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METHODOLOGY AND APPLICATION OF A STATISTICAL APPROACH TO THE UNIVERSAL SOIL LOSS EQUATION (USLE): WELLAND RIVER CASE STUDY

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ABSTRACT: The Welland River watershed drains an area of 880 km^2 and is part of the Niagara River Area of Concern. As one step towards remediation, the Universal Soil Loss Equation (USLE) was used to estimate soil erosion inputs to the river from each of the 34 sub-basins in the watershed. An innovative approach using risk and uncertainty analysis was incorporated into the conventional USLE estimates in order to address concerns about uncertainty due to the variability of the USLE parameters across the Welland River watershed. This paper describes the methodology for the statistical approach to the USLE and those sub-basins with high potential soil loss were identified.

INTRODUCTION

The Welland River watershed is part of the Niagara River Area of Concern. Areas of Concern around the Great Lakes have been designated by the International Joint Commission (IJC) as exhibiting various environmental impairments. The impairments in the Welland River watershed include bed sediment contaminated by heavy metals and organic compounds, and loss of habitat due to channel modifications and siltation from soil erosion (Environment Canada et al., 1996). In the mid 1980's investigations carried out by Brock University researchers and Acres International Limited (Acres) on behalf of Atlas Specialty Steels (Atlas), identified contaminated bed sediments in a 1.25 km stretch of the lower Welland River that had experienced historical discharges from Atlas and other local industries (Environment Canada et al., 1996). Furthermore, Stone and Saunderson (1996) investigated the relationship between sediment yield and drainage area for 92 Canadian watersheds in the Great Lakes basin and found that the Welland River had the second highest sediment yield.

As part of a larger study to identify options to improve habitat and reduce sediment loads in the Welland River, the Univeral Soil Loss Equation (USLE) was used to estimate soil erosion rates for each of the 34 sub-basins in the watershed. A risk and uncertainty analysis (including probability distribution fitting and simulations using Latin Hypercube sampling) was incorporated into the conventional USLE estimates and was performed using BESTFIT and @RISK, which are EXCEL spreadsheet add-ins. The objective of this paper is to describe the procedure of applying Geographic Information System (GIS) techniques and risk and uncertainty analysis to standard USLE estimates of soil erosion, using the Welland River watershed as a case study.

STUDY APPROACH

Welland River Watershed Description

The headwaters of the Welland River are in the Hamilton, Ontario region near Mount Hope and the river flows eastward from here, towards the Niagara River. Agricultural land use dominates the watershed. The soil of the basin is classified almost entirely as Haldimand Clay Loam. The drainage of this soil is imperfect and there is a tendency for fine particles to be washed into watercourses from exposed or unvegetated areas. The city of Welland is the largest urban centre (population of approximately 50,000), but several small rural communities are located along the river floodplain. Numerous tributaries intersect the river and hence subdivide the Welland River watershed into 34 sub-basins (Figure 5).

The Welland River drainage area is 880 km^2 and is approximately 132 km long. The upper tributaries of the river have gradients of 0.30% to 0.50% and normally are dry in the summer. The lower 74 km of the river has a lower gradient with a total fall of only 7.6m. The river historically was used as a shipping canal and was dredged from the outlet at the Niagara River to Port Davidson, a distance of 58 km. The river was rerouted during the construction of the new shipping canal in 1973 near Port Robinson. The old channel still exists and is fed by water from the shipping canal. The Welland River from the Niagara River to the Power Canal (where the flow direction is reversed) was dredged in the 1920's, creating what is locally known as the Chippawa Creek. Subsequent power developments on the Niagara River further altered natural conditions for the lower Welland River. No other recent dredging activities in the river are known (Environment Canada et al., 1996).

The Binbrook dam and reservoir (also known as Lake Niapenco) was constructed on the river near Binbrook (approximately 9.5 km downstream from the headwaters) by the Niagara Peninsula Conservation Authority in the 1970's. The dam was created for the purpose of low flow augmentation as the river often experienced periods of zero flow during drought conditions. In the mid-1970's a weir was constructed at the western end of the reservoir by Ducks Unlimited for the purpose of waterfowl management (Environment Canada et al., 1996)

Within the city of Welland the river historically has been diverted into a series of five pipes called the aqueduct or old syphon. Currently, there are 14 holes (70 cm each in diameter) cut through the bottom of the Welland Canal and into the syphons to hydraulically connect the canal to the river (i.e. the river flows through the syphon, perpendicular to and *under* the canal). Flow from the canal typically augments the river flow through this connection. The river subsequently flows easterly to its junction with Chippawa Creek where flows are diverted to the Chippawa/Queenston Power Canal. The final outlet of Welland River water is the lower Niagara River through the Sir Adam Beck hydropower generating stations. Ontario Hydro controls the flow within the Chippawa Creek, through management of the water levels at the Grass Island Pool on the Niagara River and at the forebays for the Sir Adam Beck generating stations (Environment Canada et al., 1996). The flow within the Welland River clearly has been extensively influenced by society's activities.

Background on the Universal Soil Loss Equation (USLE)

The USLE is a general multiplicative equation which estimates total soil loss as a result of sheet erosion and provides guidance in selecting adequate erosion-control practices for agricultural lands and small construction areas (Smith and Wischmeier, 1962; Mitchell and Bubenzer, 1980; Foster et al., 1981). The USLE has the general form:

[1] $A = R \bullet K \bullet LS \bullet C \bullet P$

where:
- A is the average annual soil loss (tonnes· hectare^{-1})
- R is the rainfall erosivity factor (megajoule·millimeter (hectare·hour)$^{-1}$) which is a measure of the erosive potential of average annual rainfall in the locality
- K is the soil erodibility factor · tonnes · hectare · hour· (hectare·megajoule·millimeter), a measure of the soil's ability to resist erosion
- LS is the length-steepness factor (dimensionless), which normalizes the soil loss estimate to the specific slope length and per cent steepness existing on the field
- C is the cover and management factor (dimensionless); the expected ratio of soil loss from land cropped under specified conditions to soil loss from clean-

tilled fallow land with identical soil and slope and under the same rainfall

- P is the support practices factor (dimensionless), that takes into account the erosion-control benefits gained by conservation practices such as farming on the contour, strip cropping, or combining terraces with contouring

In this study the USLE was applied at the sub-basin rather than the field scale for which the equation originally was developed (Smith and Wischmeier, 1962). Single representative values were used to operationalize the USLE for each sub-basin, and as such, this study may be considered a planning level type study.

Methodology for the Determination of USLE Parameters

Rainfall erosivity factor, R

Hourly rainfall depth and daily 30-minute maximum rainfall intensities of the past 25 years, 1970 to 1995, for the Mount Hope/Hamilton Airport raingauge station were obtained from Environment Canada's, Ontario Climate Centre (Downsview, Ontario). The hourly rainfall depth was converted into hourly rainfall intensities (units in mm hr^{-1}) and then kinetic energy was calculated as (after Foster et al., 1981):

$$[2] \qquad E = 0.119 + 0.0873\log_{10}(I)$$

where,
- I is the intensity in mm hr^{-1}

The kinetic energies were then summed for each storm event of each day. These daily summed energies were then multiplied by the corresponding daily 30-minute maximum rainfall intensity to calculate the rainfall event R-values according to the equation:

$$[3] \qquad R = EI_{30}$$

where,
- E is the summed value of all kinetic energies for the respective day (megajoule$\cdot ha^{-1}$)
- I_{30} is the daily maximum 30-minute rainfall intensity (mm hr^{-1})

The R-values for each year were summed for the months April 1 to December 31 to arrive at the annual R-value. Hence, 25 annual R-values were determined. These annual R-values were then adjusted to accomodate the effect of winter conditions according to the methodology described by Wall et. al., (1983). The adjusted R-values were averaged for the 25 years in order to arrive at one representative R-factor for the entire Welland River watershed.

Soil erodibility factor, K

Digital soil surveys were obtained for the Regional Municipalities of Niagara, Haldimand-Norfolk, and Hamilton-Wentworth from the Ontario Ministry of Agriculture, Food and Rural Affairs (OMFRA), Resources and Planning Branch. With the use of a personal computer (PC) ARC/INFO GIS, the soil surveys were intersected and clipped with a digital coverage of the Welland River watershed and associated sub-basins. The area of each soil and watershed polygon also was determined in the previous step. The new attribute table was then imported into DBASE IV where a small macro program was run in order to assign published K-values (e.g. Wall et al., 1984; Shelton and Wall, 1989) to each of the soil type area polygons according to the dominant soil type and texture attributes (Niagara and Hamilton-Wentworth) or soil type symbol (Haldimand-Norfolk) already present in the database table. A spatially weighted average K-value (based on area and individual K values for each soil) was then calculated to represent the single K-value for each sub-basin.

Length-steepness factor, LS

Initially, the field lengths and slope steepness for randomly selected sites were determined from maps and aerial photographs. These data could not be determined using the GIS since digital topographic maps were not available for this study.

The Welland River watershed is comprised of approximately 61, 1;10,000 Ontario Base Map Sheets. With the use of a random numbers table, four points were randomly selected on each map sheet. Those map sheets with only small portions of the Welland River watershed were randomly sampled with fewer points and random points within the sheet were selected until they fell within the boundaries of the watershed. At each of these points, the slope (expressed as a %) was then calculated from spot elevations indicated on the map sheet.

The lengths of the nearest fields to the corresponding randomly selected points used above were measured from 1:5,000 air photo mosaics for the Regional Municipalities of Niagara and Hamilton-Wentworth and 1:10,000 air photo mosaics for the Regional Municipality of Haldimand-Norfolk in order to arrive at the length coefficients.

The slope steepness and field length for each of the 171 sampled points subsequently were entered into a length-steepness nomograph (Plaster, 1992) to arrive at a final length-steepness factor. These length-steepness values were then averaged for each sub-basin in order to arrive at one representative length-steepness factor for each sub-basin of the Welland River watershed.

Cover and management factor, C

Digital land use maps (1983 compilation date) for the Regional Municipalities of Niagara, Haldimand-Norfolk, and Hamilton-Wentworth were obtained from OMFRA. The digital land use coverages were intersected with a digital coverage of the Welland River watershed and associated sub-basins using the PC ARC/INFO GIS. The area of each land use and watershed polygon was determined following the approach discussed above for the soil erodibility factor. Again, the remaining attribute table was imported into DBASE IV where a small macro program was run in order to assign C-values (obtained from Wall et al., 1984 and Shelton and Wall, 1989) according to the land use codes already present in the attribute database. A spatially weighted average C-value (based on area and individual C values for each land use) was then calculated to represent the single C-value for each sub-basin.

Support practice factor, P

The digital land use/watershed coverage created in the above step also was used to determine one representative P-factor for each sub-basin. A small macro program was again run in DBASE IV where published P-values (obtained from Wall et al., 1984 and Shelton and Wall, 1989) were assigned according to the land use codes already present in the database and after discussions with Niagara OMFRA personnel (J. Winnicki, pers. comm.). A spatially weighted average P-value (based on area and individual P values for each land use) was then calculated to represent the single P-value for each sub-basin.

Risk and Uncertainty Analysis

Although single "representative" values were used to operationalize the USLE for each sub-basin, it can be envisioned that there would be some distribution of values around each representative value (e.g. in some wet years the rainfall erosivity factor would be greater than in some dry years). Risk analysis was employed to quantify the uncertainty inherent in the application of the USLE as outlined above. The BESTFIT and @RISK software, which are EXCEL spreadsheet add-ins (Palisade Corporation, 1996), were used in the risk analysis.

The first step in risk analysis is to identify those parameters in the model for which there is uncertainty (i.e. those parameters that might be fit with some probability distribution). Given the sample values for the model parameter, 25 theoretical distributions can be tested for goodness of fit using the BESTFIT software.

Once the appropriate probability distributions were determined for each factor of the USLE, simulations were run (using the USLE and distributions in @RISK) to determine the range and probabilities of possible outcomes. Past experience with @RISK (Irvine, 1995) suggested that at least 5,000 sample iterations be run for the simulation, using Latin Hypercube (as opposed to Monte Carlo) sampling. Latin Hypercube sampling is a recent development in sampling approach and is designed to accurately recreate the input distribution through sampling in fewer iterations as compared to the Monte Carlo method. The key to

Latin Hypercube sampling is stratification of the input probability distributions. Stratification divides the cumulative probability curve into equal intervals and a sample is then randomly taken from each interval or "stratification" of the input distribution (Figure 1). Sampling is forced to represent values in each interval and problems of clustering that may produce unrepresentative results under the Monte Carlo scheme are avoided (Palisade Corporation, 1996).

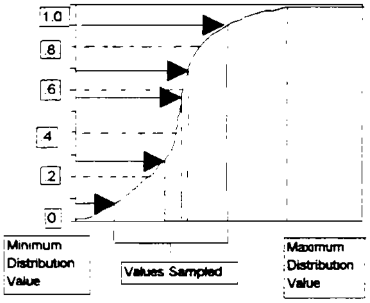

Figure 1 Schematic of the Latin Hypercube sampling methodology, using a five iteration example (after Palisade Corporation, 1996).

RESULTS AND DISCUSSION

Based on the Kolmogorov-Smirnov (K-S) test, BESTFIT indicated that the log normal distribution fit the adjusted annual R-factor values the best. The log normal distribution was satisfactory in representing the distribution of the annual R-factor values as it is able to be applied to quantities that are the product of a large number of other quantities as was the case with the annual R-factor values (Palisade Corporation, 1996). In addition, the log normal distribution holds the R-factor values above zero, while some distributions selected as appropriate by BESTFIT were not constrained to positive values. It also has been reported that the normal distribution has been extensively employed in stochastic hydrology (Phien et al., 1982). A more simplistic triangular distribution was used for the K, C, and P-factors because they already were spatially weighted. BESTFIT therefore was not used to fit distributions for these variables. To operationalize the triangular distribution in @RISK simulations, only the "minimum", "most likely", and "maximum" values of the variable are needed. The spatially averaged LS-factor for each sub-basin was used in the simulation as there were not enough data available to fit a distribution. Ongoing research is expanding the number of sample points for the LS-factor in each sub-basin. Future simulations with @RISK will include the LS-factor variability when these additional data have been collected. In general, however, the watershed has limited relief and the current representation of the LS factor in the simulation is reasonable for planning level purposes. The following are the range of values across the entire watershed that the R, K, C, and P-factors were sampled from:

- the R-factor ranged from 634.64 to 3350.50 MJ·mm/ha·hr,
- the K-factor ranged from 0.0237 to 0.0342 t·ha·hr/ha·MJ·mm,
- the C-factor ranged from 0.002 to 0.75,
- the P-factor ranged from 0.50 to 1.00.

Sensitivity analysis can be done in @RISK using Spearman Rank Correlation between the output values and each set of sampled input values. Higher correlation coefficients are indicative of input variables that have a greater impact on the simulation. Results of the sensitivity analyses showed that the R-factor and the C-factor had the greatest impact on the estimated potential soil loss (e.g. Figure 2). Hence, the vegetative cover and crop management within the watershed should be evaluated for best management practices that could be implemented in order to reduce potential soil loss.

Cumulative probability graphs and relative frequency distributions of potential soil loss were produced for each of the sub-basins (e.g. Figures 3 and 4). The cumulative probability graph can be used to make probabilistic statements about the amount of potential soil loss that is likely to occur and can be used for comparison between basins. For example, comparing West Wolf Creek sub-basin and the Coyle Creek sub-basin, there is a 0.5 probability in any given year that less than 9

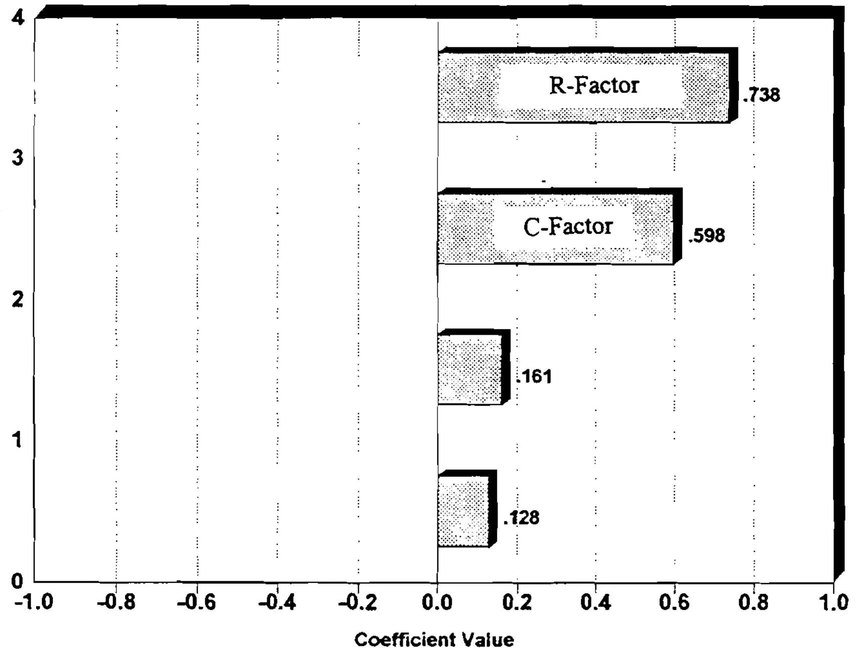

Figure 2 Sensitivity analysis output for the West Wolf sub-basin. Shown are the Spearman Rank Correlation values in the form of a "Toronado Diagram".

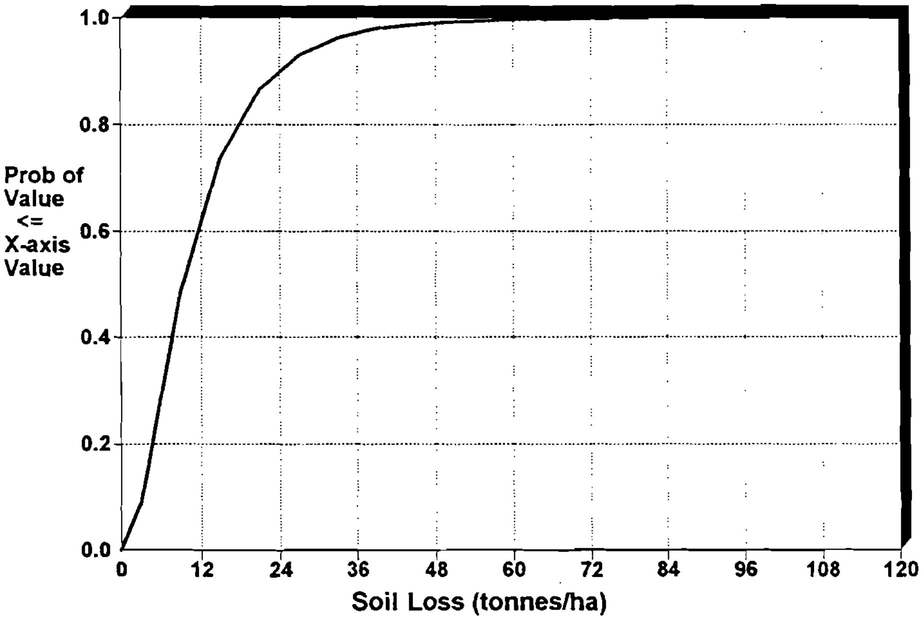

Figure 3 Cumulative probability distribution of annual soil loss for West Wolf sub-basin, based on a simulation of 8,000 iterations, using Latin Hypercube sampling.

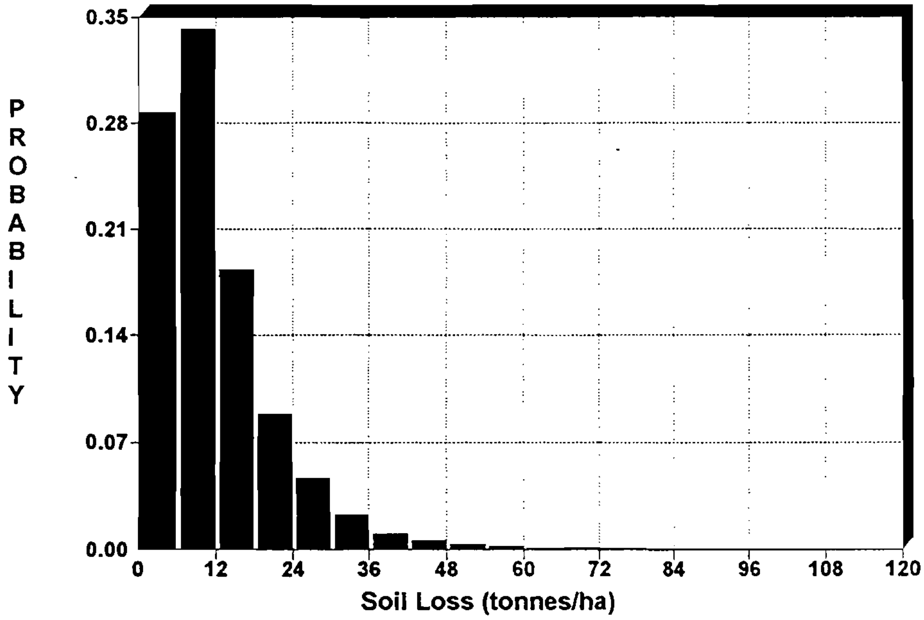

Figure 4 Relative frequency distribution of annual soil loss for West Wolf sub-basin, based on a simulation of 5,000 iterations, using Latin Hypercube sampling.

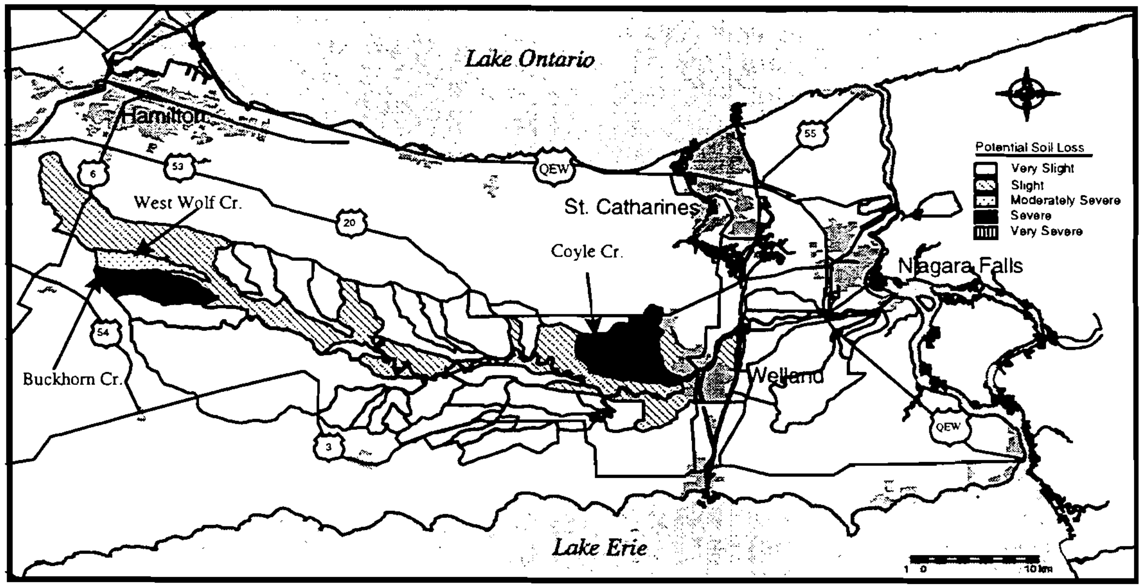

Figure 5 Potential soil loss for each sub-basin of the Welland River watershed.

Table 1 Guidelines for Assessing Soil Erosion Potential Classes (after Shelton and Wall, 1989)

Soil Erosion Potential Classes	Potential Soil Loss (tonnes/ha/year)
1. Very Slight	< 6
2. Slight	6 - 11
3. Moderately Severe	11 - 22
4. Severe	22 - 33
5. Very Severe	> 33

tonnes/hectare of soil loss will occur in the West Wolf Creek sub-basin while in the Coyle Creek sub-basin there is a 0.5 probablility for any given year that soil loss would be less than 26.5 tonnes/hectare.

Figure 5 is the resultant GIS product showing the potential soil loss of each sub-basin, based on the results of the single representative values calculated to operationalize the @RISK simulations and the soil loss classification scheme outlined in Table 1.

The majority of the sub-basins experience only very slight potential soil loss while the main floodplain area of the Welland River watershed experiences slight potential soil loss. Field observations have indicated that this floodplain may experience higher soil loss as a result of the lack of grass buffer strips, cattle grazing in and beside the river channel and may, in combination with failed septic systems, also produce high bacteria levels (Attema and Forsey, 1996). Only one sub-basin experiences moderately severe erosion, West Wolf Creek sub-basin, and two sub-basins experience severe potential soil loss; Buckhorn Creek and Coyle Creek sub-basins. These sites of higher erosion, including the main floodplain, should be the focus for best management practices.

Our "best" estimate of total potential soil loss within the entire Welland River watershed is 812,542 tonnes/year. Stone and Saunderson (1996) calculated average suspended sediment load for the upper 230 km^2 of the Welland River watershed to be 43,950 tonnes/year. Our best estimate of soil loss using the USLE for approximately the same area is 219,868 tonnes/year. Hence, the sediment delivery ratio can be estimated at 20%.

CONCLUSION

The use of the USLE within the Welland River watershed has allowed for the identification of those sub-basins with higher potential soil loss. Hence, focus for best management practices may be placed on those sub-basins with increased soil loss. As displayed by Figure 5, ARC/INFO allowed a good visual summary of the high potential soil loss areas. Ongoing research will refine soil delivery ratio estimates using suspended sediment data that have been collected by the Water Survey of Canada at several sites in the watershed during the past year. The soil loss information also could be used as input to hydraulic models for the study of channel transport and deposition patterns.

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