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Mapping of Rainfall-Induced Landslides in Ottawa

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Abstract **-** Landslides are frequent in Ottawa because of the presence of sensitive marine clays (also known as Leda clay or Champlain Sea clay). A geographic information system (GIS) based modeling approach has been developed to assess and predict rainfall-induced landslides in the sensitive marine clays of the Ottawa region. The Transient Rainfall Infiltration and Grid-based Slope-stability (TRIGRS) model is used in a GIS framework to investigate the influence of rainfall on shallow landslides over the Ottawa region, with respect to time and location. The assessment result maps illustrate that steep slopes of Leda clay are more prone to landslides.

Keywords**:** Landslides - GIS – Sensitive Marine Clay - TRIGRS – Rainfall

1. Introduction

Sensitive marine clays are widely present in Canada, particularly in the Ottawa. The sensitive marine clays are often called "Leda" clays or Champlain Sea clays in the Canadian geotechnical engineering literature [1-3]. The micro-structure of these clays is similar to a card house structure that collapses and flows upon remolding and excessive wetting [1]. These clays are susceptible to landslide as evidenced by several landslides events that occurred in the sensitive marine clays of Eastern Canada in the past years and decades. There has been a steady increase in the population of Ottawa region, with the present population reaching slightly more than one million and still increasing at a steady rate. This growth has contributed to a significant increase in infrastructure facilities, which include construction of several residential areas, highways, pipelines, including light rail transportation facilities even in problematic areas of sensitive marine clays. Thus, the existence of sensitive clays underneath massive lands which cover the Ottawa region represents a risk to the population and the infrastructures. Therefore, there is an urgent need to assess landslide susceptibility of the sensitive marine clays in the Ottawa region.

The objective of the present paper is to develop a tool for the assessment of the landslide susceptibility of the sensitive marine clays in the Ottawa region by using the technology of GeoInformation System (GIS) [4-7] and Transient Rainfall Infiltration and Grid-based Regional Slope stability (TRIGRS). The research conclusions will assist the City Ottawa, engineers, land developers, practitioners and researchers in better estimating the danger related to the sensitive clays, to design safe, economical and sustainable infrastructures in the Ottawa region.

2. Canadian Sensitive Marine Clays

An understanding of the geotechnical features of sensitive clays is essential for a good investigation and analysis of the landslides in Leda clay slopes. Therefore, the objective of this section is to provide the technical background on sensitive marine clay. Sensitive marine clay is mainly the product of proglacial and post glacial sedimentation after the advancement of the Wisconsin Ice Sheet (Figure 1). The main types of soft clay deposits that a geotechnical engineer could find are listed in Table 1[8]. Postglacial depositions of Ottawa sensitive marine clays are predominantly done so by the Champlain Sea which covered Ottawa from 12500 to 10000 years BP. As a result of proglacial and postglacial deposition, varved marine clays formed. A layer of one year of deposition consists of the silt (80% >2 μm) and clay (80% <2 μm) layers, and the transition layer in between. The main minerals of the Ottawa clays are quartz, feldspar, amphibole, mica, chlorite, smectite, and glacial amorphous material. Carbonates may also be present in these clays. Three main types of sedimentation processes in general, are responsible for marine clays in Canada, which are waterlaid tills, lacustrotills, and mudflows [1].

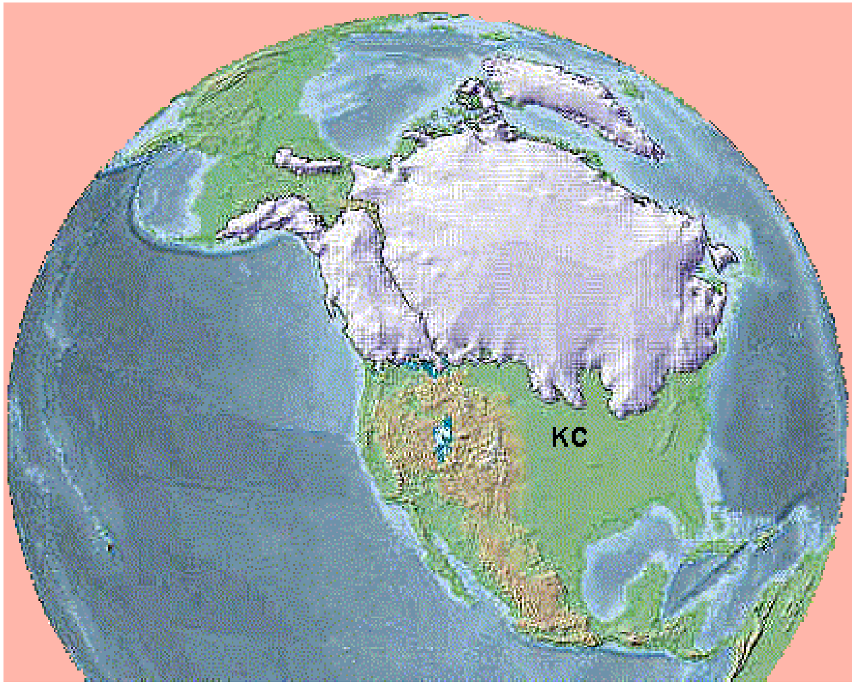

Fig. 1: Wisconsin Ice Sheet [9].

Table 1: Types of Soft Clayey Soils 0.

Types of Deposit	**Origin**
Waterlaid tills	Unsorted lacustrine sedimentation below floating ice
Lacustrotills	Subaqueous, proximal, flow deposits in proglacial lakes
Mudflow deposit	Subaerial and submarine flows
Turbidity current deposits	Heavy-density current deposits generated by mudflow dilution, floods, ice calving, slumping, etc.
Varved clays	Turbidity current summer deposits and winter clay deposition by settling
Marine clays	Salt-water flocculation and sedimentation

Leda clay is considered to have a "card-house" type of structure that would experience noticeable particle reorientation when consolidated. It was confirmed that anisotropic consolidation of sensitive clay produces reorientation of the clay flakes in a plane perpendicular to the major principle consolidation pressures σ_1 and σ_3 [10].

3. Background on TRIGRS

TRIGRS (as per [11]) stands for Transient Rainfall Infiltration and Grid-based Regional Slope stability. It calculates the changes in transient pore-pressure and the changes attendant in the factor of safety due to rainfall infiltration. The original version of TRIGRS was created by Baum et al. [12] based on the linearized solutions of the Richards equation set by Iverson [13]. It is programmed in FORTRAN. The TRIGRS model takes into consideration the rainfall infiltration caused by storms which have periods ranging from a few hours to a few days. Consequently, TRIGRS uses partial differential equations to generate analytical solutions when there are requirements such as one-dimensional, vertical flows in isotropic or homogeneous soil materials (saturated or unsaturated conditions [11]. In order to compute the effects of rainfall on soil stability over large areas, theoretical bases of the infiltration models have to be combined with the subsurface flow of rainfall water, runoff direction, and slope stability [14-15]. The TRIGRS model can be used in the analysis of slope stability and to discover the effects of transient rainfall infiltration. This approach can also simulate the safety factors and pore pressure changes induced from rainfall infiltration for various durations at different depths of soil. The landslide potential can be presented via automated analysis for all slope units within catchment areas that rely on the circumstances of rainfall infiltration [14-15].

The series of Heaviside step function used in the TRIGRS model for the application of Iverson's proposal requires the use of constant rainfall intensity to find the original solution. TRIGRS uses a series of Heaviside step functions to apply Iverson's suggested summations of his original solution for constant intensity rainfall to present a general time-varying sequence of surface fluxes of variable intensities and durations as a substitute to the solution, with an infinitely deep basal boundary [11-12].

4. Study Area and Methodology

This study deals with the Ottawa region. The Ottawa municipality covers approximately 2,778 km² and extends approximately from a latitude of 45.00 N to 45.50 N and longitude of 75.50 W to 76.00 W (Figure 2). The Ottawa region is bounded by the Ottawa River on the north, the historic Rideau river, and the Rideau Canal, which flows north to south across the city of Ottawa, which is located in the eastern part of the province of Ontario in Canada and contains several municipalities (Figure 2) [16-17].

An approach that involves multiple steps was adopted to assess the stability and susceptibility of slopes composed of sensitive marine clay to landslides that may occur due to the exposure of different areas during periods of rainfall. The approach adopted is summarized in the flowchart presented in Figure 3. Using this approach, a GIS-TRIGRS model was developed and tested in this study to assess the susceptibility of rainfall-induced landslides in sensitive marine clays in the Ottawa region. Then, the model was validated against previous landslides recorded in the studied area. The validation results of the developed model have shown a good agreement between the predicted and recorded historical landslide areas in the Ottawa region.

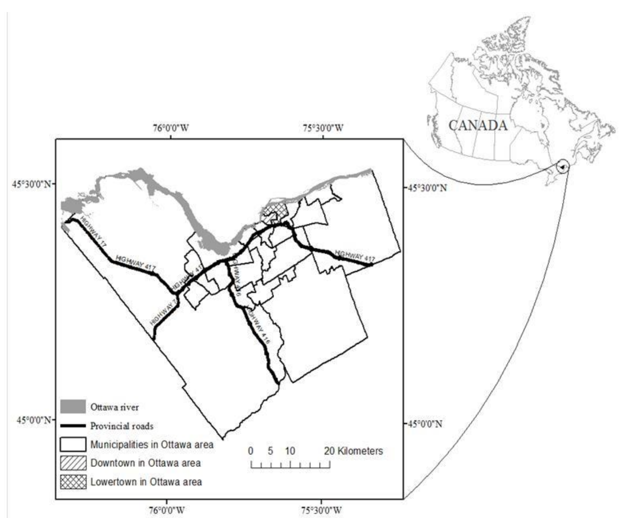

Fig. 2: Studied area (Ottawa region).

5. Sample of Results and Discussion

The results have shown that the areas that are most susceptible to rainfall-induced landslides are located in the eastern and western parts of the studied area, as well as in regions with steep slopes of Leda clay. Moreover, landslides in the studied area are actually triggered by rainfall events that are long in duration and low in intensity rather than rainfall events that are short in duration and high in intensity. This is because a lengthy duration of rainfall that is low in intensity commonly results in the infiltration of water into the Leda clay formations, of which the upper parts are unsaturated.

Figures 4 to 5 illustrate the areas that are susceptible to rainfall induced landslides in the studied area for rainfall durations of 24 hrs, respectively, for the normal and worst case scenarios (with respect to the geotechnical input data), and the corresponding rainfall intensity. For a "normal" scenario: the average values of the geotechnical parameters (e.g., cohesion, internal friction angle) in each domain of the studied areas were used as the input data. For a worst case scenario: the most negative ("pessimist") values (with respect to impacts on the FS) of the geotechnical parameters in each domain of the studied areas were used as the input data. From these figures, it can be observed that the areas that are the most susceptible to landslides are located in the eastern and western parts of the studied area, as well as in areas with steep slopes of Leda clay. Furthermore, areas prone to landslides (FS < 1) are few in cases of high rainfall intensity/short rainfall duration compared to low rainfall intensity/long rainfall duration.

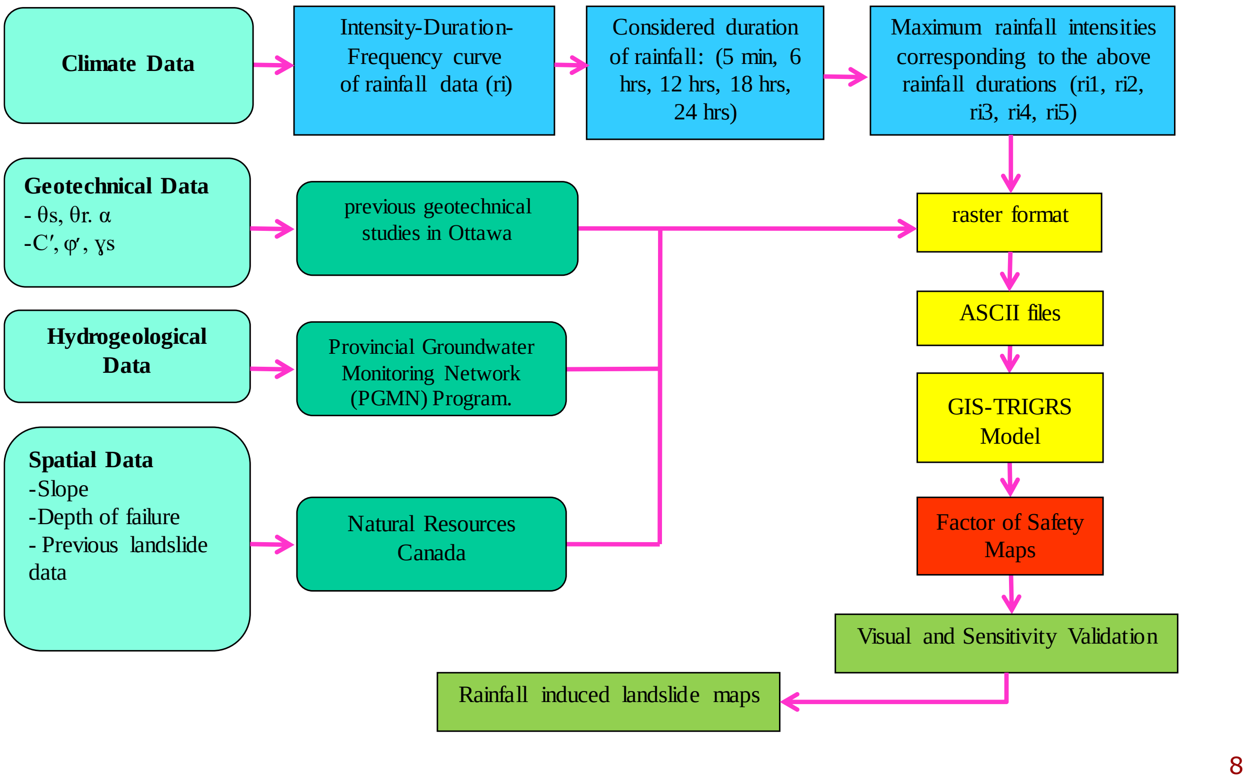

Fig. 3: Methodology adopted.

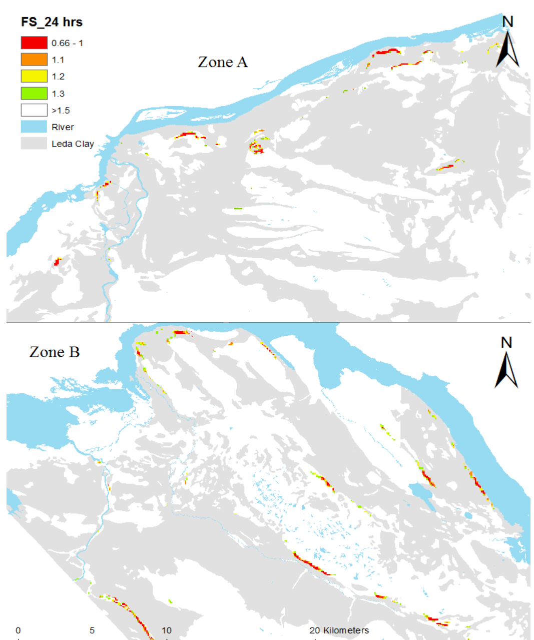

Fig. 4: Landslide susceptibility map for rainfall duration of 24hrs –normal scenario (FS: factor of safety).

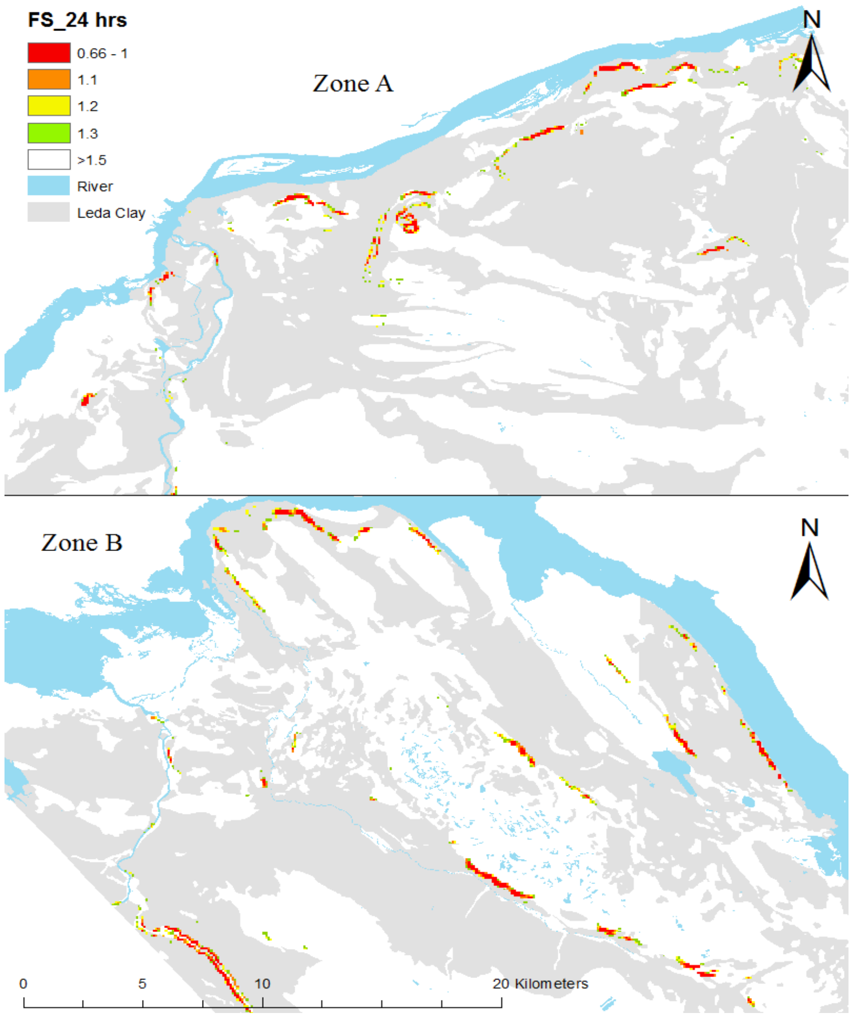

Fig. 5: Landslide susceptibility map for rainfall duration of 24hrs –normal scenario (FS: factor of safety).

6. Conclusions

A GIS-TRIGRS model is developed and tested in this study to assess the susceptibility of rainfall-induced landslides in sensitive marine clays in the Ottawa region. The validation results of the developed model show a good agreement between the predicted and recorded historical landslide areas in the Ottawa region. The results have shown that the areas that are most susceptible to rainfall-induced landslides are located in the eastern and western parts of the studied area, as well as in regions with steep slopes of Leda clay.

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