PL ISSN 0067-9038

C. B. CRAMPTON*
Burnaby, B. C.

ANALYSIS OF SYNERGISTIC SYSTEMS FOR EVALUATING TERRAIN SENSITIVITY TO DISTURBANCE OF ICY PERMAFROST IN THE MACKENZIE RIVER VALLEY, CANADA

Abstract

An extensive land classification for the Mackenzie River valley has been combined with an analysis of synergistic systems, to quantify field units for a more comprehensive terrain evaluation than could have been produced by either field or analytical work alone. The empirical prediction of ice content and its distribution within different environments has been used with field data to develop a classification for sensitivity of the landscape to damage from disturbance. The zone of most rapidly changing sensitivity which occurs around Fort Norman and Norman Wells as the Discontinuous merges into the Continuous Permafrost Zone has been quantified.

INTRODUCTION

An extensive land classification was undertaken in the Mackenzie River valley, the delineation of Land Systems being based on recurring landscape patterns of microrelief, geomorphology and vegetation observable in air photographs (CRAMPTON, 1975). Field checks at localities selected using the initial air photograph interpretation helped confirm the nature and boundaries of the Land Systems. These Land Systems can be combined on the basis of common attributes into Land Regions (MITCHELL, 1973). WEBSTER and BECKETT (1970) proposed that where necessary there should be a land division into areas to be called "Variants" with important engineering characteristics which cannot be seen in air photographs, but which can only be delineated by site inspections. Variations in substrate texture in the Mackenzie River valley can have profound implications for engineers, especially if correlated with certain slopes (CRAMPTON, 1978a), but textural variations in the landscape cannot always be matched with changes in landscape patterns observable in air photographs.

Therefore, on the basis of field evidence, the concept of variants has been combined with that of Land Regions, to group Land Systems into a few classes of sensitivity to damage from disturbance. The field envidence includes terrain surveys and drilling log data[1], and the application of a new analytical technique for equitably processing data of varying precision, incorporating synergistically interacting systems to yield

* Department of Geography, Simon Fraser University. Burnaby, B. C., Canada V5A 1S6.
[1] From Foothills Pipe Lines Ltd.

a useful predictive model. The terrain evaluation study has involved an intimate interaction between field survey and analytical computations, with considerable reliance on the former interpretation of the latter results, the field work being the ultimate reference standard.

ANALYTICAL PROCEDURE

The physiography of the study area has already been described (Crampton, 1975). Based partly on the field survey, small areas were selected to systematically and equitably sample the Mackenzie River valley, crossing the Discontinuous and Continuous Permafrost Zones from south of Fort Simpson to near Fort Good Hope. This sampling was continued to north of Inuvik so that a comparison could be made between changes occurring in the study area and those occurring adjoining the Beaufort Sea. Intensive drilling had been undertaken within these selected areas, and the 1498 observations so obtained served as the input into a program which analysed synergistic interactions influencing the % ice content in the substrate, by weight, and its distribution in surficial sediments. Each selected area can be identified by the latitude and longitude of its central point, and the nearest settlement to the north or south.

The effect on a particular dependent variable of synergistically interacting variables is greater, and can be much greater than the sum of the effects of these independent variables acting separately. This concept of synergism has had its fullest application within the restricted fields of pestology and pharmacology. Some research into the biochemistry of insecticides has been directed towards finding compounds which act as synergists, such that the effect of an insecticide is greatly enhanced, beyond the sum of the effects of the synergist and insecticide applied separately (e.g. Wilkinson, 1976, pp. 631—635). Similarly, drug interactions may be synergistic when the combined effects resulting from their concurrent use results in a greatly exaggerated effect normally characteristic, at a lesser intensity, of the spectrum of one them (e.g. Goodman and Gilman, 1970, p. 25). Therefore, instead of the input to a type of stagewise regression described by Crampton (1978b, 1977b) being only single variables, all possible combinations of two, three and four variables were also considered as part of the input.

A 20% random sample was extracted from the original population of 1498, kept out of the analysis and used to help monitor and check the effectiveness of the analysis. Thus, there are 1196 sites for the analysis and 299 for the check.

For this study there were 11 independent variables, for example site-location features such as latitude, elevation, aspect, slope, landform (morainal, peat plateau, etc.) and vegetation, and profile characteristics such as the depth of the layer of interest and any special features it may possess (whether it is bouldery, layered, etc.), its texture and the texture of sedimentary layers above and below. Some of these independent variables were capable of more precise measurement than others, but all contribute usefully to the analysis for predictive purposes. From these it was possible to create 55 two-variable combinations, 165 three-variable combinations and 330 four-variable combinations, totalling 561. The dependent variable was either the % ice content by weight of substrate or the distribution of this ice in the layer of interest.

The % ice content in sedimentary deposits increases exponentially as the physical environment becomes more conducive to its accumulation, and so the measured content was transformed to yield a linear scale. The ice could be finely disseminated throughout the substrate, or it could be lenticular. The distribution of this ice in the surficial deposits was classified according to PHILAINEN and JOHNSTON (1963).

All independent variables were classified into the same number of categories, six in this study, to allow their equitable processing within the analysis. Regarding single variables, the average % ice content, for example, was calculated for each category. For each possible combination of two independent variables a two-dimensional, 6×6 matrix was constructed to embrace all possible combinations of categories for these two variables. Within this matrix the measured % ice content for each site was recorded in the appropriate cell representing the particular combination of categories characteristic of each site. 1498 site observations distributed in a 6×6 matrix assured that every cell contained some observations. Cell means were then ranked and divided into 6 classes of ice content, which defined the combinations of categories for the two variables involved in the interaction which could be equated with each class of ice content. This procedure was the only practical way of defining a surrogate variable acting for two independent variables, and categorized into 6 classes of ice content so that the surrogate could serve as the input into the analysis equally with the single variables.

For each possible combination of three variables a three-dimensional, 6×6×6 matrix was constructed to embrace all possible combinations of categories of these three variables. The same procedure was adopted as for two-variable combinations, so that the interaction could be processed in terms of 6 categories of ice content like single variables. Similarly, a 6×6×6×6 matrix was constructed for each possible four-variable combination, to allow the calculation of a surrogate variable classified in terms of 6 categories of ice content, for processing with single variables, and two- or three-variable surrogates. There are 1296 cells within the four-dimensional matrix constructed for each possible four-variable interaction. There is a natural clustering of the 1498 observations within this matrix as an unavoidable corollary of the preferred relationship between dependent and independent variable being sought in the analysis. Thus, the number of empty cells increases as the power of the synergism increases.

Although single variables, and two-variable, three-variable and four-variable surrogates were allowed into the analysis simultaneously, the correlation between each independent variable and ice content was most significant for only four-variable surrogates, reflecting the much greater analytical power achieved by increasing the number of variables within each synergistic interaction. The synergism for the two most important four-variable surrogates affecting ice content is tabulated in Table I.

Table I

Two four-variable synergistic interactions affecting ice content in surficial sediments of the Mackenzie River valley

ANALYSIS OF ICE CONTENT: intercept = −0.33; mean = 4.03; standard deviation = 3.86, N (analysis) = 1196; N (check) = 299; R^2 (analysis) = 0.81; R^2 (check) = 0.72

DOMINANT INTERACTION

Increments Ice content	Elevation	Categories for interacting variables		
		Depth	Texture	Vegetation
1) 0.00	241−370 m 801−900 ft.	761−915 cm 26−30 ft.	sands and gravels and bedrock	conifers
2) 2.34	0−60 m 0−200 ft.	611−25 cm 21−25 ft.	sands and gravels with silt & clay	hardwoods
3) 6.06	61−120 m 201−400 ft.	306−460 cm 11−15 ft.	silts and clays with fine sands	sedge-lands
4) 9.50	211−240 m 701−800 ft.	151−305 cm 6−10 ft.	silts and clays	open treed sedge-lands
5) 13.21	121−180 m 401−600 ft.	0−150 cm 0−5 ft.	organic silts and clays	open treed lichen-lands
6) 16.00	181−210 m 601−700 ft.	461−610 cm 16−20 ft.	organic	lichen-lands

SUB-DOMINANT INTERACTION

Increments Ice content	Latitude	Aspect	Texture	Special features of layer
1) 0.00	Fort Simpson 61°20′	SW	sands and gravels	coarse gravel additions
2) 1.48	Wrigley 62°60′	S & W	sands and gravels with silt and clay	coarse sand additions
3) 2.86	Fort Good Hope 66°30′	E	silts and clays with fine sand	some boulders present
4) 4.01	Inuvik 68°50′	NW & SE	silts and clays	some cobbles present
5) 5.17	Fort Norman 64°20′	N	organic silts and clays	unspecified
6) 7.77	Norman Wells 65°50′	NE	organic	layered sediments

FOR PREDICTION: add the appropriate increments to the intercept, and read the % ice content by weight of sediment in the table below:

Sum of increments	0−4.5	4.6−8.5	8.6−12.5	12.6−16.5	16.6−20.5	20.6−24.5
% by wt. of ice	0−35	36−70	71−140	141−280	281−560	561−1120

Using this output, it is necessary to predict ice content for the categories or category combinations characterizing the morphology of each site. While a simple calculation is required for single variables, the procedure becomes progressively more complex and unmanageable for two-, three-, and four-variable interactions.

The number of possible connections between the check sample and the predictive matrix is limited by the number of cells in the matrix with means. As the power of the synergism increases, so the effective number of sites in the check sample decreases. Hence, using category numbers for site characteristics, the mean weighted by the frequency distribution of each category was calculated for the categories within each of the 6 classes of the dependent variable. The prediction of ice content is based on the calculation of the best fit between the environmental character of a certain site in the check sample, and the results of the analysis expressed in Tables I and III, illustrated for one site in Table II. In this

Table II

Calculation of least summ of differences for predicting from four-variable interactions for a particular environment

ENVIRONMENTAL CHARACTER. Sedimentary layer at 18 ft. (5.5 m) depth, of organic silt and clay, over substrate of similar texture, below sandy deltaic stratum, under gently sloping spruce-lichen forest, with NE aspect, at 300 ft. (90) elevation, near Norman Wells.
FIRST ANALYSIS (see table I)
DOMINANT INTERACTION Environment character expressed by selection of appropriate category numerals listed with ranked increments, left hand side

Increment Ice content	(2) Elevation		(6) Depth		(5) Texture		(5) Vegetation	Sum of the differences
1) 0.00	241–370 m 801–900 ft.		761–915 cm 26–30 ft.		sands and gravels and bedrock		conifers	
	1	+	5	+	+ 4	+	4	= 14
	Difference between environmental symbol and category symbol							
2) 2.34	0–60 m 0–200 ft.		611–760 cm 21–25 ft.		sands and gravels with silt & clay		hardwoods	
	0	+	4	+	3	+	3	= 10
3) 6.06	61–120 m 201–400 ft.		306–460 cm 11–15 ft.		silts and clays with fine sands		sedge-lands	
	1	+	3	+	2	+	2	= 8
4) 9.50	211–240 m 701–800 ft.		151–305 cm 6–10 ft.		silts and clays		open treed sedge-lands	
	2	+	2	+	1	+	1	= 6
5) 13.21	121–180 m 401–600 ft.		0–150 cm 0–5 ft.		organic silts and clays		open treed lichen-lands	
	3	+	1	+	0	+	0	= 4
6) 16.00	181–210 m 601–700 ft.		461–610 cm 16–20 ft.		organic		lichen lands	
	4	+	0	+	1	+	1	= 6

Dominant interaction: least sum of differences corresponds to increment	+13.21
Sub-dominant interaction: least sum of differences corresponds to increment	+7.77
intercept	−0.33
Sum of increments and intercept corresponds to ice content of 617% (from table I)	20.98

Average of first analysis (617%) and second analysis (table III) (453%) is 535% (table IV) way the total check sample could be utilized to test the effectiveness of the analysis. The sum of the increments chosen for the successive surrogates was applied to the intercept for the regression, to give the ice content class for the site.

A characteristic of this style of analysis is the bunching of different four-variable interactions close to the dominant within each stage in terms of their significance. These relationships represent an extraordinary complex and fluid condition, implying that the normal concept of a single chain of primary variables is probably a grossly simplified explanation of any phenomenon. For each resolution of a problem there is always an equally valid alternative explanation. Hence, a second analysis was undertaken with textural interactions being given priority over other possible four-variable interactions (Table III).

The first analysis (with no one surrogate being given priority) yielded an R^2 value for the analysis of 0.81, and for the check of 0.72. The second analysis (with textural interactions being given priority) yielded an R^2 value of 0.73 for the analysis, and 0.65 for the check. Using only single variables in the regression, the analytical R^2 was 0.44, justifying the use of synergism in the analysis to yield useful results. Tables I and III are limited to the two most important four-vaiable surrogates to simplify predictions, although a decreasing improvement in R^2 could have been obtained by the incorporation of the third and fourth most important surrogates.

Table III

Two four-variable synergistic interactions affecting ice content and distribution in surficial sediments of the Mackenzie River valley

ANALYSIS OF ICE CONTENT: intercept = 1.15; mean = 4.03; standard deviation = 1.17; N (analysis) = 1196; N (check) = 299; R^2 (analysis) = 0.73; R^2 (check) = 0.65

ANALYSIS OF ICE DISTRIBUTION: intercept = −1.10; mean = 3.19; standard deviation = = 2.06; R^2 (analysis) = 0.68; R^2 (check) = 0.59

DOMINANT INTERACTION

Increments Ice content	Texture of layer	Categories for interacting variables		
		Texture above layer*	Texture below layer	Special features of layer
1) 0.00	sands and gravels	sands and gravels with silt and clay	sands and gravels	coarse gravel additions
2) 1.57	sands and gravels with silt and clay	silts and clays with fine sand	sands and gravels with silt and clay	coarse sand additions
3) 4.25	silts and clays with fine sand	silts and clays organic	silts and clays with fine sand	some boulders present
4) 7.54	silts and clays	silts and clays	silts and clays	some cobbles present
5) 10.85	organic silts and clays	sands and gravels with silt and clay	organic silts and clays	unspecified
6) 12.02	organic	sands and gravels	organic	layered sediments

* At the depth range 0–5 ft. (0–150 cm), a surface organic mat within the active layer is considered outside the scope of this analysis; textures above are assumed to be the same as those of the layer of interest.

SUB-DOMINANT INTERACTION

Increments Ice content	Latitude	Elevation	Aspect	Landform
1) 0.00	Fort Simpson 61°20′	241–370 m 801–900 ft.	SW	thin till over rock
2) 1.60	Wrigley 62°60′	211–240 m 701–800 ft.	S & W	morainal
3) 2.89	Fort Norman 64°20′	181–210 m 601–700 ft.	NW & SE	alluvial-lacustrine
4) 4.00	Norman Wells 65°50′	121–180 m 401–600 ft.	E	peat plateaus
5) 5.06	Fort Good Hope 66°30′	61–120 m 201–400 ft.	N	deltaic
6) 6.30	Inuvik 68°50′	0–60 m 0–200 ft.	NE	slopes

FOR PREDICTION: add the appropriate increments to the intercept, and read the % ice content by weight of sediment, or the distribution of the ice within the sediment, in the tables below:

Sum of increments	0–3.3	3.4–6.6	6.7–9.9	10.0–13.3	13.4–16.6	16.7–19.9
% by wt. of ice	1–25	26–50	51–100	101–200	201–400	401–800
Ice distribution	no visible ice	well bonded by ice	scattered ice crystals	ice segregations	lenticular ice	solid ice bodies

To predict the ice content for a particular site environment, both analyses can be used, matching the site characteristics with those associated with each ice content class, utilizing the same procedure as for the check by calculating the least sum of differences to find the best fit (Table II). The two results can be averaged. Because a precise fit relating a site to the analytical results is rarely found, because prediction has been simplified to two interacting surrogates, and because of the normal error involved in any regression analysis, the chief purpose for predicting ice content is to provide relative values characterizing different Land Systems in the landscape analysis so that, in conjunction with field evidence, the Land Systems may be ranked according to their sensitivity to damage from disturbance.

A third analysis allocated priority to the same textural interactions given priority in the second analysis, but the distribution of ice in the substrate was the dependent variable. The analytical results were so similar to those obtained with ice content as the dependent variable that they have been incorporated into the same Table III.

RESULTS

Summarizing the first analysis of systems (Table I), each system consisting of four synergistically interacting variables, the least ice (less than the weight of soil) occurs at the highest elevations (over 800 ft. : 241 m), south of Fort Simpson over bedrock, or where predominantly conifers occupy dry, sandy and gravelly sites, facing southwest, at the greatest recorded depths (over 26 ft. : 761 cm). Moderate amounts of ice (about 1 to 3 times the weight of soil) occur at low to heigh elevations (from sea level to 800 ft. : sea level to 240 m), in the northern (lower) Mackenzie River catchment (Fort Good Hope to Inuvik), in cobbly or bouldery, morainal silts and clays supporting sedge-lands, some with open, stunted forest, at shallow depths below the land surface (6 to 15 ft. : 151 to 460 cm). The most ice (about 3 to 11 times the weight of soil) occurs in layered, organic, silty or clayey sediments at middle elevations (400 to 700 ft. : 120 to 210 m), at middle latitudes around Fort Norman and Norman Wells, beneath open, stunted spruce-lichen forest or lichen vegetation, on gently sloping lands facing around northeast, near the land surface and especially at a depth of about 16 to 20 ft. (460 to 610 cm).

Each system is a specific environment, but within the defined complex interactions it is interesting to consider the influence of certain variables on the ice content. For example, there is a great accumulation of ice just below the land surface, but the amount declines with increasing depth, except at an average depth of about 18 ft. (550 cm) where there occurs the maximum accumulation of ice in the profile. Within the interaction this accumulation is associated particularly with organic matter, although silts and clays must also be involved since the table of interactions represents a set of averaged relationships. Ice content also increases with increasing elevation, particularly around 650 ft. (195 m), although there appears to be a sharp reduction of ice content at the highest elevations around 850 ft. (255 m), associated within the interaction particularly with gravelly bedrock heights and (presumably stunted) conifers. Mackay (1972) has reported an increasing ice content in the substrate with increasing elevation, except near the summits of ranges. The greatest ice content is also associated with organic silts and clays, and the least with sands and gravels as part of an interacting system, a widely established relationship (eg. Brown and Johnston, 1964). The association of little ice in the substrate beneath forest, and much ice below thick crusts of lichen is consistent with the landscape analysis (Crampton, 1975).

From the sub-dominant interaction it is interesting to note that under certain less common environmental conditions, sediments around Norman Wells, particularly, and Fort Norman can contain more ice than sediments to the north and south.

Summarizing the second analysis of systems (Table III), the least ice (less than the weight of soil, although bonding the soil) occurs in sandy and gravelly, morainal sediments with similar coarse-textured substrates above and below, in southern latitudes (around Fort Simpson and Wrigley) where the surficial deposits occur on gentle slopes or nearly flat land facing around southwest, even at high elevations (over 700 ft. : 210 m). Moderate amounts of ice (about 1 to 2 times the weight of soil and distributed as scattered ice crystals or irregular inclusions) occur in silty or clayey, bouldery or cobbly, water-reworked alluvial-tills or in peat plateaus, with silts and clays (either organic or sandy) above and below, at intermediate latitudes (around Fort Norman and Norman Wells) and elevations (400 to 700 ft. : 120 to 210 m). The most ice (about 3 to 7 times the weight of soil and distributed as lenticular ice or as solid ice bodies) occurs in layered, silty and clayey deltaic sediments, over similarly textured substrates, but below sandy and gravelly sediments, on slopes facing around northeast, in northern latitudes (around Fort Good Hope and Inuvik), at generally low elevations (0 to 400 ft. or 0 to 120 m).

The general reversal of the ice content and elevation relationship revealed within the sub-dominant system of this analysis compared with the dominant system of the previous analysis is a direct reflection of the relative importance of the different systems of interacting variables, emphasizing the need to consider the described changes of ice content as part of synergistic interactions of varying significance. Considering only the dominant interactions of the two analyses, a great ice content appears to be associated with, in part, an average depth around 18 ft. (550 cm) and where organic, silty and clayey sediments are overlain by relatively coarse-textured sands and gravels (Pl. 1), the ice being distributed as lenticles or large bodies. STRANG (1973) and MACKAY (1972) have observed layered or massive accumulations, respectively, of almost pure ice along the interface of sandy over silty sediments in different parts of the Mackenzie River valley. The water contents in frozen sediments (about 8 times the weight of soil within the specific environment described in Table II) are often greater than their liquid limit in the unfrozen state (CODE, 1973; MCROBERTS and MORGENSTERN, 1973).

INTERPRETATION OF RESULTS

The averaged predictions from the two analyses were calculated for a range of specific environments (Table IV). The variation of ice content according to latitude and texture, at about 18 ft. (550 cm) and below a sandy deltaic stratum, reveals a very great range of values from 815% at this apparently critical depth where the substrate consists of layered organic silt and clay, to 17% where this substrate is sandy like the overlying sediments. In the fine-textured substrate the ice is distributed as pure ice bodies everywhere from Inuvik in the north to Fort Simpson in the south, while there is no visible ice in sandy substrate throughout the Mackenzie River valley. Northeast facing slopes contain more ice than those facing southwest, either slope showing a small increase with increasing latitude, the ice being distributed as scattered segregations.

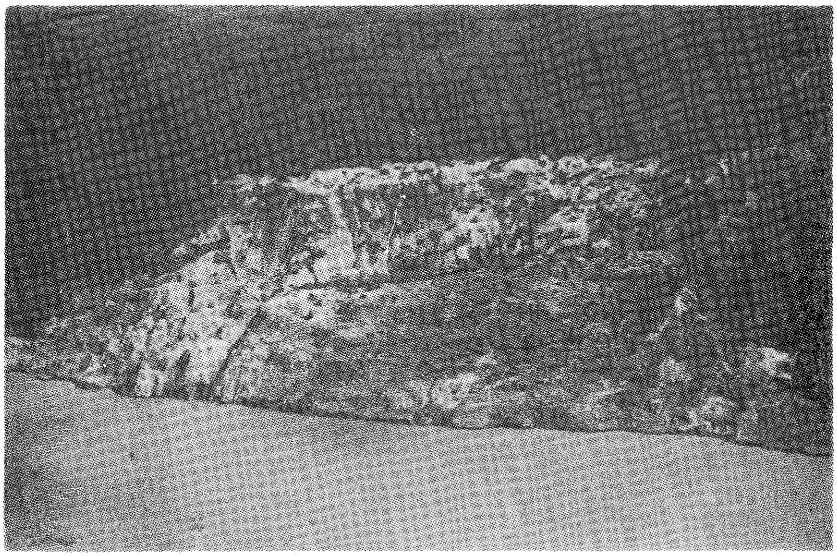
Peat plateaus contain, on average, over 3 times more ice (in lenticles) than in organic material. Both peat plateaus and northeast facing slopes contain more ice where they occur around Norman Wells than to the south and north. A land surface with much lichen in the vegetation contains almost twice as much ice (as scattered ice segregations) than a land surface with much sedge in the vegetation (where the ice occurs as scattered crystals). The considerable albedo of a rich lichen cover (mostly caribou moss: *Cladonia alpestris* (L) Rabenh.) appears not only to keep surface soil layers cool, but to encourage a greater accumulation of ice in the substrate, which is consistent with field work (CRAMPTON, 1975). There is an increase in ice content in sandy soils under forest, northwards, although the calculated values seem a little more than those encountered in field work, just as the maximum ice content calculated for other environmental conditions seems a little less than that

Table IV

Approximate ice contents and distribution associated with specific landscape environments

Latitude	Sedimentary layer at 18 ft. (5.5 m) depth, over substrate of similar texture, below sandy deltaic stratum, under spruce-lichen forest, with NE aspect, at 300 ft. (90 m) elevation			Peat plateaus over silts and clays, under lichen, with S or W aspect, at 300 ft. (90 m) elevation	Runneled slopes with morainal silts and clays below surface organic matter supporting open spruce forest, over silts and clays, at 300 ft. (90 m) elevation		Morainal silts and clyas with fine sand, below surface organic matter, over silts and clays with fine sand, with S or W aspect, at 300 ft. (90 m) elevation		Forested, lacustrine, subsurface sands and gravels with silt and clay, with S or W aspect, at 300 ft. (90 m) elevation
	Layered organic silt and clay	Silt and clay with fine sand	Coarse sands and gravels		NE, with lichen	SW, with sedges	Treed lichen-lands	Sedge-lands	
Inuvik 68°50′	815% by wt. ice content, with pure ice bodies	236% by wt. ice content, with lenticular ice	22% by wt. ice content, with no visible ice	327% by wt. ice content, with lenticular ice	197% by wt. ice content, with some ice segregations	122% by wt. ice content, with some ice segregations	174% by wt. ice content, with some ice segregations	99% by wt. ice content, with scattered ice crystals	51% by wt. ice content, with scattered ice crystals
Fort Good Hope 66°30′	600% by wt. ice content, with pure ice bodies	223% by wt. ice content, with lenticular ice	17% by wt. ice content, with no visible ice	345% by wt. ice content, with lenticular ice	166% by wt. ice content, with some ice segregations	114% by wt. ice content, with some ice segregationis	168% by wt. ice content, with some ice segregations	97% by wt. ice content, with scattered ice crystals	51% by wt. ice content, with scattered ice crystals
Norman Wells 65°50′	535% by wt. ice content, with pure ice bodies*	223% by wt. ice content, with lenticular ice	17% by wt. ice content, with no visible ice	381% by wt. ice content, with lenticular ice	223% by wt. ice content, with lenticular ice	109% by wt. ice content, with some ice segregations	164% by wt. ice content, with some ice segregations	91% by wt. ice content, with scattered ice crystals	39% by wt. ice content, with well bonded substrate
Fort Norman 64°20′	420% by wt. ice content, with pure ice bodies	223% by wt. ice content, with lenticular ice	17% by wt. ice content, with no visible ice	332% by wt. ice content, with lenticular ice	171% by wt. ice content, with some ice segregations	109% by wt. ice content, with some ice segregations	143% by wt. ice content, with some ice segregations	76% by wt. ice content, with scattered ice crystals	39% by wt. ice content, with well bonded substrate
Wrigley 62°60′	420% by wt. ice content, with pure ice bodies	223% by wt. ice content, with lenticular ice	17% by wt. ice content, with no visible ice	325% by wt. ice content, with lenticular ice	162% by wt. ice content, with some ice segregations	105% by wt. ice content, with some ice segregations	124% by wt. ice content, with some ice segregations	71% by wt. ice content, with scattered ice crystals	35% by wt. ice content, with well bonded substrate
Fort Simpson 61°20′	420% by wt. ice content, with pure ice bodies	223% by wt. ice content, with lenticular ice	17% by wt. ice content, with no visible ice	325% by wt. ice content, with some ice segregations	153% by wt. ice content, with some ice segregations	100% by wt. ice content, with some ice segregations	124% by wt. ice content, with scattered ice segregations	70% by wt. ice content, with scattered ice crystals	35% by wt. ice content, with well bonded substrate

* Sample calculation in table II.



Pl. 1. Lacustrine sands over darker silty clays with a distinct interface, exposed by a slide on the banks of the Mackenzie River near the confluence with Big Smith Creek about 40 miles south of Fort Norman

encountered in field work, presumably a smoothing effect produced by utilizing only two systems of interacting variables for ease of calculation. Additional systems would have identified less common interactions, refining the analytical results.

The results such as those tabulated in Table IV were used to help characterize the Land Systems in terms of the % ice content and its distribution (Table V), adding information about these Land Systems to that gained from the landscape analysis (CRAMPTON, 1975). The generalized distribution of Land Systems is shown in Fig. 2.

Table V

General character and grouping of Land Systems shown in fig. 2

Group	No.	General character of Land Systems	Ice distribution	Approx. ice %	Sensitivity Class
Runneled slopes	14	Finely runneled slopes of mounded moraine with icy substrate	Lenticular ice	205%	4
	13	Rocky plateaus and steep, finely runneled slopes with icy substrate	Ice segregations	150%	4
	12	Gentle, coarsely runneled slopes with icy substrate	Lenticular ice	205%	4
	11	Moderate, finely runneled slopes with icy substrate	Ice segregations	150%	4
	10	Gentle, runneled slopes with less ice in the substrate	Ice segregations	30%	3
Organic soils	9	Peat plateaus with lichen and icy substrate	Solid ice bodies	500%	3
	8	Hummocky, peaty mineral soils with icy substrate	Ice segregations	150%	3
	7	Peat plateaus with labrador tea, with icy substrate	Lenticular ice	205%	2
Seasonally waterlogged soils	6	Drumlinoid terrain, locally with icy substrate	Scattered ice crystals	80%	2
	5	Seasonally waterlogged lands with some icy substrate	Lenticular ice	60%	2
	4	Seasonally waterlogged lands with less ice in the substrate	Well bonded with ice	30%	1
Mineral soils and rock outcrops	3	Freer-drained mineral soils with icy substrate	Scattered ice crystals	55%	2
	2	Freer-drained mineral soils with little ice in the substrate	No visible ice	15%	1
	1	Mountain rock outcrops and screes		0%	1

Across the study area the selected sections are more or less equi-distant (except between the Fort Good Hope and Inuvik sections) (Fig. 1). Based on predictions listed in Table IV, the averaged % increase in ice content is, from Fort Simpson in the south to Inuvik in the north, 3%, 8%, 25% (between Fort Norman and Norman Wells), 2% (there is a decrease in ice content between Norman Wells and Fort Good Hope for two of the chosen environments for which the % ice contents

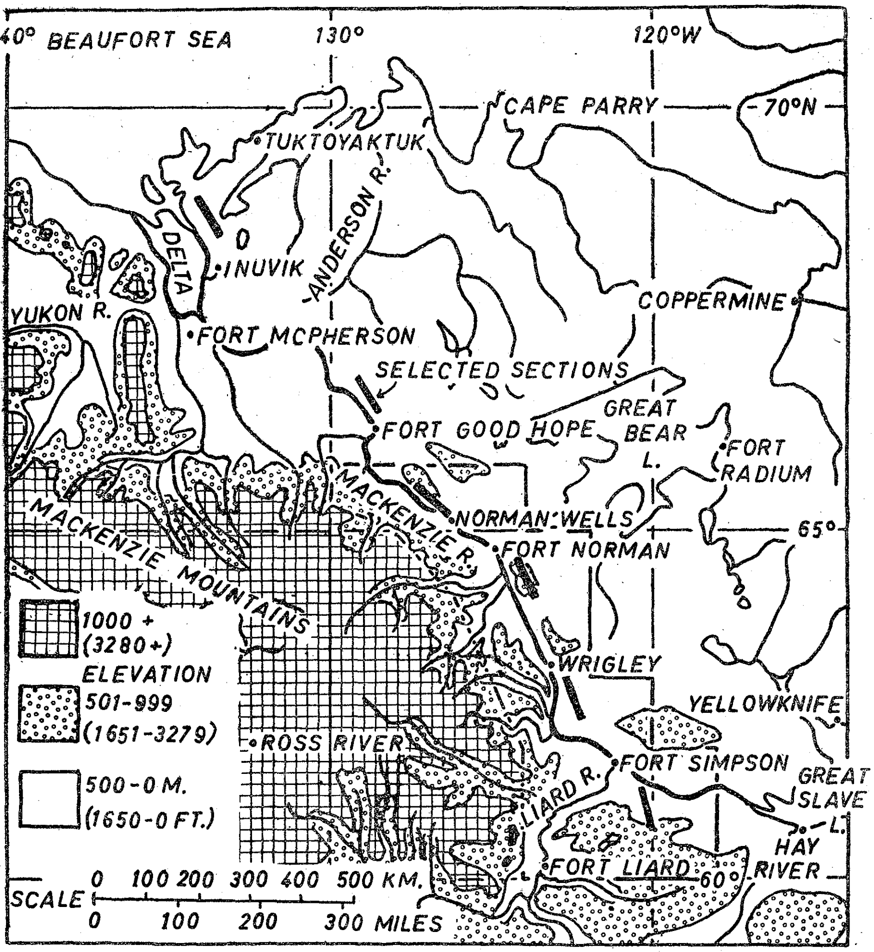


Fig. 1. A topographic map showing the outlined area of the lanscape analysis, and the location of the sections chosen for statistical analysis of the drilling data

were predicted from the analysis), and 10%. The most rapid increase in ice content with increasing latitude appears to occur around Fort Norman and Norman Wells. This confirms an impression gained during field work that there is a rapid transition from the Discontinuous to the Continuous Permafrost Zones, from the Boreal Forest to the Tundra Biomes, within the ecotone represented by the relatively short stretch of river valley from north of Wrigley, through Fort Norman to Norman Wells. This is where detached parts of the Mackenzie Mountains occur on the eastern side of the Mackenzie River in the form of the Norman and Mc Connell Ranges. The mountains restrict the width of the valley and allow runneled lands with icy substrate to slope down from the heights towards the river, reaching the banks between Wrigley and Fort Norman (Fig. 2).

McRoberts and Morgenstern (1973), Strang (1973) and Code (1973) have all observed that many slides in the Mackenzie River valley occur where there are

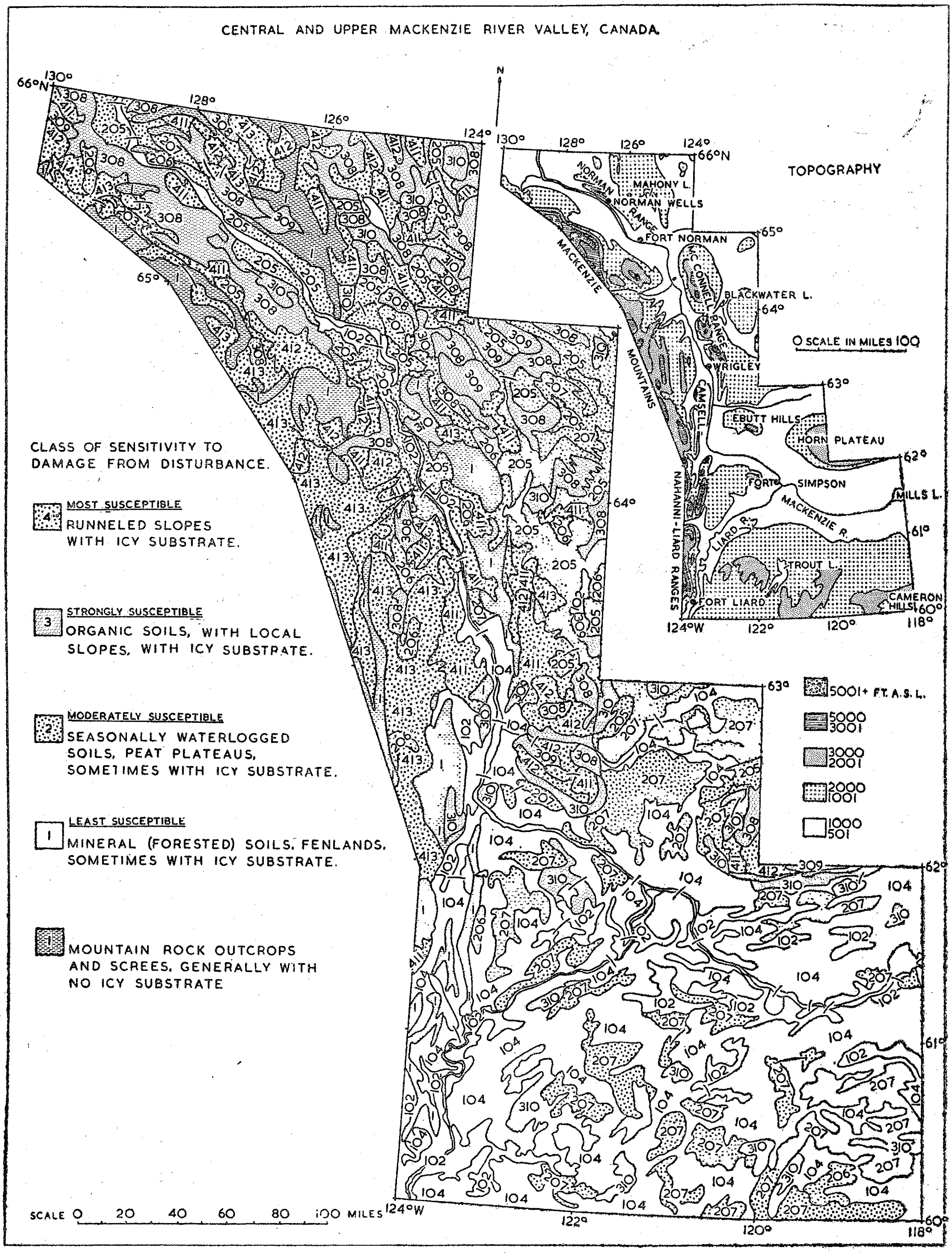


Fig. 2. Zonation of terrain sensitivity to damage from disturbance in the central and upper Mackenzie River catchment (left hand digit), superimposed upon the generalized distribution of Land Systems (two right hand digits)

lacustrine sands over clay, silt or layered silt-sand rhythmites (eg. Pl. 1). The analysis has revealed that at the interface between sandy over fine-textured substrate, at an average depth of around 18 ft. (550 cm) for the samples sites, there is the maximum possible accumulation of ice. MACKAY (1972) has suggested that the downward growth of permafrost through coarse-textured sediments expels water from these sediments, concentrating it within the upper layers of the relatively fine-textured sediments. At the interface between sandy and silty or clayey substrate this water accumulates as lenticular or massive ice bodies. Most slides are initiated by fires. The destruction of the vegetative cover, especially if accompanied by damage to the organic layer (STRANG, 1973), allows the summer's warmth to penetrate deeply into the substrate, thawing it. The little water normally held as ice in porous sandy sediment, on thawing will percolate downwards towards the interface with the fine-textured sediments. If the ice accumulation at this interface also melts, the water content in the substrate will exceed its liquid limit, making material on either side of the interface highly mobile. Sliding could occur over the plane of weakness so produced. MCROBERTS and MORGENSTERN (1973) have suggested that thaw-induced excess pore pressures were the direct cause of many low-angle slides that they observed along the banks of the Mackenzie River.

MCROBERTS and MORGENSTERN (1973) examined slides in the vicinity of the Mackenzie River, mostly where lacustrine coarse-textured deposits were over fine-textured material. They did not record an increasing intensity of disturbance from south to north. Under specific environmental conditions (Table IV), the analysis reveals that the interface of organic silt and clay below sandy deltaic substrate contains over 4 times its soil weight as ice in the south of the study-area, increasing to 8 times its soil weight in the north. Apparently, this range in amounts of ice in the surficial deposits is not sufficiently associated with difference in sensitivity to damage from disturbance to warrant special mention.

STRANG (1973) examined disturbed sites within a wider corridor alongside the Mackenzie River, encompassing a much wider range of landscape types, including peat plateaus, runneled slopes, morainal and lacustrine deposits, forest lands, lichen-lands and sedge-lands. He was greatly impressed by the increasingly more damaging response to disturbance, northwards. For lands of this nature, Table IV shows differential ice contents at the critical interface between sandy over fine-textured sediments, from south to north of about 1 $\frac{1}{2}$ to 2 and 3 $\frac{1}{4}$ to 3 $\frac{3}{4}$ times the soil weight. Apparently, this range in amounts of ice in the surficial sediments is sufficiently associated with differences in sensitivity to damage from disturbance to warrant special mention. It could be speculated that there is a threshold range of ice content at this interface, around 4 times the soil weight, below which an increasing ice content often means an increasing sensitivity to disturbance. Above this threshold value the ice content is so much greater than the soil content, by weight, that the precise amount of ice is unimportant, and sediments containing this amount of ice are all liable to slide or flow under suitable environmental circumstances.

The analytical results show that there is a greater amount of ice accumulation at the interface between coarse-textured over fine-textured deposits below northeast facing slopes. STRANG (1973) noticed that the damage to the landscape was generally greater on northeast facing slopes, although CODE (1973) observed more frequent slides on south facing slopes which thaw more rapidly.

RATING OF SENSITIVITY

Field work indicates that slopes are highly sensitive to erosion after disturbance (CRAMPTON, 1978a). Following disturbance, the thawing of substrate very rich in ice releases quantities of water sufficient to take the material beyond its liquid limit, and slurrying occurs. As long as there is no slope, however, no erosion occurs and an associated Land System need not be placed in the class most sensitive to damage from disturbance. Therefore, a combination of slope and amount of ice present in the substrate constitutes the basis of a sensitivity rating of the landscape of the Mackenzie River valley. All slopes containing icy permafrost have been placed in the sensitivity class 4, delineating lands most susceptible to damage from disturbance, chiefly by erosion. Even slopes with less near-surface icy permafrost can be easily damaged by trenching operations due to the channeling of water (CRAMPTON, 1978a), and so they have been placed in the sensitivity class 3. Erosion exposes more icy substrate each summer, and so the damaging process becomes self-perpetuating, presumably until slopes are sufficiently reduced in inclination.

Ice-rich peat plateaus and hummocky, peaty mineral soils are generally flat, and thawing following disturbance will normally produce local subsidence. Hummocky land surfaces are easily damaged by summer or winter traffic which scours the mound summits, to allow subsidence (CRAMPTON, 1977a). Sedges and willows usually revegetate such areas within a few years. However, invariably there are local, shallow slopes down which erosion can occur, and so such landforms have also been placed in the sensitivity class 3. Peat plateaus, hummocky, peaty mineral soils and slopes contain amounts of ice within the range where small, local changes in precise amounts can probably produce great variations in sensitivity to damage from disturbance. For example, within any particular Land System, sites on northeast facing slopes, and at moderately high elevations or latitudes contain excess ice within this critical range of uncertain response to disturbance. There will also be fortuitous differences in ice content from place to place, and the resulting uncertainty regarding sensitivity to damage is a type of hazard.

Seasonally waterlogged lands are generally flat and contain less ice in the substrate, and so are less sensitive to damage from disturbance. A sphagnaceous pioneer vegetation quickly covers most damaged areas. Field experience indicates that forested mineral soils contain less ice near the land surface than other Land Systems. An alder or grassy vegetation revegetates many damaged sites. Normally placed in sensitivity classes of 1 and 2, wherever there are river banks subject to scouring in those otherwise less sensitive Land Systems, sedimentary successions involving coarse-textured over fine-textured deposits may be exposed. There is often an accumulation of ice at the interface between the two textures. The summer's warmth can penetrate and thaw this ice, producing a supersaturated zone and a plane of weakness within the succession, and sliding may result.

Classes of least sensitivity, 1 and 2, are most widespread in the south of the study area. The slopes, class 4 lands and most sensitive to damage from disturbance, encroach upon each side of the Mackenzie River north of Wrigley to Fort Norman. Within the Mackenzie River valley the greatest rate of increase of ice content occurs around Fort Norman and Norman Wells and, for example, on the icy slopes that reach down from the heights on either side of the river there is more ice in the substrate than in the substrate of slopes around Fort Good Hope and Inuvik. Because this critical ecotone is characterized by a rapidly changing permafrost environment, the region must be regarded as highly sensitive to damage from disturbance since rapidly changing engineering practices will be required during any construction activity to keep disturbance to a minimum and reduce the chances of damaging the landscape.

CONCLUSIONS

Following an extensive land classification in the Mackenzie River valley, an analytical technique based on synergism utilized drilling data from selected sections distributed throughout the study area to characterize Land Systems in terms of ice content and distribution. A close interaction between field survey and quantitative analysis allowed a more comprehensive terrain evaluation to be synthesized, than could have been achieved if field and analytical work had each contributed to an independent evaluation. The empirical prediction of ice content and its distribution within a range of specific environments augmented field experience in qualifying conditions conductive to sliding, and in delineating states where there can be a great variation in severity of damage to a landscape, depending upon local amounts of ice present in the substrate. The information gained was used to classify a map of Land Systems according to sensitivity to damage from disturbance. Lands very sensitive to damage occur around Fort Norman and Norman Wells, partly because a most rapid transition from the Discontinuous to Continuous Permafrost Zones occurs in this region, requiring any construction activity to be extremely cautious in this ecotone.

ACKNOWLEDGEMENTS

The land classification was carried out under the Environmental-Social Program, Northern Pipelines, Government of Canada. The drilling data was supplied by Foothills Pipe Lines Ltd. The research was supported by a Natinal Research Council grant, Canada.

References

Brown, R. J. E. and G. H. Johnston, 1964 — Permafrost and related engineering problems. *Endeavour*, 23; p. 66—72.

Code, J. A., 1973 — The stability of natural slopes in the Mackenzie valley. *Report* No. 73—9 (Information Canada Cat. No. R72—10573), Environmental-Social Program, Northern Pipelines, Government of Canada.

Crampton, C. B., 1975 — Landscape mapping in the Mackenzie River valley. *Arctic*, 28; p. 284—294.

Crampton, C. B., 1977a — A study of the dynamics of hummocky microrelief in the Canadian north. *Canadian Journal of Earth Sciences*, 14; p. 639—649.

Crampton, C. B., 1977b — Forest productivity in central Canada, using a new predictive model. Soils as a site factor for forests of temperature and cool zones. Intern. Soc. Soil. Sci., Zvolen, Czechoslovakia; 38—45.

Crampton, C. B., 1978a — The distribution and thickness of icy permafrost in northern British Columbia. *Canadian Journal of Earth Sciences*, 15.

Crampton, C. B., 1978b — Modelling of the chemical uptake from soil perofiles by trees. *Transactions of Congress*, Commissions II, IV and VII, Intern. Soc. of Soil Sci., Agrochemicals in Soils, Jerusalem. (in press).

Goodman, L. S., and A. Gilman, 1970 — The Pharmacological Basis of Therapeutics. The Macmillan Company, London and Toronto.

Mackay, J. R., 1972 — The world of underground ice. *Annals of the Association of American Geographers*, 62; p. 1—22.

McRoberts, E. C. and N. R. Morgenstern, 1973 — A study of landslides in the vicinity of the Mackenzie River mile 205 to 660. *Report* No. 73—35 (Information Canada Cat. No. R72—12373), Environmental-Social Program, Northern Pipelines, Government of Canada.

Mitchell, C. W., 1973 — Terrain Evaluation. Longman Group Ltd., London, 221 pp.

Philainen. J. A. and G. H. Johnston, 1963 — Guide to a field description of permafrost for engineering purposes. *Technical Memorandum* 79 (NRC 7576), Associate Committee on Soil and Snow Mechanics, National Research Council, Ottawa.

Strang, R. M., 1973 — Studies of vegetation, landform and permafrost in the Mackenzie valley: some case histories of disturbance. *Report* No. 73—14 (Information Canada Cat. No. R72—8173), Environmental-Social Program, Northern Pipelines, Government of Canada.

Webster, R. and P. H. T. Beckett, 1970 — Terrain classification and evaluation using air photography: a review of recent work at Oxford. *Photogrammetria*, 26; p. 51—75.

Wilkinson, C. F., 1976 — Insecticide Biochemistry and Physiology. Plenum Press, New York and London.