Hazard Risk Analysis

Geological (related to soil and earth)

Geological

Geological hazards are related to the soil or the earth. These six hazards include: Dust and Sand Storms; Erosion, Deposition and Desertification; Expansive Soils, Landslides and Debris Floods (Gravitational Mass Movements); Land Subsidence and Sinkholes, and Submarine Slides. Many geological hazards can have natural causes and can also be caused by humans.

Dust and Sand Storms

Definition

In the Prairie Provinces (Alberta, Saskatchewan and Manitoba), Environment Canada issues a Dust Advisory when blowing dust is expected to occur, reducing visibility to 800 metres or less for one hour or more.

When blowing dust covers a large area, the event is termed a dust storm. Large-scale dust storm events are often have lasting high winds at the surface that are related to very large-scale wind storms (of a 1000 km in lenght or more; also called cyclonic or synoptic storms). Dust storms can last from 3 to 4 hours to 2 to 3 days, and most often occur in spring. Dust storms can also be related with a looming thunderstorm.

Discussion

Blowing dust (and sand) events are becoming more common. They can affect highway travel due to a severe drop in visibility. Dust storms in Canada occur in the agricultural prairies. On average they occur at least once to as often as five times per year and are often linked to serious soil

erosion. Most dust storms occur in the spring, but some dust storms are also generated in August.

It Happened Here…

On April 27, 2013 a dust storm hit the First Nations community of Standoff, Alberta. Dust entered homes, people experienced difficulty breathing and some families lost power. As a result of the storm about seven or eight families of the Blood Tribe were forced to evacuate.

On May 19, 2001, a dust storm blew through Alberta, near the small town of Bowden (population 1,205), causing a 15-vehicle accident on a major highway. Dust carried by 100 km/h winds impaired visibility on Highway 2 north of Calgary. Eight were injured in the accident.

Dust and Sand Storms - Natural

Hazard Rating	High Risk ☐	Low Risk ☐	Need More Info ☐	Not Applicable ☐

Yes	No	Need More Info	Not Applicable	FACTORS
☐	☐	☐	☐	Sand and dust storms are most likely to happen where they have happened in the past. Is there a history of sand/dust storms in or near to your community?
☐	☐	☐	☐	Sand/dust storms are more likely to occur in a dry area or region which receives less than 25 cm. of rain per year (arid). Is your community located in or near a desert or other dry (arid) region?
☐	☐	☐	☐	Periods of drought can increase the chance of sand/dust storms. Is your community experiencing a drought?
☐	☐	☐	☐	Soil erosion can lead to dust storms. Has there been major erosion activity in or near your community?
☐	☐	☐	☐	Communities in the southern Prairies are more prone to dust storms than those in the northern Prairies. Is your community in the southern Prairies?
☐	☐	☐	☐	Are Traditional Knowledge holders in your community aware of past sand/dust storms in or near by your community?

Dust and Sand Storms - Human-caused

Hazard Rating	High Risk ☐	Low Risk ☐	Need More Info ☐	Not Applicable ☐

Yes	No	Need More Info	Not Applicable	FACTORS
☐	☐	☐	☐	Sand and dust storms are most likely to happen where they have happened in the past. Is there a history of sand/dust storms in or near to your community?
☐	☐	☐	☐	Sand/dust storms are more likely to occur in a dry area or region which receives less than 25 cm. of rain per year (arid). Is your community located in or near a desert or other arid region?
☐	☐	☐	☐	Dust storms can be caused by soil erosion. Has your community experienced significant erosion activity?
☐	☐	☐	☐	Vegetation groundcover can reduce the likelihood of sand/dust storms. Have large areas of soil been stripped of vegetation?
☐	☐	☐	☐	Agricultural activities such as deep tillage are a major cause of soil erosion in Canada. Is your community located in an agricultural region that practices deep tillage?
☐	☐	☐	☐	Scientists have observed that some regions in Canada are receiving less rainfall than before, which increases the chance of sand and dust storms. Has your community experienced less rainfall in the past several years?

Erosion, Deposition and Desertification

Definition

Erosion is the wearing away of land by the action of natural forces, such as wind or water. For example, coastal erosion is marked by the carrying away of beach material by wave action or tidal currents. Similarly, river bank erosion is the result of river currents removing river bank material. Deposition, or sedimentation, is defined as the buildup of land by natural or artificial means. Desertification is the change of the landscape to a more desert-like environment. Desertification is often human-induced, but likely worsened by climate change in many regions.

Discussion

Desertification, is characterized by the loss of valuable top-soil and by degradation of vegetation. The process occurs around the world. It causes additional erosion of the earth, in addition to naturally occurring erosion, and it affects the earth's ability to produce food.Erosion generally involves the removal of earth materials from one area with deposition in another and is a normal and inevitable geologic process.Erosion can be concentrated and quick, for example when land surfaces are gullied and stream banks are undercut.Erosion can also be widely spread and slow, for example the wearing down of hillslopes by millimeters or centimeters over hundreds or thousands of years. Erosion at one place will cause sedimentation (or deposition of earth's materials) in another place. This process of erosion and deposition can damage or destroy

waterway and riparian habitat, clog drainage structures, lakes and reservoirs, and floodplains. Activities by people, such as grading, frequently fast-track erosion and sedimentation.

For coastal communities erosion of the foreshore for example (the area of the beach that is under water at high tide, but above water at low tide) is important to monitor. Changes to the shoreline could indicate changes in sea level and long-term erosion rates. Erosion processes affecting the coast are a function of things such as sediment supply, tides, waves, and currents, and the geomorphic character of the coastline (for example a rocky versus a sandy beach).

Erosion processes in other regions are affected by factors such as groundwater conditions, vegetative cover, land use, subsidence and freeze-thaw cycles.Logging activities that change vegetation cover can seriously impact erosional processes on hillslopes and lead to landslides. .

It Happened Here…

On March 29, 2021 it was found that the surrounding wooden boardwalk around Low Point Lighthouse, in Cape Breton, Nova Scotia has been beaten to pieces by wind and waves and as a result the lighthouse itself is inching close to the cliff edge as soil gives way. It is estimated the lighthouse is less than 10 metres from the edge of the bank.

On August 6, 2010 a landslide off Mount Meager, BC, provided large amounts of sediment to the Lillooet River. The river, running through the Mount Currie First Nation and the village of Pemberton, rapidly began to erode the landslide sediments and transport them downstream. In some reaches river banks were rapidly eroded, in other reaches large amounts of sediment were deposited in gravel and sand bars. Rapid build-up of sediment in the diked sections of the river is a concern to the communities, as it reduces dike freeboard and as such increases the chance flooding.

In 2006, dredging of the Upper Great Lakes caused an increase in erosion, leading to water levels dropping 45cm below average. In Georgian Bay (population 1,991), Ontario water levels were at their lowest in over forty years. Environment Canada scientists speculate that climate change has also contributed to the water level drop, because of changes in rainfall patterns.

Human-Caused Erosion

In 2000, spring monsoon rains washed away farmers' seeds and plants in Central Canada. Soil eroded away because agriculture in the region exposed it to rain. As a result, farmers' crops were affected by insects and diseases that bred in the wet conditions, causing a 15% drop in production from previous years. The small town of Hiller, Ontario (population 100) was among the many communities affected.

Human-Caused Desertification

In 2018, Canada rejoined the UN Convention to Combat Desertification (it had withdrawn in 2013), a legally-binding agreement. One factor that supported this decision was the expectation that with climate change, it is expected that the Prairies can expect to see longer and more intense periods of drought, interspersed with flooding, leading to increased desertification.

Desertification has been a major problem in Northern Saskatchewan since the early 1960's, due to deforestation from clear cutting forest practices. Saint Walburg, Saskatchewan (population

672), near Meadow Lake, is among the many communities affected by desertification and left with unproductive land.

Erosion, Deposition and Desertification - Natural

Hazard Rating	High Risk ☐	Low Risk ☐	Need More Info ☐	Not Applicable ☐

Yes	No	Need More Info	Not Applicable	FACTORS
☐	☐	☐	☐	Are there areas in your community that receive above average rainfall? The impact of rain breaks down large pieces of soil into smaller pieces, creating a finer texture (erosion).
☐	☐	☐	☐	Are there areas in your community with fine-textured soils and smooth surfaces such as clays and silts? Fine-textured soils produce more runoff than coarse textured, or permeable sandy soils, which have the ability to let water pass through more quickly. Fine particles are also more easily swept away by wind (erosion).
☐	☐	☐	☐	Are there areas in your community where it takes a long time for the soil to absorb water? This can indicate the soil has low amounts of organic matter (e.g. dead leaves) and poor structure (it does not clump together).
☐	☐	☐	☐	Are there areas in your community where erosion has occurred in the past? Past erosion often leads to poor soil structure and lower organic matter (e.g. dead leaves).
☐	☐	☐	☐	Are there areas in your community with steep slopes? The longer and steeper the slope the greater the risk of erosion due to more water runoff.
☐	☐	☐	☐	**Are there areas in your community where soil is not protected by vegetation (e.g., grasses, trees)? Covering plants protect the soil from rain impact and splash, slow water runoff, and allow the soil to absorb more water. Erosion and desertification risk increases if the times of the year when rainfall is high are the same as when plant coverage is low. Lack of vegetation also increases erosion risk from wind, as plant roots hold the soil together.
☐	☐	☐	☐	Are Traditional Knowledge holders in your community aware of changes in the landscape as a result of erosion in traditional fishing or hunting territories in or near by your community?
☐	☐	☐	☐	Are there areas in your community with winds that are fast and last a long time? These factors increase risk of soil erosion.

Desertification Human-caused

Hazard Rating	High Risk ☐	Low Risk ☐	Need More Info ☐	Not Applicable ☐

Yes	No	Need More Info	Not Applicable	FACTORS
☐	☐	☐	☐	Are there agricultural areas in your community that are over-farmed? Farming without recovery periods can change the chemistry of the soil so that it is no longer productive.
☐	☐	☐	☐	Are there areas in your community where intensive grazing occurs without recovery periods? Over-grazing can weaken plant roots, making them more vulnerable to dry weather.
☐	☐	☐	☐	Are there areas in your community that are overly irrigated? The result of excessive irrigation may be that the soil accumulates salts as some water evaporates.
☐	☐	☐	☐	Are there areas in your community that are deforested? When vegetation is clear-cut from an area, the area is vulnerable to erosion and loss of soil nutrients.
☐	☐	☐	☐	Are there areas in your community in which toxic chemicals may be building up (due to heavy pesticide or herbicide use, for example)? Toxic buildup can make the land no longer productive.
☐	☐	☐	☐	Are there areas in your community where vegetation is changing (for the worst), or where vegetation used to grow and now does not? These areas are vulnerable to erosion, because they are no longer protected by vegetation
☐	☐	☐	☐	Scientists have observed that with climate changes areas of forestation are changing and some areas are experiencing reduced levels of rainfall thus leading to increased likelihood of desertification. Has your community recently experienced reduced levels of rainfall and changes in forestation?

Erosion and Deposition Human-caused

Hazard Rating	High Risk ☐	Low Risk ☐	Need More Info ☐	Not Applicable ☐

Yes	No	Need More Info	Not Applicable	FACTORS
☐	☐	☐	☐	Are there areas in your community where vegetation has been disturbed by plowing or other human activities? Decreasing the area that plants cover the soil, increases the risk of erosion from wind and rain.
☐	☐	☐	☐	Are there areas in your community next to or near a hydroelectric dam? Dams increase the deposition of sediment in the lake or reservoir behind the dam, and often lead to erosion downstream.
☐	☐	☐	☐	Are there areas in your community that are deforested? When vegetation is clear-cut from an area, the area is vulnerable to erosion and loss of soil nutrients.
☐	☐	☐	☐	Are there areas in your community where vegetation is changing (for the worst), or where vegetation used to grow and now does not? These areas are vulnerable to erosion, because they are no longer protected by vegetation.
☐	☐	☐	☐	Are there areas in your community where intensive grazing occurs without recovery periods? Over-grazing can weaken plant roots, making them more vulnerable to dry weather.
☐	☐	☐	☐	Are there areas in your community at risk of desertification? (Refer to the section on Desertification) If your community is at risk of desertification, it is also likely at risk of erosion.
☐	☐	☐	☐	Are there areas in your community where vegetation has been disturbed by plowing or other human activities? Decreasing the area that plants cover the soil, increases the risk of erosion from wind and rain.

Expansive Soils

Definition

Some soils have a potential to swell when they absorb water and shrink when they dry out. These expansive soils generally contain clays that expand when moisture is absorbed into (the crystal structure of) the clays. Volume changes, or expansions, of 10% or more are not uncommon. These changes in volume can exert enough force on a building or other structure to cause damage.

Discussion

The effects of soil expansion usually involve some vertical movement of the soil/ earth surface. Few buildings and highways are built to withstand much vertical movement. Houses and one storey buildings are most at risk of soil expansion but even multi-storey buildings can be

damaged. Most damage occurs in basements and foundations, but since the process is slow, it often goes unnoticed for a long time or is thought to be due to poor building design.

It Happened Here…

In 2012, expansive soils were held responsible for damage to civil infrastructure in a semi-arid area in and around Regina.

Damages to the foundation of homes from expansive soils are extensive in southwestern Saskatchewan because the ground is comprised of clay sediments that expand. Among the many communities affected by expansive soils is Sceptre, Saskatchewan (population 99). The damage occurs when rain or irrigation water gets under the foundation and causes the clay soil to expand.

In November 2004, expansive soils damaged the south approach to the Roger Pierlet Overpass in Cloverdale, British Columbia. The concrete bridge structure was supported on precast concrete piles toe bearing in the till-like soils, and the south approach of the bridge was damaged by foundation soil movement caused by failure beneath a soil stockpile placed adjacent to the east side of the bridge. The soil failure displaced the pile-supported piers by as much as 425 mm horizontally. Substantial cracking of pier columns, foundation tie beams, and piles (inspected at underside of pile caps) resulted. Several deck expansion joints developed large separations. The cantilevered steel sidewalks and roadway railings were also damaged, resulting in temporary closure of the sidewalk.

Hazard Rating	High Risk ☐	Low Risk ☐	Need More Info ☐	Not Applicable ☐

Yes	No	Need More Info	Not Applicable	FACTORS
☐	☐	☐	☐	Have expansive clay soils been identified in your community?
☐	☐	☐	☐	Expansive soils are one of the main causes of broken water mains. Have there been situations where a number of water mains in your community have broken?
☐	☐	☐	☐	Are Traditional Knowledge holders in your community aware of changes in the landscape as a result of expansive soils in traditional fishing or hunting territories in or near by your community?
☐	☐	☐	☐	Material deposited in lake water and later exposed, either by lowering of the water level or by uplifting of the land, are particularly prone to expansive soils in Western Canada. Are you aware of situations where there is exposed soil that used to be covered by lake water in or near your community?

Landslides and Debris Floods (Gravitational Mass Movement)

Definition

Mass movement events, commonly known as 'landslides', are the result of downward movements of slope materials reacting to the force of gravity.These events cover a wide variety of land forms and processes. Slide material may be composed of natural rocks, soils, artificial landfills or combinations of these components.

Figure 1. Rock Slide

Discussion

Landslides can be classified according to three criteria:

1. rate of movement: While many catastrophic landslides occur in a matter of seconds to minutes, mass wasting processes can also be very slow (millimeters to centimeters per year, e.g. soil creep);
2. type of movement: Types of movement are avalanches, falls, topples, slides, slumps, lateral spreads and flows (or 'torrents' when channelized);
3. type of material:Types of material are (bed)rock and soils, including debris, earth and artifical landfill.

There are several causal factors that play a role in the occurrence of landslides, these are internal or external factors that reduce the stability of a slope: slope angle, geology (type of material, structure and layering), and water content. Chassie and Goughnour stated that "water is the controlling or a major contributing factor in about 95 percent of all land slides." A 'trigger' is the final straw that makes an unstable slope fail. Examples of triggers include: earthquakes, climate (seasonal contrasts or lack of vegetation), undercutting and oversteepening of slopes (for example to build roads or railways), weather (local high rainfall events), removal of vegetation (logging or forest fires), freeze-thaw cycles (repeated freezing and thawing gradually moves a mass (derbis, sediment) down slope). See below for some more detailed description of five of the most common triggers:

1. Vibrations from earthquakes, blasting, machinery, traffic, and even thunder have been known to trigger mass movements. In seismically active parts of the world, some of the most disastrous of all historic landslides have been triggered by seismic shock.
2. Removal of lateral support by such means as erosion by streams and rivers or waves and longshore or tidal currents (e.g. eroding of part of a hillside by a river ror stream which increases the slope angle, making it more unstable); previous slope failure; and results from construction, especially where cuts, quarries, pits and canals are established or lakes and reservoirs are created and their levels altered.
3. Loading by such natural or human means as weight of rain, hail, snow; accumulation of loose rock fragments or accumulated volcanic material; stockpiles of ore or rock; waste piles; and weight of buildings and other structures.
4. Changes in direct water content and pore pressure and in structure. The relative stability of a slope in either soil or rock may change radically with changes in ground water level. If the soil or rock contains narrow but open fractures, minor increase in total water content through precipitation may produce a large rise of the water level in the fractures and

markedly decrease the internal stress and shearing resistance. Thus, heavy rainfall has often been found to trigger landslides.

5. Weathering and other physical or chemical action may decrease the strength of rock and soil, usually over long periods of time. However, structures and buildings - especially on slopes - remain at risk from any such action.

When considering the geology of a specific area, it is necessary to consider the composition or attributes that affect the behaviour of rocks and soils.Some rock types are more easily eroded than others. Granite for example is a very hard and durable rock (hence its use as kitchen countertops), but limestone is much softer and will wear away much easier. The structure of the rocks and soils is also important as faults, folds, joints and layering effects are also known to affect the stability.

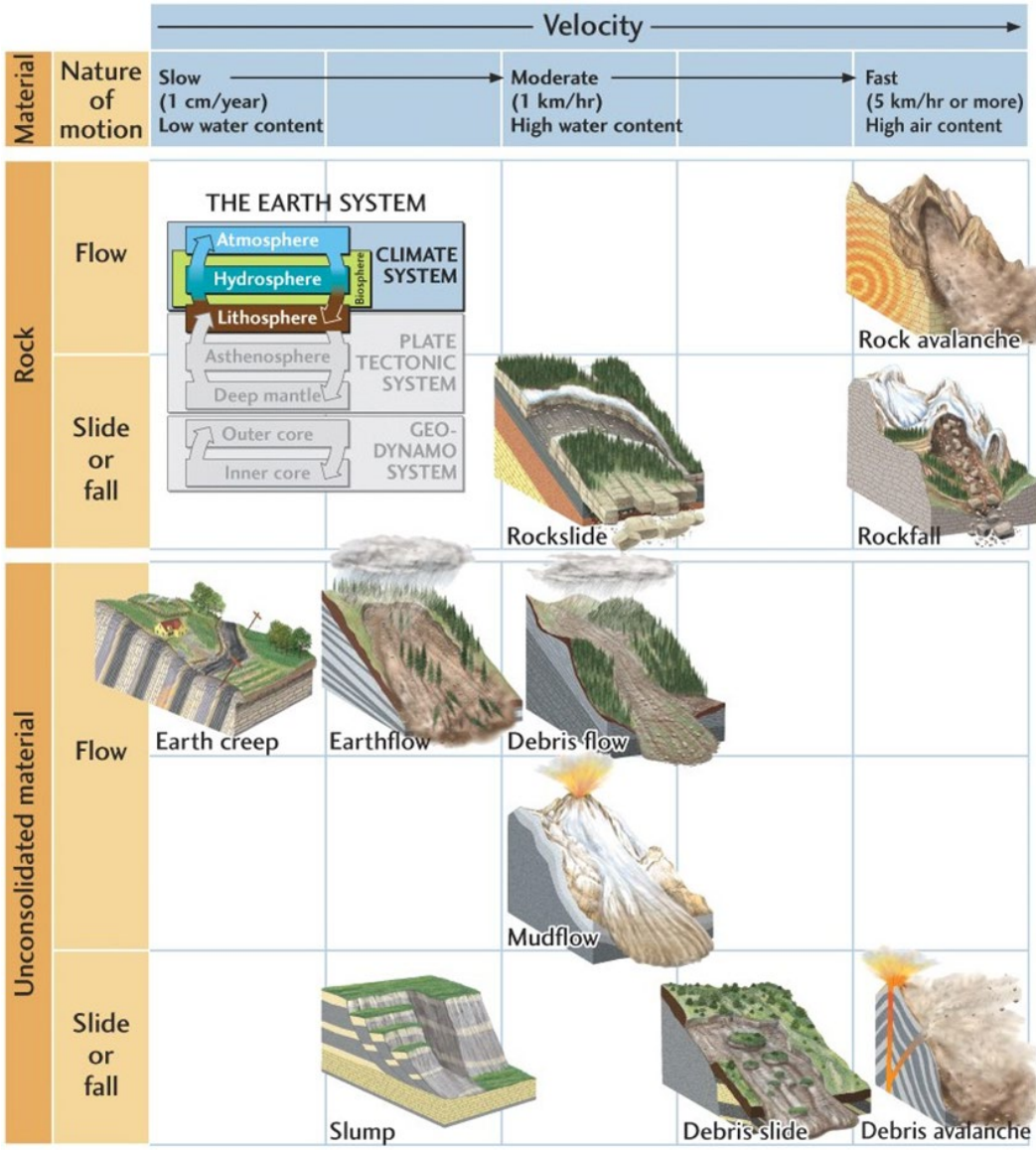

Figure 2 Mass movement types according to material, nature of motion and velocity of movement (Image: unidentified resource).

Mass Wasting process	Velocity of movement
Debris Avalanches are terrifying avalanches of mud, rock, brush, trees and other debris loosened and propelled by torrential rains. Debris avalanches are very rapid to extremely rapid debris flows.	Fast
Debris flows are a form of rapid mass movement in which loose soil, rocks and organic matter, combined with air and water, form a slurry that then flows down-slope.	Moderate
Debris Slides occur when soil and other loose earth materials slide off a hillside.	Moderate-fast
Earth Creep is the slowest form of mass movement. Soil and rock very slowly move downslope. The process occurs over periods of years to centuries and is only visible to people through curved trees, leaning fences or poles, and broken retaining walls or other structures.	Slow
Earth Flow is the downslope movement of water-saturated, fine-grained soil or weathered rock. It is typically a slow process, but can occur in time periods varying from minutes to years.	Slow-moderate
Mudflows are special forms of debris flows that are mainly made of the smallest mud and silt particles. Extremely heavy rain, or a sudden thaw can trigger these types of flows. Mudflows are often very fluid and thus can travel with great speed. In the case of **lahars**, a sudden thaw of mountain snow and/ or ice due to a volcanic eruption can send a torrent of mud, ash, and hot water down the slope of the volcano and over neighboring towns.	Moderate
Rock Avalanches are similar to debris avalanches, and involve the very rapid to extremely rapid downward motion of broken-up bedrock.	Fast
Rock Falls occur when masses of rock, or other material, move down-slope primarily by falling or bouncing through the air. They commonly occur along steep roads and railroads and along steeply undercut cliffs in coastal areas. Considerable damage from large boulders or blocks of rock can occur. Rock falls often accumulate in a large pile on the bottom of a steep hill.	Fast
Rockslides occur when large blocks or layers/slabs of bedrock slide down a sloping surface.	Moderate
Rock topples occur when rocks overturn, and unblocked by any other material, is able to continue to fall or slide to the bottom. Slides occur due to failure along one or more surfaces. The	Slow onset to very fast

Mass Wasting process	Velocity of movement
material from the slide can be broken up into a number of pieces or remain as one intact mass.	
Slumps are slides of rock layers or other earth materials that rotate backwards as they move downward. Thus they are also called 'rotational slides'.	Slow-moderate

Debris avalanches are often triggered by intense autumn and winter rainstorms, when water infiltrates and saturates the surface layer of (weathered) soil. Debris avalanches may temporarily block gullies swollen with runoff water, thus changing into rapidly moving debris flows. Debris avalanches, commonly originating in shallow drainage depressions, begin as large masses that suddenly break away from the land form, leaving well-marked, semi-circular head scarps. The high speeds are often leave a trail of gravel, boulders and mud marked on trees along the area of the avalanche.

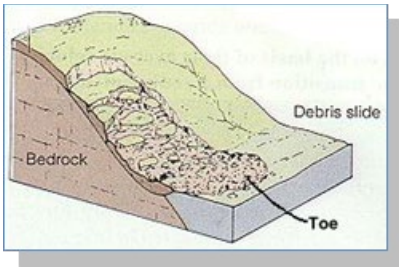

Figure 3 Debris Slide

Debris flows or slides are often smaller in area and wider in scope compared to debris avalanches. The debris slide failure surface often occurs within the upper soil. Today, debris torrents are often due to poor logging practices. Log jams are created on mountainous streams and then burst during a storm.

Another emerging factor that contributes to debris floods or torrents occurs on land that has experienced previous forest or wildfires. Post-fire the soil is often exposed, there has been a loss of vegetation and there is a lot of loose debris. However, it is unusual for post-fire debris flows to occur beyond the second rainy season with the largest debris-flow events happening in the first post-fire storm season. It is important to note that it takes much less rainfall to trigger debris flows from burned basins than from unburned areas. Any storm that has intensities greater than about 10 millimeters/hour (0.4 inches/hour) poses the risk of producing debris flows.

While multiple factors can affect debris-flow occurrence, post-fire debris flows generally are triggered by one of two processes: surface erosion caused by rainfall runoff, and landslidings caused by rainfall seeping into the ground.

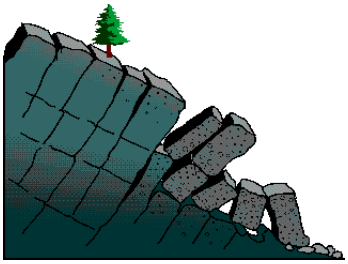
Figure 4 Rock Topple

The most important factor in determining the likelihood of landslides is the presence or absence of former landslides, as this may be the best guide to future behaviour of a slope in a region.

Mass movement processes in unstable mountainous areas of Canada will become more common as winter precipitation rises, permafrost melts and glaciers retreat. Water quality, fish and wildlife habitat, as well as roads and other structures will be at increased risk.

Debris Avalanches, Debris Flows and Torrents

It Happened Here…

On February 5, 2020, residents of 27 properties along the Trans-Canada highway, about 14 kilometres north of Hope, B.C., were ordered out of their homes as the Fraser Valley Regional District declared a local state of emergency. Heavy rains were causing debris flow and flooding in the area and the small lake and forested slope above the neighbourhood led to a potential for damage to structures and personal property.

Mid-June 2013, heavy precipitation in western Alberta lead to several debris flows in the area of Mount Livingston in Alberta. Preliminary analysis indicated that these debris-flows started at unusually low slopes in regard to the contributing area. The extreme character of this event, was attributed to two identified causes: the accumulation and weathering of rock debris in the scree slopes over time and the variability of permeability between the layers of the scree or at the interface with the bedrock, including the possibility of karst.

In the fall and winter of 2013, following the extreme wildfires on 2013 in British Columbia, there were several post-fire debris flows. Post-wildfire landslides have occurred in spring, summer and fall (autumn); events have been triggered by spring snowmelt, high-intensity summer rainstorms and low-intensity fall rainstorms. Of a total of 36 documented landslide events, 23 were debris flows, and the most common initiating mechanism was high peak flow in channels.

On August 6, 2010, a large rock avalanche occurred in the Mount Meager Volcanic Complex in southwest British Columbia. The landslide started as a rock slide, and the detached rock mass led into a debris flow. The disintegrating mass travelled down Capricorn Creek at an average velocity of 64 m s^{-1}, exhibiting dramatic super-elevation in bends to the intersection of Meager Creek, 7.8 km from the source. At Meager Creek the debris impacted the south side of Meager valley, causing a runup of 270 m above the valley floor and the deflection of the landslide debris both upstream (for 3.7 km) and downstream into the Lillooet River valley (for 4.9 km), where it blocked the Lillooet River river for a couple of hours, approximately 10 km from the landslide source. Deposition at the Capricorn–Meager confluence also dammed Meager Creek for about 19 h creating a lake 1.5 km long. The overtopping of the dam and the predicted outburst flood was the basis for a night time evacuation of 1,500 residents in the town of Pemberton, 65 km downstream. No lives were lost in the event, but direct costs are estimated to be in the order of $10 million.

On June 13, 2010, the Testalinden Creek debris flow near Oliver, B.C. destroyed or damaged several homes and covered roughly 15 hectares of agricultural land with debris. A similar area on the lower part of the fan was inundated with sediment-laden floodwaters. The debris flow was triggered by the failure of an old earth-fill dam at its headwaters.

On December 4, 2007, a large debris avalanche crashed into Lake Chehalis, BC. The landslide created 10-meter high (tsunami) waves that traveled across the lake, and caused extensive damage to the shore line. Fortunately, the landslide happened in the winter when nobody was at the shore of the lake, as two out of three campgrounds were wiped out and hundreds of trees were felled. The debris from the landslide however, piled up at the outlet of the lake and formed a threat to the newly built dike, healing centre and the community of the Chehalis First Nation.

A significant landslide affected the town of Chilcotin River (population 552), British Columbia on August 24, 2004. There were no fatalities. The landslide occurred along the banks of the Chilcotin River and blocked the flow of the river. The blockage was located about 15 kilometres upstream of the Chilcotin-Fraser junction. The river banks remained unstable.

Landslides

It Happened Here…

On October 31, 2020, a million cubic metre landslide took place in an industrial area on the outskirts of Williams Lake, B.C.

On June 23, 2019 a huge landslide of over 85,000 cubic metres of rock sheared off a 125 metre-high cliff and fell in the Fraser River, and created a waterfall that trapped migrating salmon below the slide. In September 2019, due to decreasing water levels and the efforts of rock scalers, some migrating salmon were able to pass naturally past the site of the landslide. The Province, the Government of Canada and First Nations have continued to work together to ease fish movement past the site. The effort to re-establish fish passage has included blasting rocks and widening the river channel. The installation of a nature-like fishway, a Whooshh Passage Portal System and other mitigation measures were undertaken to limit disruption to fish during the 2020 migration season.

On March 28, 2016, an Ontario landslide in the Horton Township, occurred and ten hectares of land slid into the Bonnechere River downstream from Renfrew, clogging the fast-running river with trees and clay. With the river blocked by trees and debris, water backed up behind the blockage. It rose more than seven metres near the landslide, and about five to six metres upstream in Renfrew. Floodwaters washed away a cottage, damaged a small hunting camp, poured water seven feet deep into a house, submerged the Renfrew sewage plant and got into the basement of the hydroelectric plant.

On October 11, 2015, the massive slide on remote Mount Steele in Kluane National Park in the Yukon, was the equivalent in weight of 33 million pickup trucks and would have gone undetected if scientists at Columbia University hadn't noticed that some unusual seismic activity had been reported by an unmanned monitoring station 25 km from the collapse site. The landslide was then confirmed by a NASA satellite, which zoomed in on the area and discovered an enormous debris field surrounding the mountain. Had the 45-megaton slide occurred in a populated mountainous region, it likely would have resulted in casualties.

On July 12, 2012, four people were unaccounted for after a landslide engulfed four homes in southeastern in Johnson’s Landing (population 35).

On January 19, 2005, following a heavy winter rainfall, the Berkley escarpment in North Vancouver, B. C. gave way and crashed into homes, A state of emergency was declared after a mudslide destroyed two homes; one woman was killed when she was trapped under debris in her home and one person was injured. One section of a wide greenbelt of evergreens gone, washed away by the mudslide that swept down the mountain. Officials were forced to evacuate more than 80 homes. The slide occurred because of a mixture of weather conditions in recent days as snow

and cold temperatures froze the ground and then 200 mm of rain fell in less than 48 hours with nowhere to go.

Debris Avalanches, Debris Flows and Torrents [Natural]

Debris flows do not occur in flat areas. If your community and the areas in close proximity to it are flat you can safely state that it is “Not Applicable.”

Hazard Rating	High Risk ☐	Low Risk ☐	Need More Info ☐	Not Applicable ☐

Yes	No	Need More Info	Not Applicable	FACTORS
☐	☐	☐	☐	**Debris torrents and debris flows are most likely to occur where they have occurred in the past. Has your community experienced debris flows?
☐	☐	☐	☐	Debris torrents and debris flows are likely to occur under similar conditions to landslides. Is your community susceptible to some or all of the risk indicators for landslides? (see the section on Landslides)
☐	☐	☐	☐	Debris flows are most likely to occur when loose (unconsolidated) soil and other ground material becomes saturated with water. Is your community located on steep slopes which experience intense periods of rain and/or rapid snowmelt? Is flooding likely or possible in your community? (see the section on Flooding)
☐	☐	☐	☐	Debris flows often occur on slopes with eroded pathways down the (channeled) slope. Is there evidence of channeling on slopes in or near to your community?
☐	☐	☐	☐	Debris flows can occur if there is a volcanic eruption which suddenly melts large quantities of snow and ice. Is your community near a volcano with snow and ice at the peak?
☐	☐	☐	☐	Debris flows can be triggered on the site of a previous landslide. Is your community near a previous landslide?
☐	☐	☐	☐	Do Traditional Knowledge holders in your community have an oral history of where debris avalanches, floods torrents have occurred in areas in traditional fishing or hunting territories in or near by your community?
☐	☐	☐	☐	Fast-moving, highly destructive debris floods are triggered by intense rainfall in areas that have recently experienced wildfires as a result of vegetation loss and soil exposure. Has there been a wildfire in sloped areas around your community since the last rainy season?

Debris Avalanches, Debris Flows and Torrents - Human-caused

Hazard Rating	High Risk ☐	Low Risk ☐	Need More Info ☐	Not Applicable ☐

Yes	No	Need More Info	Not Applicable	FACTORS
☐	☐	☐	☐	**Debris flows are most likely to occur where they have occurred in the past. Have there been previous debris flow events in or near to your community? Are there slopes in or near to your community that are known to be unstable?
☐	☐	☐	☐	Debris flows may occur if there are large forested areas which have been logged along a steep slope. Is your community near a recently logged slope?
☐	☐	☐	☐	Construction activity on or adjacent to slide-susceptible slopes can increase the likelihood of debris flows. Does your community allow construction on slide-susceptible slopes?
☐	☐	☐	☐	Scientists have observed that with increased number of rainstorms and increased amounts of rain the likelihood of debris flows could increase. Has your community experienced increased numbers of rainstorms and increased rainfall?

Landslides

Landslides do not occur in flat areas. If your community and the areas in close proximity to it are flat you can safely state that it is “Not Applicable.”

Mass Movements Natural

Hazard Rating	High Risk ☐	Low Risk ☐	Need More Info ☐	Not Applicable ☐

Yes	No	Need More Info	Not Applicable	FACTORS
☐	☐	☐	☐	Landslides are most likely to happen where they have happened in the past. Have landslides previously occurred in or near to your community?
☐	☐	☐	☐	Landslides occur primarily when slopes are saturated with water as a result of intense rainfall, and melting snow. Is your community near a steep slope and does it receive large amounts of rain and/or does your community experience rapid snow melt along steep slopes?
☐	☐	☐	☐	Landslides can occur when earth dams become saturated with water and fail. Is your community near an earth dam built along a steep slope?
☐	☐	☐	☐	Earthquakes can cause landslides. Is your community at risk for seismic activity? (See the section on Earthquakes)
☐	☐	☐	☐	Steep slopes and inward curving (concave) slopes are more prone to landslide. Is your community near steep slopes and concave slopes?
☐	☐	☐	☐	Are Traditional Knowledge holders in your community aware of changes in the landscape as a result of landslides in traditional fishing or hunting territories in or near by your community?
☐	☐	☐	☐	Soils which hold together (cohesive) soils such as clay are more prone to slide. Is clay a common soil type in your region?

Mass Movements Human-caused

Hazard Rating	High Risk ☐	Low Risk ☐	Need More Info ☐	Not Applicable ☐

Yes	No	Need More Info	Not Applicable	FACTORS
☐	☐	☐	☐	Landslides are most likely to occur where they have occurred in the past. Have there been previous landslides events in or near to your community? Are there slopes in or near to your community that are known to be unstable?
☐	☐	☐	☐	Landslides may occur if there are large forested areas which have been logged or where vegetation has been burned away along a steep slope. Is your community near a recently logged slope or where there has recently been a major fire?
☐	☐	☐	☐	Construction activity on or adjacent to slide-susceptible slopes can increase the likelihood of landslides. Does your community allow construction on slide-susceptible slopes?
☐	☐	☐	☐	Scientists have observed that with increased number of rainstorms and increased amounts of rain the likelihood of landslides could increase. Has your community experienced increased numbers of rainstorms and increased rainfall?

Land Subsidence and Sinkholes

Definition

Land subsidence, or sinking of land, occurs when a surface (either a flat surface or a hillslope) has been undermined and change (or 'deformation') and ground movement occur.

Discussion

Causes of subsidence can be due to human activities, such as the mining of rocks, minerals and ores; sub-surface excavations; extraction of underground liquids such as water (ground water pumping), and oil or gas. However, most subsidence is caused by natural processes such as groundwater flowing through soluble rocks such as limestone.

Underground mining or the pumping of groundwater, for example, creates a void within the geological rocks or subsurface (kind of like tunneling a sand castle on a beach, which collapses easily because of the weight on top). This causes changes and movement of the rocks (or 'strata') throughout an area. Depending on the size and depth of the excavation or pumping, the deformation can reach to the surface. When an excavation or extraction becomes too big, the roof rocks can break, and cave into the void.

Subsidence can also occur by thawing of permafrost, reduced sedimentation on river deltas, drainage of organic soils (such as peat), and the shrinking of expansive soils.

The subsidence processes described above can cause the general lowering or sinking of the earth's surface, but can also form (networks of) caves (or karst topography) and sinkholes.

The main hazards related to subsidence are the collapse of sinkholes, ground water pollution and unreliable drink water supplies. Subsidence can also cause extensive damage to buildings and infrastructure. Subsidence due to human activities can be avoided or minimized, but natural subsidence is hard to avoid. A study of the surrounding geology may create awareness of possible subsidence in an area.

It Happened Here…

On December 25 2018 a large sinkhole (12 m deep and 3.7 m wide at ground level but three time larger at the base) appeared in the Seawatch neighbourhood of Sechelt on the Sunshine Coast of British Columbia. Sinkholes had appeared in the area previously, but after the December 25th sinkhole, the engineers determined there was an unacceptable risk to the public. In February 2019, residents of 14 homes were ordered evacuated and the area became a no-go zone. Owners of multi-million-dollar homes now have worthless homes that have been assessed as worth $2.

On August 23, 2018 a large sinkhole opened up in Oxford, Nova Scotia on the Lions Club property, swallowing trees and picnic tables. It eventually filled up with salty water and is now approximately the size of an Olympic swimming pool. Just 1.3 km away, a sinkhole under the Trans-Canada Highway keeps reoccurring, necessitating filling and patching.

On June 8, 2016 a large portion of Rideau Street in downtown Ottawa, Ontario caved in, causing a massive sinkhole that knocked out power to the majority of the downtown area. The massive sinkhole formed next to a shopping mall and caused a gas leak and forced the evacuation of all nearby businesses.

On August 6, 2013 a backhoe was swallowed by a sinkhole in Montreal. It measured about eight metres long, five metres across, and three metres deep. In June 2012, a sinkhole shut down a portion of St-Mathieu Street near Ste-Catherine, just a block away. A month before that, a four-metre square sinkhole opened up on Sherbrooke Street, prompting a traffic detour on a busy intersection that lasted for nearly a month. The latest road collapse may be linked to a faulty city sewer pipe.

On April 10, 2010, a family of four died when their home in Saint-Jude, Quebec (population 1100) was destroyed by a sinkhole. The house became buried in clay mud by the kilometer long, 10-meter deep and 500-meter-wide sinkhole.

Land Subsidence and Sinkholes [Natural]

Hazard Rating	High Risk ☐	Low Risk ☐	Need More Info ☐	Not Applicable ☐

Yes	No	Need More Info	Not Applicable	FACTORS
☐	☐	☐	☐	Sinkholes and land subsidence are most likely to happen where they have happened in the past. Is there a past history of sinkhole formation or land subsidence in or near your community?
☐	☐	☐	☐	Sinkholes may occur in limestone (Karst landscape) formations or other water-soluble rock. Is your community located on or near to limestone formations?
☐	☐	☐	☐	Earthquakes may cause subsidence and sinkholes. Is your community at risk of seismic activity? (See the section on Earthquakes)
☐	☐	☐	☐	Are Traditional Knowledge holders in your community aware of changes in the landscape as a result of land subsidence and sinkholes in traditional fishing or hunting territories in or near by your community?
☐	☐	☐	☐	Water saturated soil may subside or cause sinkholes. Is there a chance of rapid rainfall or snowmelt, or flooding in your community? (See the section on Hydrological hazards).

Land Subsidence and Sinkholes - [Human-caused]

Hazard Rating	High Risk ☐	Low Risk ☐	Need More Info ☐	Not Applicable ☐

Yes	No	Need More Info	Not Applicable	FACTORS
☐	☐	☐	☐	Land subsidence and sinkholes are most likely to occur where they have occurred in the past. Is there a past history of sinkhole formation or land subsidence in or near your community?
☐	☐	☐	☐	Groundwater pumping or oil/gas extraction can cause land subsidence or sinkholes. Do these activities take place in or next to your community?
☐	☐	☐	☐	When minerals have been mined under the surface of the ground, the process can cause damage to the surface which may not occur for decades after the mining has been completed. Are there areas near your community that been subjected to below ground mining?

Submarine Slides

Definition

Submarine, or underwater, landslides, like their terrestrial counterparts, involve the movement of slope materials in response to gravity. The gravity-driven movement of slope material consists of watermixed with coarse-grained material (sands) flowing rapidly on submarine slopes or channels.

Discussion

Submarine landslides may be triggered by seismic events or by gradual slumping of the sediments that make up submarine slopes. Changes in the supply and deposition of sediment (by rivers, dredge and fill, mine tailings etc.) on the submarine slope can increase the risk of failure of that slope.

Submarine slides are also a common source of small scale coastal tsunamis. Large submarine landslides volume can generate damaging surface waves..

It Happened Here …

In 2019, a reseach study revealed that large submarine landslides are occurring on the Scotian Slope south of Nova Scotia. According to the study, huge submarine landslides are happening on the Scotian Slope south of Nova Scotia at a rate that's 10 times higher than first thought; however, it's still a large time scale with researchers saying that higher rate means once every one thousand years instead of every ten thousand.

On April 27, 1975, a submarine landslide occurred in Kitimat Arm, northwest of the Douglas Channel. The wave that was generated by the slide had recorded wave run up heights of 8.2 meters and damaged the Haisla docks of the Kitamaat First Nations village opposite of the Inlet.

Submarine Slides - Natural

Hazard Rating	High Risk ☐	Low Risk ☐	Need More Info ☐	Not Applicable ☐

Yes	No	Need More Info	Not Applicable	FACTORS
☐	☐	☐	☐	Submarine slides are most likely to happen where they have happened in the past. Are submarine slides known to have previously occurred in or near your community?
☐	☐	☐	☐	Submarine slides occur on steep underwater slopes. Is your community located on or near waterfront?
☐	☐	☐	☐	Earthquakes can cause submarine slides. Is your community at risk of seismic activity?
☐	☐	☐	☐	Rapid underwater sedimentation can lead to submarine slides. Has rapid sedimentation occurred along near to shore?
☐	☐	☐	☐	Do Traditional Knowledge holders in your community have oral history of how your community, or fishers, have been affected by submarine slides?
☐	☐	☐	☐	Fine-grained sediment is most likely to slide. Is the lake or ocean floor covered with fine-grained sediment?

Submarine Slides - Human-caused

Hazard Rating	High Risk ☐	Low Risk ☐	Need More Info ☐	Not Applicable ☐

Yes	No	Need More Info	Not Applicable	FACTORS
☐	☐	☐	☐	Submarine slides are most likely to occur where they have occurred in the past. Do you know of any submarine slides near your community in the past? Are shoreline areas near your community known to be unstable?
☐	☐	☐	☐	Submarine slides are more likely to occur along shorelines where construction activity has taken place. Is your community located near the ocean or other large body of water? Have construction activities changed the shoreline in or near to your community?
☐	☐	☐	☐	Submarine slides are more likely to occur where there has been river or ocean dredging. Has dredging taken place near the shoreline near your community?

Risk Analysis Resources

Landslides

Natural Resources Canada's "The Atlas of Canada" provides a lot of information about landslides including areas vulnerable to landslides and major landslides which have resulted in deaths.

Keywords: Natural Resources Canada, Atlas of Canada, landslide, natural hazard)

References

Agriculture and Agri-Food Canada. (2021). *Soil erosion indicator*.

Associated Press. (2012, July 12). *Canada landslide engulfs four homes* [Video]. YouTube.

Azam, S. & Ito, M. (2012). Coupled soil-atmosphere modeling for expansive Regina clay. *Journal of Environmental Informatics, 19*(1). doi:10.3808/jei.201200205

Baker, R. (2020, February 5). *Local state of emergency declared, evacuations ordered north of Hope due to risk of flooding, debris flow*. CBC News.

California Water Science Center. (n.d.). *Post-fire flooding and debris flow.*

Canadian Council of Forest Ministers. (2019). A shared vision for Canada's forests: Toward 2030. Natural Resources Canada.

Cant, D. J., & Walker, R. G. (1978). Fluvial processes and facies sequences in the sandy braided South Saskatchewan River, Canada. *Sedimentology, 25*(5), 625–648. https://doi.org/10.1111/j.1365-3091.1978.tb00323.x

Colgate University. (1997). *Topples*.

Dearing, S. (2010, May 11). *Sinkhole swallows house in Quebec, four people missing*. Digital Journal.

Department of Primary Industries. (n.d.). *Soil erosion fact sheets.* NSW Government.

Dregne, H. E., and N-T. Chou. (1992). Global desertification dimensions and costs. In *Degradation and restoration of arid lands*. Texas Tech. University.

Dunn, S. (2013, April 29). *Stand Off residents cleaning up after dust storm*. Global News.

Earth Eclipse. (2006). *What is erosion?*

Emergency Management B.C. (n.d.). *Get prepared for a landslide in British Columbia*.

Emergency Management Ontario. (2018). *Get prepared. Ontario.*

Environment and Climate Change Canada. (2020). *Criteria for public weather alerts*.

Environmental Protection and Sustainability. (n.d.). *Big Bar landslide*. Government of British Columbia.

Eswaran, H., Lal, R. & Reich, P.F. (2001). Land degradation: An overview. In E. M. Bridges, I.D., Hannam, L. D., Oldeman, F. W.T., Pening de Vries, S. J., Scherr, & S. Sompatpanit (Eds.). *Responses to land degradation. Proceedings 2nd international conference on land degradation and desertification, Khon Kaen, Thailand*. Oxford Press.

Federal Emergency Management Agency (2010). *Natural hazards*.

Foley, M. E. (2010). *Landslide susceptibility mapping in Maine*.

Franz, M. Rudaz, B., Humair, F., Jaboyedoff, M. & Froese, C. (2014). *Peculiar debris-flow event of June 2013 in Livingstone mountain range (Alberta, Canada)*. [Paper Presentation]. EGU General Assembly April 27 – May 2, 2014 in Vienna, Austria. Id 14559.

Goudie, A.S. & Middleton, N.J. (1992). The changing frequency of dust storms through time. *Climatic Change 20*(3), 197-225. https://doi.org/10.1007/BF00139839

Guthrie, R. H., Friele, P, Allstadt, K., Roberts, N. Evans, S.G., Delaney, K. B., Roche, D. Clague, J. J. & Jakob, M. (2012). The 6 August Mount Meager rock slide-debris flow, Coast Mountains, British Columbia: Characteristics, dynamics, and implications for hazard and risk assessment. *Natural Hazards Earth Systems Science, 12*, 1277-1294. doi:10.5194/nhess-12-1277-2012

Haig, T. (2019, February 15). *A sinkhole expands into B.C. nightmare*. Radio Canada International.

Hancock, C.-A. (2011). *Geomorphic changes to Lillooet River due to the 2010 Mount Meager landslide.* [Thesis Abstract]. Simon Fraser University.

Hodgins, M. (2019, November 20). Underwater landslides south of Nova Scotia could spawn tsunami: Study. *Halifax Today*.

Johnson, A. I. (Ed.). (1991). *Land subsidence*. A contribution to the International Hydrological Program of UNESCO (IHP-IV), Project M-3.5c). IAHS Publication.

Jordan, P. (2015). Post-wildfire debris flows in southern British Columbia, Canada. *International Journal of Wildland Fire, 25*(3), 322-336. https://doi.org/10.1071/WF14070

Jordan, P., Nicol, D., & Turner, K. (2011). *Debris flow hazards in the southern interior of British Columbia: The problem of events with unusually long runout*. GeoHaz Paper.

Keller, E.A. & DeVecchio, D. (2015). Natural hazards: Earth's processes as hazards, disaster and catastrophes (4th ed.). Pearson.

King, H. M. (n.d.). *Expansive soils and expansive clays*. Geoscience News and Information

King, H. M. (n.d.). *What is a debris flow?* Geology.com

Lan, H., Martin, D., & Zhou, C. (2008). Estimating the size and travel distance of Klapperhorn Mountain debris flows for risk analysis along railway, Canada. *International Journal of Sediment Research, 23*(3), 275-282. https://doi.org/10.1016/S1001-6279(08)60025-6

Larsen, K. (2020, January 3). *$1 and $2 property assessments confirm worst fears of residents of sinkhole-plagued B.C. neighbourhood*. CBC News.

Li, S., Lobb, D. A., & Lindstrom, M. J. (2007) Tillage translocation and tillage erosion in cereal-based production in Manitoba, Canada. *Soil and Tillage Research 94*(1) 164-182.

Maclean's. (2018, August 31). 12 shocking sinkholes (both big and small) from around the world.

Masson, D. G., Harbitz, C. B, Wynn, R. Pedersen, B. G., & Løvholt, F. (2006). Submarine landslides: processes, triggers and hazard prediction. *Philosophical Transactions of the Royal Society 364*(1845) 2009-2039. doi:10.1098/rsta.2006.1810

McKay, G.A. (1988). Drought: A global perspective. In M. I. El-Sabh, & T. S. Murty (Eds.), *Natural and man-made hazards*. D. Reidel Publishing Company. https://doi.org/10.1007/978-94-009-1433-9_23

Mine Subsidence Engineering Consultants. (2007). *General discussion on systematic and non systematic mine subsidence ground movements.*

Mortimer, G. (2021, March 29). *Decades-old Cape Breton lighthouse at risk from soil erosion*. CBC News.

Murty, T. S. (1979). Submarine slide-generated water waves in Kitimat Inlet, British Columbia *Journal of Geophysical Research, 84*(C12), 7777–7779.

Newfoundland and Labrador Heritage Web Site Project. (2000). *Impacts of normal climate*.

One dead as mudslide destroys North Vancouver neighbourhood. (2005, January 19). CBC News.

Petley, D. (2020, November 3). Williams Lake: 1 million cubic metre, damaging landslide in Canada. *Blogosphere. The Landslide Blog.*

Pope, A., (2015, November 2). Huge landslide nearly goes unnoticed in Yukon. *Canadian Geographic.*

Postmedia News. (2016, April 7). A massive Ontario landslide washed away a cottage and wiped out 10 hectares of land overnight. *National Post.*

Ruskin, B. (2019, September 24). *Trans-Canada Highway near Oxford N.S., built over sinkhole, archival images confirm.* CBC News.

Saskatchewan Environmental Society. (2015). *Build a sustainable society: Live sustainable lives*.

Sassa, K. & Canuti, P. (2009). *Landslides: Disaster risk reduction*. Springer.

Sinkhole swallows backhoe in downtown Montreal. (2013, August 5). CBC News.

Slaughter, A. (2018, July 12). The battle against desertification – Why Canada should care. WATER Canada.

Stewart, R.E. (1992). Precipitation types in the transition region of winter storms. *Bulletin of the American Meteorological Society, 73*(3), 287-296. https://doi.org/10.1175/1520-0477(1992)073<0287:PTITTR>2.0.CO;2

Thavaraj, S. A. & Hamersley, B. (2011). *Retrofit of pile-supported bridge in soft clay damaged by failure of adjacent soil stockpile*. [Paper Presentation]. 2011 Pan-Am CGS Geotechnical Conference.

Thurman, W.G., Robinson, E. (1954). Studies of Alaskan ice-fog particles. *Journal of Meteorology, 11*(2), 151-156. https://doi.org/10.1175/1520-0469(1954)011<0151:SOAIFP>2.0.CO;2

United Nations Disaster Relief Co-ordinator. (1991). Mitigating natural disasters: Phenomena, effects and options: a manual for policy makers and planners. United Nations.

United Nations Framework Convention on Climate Change. (2021). *REDD+ and desertification fact sheet*.

University of Saskatchewan. (2021). *Integrated modelling program for Canada. Global water futures*.

USGS. (n.d.). *Land subsidence*.

van Westen, C. J., van Asch, T. W. J., & Soeters, R. (2006). Landslide hazard and risk zonation - why is it still so difficult? *Bulletin of Engineering Geology and the Environment, 65*(2), 167-184. https://doi.org/10.1007/s10064-005-0023-0

Varnes, D. J. (1978). Slope movement types and processes. In R. L. Schuster & R. J. Krizek (Eds.), *Landslides analysis and control. Special report 176*. National Academy of Science.

Wheaton, E. E. & Chakravarti, A.K. (1990). Dust storms in the Canadian Prairies. *International Journal of Climatology, 10*(8), 829–837, doi:10.1002/joc.3370100805

White, William B. (1988). *Geomorphology and hydrology of karst terrains*. Oxford University Press.

Working Group II Contribution to the Fourth Assessment Report of the intergovernmental Panel. (2007). *Climate Change. 2007. Impacts, adaptation and vulnerability*. L. Parry, O. F. Canziani, J. P., Palutikof, P. J. van der Linden & E. E. Hanson, (Eds.). Cambridge University Press.