Prediction of soil salinity risk by digital terrain modelling in the Canadian prairies

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Florinsky, I. V., Eilers, R. G. and Lelyk, G. W. 2000. **Prediction of soil salinity risk by digital terrain modelling in the Canadian prairies**. Can. J. Soil Sci. **80**: 455–463. Soil salinisation is a typical problem for the Canadian prairies. At macro-topographic scale, build-up of salts occurs in depressions. However, this relationship is not displayed on existing small-scale maps of soil salinity. To improve these maps, one can use a concept of accumulation, transition and dissipation zones of the landsurface. The concept allows one to reveal depressions (topographically expressed accumulation zones) using digital models of horizontal and vertical curvatures, or accumulation and mean curvatures derived from a digital elevation model. We applied the concept of accumulation, transition and dissipation zones to improve an existing small-scale map of the salinity risk index for the prairies and adjacent areas. A comparison of the old and the improved maps demonstrated that once data on depressions have been taken into account, areas marked by salinity risk decreased significantly. We suggest that the method used may prevent an overestimation in predictions of soil cover degradation due to salinisation. The method used can also reveal saline areas linked with discharges of saline aquifers. This is because sites marked by high discharges of groundwater usually relate to sites of intensive fracturing of geological materials, which are closely associated with topographically expressed accumulation zones.

Key words: Digital terrain models, topography, soil salinisation, mapping

Florinsky, I. V., Eilers, R. G. et Lelyk, G. W. 2000. **Prédiction des risques de salinité du sol par modélisation digitale du terrain dans les Prairies canadiennes**. Can. J. Soil Sci. **80**: 455–463. La salinisation du sol est un phénomène caractéristique dans les Prairies canadiennes. À l'échelle macrotopographique, l'accumulation des sels se produit dans les dépressions. Ce rapport ne paraît cependant pas dans les cartes à petite échelle existantes du niveau de salinité des sols. Pour corriger cette lacune, on peut recourir au concept d'une répartition du modelé du terrain en zones d'accumulation, de transition et de dissipation. Le concept permet la mise en évidence des dépressions (zones d'accumulation au sens topographique), au moyen de modèles digitaux de courbure dans le sens horizontal et dans le sens vertical, autrement dit de courbes d'accumulation et de courbes moyennes. Ce concept pourrait, selon nous, améliorer les cartes existantes du niveau de risque de salinité pour les Prairies canadiennes et les régions avoisinantes. En comparant les anciennes cartes et les courbes améliorées, on constate qu'une fois prise en compte l'information relative aux dépressions, les surfaces à risque de salinisation diminuent de façon significative. La méthode pourra éviter la surestimation des prédictions de dégradabilité du sol par la salinisation. Elle peut également servir à mettre au jour les zones salines liées à la remontée de l'eau de nappes saumâtres. En effet, les points marqués par de fortes remontées de la nappe coïncident habituellement à des zones de fracture intense des matériaux géologiques, lesquelles sont étroitement associées aux zones d'accumulation des cartes topographiques.

Mots clés: Modèles digitaux du terrain, topographie, salinisation du sol, cartographie

Soil salinisation is a typical process for steppe landscapes including the Canadian prairies. Soils marked by increased content of soluble salts can be observed in flat, closed and poorly drained areas with non-percolative water regimes, saline surface deposits and discharges of saline groundwater.

Topography is one of the main factors determining spatial distribution and redistribution of soil salinisation. Different manifestations of the topographic control of soil salinisation can be seen at different scales. At macro-topographic scale (typical sizes reach several hundreds and thousands of meters), build-up of salts occurs in closed and partly drained macro-depressions, which are natural accumulators of substances moved by gravity from macro-crests and slopes (Kovda 1946). At meso-topographic scale (typical sizes range between several tens and hundreds of meters), meso-depressions have additional moisture due to overland runoff, and so they have more leached soils than meso-slopes and crests. Saline soils are typical for meso-slopes around meso-depressions through redistribution and secondary accumulation of leached salts (Kovda 1946; Ballantyne 1963; Seelig et al. 1990). At micro-topographic scale (typical sizes are several meters), build-up of salts is typical for micro-crests marked by low moisture and high evaporation (Kovda 1946).

Maps of soil salinisation should display regularities in spatial distribution of soil salinity corresponding to the given scale. Hence, small- and middle-scale maps (from 1:100 000 to 1:10 000 000) should represent relations between soil salinity and macro-depressions, salinisation of

Table 1. Definitions and physical interpretations of some topographic variables

Variable	Definition	Interpretation
G, °	An angle between a tangent plane and a horizontal one at a given point on the landsurface (Shary 1991)	Velocity of substance flows
k_v, m^{-1}	A curvature of a normal section of the landsurface by a plane, including gravity acceleration vector at a given point (Shary 1991)	Relative deceleration of substance flows
k_h, m^{-1}	A curvature of a normal section of the landsurface. This section is orthogonal to the section of vertical curvature at a given point on the landsurface (Shary 1991)	Convergence of substance flows
H, m^{-1}	A half-sum of k_h and k_v (Shary 1991)	Flow convergence and relative deceleration with equal weights
K_a, m^{-2}	A product of k_h by k_v (Shary 1995)	Degree of flow accumulation

meso-slopes should be shown on large-scale maps (from 1:24 000 to 1:100 000), while salinisation of micro-crests should be indicated on detailed maps (larger than 1:24 000). Generally, relationships between topography and soil salinisation may be seen on detailed and large-scale maps obtained by direct field measurements with high planimetric resolution (Lesch et al. 1992; Cannon et al. 1994). However, middle- and small-scale maps of soil salinity compiled by generalisation of large-scale maps or by an integration of available landscape data, as a rule, do not display relationships between topography and soil salinisation. On these maps, polygons characterising the type and extent of soil salinisation can include depressions, slopes and crests. In explanatory texts, authors of these maps stress that actual salinisation can be observed within landforms corresponding to the given scale rather than within all polygons (Kondorskaya 1967; Eilers, R. G. 1990; Eilers et al. 1995, 1997). However, since these relationships are not graphically displayed, users of maps must insert the corresponding corrections to the best of their ability. This is because there are no rigorous quantitative definitions of depressions, slopes and crests, and therefore there are no methods for reproducible delineation of these landforms using topographic data.

To solve this problem, Stepanov (1979) and Khakimov et al. (1983) used data on horizontal curvature (k_h) (Table 1) in mapping of soil salinisation of the Middle Asia. For depressions, they considered areas of flow convergence described by negative values of k_h. However, k_h data are not sufficient to recognise depressions because, from the geomorphic point of view, values $k_h < 0$ correspond to valley spurs rather than depressions (Evans 1980; Shary 1995). To recognise depressions, Metternicht and Zinck (1997) used a qualitative geomorphic map in mapping of secondary soil salinisation in Bolivia. However, landforms are revealed by subjective methods in traditional geomorphic mapping, so this weakness can lead to mistakes on a salinisation map. To improve a predictive map of secondary soil salinisation of the Crimean Steppe, Florinsky (2000) applied **digital terrain models** (**DTM**) and a concept of accumulation, transition and dissipation zones of the landsurface (Shary et al. 1991; Shary 1995). Using this approach, one can partition a landscape into polygons marked by relative accumulation, transition and dissipation of flow (details are in the Materials and methods section). These quantitative terms have the qualitative geomorphic analogs of depression, midslope and crest, respectively.

In this paper, we present some results of compilation of a small-scale map of salinity risk index for the Canadian prairies using the concept of accumulation, transition and dissipation zones and DTMs.

STUDY AREA

Soil salinisation is a typical process for the prairies and adjacent areas of the Boreal Plains within three Canadian provinces of Manitoba, Saskatchewan and Alberta (Fig. 1) (Eilers et al. 1995, 1997).

The Canadian prairies are the northern extension of open grasslands in the Great Plains of North America. The area has a continental climate, subhumid to semiarid with long cold winter, short hot summer, low levels of precipitation, and high evaporation. Mean winter temperature is –10°C, and mean summer temperature is 15°C. Mean annual precipitation ranges from 250 mm in Saskatchewan and Alberta to 700 mm in Manitoba. The Boreal Plains are situated to the north of the prairies. Mean winter temperature is –14°C, and mean summer temperature is 14°C. Mean annual precipitation ranges from 300 mm in Alberta to 625 mm in Manitoba (Ecological Stratification Working Group 1995).

The prairies and Boreal Plains are largely glaciated with Cretaceous shales underlying the area or at the surface. There are nearly level to rolling landscapes consisting of glacial moraines and lacustrine deposits. Black Chernozems with groves of trembling aspen, balsam poplar, and intermittent grassland in the north of the prairies. The driest shortgrass areas with Brown Chernozems occur in southwestern Saskatchewan and southeastern Alberta. The moist mixed grasslands and Dark Brown Chernozems are observed in other parts of the prairies. Luvisols occur within the Boreal Plains. White birch, trembling aspen, and balsam poplar are typical in the south of the Boreal Plains, while white and black spruce, jack pine, and tamarack are common in the north (Ecological Stratification Working Group 1995).

Sulphates of sodium, calcium and magnesium are the primary salts affecting salinity on the prairies (Keller and Van der Kamp 1988). Chlorides of sodium and magnesium are also observed, but they are much less extensive. The origin of salinity in the prairies is related to the mineralogical composition of the soil parent material (Ballantyne 1968), the underlying geological formations (Greenlee et al. 1968), and the hydrogeological systems. A source of sulphate salts is

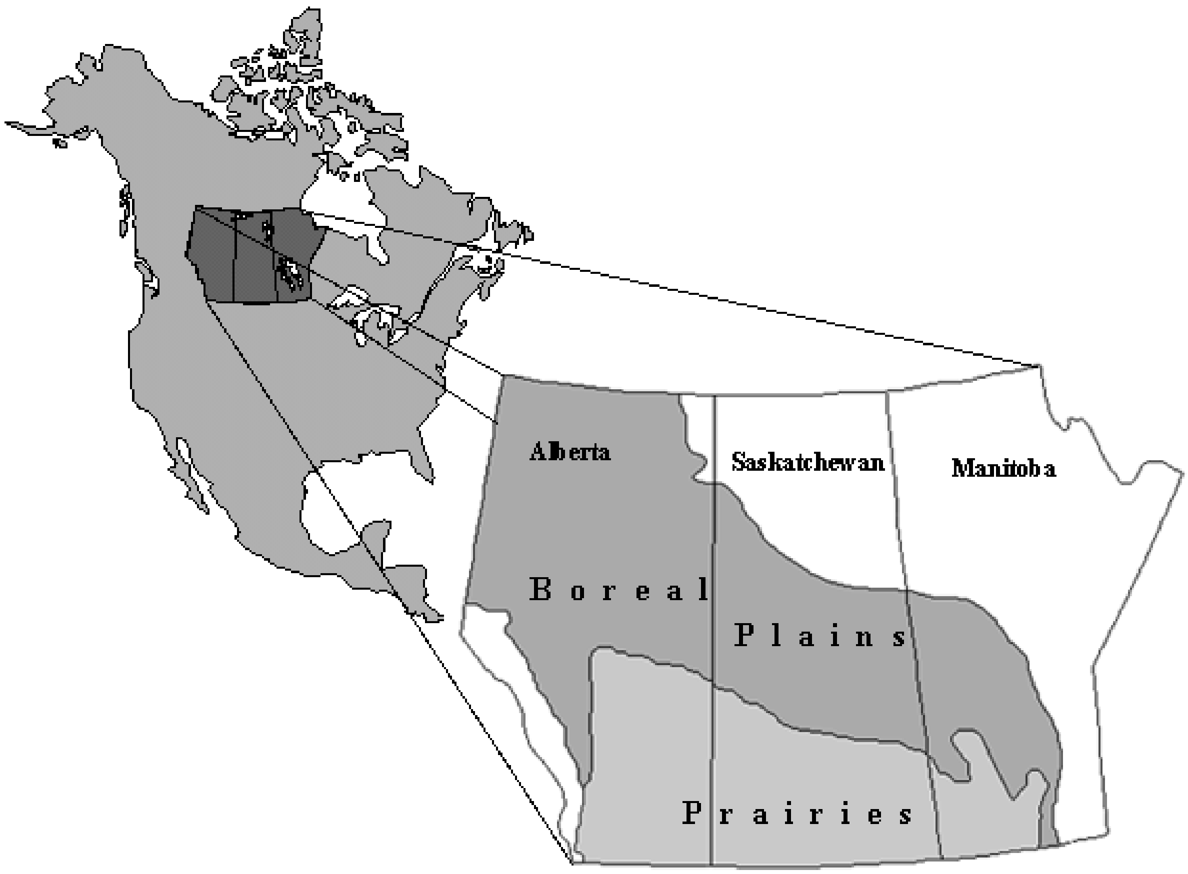

Fig. 1. Geographical position of the study area.

oxidation of organic sulphur and pyrite from surficial till materials, which are typically high in sulphate minerals (Wallick 1981; Mermut and Arshad 1987). Sources of chloride salts are Cretaceous marine shales and Devonian limestones and sandstones. Nearly all deep groundwaters in western Canada are classified as brackish and brine (Cherry 1972). Local and regional groundwater discharges are causative factors for soil salinity (Greenlee et al. 1968; Henry et al. 1985; Stein and Schwartz 1990). A factor for spatial redistribution of salinity is overland and intrasoil flows of water from snow melting and precipitation (Stein and Schwartz 1990).

Agriculture is the dominant land use in the prairies as well as in the southern and north-western parts of the Boreal Plains. Saline soils are present in many areas throughout the region (Fig. 2). Estimates of the total area of saline lands vary widely but at least 1 431 000 ha are affected (Eilers, R. G. 1990; Eilers, W. D. 1990; Pettapiece and Eilers 1990). In the prairies, about 62% of agricultural soils have a low extent of salinity. These are well-drained soils of major uplands, rapidly drained sandy soils, and soils situated next to deep river channels. About 36% of agricultural soils of the prairies are moderately affected by salinity. These are mainly medium-textured soils occurring next to small wetlands and in depressions. Areas with a greater extent of salinity are fairly small and scattered throughout southern regions. These areas often receive regional groundwater discharge and can be generally found on nearly level plains at the base of prominent uplands (Fig. 2) (Eilers et al. 1995).

MATERIALS AND METHODS

The following initial data were used:

• A digital elevation model (DEM) of an area between 48°55′ and 60°05′N, and 88°55′ and 120°05′W;

• A map of salinity risk for Manitoba, Saskatchewan and Alberta (Eilers et al. 1995, 1997) (Fig. 2).

The DEM of the study area was derived from the 5-arc-minute gridded global DEM produced and distributed by the NOAA's World Data Center for Marine Geology and Geophysics (NOAA 1988). The DEM of the study area included 50 625 points and was given by a spheroidal trapezoidal grid with the grid size of 5 arc minutes.

Salinity risk index (Fig. 2) is used to rank individual land areas according to the chance that the salinity level will change with changing conditions. Evaluation of salinity risk is based on the concept that salinity is a dynamic condition of the soil cover, and on the premise that functional relationships exist among components affecting the salinisation, that these components can be given a relative numerical weighting for their influences, and that each of these weight-

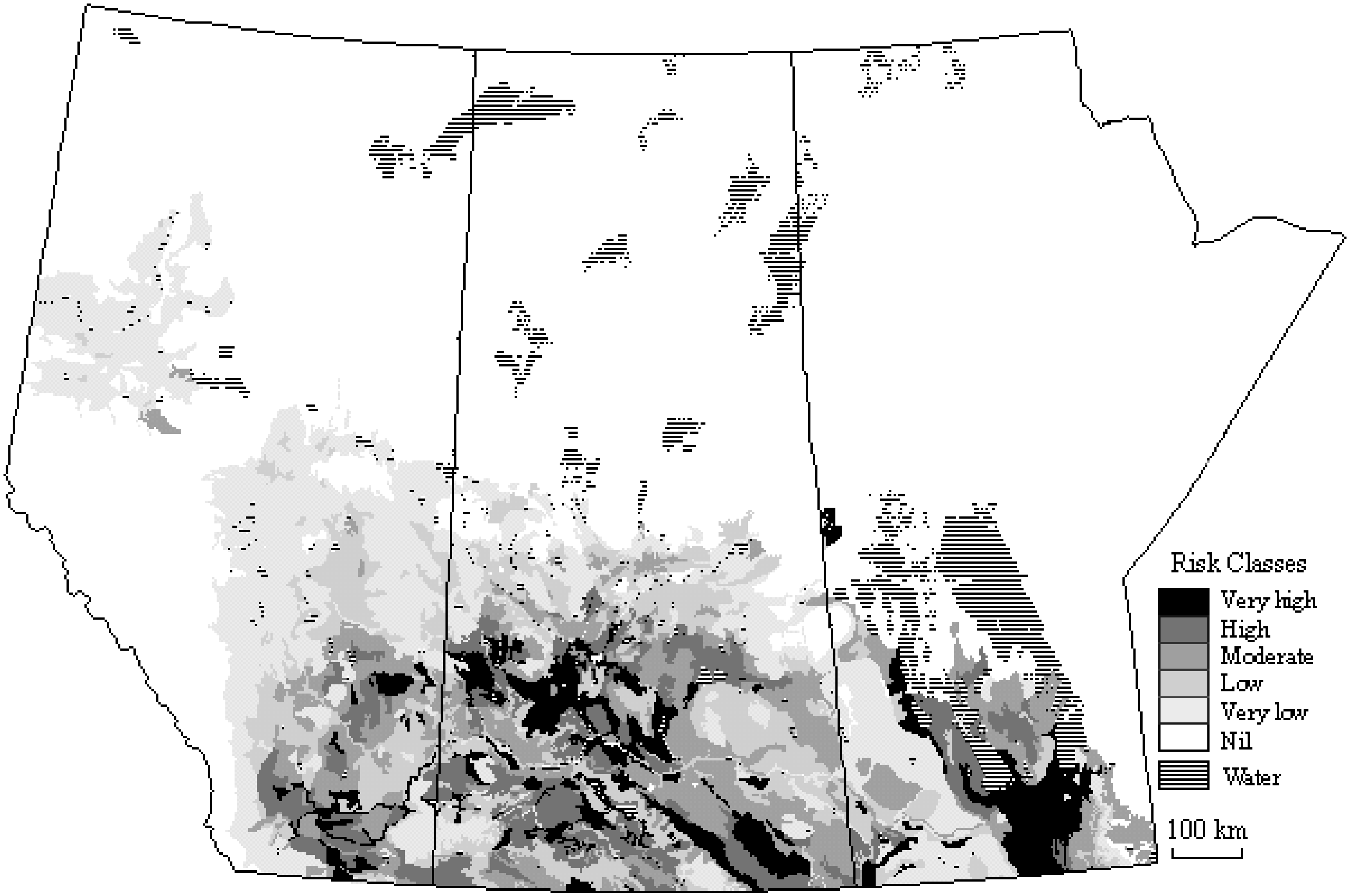

Fig. 2. Map of salinity risk (Eilers et al. 1997).

ings can be combined resulting in a dimensionless index. The following factors are used to assess salinity risk: (a) current extent of salinity derived from maps at a scale of 1:1 000 000 (Eilers, R. G. 1990; Eilers, W. D. 1990; Pettapiece and Eilers 1990) indicating presence, extent, and position of moderate or greater salinity levels in each soil landscape (the electrical conductivity of a saturated-paste extract of a soil sample is more than 8 decisiemens per meter); (b) slope gradient (G) (Table 1); (c) soil drainage class; (d) aridity (the difference between precipitation and potential evapotranspiration); and (e) surface cover representing land use and land management practices (Eilers et al. 1995, 1997). The notion that soil salinisation is typical for macro-depressions, meso-slopes and micro-crests was not used in estimation of salinity risk index by these authors.

The concept of topographically expressed accumulation, transition and dissipation zones is based on the following assumptions. Gravity-driven overland and intrasoil transport can be interpreted in terms of divergence or convergence, and deceleration or acceleration of flows (Shary 1995). Flow tends to accelerate when vertical curvature (k_v) is positive, and to decelerate when k_v is negative (Table 1) (Speight 1974; Shary 1991). Flow diverges when $k_h > 0$, and converges when $k_h < 0$ (Table 1) (Kirkby and Chorley 1967; Shary 1991). Flow convergence and deceleration result in accumulation of substances in soils. At different scales, the spatial distribution of accumulated substances can depend on the distribution of the following landforms (Shary et al. 1991): (a) landforms marked both by convergence and deceleration of flow, that is, both by $k_h < 0$ and by $k_v < 0$ (accumulation zones); (b) landforms offering both divergence and acceleration of flow, that is, both $k_h > 0$ and $k_v > 0$ (dissipation zones); and (c) landforms that are free of a concurrent action of flow convergence and deceleration as well as divergence and acceleration, that is, values of k_h and k_v have different signs or are zero (transition zones). Closely related approaches of terrain segmentation by k_h and k_v signs were used previously in some geomorphic and soil studies (Yefremov 1949; Troeh 1964; Krcho 1983; Pennock et al. 1987; MacMillan and Pettapiece 1997).

Recognition of accumulation, transition and dissipation zones can be carried out by simple registration of k_h and k_v maps. However, in this case one can visualise only spatial distribution of these zones without quantitative estimation of a probable degree of flow accumulation. To solve this problem, Shary (1995) proposed the use of data on accumulation (K_a) and mean (H) curvatures (Table 1). Negative values of K_a correspond to transition zones, while positive values of K_a correspond to both accumulation and dissipation zones. Accumulation and dissipation zones can be distinguished using values of H. Positive values of K_a with negative values of H correspond to accumulation zones, whereas positive values of K_a with positive values of H correspond to dissipation zones (Shary 1995).

We derived digital models of H and K_a from the DEM by the method of Florinsky (1998b). These were calculated using a grid spacing of 5 arc minutes because it is best matched to the regional scale and readability of maps to be obtained. H and K_a digital models include 49609 points. Derivation of H and K_a digital models was carried out with LandLord software (Florinsky et al. 1995). A map of accumulation zones (Fig. 3) was obtained by combination of H and K_a data.

To produce an improved map of salinity risk index taking into consideration typical occurrence of soil salinisation in macro-depressions, we linked the map of salinity risk index (Fig. 2) and the map of accumulation zones (Fig. 3) using ArcView GIS Version 3.0a (© 1992–1997, Environmental Systems Research Institute, Inc.) . The resulted map (Fig. 4) represents only those landscape polygons marked by several rates of soil salinisation which are located within accumulation zones.

RESULTS AND DISCUSSION

A comparative analysis of the old and the improved maps of salinity risk index (Figs. 2 and 4) demonstrates that once data on macro-depressions have been taken into account, areas marked by salinity risk decreased significantly. So, we suppose that the method proposed may prevent an overestimation in predictions of soil cover degradation due to salinisation. This is not to say that soil salinisation cannot occur within areas marked by nil salinity risk. However, this possible salinisation relates to other scale levels and should be indicated on more detailed maps. Obviously, it is unnecessary and impossible to display saline areas of all scales on a single map. A user should remember that a map is a generalised model.

In parallel with overland hydrological processes, a significant factor of soil salinisation on the prairies is discharges of regional groundwater aquifers (Greenlee et al. 1968; Henry et al. 1985; Stein and Schwartz 1990). These aquifers occur as sand and gravel strata within the glacial sediments and as channel deposits in buried pre-glacial valleys. There are no strong relations between landsurface topography and distribution of the aquifers (Freeze and Cherry 1979). Extensive deposits of unfractured glacial clayey and silty till and glaciolacustrine clay can isolate buried aquifers. However, in some locations, these groundwaters can discharge through networks of vertical and nearly vertical fractures passing through layers of till and clay (Grisak and Cherry 1975; Grisak et al. 1976). The hydraulic conductivity of fractured till and clay can provide significant secondary permeability to depths of hundreds of meters (Williams and Farvolden 1967; Freeze and Cherry 1979). So, to identify areas affected by soil salinisation due to discharges from regional groundwater aquifers, we need to consider areas of fractured tills and clays.

On the face of it, the method used cannot take into consideration the influence of saline aquifers, and reveal saline areas linked with deep groundwater discharge. However, this is not the case. It has been observed that in a number of regions high discharges of groundwater usually relate to sites of fault intersections marked by increased permeability due to intensive fracturing of geological materials (Lattman and Parizek 1964; Morozov et al. 1988). These sites are closely associated with depressions – topographically expressed accumulation zones (Poletaev 1992; Florinsky 2000). Within these zones, soil salinisation can be

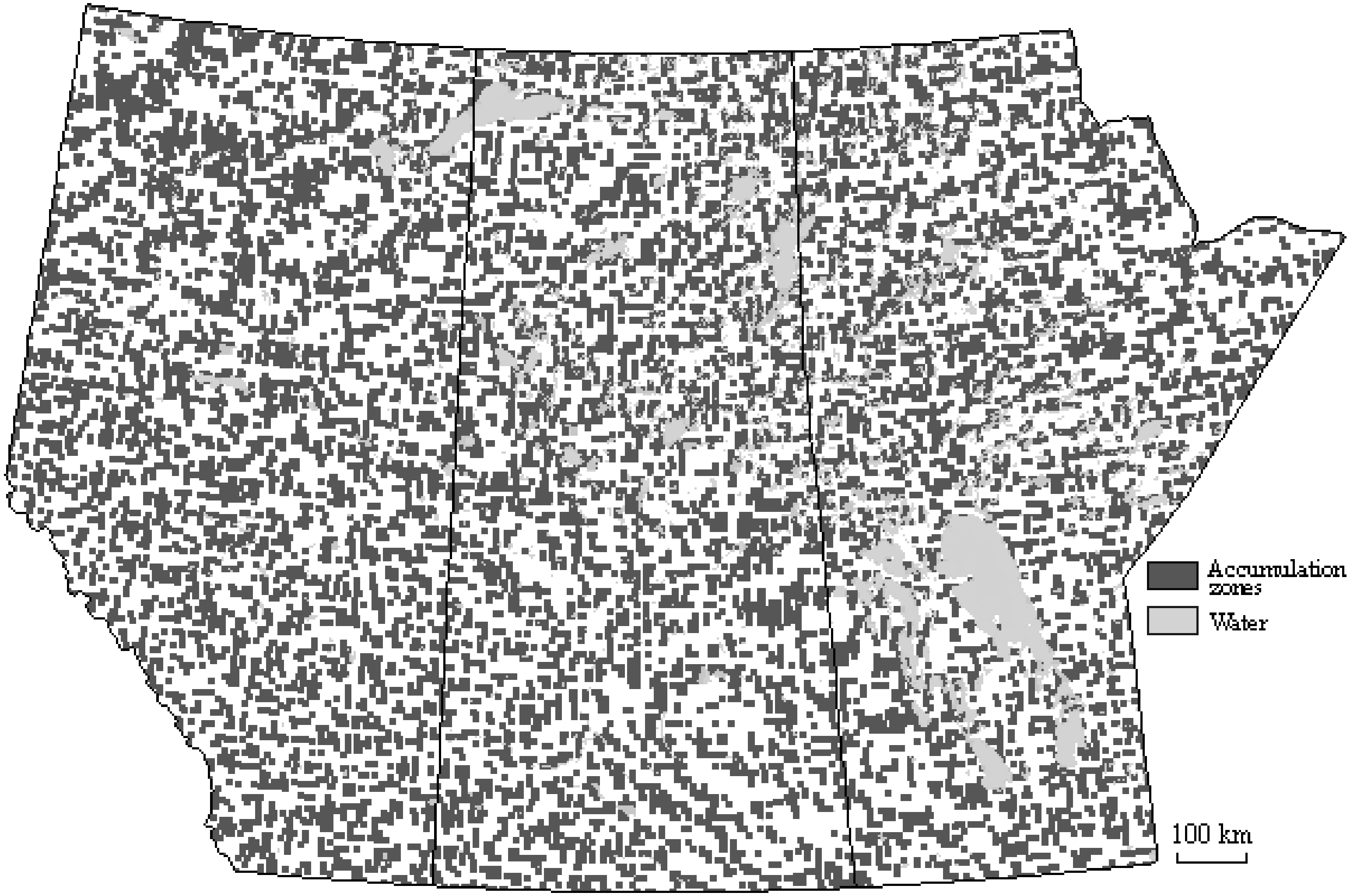

Fig. 3. Map of accumulation zones.

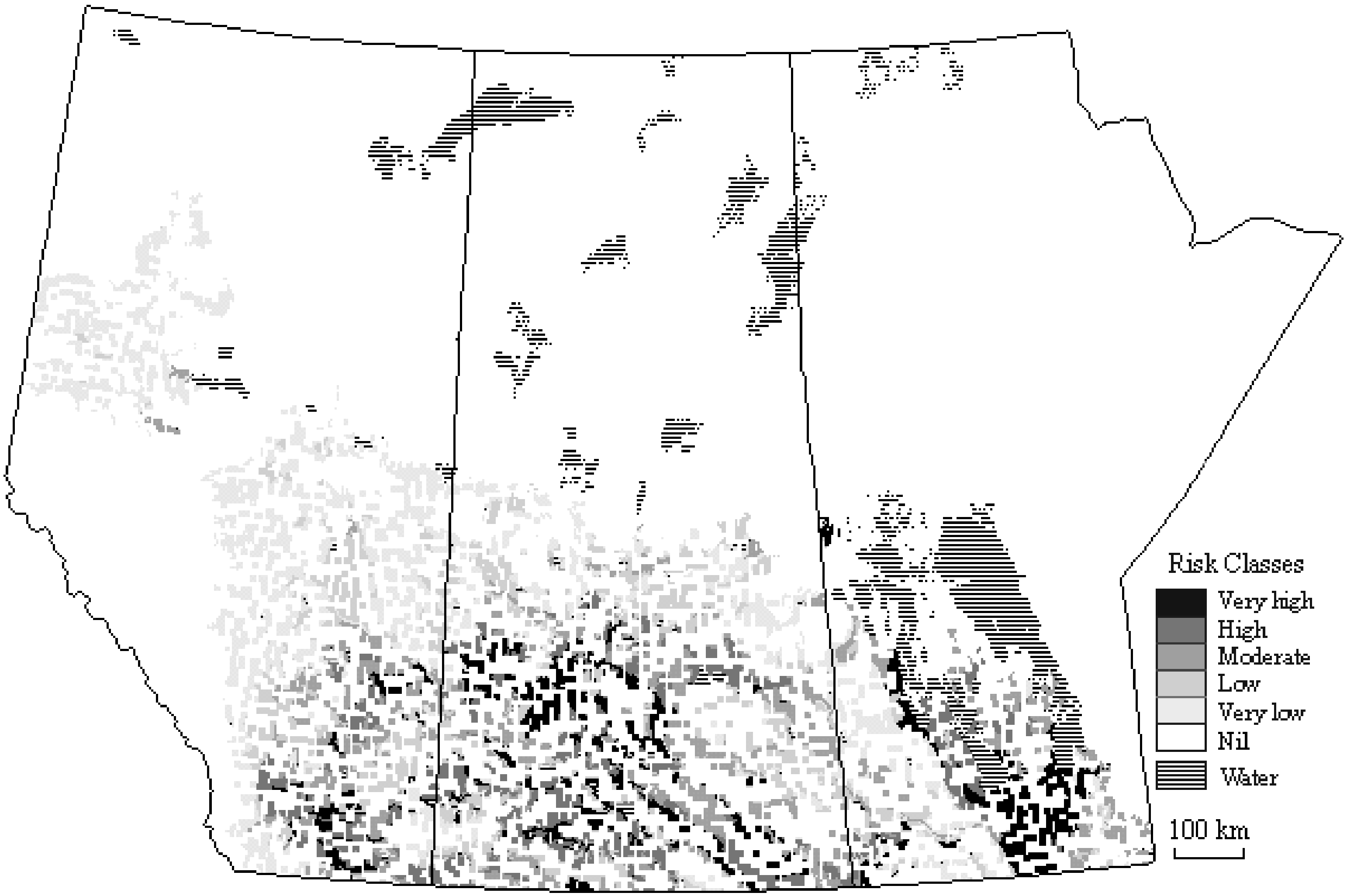

Fig. 4. Improved map of salinity risk.

derived from both accumulation of overland lateral flows and upward transport of saline groundwater. When we delineate accumulation zones by digital terrain modelling (Materials and Methods section), we also reveal sites of intensive fracturing of geological material and fault intersections (Florinsky 2000). Therefore, using the map of accumulation zones (Fig. 3) we take into consideration both of the main factors of soil salinisation on the prairies: topographic features and groundwater discharges.

The following question arises: can we estimate an accuracy of the produced map of salinity risk index (Fig. 4)? To do this, we have to compare the map with some "reference" data representing actual areas of salinisation. A resolution of "reference" data should be the same or close to the resolution of the improved map of salinity risk index (Fig. 4) which is 5 arc minutes (Materials and Methods section). It would make no sense to compare data marked by dissimilar resolution. Recall that sizes of a grid cell of 5′ by 5′ are about 6098 m by 9268 m on 49°N, and about 4650 m by 9285 m on 60°N (Bugaevsky and Vakhrameyeva 1992). Salinity maps at a scale of 1:1 000 000 (Eilers, R. G. 1990; Eilers, W. D. 1990; Pettapiece and Eilers 1990) are the only available "reference" data marked by relatively close resolution. However, these maps do not display areas of salinisation. They represent extent of soil salinity for polygons of "soil landscapes". Therefore, these maps cannot be applied to evaluate the final map of salinity risk index (Fig. 4). Middle-scale soil maps (e.g., at a scale of 1:100 000) cannot also be used as "reference" data in this case, although they display areas of soil salinisation. This is because their resolution may correspond to a map of salinity risk obtained using DTMs with grid sizes of 250–1000 m. So, there are no "reference" data that can be used to validate the improved map of salinity risk index (Fig. 4). The only criterion of its validity is the correctness of the model describing relationships between topography and soil salinisation (Introduction and Materials and Methods).

The method applied can be used to compile maps of soil salinisation at other scales. To produce middle-scale maps of soil salinisation one has to take into consideration data on accumulation zones, to compile large-scale maps one should use information on transition zones, and to produce detailed maps one should apply data on dissipation zones (Introduction). In all these case, data on spatial distribution of accumulation, transition and dissipation zones of the landsurface can be derived from DEMs characterised by an appropriate resolution (Materials and Methods).

The method proposed can extend the use of DTMs in landscape investigations (Moore et al. 1991; Shary et al. 1991; Florinsky 1998a), and may be integrated with approaches for monitoring of soil salinity by remote sensing (Mougenot et al. 1993; Pankova and Soloviev 1993).

CONCLUSIONS

1. To improve existing small-scale maps of soil salinity, one can use the concept of accumulation, transition and dissipation zones of the landsurface. The concept allows one to reveal depressions, midslopes and crests by digital modelling of k_h and k_v, or H and K_a.
2. We applied the concept of accumulation, transition and dissipation zones to improve the existing small-scale map of the salinity risk index for the prairies and adjacent areas.
3. A comparison of the old and the improved maps of the salinity risk index demonstrated that once data on depressions have been taken into account, areas marked by salinity risk decreased significantly. We suppose that the method used may prevent an overestimation in predictions of soil cover degradation due to salinisation.
4. The method used can also reveal saline areas linked with discharges of saline aquifers. This is because sites marked by high discharges of groundwater, as a rule, relate to sites of intensive rock fracturing, which are closely associated with topographically expressed accumulation zones.

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