Spatial interpolation of snow depth and water equivalent measurements in Prince Edward Island, Canada

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¹Crops & Livestock Research Centre, Agriculture & Agri-Food Canada, Charlottetown, PEI, Canada C1A 7M8; ²Department of Physical Geography, University of Trier, 54286 Trier, Germany; ³Department of Statistics, City of Koblenz, Koblenz, Germany; ⁴Biological Engineering, Dalhousie University, Halifax, NS, Canada B3J 2X4; ⁵Civil Engineering, Dalhousie University, Halifax, NS, Canada B3J 2X4; and ⁶Atlantic Veterinary College, University of Prince Edward Island, Charlottetown, PEI, Canada C1A 4P3. Received 26 September 1997; accepted 13 July 1998.

Edwards, L., Bernsorf, B., Pauly, M., Burney, J.R., Satish, M.G. and Brimacombe, M. 1998. Spatial interpolation of snow depth and water equivalent measurements in Prince Edward Island, Canada. Can. Agric. Eng. 40:161-168. Snowmelt is the cause of more than one-half of the total annual soil erosion from arable land on Prince Edward Island (PEI). Thus, as part of a wider study on cool-period soil erosion, this study was conducted to assess the application of kriging for extrapolating snowcover measurements spatially over arable PEI land and for eventual use in soil erosion models. Snow cover was randomly sampled for depth and density. Sample-sites were geo-referenced and located on the ground with the aid of a Global Positioning System (GPS). Documentation of the results was cartographic and was aided by a Geographic Information System (GIS). This procedure was found to be applicable to the existing data set. Keywords: snowmelt erosion, snow distribution, Global Positioning Systems, Geographic Information Systems, kriging.

La fonte des neiges cause plus de la moitié de l'érosion totale annuelle des sols de l'Île-du-Prince-Édouard. Cette étude, qui fait partie d'une étude plus vaste sur l'érosion des sols lorsque les températures sont froides, examine la possibilité d'utiliser le krigeage pour estimer les variations spatiales de la couverture de neige sur les sols arables de l'Île-du-Prince-Édouard et éventuellement d'utiliser ces données dans des modèles d'érosion des sols. On a échantillonné la couverture de neige au hasard afin d'en mesurer l'épaisseur et la densité. Les sites d'échantillonnage ont été géo-référencés et leur position au sol a été déterminée avec un système de positionnement global (GPS). Les résultats sont présentés sur des cartes préparées avec un système d'information géographique (SIG). La procédure utilisée semble s'appliquer aux données existantes. Mots-clés: érosion, fonte des neiges, distribution de la neige, système de positionnement global, système d'information géographique, krigeage.

INTRODUCTION

More than one-half of the annual soil loss from Prince Edward Island (PEI) farmland occurs under the influence of snowmelt (Burney and Edwards 1995). Snow depth and snow density and their spatial distribution in any particular winter are, therefore, important components of any system or model that attempts to examine, compute, or enhance the understanding of the local erosivity factor. At present, the only reliable historic data in PEI that can give an indication of snowmelt erosive potential are snowfall records for the Charlottetown airport and it is clear, from field observations, that there would be severe limitations to the usefulness of these airport data if any attempt was made to apply them elsewhere in the province. The derivation of snowcover data for the arable lands of the province requires, however, a distribution-assessment method that is both quick and reliable. This study is aimed, therefore, at identifying a suitable method of point sampling, interpolation, and spatial documentation.

This study relates to an ongoing program of studies, monitoring, and research that include the application of a Geographic Information System (GIS) (Burough 1987) for predicting soil erosion risk on PEI farmland, laboratory assessment of freeze/thaw effects on soil aggregates (Edwards 1991) and interrill erosion (Edwards and Burney 1987, 1991), field and laboratory measurement of cool-period erosion due to rilling (Frame et al. 1992; Burney and Edwards 1993; Leyte et al. 1997), and the modelling of year-round soil erosion in arable watersheds on PEI (Burney and Edwards 1994, 1996).

The objective of this study was to assess the application of kriging for extrapolating snowcover data spatially over arable PEI land and for eventual use in soil erosion models.

MATERIALS and METHODS

The objective of the sampling procedure was to generate sampling points at random in order to meet the criterion of minimum bias for data analysis. Since it was convenient to generate and characterise these sampling points by geo-references, a quick and accurate system had to be found to locate these sites on the ground.

Site selection and field procedure

The random selection of possible sites was facilitated by a computer program which generated sampling points using the Stratified Systematic Unaligned Sampling (SSUS) approach (Dixon and Leach 1977). This is a common approach to sampling-site selection which facilitates the conversion of point data to area data by modelling. Firstly, in this study, a population of potential sampling sites was developed using a geographic grid of PEI in steps of 5 min. This produced 91 possible land-based quadrats within each of which sampling points were randomly selected (computer aided).
PRINCE EDWARD ISLAND - SNOW COVER MEASUREMENT PROJECT
April 4th/5th, 1996

Methods of Interpolation: Block-Kriging (GeoEAS) and Topogrid (Arc/Info 7.04)

Snow Depth

Legends
Snow Depth (cm)
- bare (no snow cover)
- > 0.0 - 3.0
- > 3.0 - 6.0
- > 6.0 - 9.0
- > 9.0 - 12.0
- > 12.0 - 15.0
- > 15.0 - 18.0
- > 18.0

Variance

Variance (% of Snow Depth)
- 0.0 - 10.0
- > 10.0 - 20.0
- > 20.0 - 30.0
- > 30.0 - 40.0
- > 40.0 - 50.0
- > 50.0 - 100.0
- > 100.0 - 150.0
- > 150.0 - 200.0
- > 200.0 - 500.0
- > 500.0

Sampling Positions

Fig. 1. Distribution (GIS-aided) of snow depth and variance for Prince Edward Island for April 4/5, 1996 based on interpolation of randomly selected sampling points (GPS-navigated).

Sampling points were located on the ground using a Global Positioning System (GPS) procedure described by Bernsdorf and Weidemann (1997). Only points on arable land were used in order to avoid the added problem of snowfall interception associated with forests. Thirty nine sites were selected.

GPS equipment was supplied by Cansel Survey Equipment\(^1\) which, together with Trimble Navigation Ltd\(^1\), provided training which facilitated the establishment of an in-house

\(^1\)This is not a commercial endorsement of any company or brand.
Methods of Interpolation: Block-Kriging (GeoEAS) and Topogrid (Arc/Info 7.04)

Water Equivalent

Variance

Sampling Positions

Legends

Water Equivalent (mm)

\[ > 0.0 - 2.8 \]
\[ > 2.8 - 5.6 \]
\[ > 5.6 - 8.4 \]
\[ > 8.4 - 11.2 \]
\[ > 11.2 - 14.0 \]
\[ > 14.0 - 16.7 \]
\[ > 16.7 - 19.5 \]
\[ > 19.5 - 22.3 \]
\[ > 22.3 \]

Variance (% of Water Equivalent)

\[ 0.0 - 10.0 \]
\[ > 10.0 - 20.0 \]
\[ > 20.0 - 30.0 \]
\[ > 30.0 - 40.0 \]
\[ > 40.0 - 50.0 \]
\[ > 50.0 - 100.0 \]
\[ > 100.0 - 150.0 \]
\[ > 150.0 - 200.0 \]
\[ > 200.0 - 500.0 \]
\[ > 500.0 \]

Fig. 2. Distribution (GIS-aided) of water equivalent and variance for Prince Edward Island for April 4/5, 1996 based on interpolation of randomly selected sampling points (GPS-navigated).

technical procedures protocol. After having located the sampling sites, positions were marked on the ground for sampling.

Snow depth was measured with a graduated, aluminium probe having an inside diameter of 37 mm (cross-sectional area of 1075 mm²). This equipment was also used to collect snow samples. The samples were transferred in the field to lidded 4-L plastic buckets, brought to the laboratory, and melted for snow density and water equivalence determinations.
2y(x,h) = E[Z(X) - Z(x + h)Y]

where:
E = expectation
x = spatial location,
h = vector, and
Z() = random variable value at argument location.

Assuming that the variogram function depends only on the separation vector, h, (which implies second order stationarity in Z) an estimator is given by:

2y*(h) = \frac{1}{N(h)} \sum_{i=1}^{N(h)} [z(x_i) - z(x_i + h)]^2

where:
x_i = location of observed value,
z ( ) = value of the variable at argument location, and
N(h) = number of pairs of values.

If the variable is reasonably isotropic, y*(h) is independent of direction and depends only on the modulus of the lag, h. Additionally, a continuous and smooth increase in y*(h) for a range (r), where 0 ≤ h ≤ r, indicates structural stability (dependency) in the variance to which a model may be fitted for later interpolation. Where these attributes existed, estimation of variable values at unsampled locations was achieved by the geostatistical analysis procedure known as kriging, a spatial regression tool used successfully by Hosseini et al. (1993, 1994) in the study of soil characteristics. Kriging was selected from among several interpolation methods (Cooke et al. 1993) examined for suitability. Based on the aforementioned and other reported experiences with kriging (Ahmed and De Marsily 1987; Voltz and Goulard 1994), ordinary kriging was selected for application to this study's data set.

Since project start-up on March 20, 1996, the only snowfall that accumulated was on April 4 and depth and density measurements were taken over a two-day period (April 4 and 5). The snow fell on bare ground; thus, all samples consisted of freshly fallen snow.

**Data computation and organisation**

The principal variables measured or computed were: (i) snow depth (cm); (ii) water equivalent (WE) (mm), calculated by dividing the average volume of melted snow (mL) times one thousand, by the cross-sectional area of the probe (1075 mm²); and (iii) snow density, calculated by dividing WE (mm) by snow depth (mm).

The data were organised for the above variables and then subjected to statistical analysis for area distribution of the observed point data to suit a GIS model for mapping. The principle objective was to estimate values for unsampled locations to achieve continuous area mapping. The variables were modelled for the whole province and separately for Queens County which had a relatively intense data set that was deemed worthwhile for separate testing.

Variable values were initially subjected to variogram analysis to seek to model differential variance as a function of distance and direction from the measured sites. The variogram function defined by Journel and Huijbregts (1978) is:

\[ 2y(x,h) = E\left[\left(Z(x) - Z(x + h)\right)^2\right] \]

\[ 2y^*(h) = \frac{1}{N(h)} \sum_{i=1}^{N(h)} [z(x_i) - z(x_i + h)]^2 \]

where:
E = expectation
x = spatial location,
h = vector, and
Z() = random variable value at argument location.

Assuming that the variogram function depends only on the separation vector, h, (which implies second order stationarity in Z) an estimator is given by:

Fig. 3. Semi-variograms of snow depth, water equivalent, and snow density (April 4/5 1996) based on randomly selected sampling points (GPS-navigated).
PRINCE EDWARD ISLAND - SNOW COVER MEASUREMENT PROJECT
April 4th/5th, 1996
Queens-County
Methods of Interpolation: Block-Kriging (GeoEAS) and Topogrid (Arc/Info 7.04)

Legend
Snow Depth (cm)
- bare (no snow cover)
- > 0.0 - 3.0
- > 3.0 - 6.0
- > 6.0 - 9.0
- > 9.0 - 12.0
- > 12.0 - 15.0
- > 15.0

Variance (% of Snow Depth)
- 0.0 - 0.2
- > 0.2 - 0.4
- > 0.4 - 0.6
- > 0.6 - 0.8
- > 0.8 - 1.0
- > 1.0 - 1.5
- > 1.5 - 2.0
- > 2.0 - 5.0
- > 5.0 - 10.0
- > 10.0

Sampling Positions

Fig. 4. Distribution (GIS-aided) of snow depth and variance for Queens Country (April 4/5, 1996) based on interpolation of randomly selected sampling points (GPS-navigated).

In kriging, the estimated value of a variable, \( z^*(x) \), at an unsampled location, \( x \), is obtained from neighbouring observed values, \( z(x_i) \), within the applicable variogram model range \( r \) as:

\[
z^*(x) = \sum_{i=1}^{n} \lambda_i z(x_i)
\]
Fig. 5. Distribution (GIS-aided) of water equivalent and variance for Queens county for April 4/5, 1996 based on interpolation of randomly selected sampling points (GPS-navigated).

where:
\[ \lambda_i = \text{weighting value, based on spatial covariance, which minimises estimation variance, and} \]
\[ n = \text{number of observed values.} \]

The approach to data analysis used here is one that adds to the GIS tool box a spatial analysis tool for exploring and modelling patterns of space dependency (snowcover distribution patterns on the ground) between the available ungrided data. However, just as there is no unique or optimal
sequence in using GIS as a tool for interpolation, there is no unique geostatistical approach to spatially distributing data such as were obtained in this study. Alternatives include weighted λ values inversely based on distance (Hosseini et al. 1993); however, kriging which utilizes the variogram model (and therefore statistical attributes) ensures statistical objectivity of unbiased estimation and minimal estimation variance.

RESULTS
For the event under study, snow depth distribution ranged from bare ground or traces of snow, mostly at the eastern end of the province, to greater than 180 mm at the western end of the province (Fig. 1). Water equivalent also showed minima, 0.0-3.7 mm, at the eastern end of the province and maxima, greater than 29.8 mm, at the western end (Fig. 2). There were no anomalies between snow depth and water equivalent, which is an indication that there was no variable snow compaction and is characteristic of freshly fallen snow on bare ground with no chance to compact. The snow cover amounts at unsampled locations were inversely reflected in the variances for depth (Fig. 1) and water equivalent (Fig. 2).

Tests for anisotropy indicated that the variograms were unaffected by sampling direction. Semi-variograms for each of the three variables of interest are plotted for selected spacing, h values, in Fig. 3. The semi-variograms for snow depth (Fig. 3a) and water equivalent (Fig. 3b) permitted structural analysis and, as shown, a gaussian model was fitted to each semi-variogram. In each case the model range is about 40 km at which the model is close to its asymptote and beyond which values are spatially independent. The plotted variogram for snow density (Fig. 3c), on the other hand, showed no structure that was valid for modelling leading to interpolation.

The variance maps suggest that the reliability of estimating snow depth (Fig. 4) and related water equivalent (Fig. 5) at unsampled locations was relatively high in the central portion of the island. Whereas, generally, variance magnitudes were in excess of five times the estimates of snow depth and water equivalent (Figs. 1 and 2); in contrast, variograms for Queens Country showed snow depth variance magnitudes generally less than one-tenth the depth estimate (Fig. 4). However, as shown in Fig. 5, variances for water equivalent were large.

It is anticipated that there will be subsequent opportunity to test the suitability of this type of approach to snowcover data on PEI as part of the wider study whose objectives include estimating cool-period erosivity.

PERSPECTIVE
There is little doubt of the overall merits of kriging in spatially distributing ground snowcover measurements under the conditions of this study. Although the data were limited to a single storm, this study allowed the application of a set of modern techniques, including GPS and GIS, that are not frequently associated with scientific research in soil erosion, but afford tremendous prospects for application to full data sets which will emerge from the wider study of soil erosion in PEI.

The approach affords, for the first time, snowcover measurements over the island and provides new information on the spatial pattern of snowfall in PEI, thus allowing estimates of snowcover on sites which have poor winter accessibility but are strategic in the assessment of snowmelt water erosivity which is a goal of the wider study. The approach shows, therefore, a potential to generate useful inputs to hydraulic erosion computations or models for PEI. It opens opportunities to examine variables heretofore ignored in snowcover estimates in this province and extends the basis of snow cover estimation beyond province-wide use of snowfall recorded only at a single Charlottetown location.

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