be kept short by grazing animals. Following Aslyng and Hansen (1982), it was assumed that between 'full cover' and the growing season end (defined by Sly, 1982), 70% of potential evapotranspiration was potential transpiration and 30% was potential soil evaporation. From the growing season start until 'full cover', crop cover increased sigmoidally from 0.30 to 0.70. The rooting depth increased linearly from 30 cm at the beginning of the growing season to 50 cm at the date of 'full cover' and then remained constant till the end of the growing season.

### Tillage

With regular tillage (RT) practices we assumed that no crop residues covered the soil surface. In order to simulate conservation tillage (CT), 40% of the soil surface during the non-growing season was covered by crop residues (Laflen et al. 1981). This increased level of surface residues reduced the CN by 5%. Furthermore, based on work done by Coote and Malcolm-McGovern (1989) and Benjamin (1993), we assumed that CT changed the soil hydraulic properties of the upper soil horizon as follows: (i) the porosity decreased by 10% and (ii) the saturated hydraulic conductivity increased two-fold.

### Soil and weather input

SWATRE simulations were made for a locally dominant soil profile near each climate station (Table 2). Soil profile characteristics, such as water retention curves, hydraulic conductivity and texture, were obtained from soil survey data. Missing data were estimated using pedotransfer functions developed by Da Silva and Kay (1997) and Jabro (1992). A free draining profile with unit hydraulic gradient at 120 cm depth was assumed to be the lower boundary condition.

Daily weather data from 1961 to 1990, including maximum and minimum air temperature, precipitation and potential evapotranspiration (PET) were used as input from 13 climate stations in the Mixed Wood Ecozone (Table 2). Stations were selected on the basis of data availability and their proximity to agriculturally important regions.

### Output data

Daily SWATRE-computed values of canopy interception, surface runoff, soil water storage to a depth of 100 cm, actual evapotranspiration (AET) and drainage through 100 cm depth (as well as daily inputs of precipitation and PET) were accumulated on a growing season- and on an annual basis. The values thus produced were subjected to statistical analyses to determine means, standard deviations and values at probability levels ranging from 5 to 95%.

## RESULTS AND DISCUSSION

### General climate and soil characteristics

The annual precipitation across the Ecozone varied considerably from 1211 mm at Quebec City to 796 mm at Peterborough. In contrast, the range in annual PET was only 134 mm (Table 2). At all locations the annual precipitation exceeds PET. The precipitation surplus varied from 634 mm at Quebec City to 105 mm at Peterborough. Winter loss of precipitation due to evaporation and snow blowing in ditches and fence rows accounted for approximately 10% of the annual precipitation.

Soil physical characteristics were related to a limited extent to texture, which ranged from sand to clay. Coarser textured soils tended to have a higher saturated conductivity ($K_{sat}$) than finer textured soils, but there were notable exceptions (e.g. the Wiarton loam had a low $K_{sat}$ of 15 cm d$^{-1}$). Soil water holding capacity between saturation

**Table 2. Climate and soil characteristics at locations in the Mixed Wood Ecozone.**

| Location | Latitude | | Longitude | | Precipitation | | PET | Soil series | Texture | $K_{sat}$[†] | Water content at[‡] | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | annual | winter loss | annual | name | | cmd$^{-1}$ | 0 kPa | FC[§] | -1500 kPa |
| | ° | ' | ° | ' | | mm | | | | | | cm | |
| Quebec City | 46 | 48 | 71 | 23 | 1211 | 123 | 557 | Morin | SL | 241 | 44.9 | 19.7 | 2.6 |
| L'Assomption | 45 | 49 | 73 | 26 | 964 | 96 | 643 | Sainte-Rosalie | C | 65 | 48.0 | 30.3 | 24.8 |
| Ste Clotilde | 45 | 10 | 73 | 41 | 981 | 85 | 650 | Sainte-Jude | S | 236 | 44.9 | 19.9 | 3.4 |
| Cornwall | 45 | 01 | 76 | 45 | 955 | 76 | 623 | North Gower | CL | 159 | 54.5 | 37.7 | 28.9 |
| Ottawa | 45 | 23 | 75 | 43 | 870 | 71 | 630 | Brandon | CL | 191 | 38.6 | 28.1 | 22.8 |
| Brockville | 44 | 36 | 75 | 42 | 953 | 82 | 614 | Napanee | C | 69 | 42.5 | 36.4 | 31.5 |
| Peterborough | 44 | 14 | 78 | 21 | 796 | 66 | 691 | Otonabe | C | 41 | 41.7 | 27.0 | 9.4 |
| Wiarton | 44 | 45 | 81 | 06 | 1003 | 95 | 580 | Wiarton | L | 15 | 40.5 | 21.0 | 8.6 |
| Brucefield | 43 | 33 | 81 | 33 | 985 | 91 | 677 | Perth | CL | 7 | 48.0 | 38.0 | 35.0 |
| Guelph | 43 | 33 | 80 | 13 | 874 | 72 | 664 | Burford | L | 337 | 30.4 | 17.4 | 5.4 |
| Welland | 43 | 00 | 79 | 16 | 971 | 88 | 662 | Welland | C | 235 | 52.9 | 41.0 | 26.2 |
| London | 43 | 02 | 81 | 09 | 957 | 86 | 691 | Watford | SL | 442 | 43.4 | 23.7 | 7.1 |
| Harrow | 42 | 02 | 82 | 54 | 901 | 66 | 665 | Brookston | C | 100 | 52.4 | 40.0 | 22.9 |

[†] $K_{sat}$ was weighted by horizon thickness

[‡] Computed to a depth of 100 cm

[§] Field capacity of clays and clay loams were assumed to be at -30 kPa, coarser textures at -10 kPa and -1500 kPa, to a depth of 100 cm, ranged from 11.0 cm in the Napanee clay to 42.3 cm in the Morin sandy loam.

## Spatial Output data

Daily SWATRE-computed values of canopy interception, surface runoff, soil water storage to a depth of 100 cm, actual evapotranspiration (AET) and drainage through 100 cm depth (as well as daily inputs of precipitation and PET) were accumulated on a growing season- and on an annual basis. The values thus produced were subjected to statistical analyses to determine means, standard deviations and values at probability levels ranging from 5 to 95%

## Variability

The differences between the annual water balance components of a corn-soybean-winter wheat rotation and those of continuous corn were less than 5%, and consequently the latter data are not presented. Soil water contents on April 1 (Tables 3 and 4) varied significantly among all locations in response to local climate and soil conditions (Table 2), but differences between the three crop rotations were small. At all locations, except Quebec City, the water contents on April 1 were well above field capacity. Water contents at harvest time were approximately 20% lower than those in early spring (data not shown).

Interception of precipitation by the crops was fairly uniform among the locations (coefficient of variation < 10%). For the 3 year corn-soybean-winter wheat rotation, interception was about 35 mm year$^{-1}$, while for pasture, with a continuous crop cover all year round, it was about twice as high at each location.

Annual AET, drainage, and especially surface runoff, varied considerably among the locations. In the corn-soybean-winter wheat rotation, drainage, followed by AET, was the largest of these three components of the water balance, except at Peterborough, Welland, and Harrow. Drainage was significantly correlated with annual precipitation (r=0.76), but somewhat surprisingly, not with the soil profile averaged $K_{sat}$. There was less surface runoff, increased AET and decreased drainage from the pasture compared to the three year short growing season rotation. Spatial variability in AET and drainage among the two cropping systems was about the same, but the spatial

**Table 3. Spatial distribution of the annual components of the water balance for a corn - soybean - winter wheat rotation (averages over 1961 - 1990).**

| Location | Soil water[†] on April 1 | Interception | Surface runoff | Actual evapo-transpiration | Drainage |
|---|---|---|---|---|---|
| Quebec City | 191 | 38 | 114 | 364 | 563 |
| L'Assomption | 436 | 35 | 163 | 291 | 375 |
| Ste Clotilde | 222 | 39 | 52 | 384 | 420 |
| Cornwall | 469 | 37 | 70 | 344 | 427 |
| Ottawa | 292 | 36 | 32 | 273 | 457 |
| Brockville | 388 | 36 | 94 | 311 | 430 |
| Peterborough | 332 | 29 | 69 | 378 | 253 |
| Wiarton | 351 | 32 | 165 | 343 | 366 |
| Brucefield | 446 | 28 | 191 | 273 | 401 |
| Guelph | 182 | 32 | 35 | 345 | 390 |
| Welland | 458 | 36 | 76 | 394 | 376 |
| London | 251 | 34 | 46 | 364 | 427 |
| Harrow | 449 | 35 | 86 | 385 | 328 |

[†] To a depth of 100 cm

**Table 4. Spatial distribution of the annual components of the water balance for pasture (averages over 1961 - 1990).**

| **Location** | **Soil water† on April 1** | **Interception** | **Surface runoff** | **Actual evapo-transpiration** | **Drainage** |
|---|---|---|---|---|---|
| Quebec City | 193 | 71 | 18 | 449 | 541 |
| L'Assomption | 436 | 66 | 29 | 381 | 387 |
| Ste Clotilde | 225 | 70 | 4 | 466 | 354 |
| Cornwall | 469 | 68 | 7 | 416 | 387 |
| Ottawa | 293 | 66 | 2 | 357 | 373 |
| Brockville | 388 | 67 | 14 | 377 | 413 |
| Peterborough | 329 | 58 | 7 | 448 | 216 |
| Wiarton | 350 | 67 | 33 | 428 | 379 |
| Brucefield | 464 | 55 | 40 | 369 | 428 |
| Guelph | 182 | 62 | 2 | 414 | 323 |
| Welland | 459 | 69 | 8 | 463 | 342 |
| London | 252 | 65 | 3 | 433 | 370 |
| Harrow | 450 | 64 | 12 | 435 | 322 |

[†] To a depth of 100 cm

variability in annual runoff was considerably higher for the pasture system.

## Temporal variability

The temporal variability of selected water balance components for continuous corn at Ste Clotilde (Fig. 1) and Harrow (Fig. 2) are presented for the growing season (GS, planting to harvest) and the non-growing season (NGS). The variability in GS precipitation (between 5 and 95% cumulative probability, 331 mm at Ste Clotilde and 487 mm at Harrow) was much higher than that of PET (108 mm at Ste Clotilde and 100 mm at Harrow). As a result of the simulated interactions among soil and crop characteristics, the variability in AET (121 and 134 mm respectively at Ste Clotilde and Harrow) was slightly higher than that of PET. At both locations the average amount of precipitation was approximately equally divided among GS and NGS, but the temporal variability (i.e. between 5 and 95% probability levels) was higher during the GS, especially at Harrow. As a result, and because of high AET during the growing season, the simulated average soil water contents were lower, but more variable at harvest- as compared to planting time. More than 70% of the surface runoff and drainage occurred during the non-growing season. The temporal variability of these two components of the water balance was higher during the non-growing season at Harrow (about 100 mm for surface runoff and about 180 mm for drainage). However, both surface runoff and drainage variability at Ste Clotilde were significantly higher during the non-growing season (9 vs. 82 mm for runoff; 132 vs. 225 mm for drainage).

## Tillage effects

Increasing the relative soil cover to a minimum value of 40% as a result of practicing conservation tillage directly affected the amount of precipitation intercepted. This, and the reduced CN used for conservation tillage, reduced surface runoff by approximately one third at L’Assomption and by approximately one half at Ottawa and Guelph (Table 5). As a consequence annual soil infiltration increased by about 15 mm under CT at L’Assomption, but decreased by about 15 mm at Ottawa and Guelph. At all three locations AET was reduced by approximately 50 mm. Conservation tillage increased drainage by 28 mm at L’Assomption, but had no effect on drainage at Ottawa and Guelph. Soil water contents at planting and ‘full cover’ were reduced under CT.

# CONCLUSIONS

The Mixed Wood Ecozone has a relatively high degree of spatial and temporal variability in climatic conditions. The soil conditions also vary quite dramatically over space with respect to the soil hydraulic properties. The combination of these factors, as simulated by the SWATRE model, results in highly variable individual water balance components. Crop rotation practices had little influence on the magnitude of the water balance components, but there was less surface runoff and less drainage from continuous pasture as compared to the annual crops. Compared to regular tillage, conservation tillage increased interception by about 50%, reduced surface runoff and evapotranspiration, but had little effect on drainage.

**Table 5. The effect of tillage on the water balance components for continuous corn at L'Assomption, Ottawa and Guelph.**

| Variable | Tillage† | Location | | |
|---|---|---|---|---|
| | | L'Assomption | Ottawa | Guelph |
| | | | mm | |
| Soil water at planting | RT | 444 | 298 | 173 |
| | CT | 397 | 271 | 146 |
| Soil water at‘full cover’ | RT | 400 | 270 | 114 |
| | CT | 371 | 258 | 105 |
| Interception of precipitation | RT | 36 | 38 | 34 |
| | CT | 69 | 70 | 66 |
| Surface runoff | RT | 161 | 31 | 33 |
| | CT | 112 | 14 | 16 |
| Actual evapo-transpiration | RT | 289 | 296 | 362 |
| | CT | 240 | 247 | 312 |
| Drainage | RT | 377 | 434 | 373 |
| | CT | 405 | 436 | 374 |

†Compared to regular tillage (RT), conservation tillage (CT) is defined by a minimum relative soil cover of 0.40, CN is reduced by 5%, $\theta_{sat}$ is reduced by 10% and $K_{sat}$ is increased two-fold.

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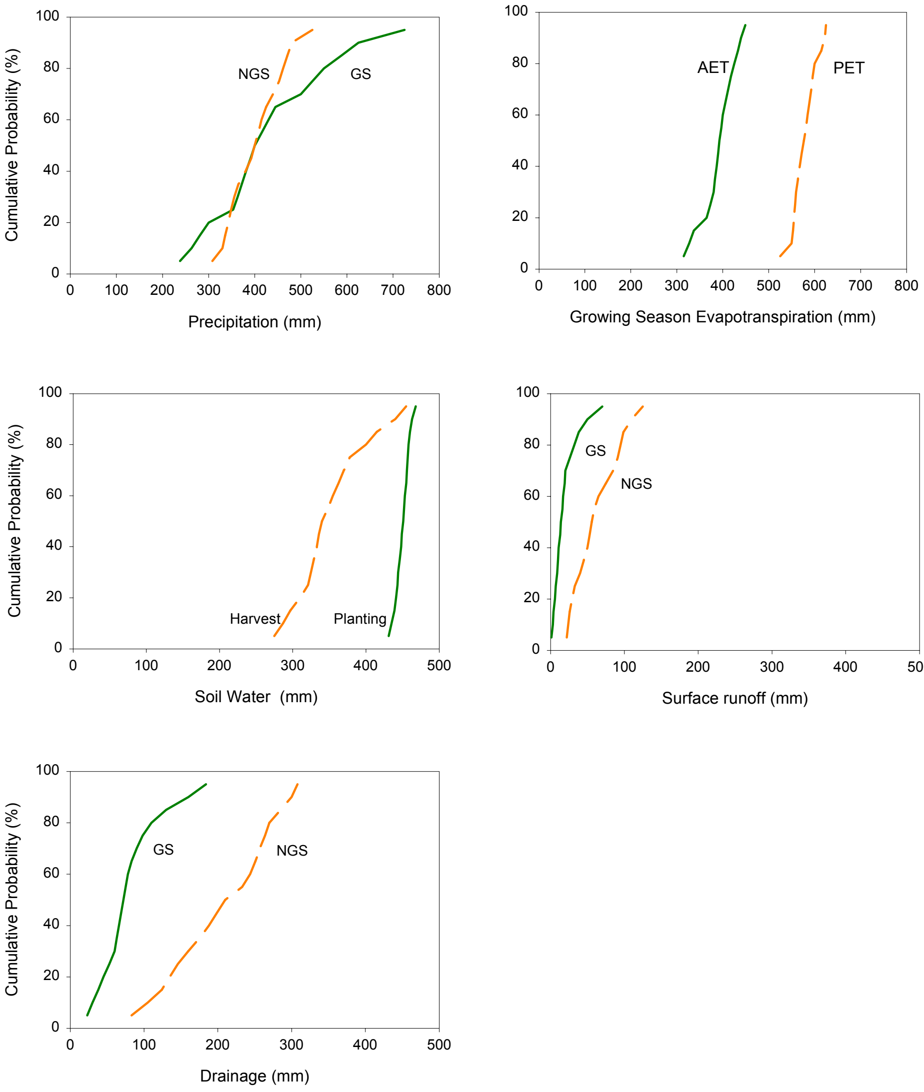

Fig. 2. The temporal variability in water balance components of continuous corn at Harrow (GS - Growing Season data; NGS - non-growing season data).

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