The estimated economic impacts of prairie landslides in western Canada

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ABSTRACT
Landslides in the Western Canadian Sedimentary Basin are widespread, primarily along valley slopes, yet rarely make the news and their impact to the Canadian economy is underappreciated. In preparing this paper, Canadian landslide practitioners from industry and government came together to estimate order-of-magnitude financial costs of prairie landslides to the oil and gas industry, public and private transportation, and communities. Based on our work, we estimate the total impacts exceed $281 to $450 million per year. The results are important because they can help calibrate site-specific and regional estimates of landslide risk, and because the level of awareness of landslide hazard and risk amongst decision-makers influences industry and government budgets for landslide management. We conclude the estimated economic impacts of prairie landslides may warrant additional investment in provincial and national landslide inventory, consequence tracking, and monitoring which would improve the efficiency and effectiveness of landslide risk management across many sectors to the benefit of all Canadians.

RÉSUMÉ
Les glissements de terrain dans le bassin sédimentaire de l'Ouest canadien sont généralisés, principalement le long des pentes des vallées, mais font rarement la une des journaux et leur impact sur l'économie canadienne est sous-estimé. En préparant ce document, les praticiens canadiens des glissements de terrain de l'industrie et du gouvernement se sont réunis pour estimer les coûts financiers par ordre de grandeur des glissements de terrain des Prairies pour l'industrie pétrolière et gazière, les transports publics et privés et les communautés. Sur la base de nos travaux, nous estimons que le total des impacts dépassera 281 450 millions de dollars par an. Les résultats sont importants car ils peuvent aider à calibrer des estimations régionales et spécifiques du risque de glissement de terrain, et parce que le degré de sensibilisation aux risques de glissement de terrain et aux risques parmi les décideurs influence les budgets de l'industrie et du gouvernement pour la gestion de ces glissements. Nous concluons que les retombées économiques estimées des glissements de terrain dans les Prairies pourraient justifier des investissements supplémentaires dans l'inventaire, le suivi et la surveillance des conséquences des glissements de terrain aux niveaux provincial et national, ce qui améliorerait l'efficience et l'efficacité de la gestion des risques de glissements de terrain dans de nombreux secteurs, dans l'intérêt de tous les Canadiens.

1 INTRODUCTION

When asked about landslides, Canadians often picture catastrophic events that make the news: rockfalls and mudslides that block highways on steep mountain hillsides in British Columbia, or the sensitive clay slides that destroy homes in the Saint Lawrence Lowlands. These are landslide types that occur rapidly, sometimes with little warning, in response to rainfall, freezing and thawing, erosion by rivers and streams, and other factors.

In 2004, Oldrich Hungr, estimated that landslides in BC cause an average of three deaths and financial costs of $54 to $135 million per year. Hungr prepared his estimates based on advice from a number of individuals involved first-hand in landslide study and management. He acknowledged the estimates (reported in 2004 Canadian dollars) were very approximate, but in the correct order of magnitude. His results are reproduced in Table 1.

Natural Resources Canada reports that landslides account for an estimated $200 to $400 million in direct and indirect costs in Canada each year (NRCan 2019). Guthrie (2013) recognized that landslides occur in all physiographic regions of Canada and summarized historical estimates of life loss and qualitative assessment of economic impacts of landslides in the Canadian Cordillera and St Lawrence Lowlands.

To the authors' knowledge, similar compilations of estimates of the economic impacts of rock slides and earth slides and flows (herein referred to as 'prairie landslides') in the Western Canadian Sedimentary Basin (WCSB) are not publicly available. Prairie landslides are widespread, especially along valley slopes, yet rarely make the news, and their impact to the Canadian economy is underappreciated.

In preparing this paper, Canadian landslide practitioners from industry and government came together to estimate the financial costs of prairie landslides to communities, public and private transportation industries, and the oil and gas industry. This paper begins with an overview of geology and common landslide mechanisms in the prairie provinces of western Canada. Ways in which prairie landslides impact infrastructure are illustrated. Methods for assembling estimates of damages and the costs associated with the management of such landslide hazards are described, and estimated costs are presented.

Table 1. Landslide damage in British Columbia (1880 – 2001) after Hungr (2004)

Sector and Landslide Types	Estimated Annualized Losses ($ million/year)	
	Direct Damage[1]	Prevention
Residential (debris flows, slides)	2.5 to 3.5	1 to 2
Roads and Bridges (debris flows, rock fall, slides)	4	5.5
Railways (debris flows, rock fall, slides)	2.5 to 3.5	2 to 4
Hydro power Network (rock slides)	1	4
Pipelines (earth and rock slides)	1 to 2	2 to 4
Forestry[1] (debris avalanches and flows)	2 to 3	1
Subtotal	12 to 16	16 to 21
Residential land sterilization		10 to 50
Forest harvestable land loss	16 to 48	
Total	28 to 64	26 to 71

1. Exclusive of environmental and fisheries losses
2. Reported in 2004 dollars

2 PRAIRIE LANDSLIDES IN THE WESTERN CANADIAN SEDIMENTARY BASIN

The Canadian portion of the WCSB (Figure 1) extends across southwestern Manitoba, southern Saskatchewan, Alberta, northeastern British Columbia and the southwest corner of the Northwest Territories, supporting one of the world's largest reserves of petroleum and natural gas. Slopes in the WCSB are predisposed to landslides, and most valleys have been modified by landslide processes.

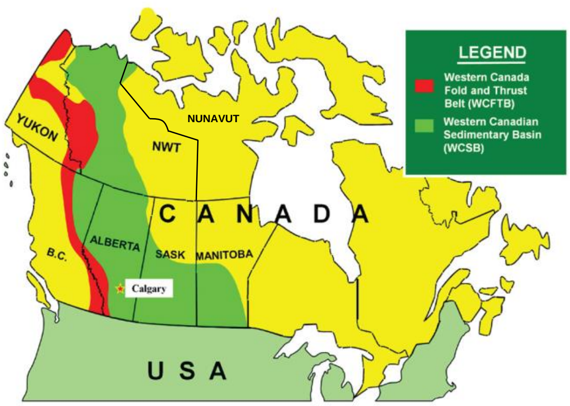
Bedrock geology in the WCSB generally comprises Jurassic and Paleozoic-age carbonate rocks overlain by Cretaceous shale and less-commonly sandstone and coal seams. Flat-topped erosional uplands comprising Tertiary gravel derived from the Rocky Mountains to the west, are locally present (Cummings et al. 2012).

East-flowing pre-glacial fluvial systems developed from tectonic uplift of the Cordillera and tilting of the Prairie land surface, have formed large buried valleys incised in bedrock (Cummings et al. 2012). Buried valleys and adjacent lowland bedrock surfaces are overlain by gravel, till, and glaciolacustrine sand, silt and clay deposits.

Glacier ice-thrusting resulting in the deformation and shearing of bedrock and glacial sediments appears to have been wide-spread in the WCSB where continental glaciers overran clay shale or weakly cemented bedrock (Sauer 1978). These glaciotectonic processes resulted in a significant reduction in shear strength properties of the sediments, increasing the potential for landslides.

A landslide susceptibility map generated by the Alberta Geological Survey (Pawley et al, 2016, 2017, 2018) shows natural slopes more susceptible to landslides are associated with areas of higher relief including valley walls and the flanks of plateaus and uplands. Almost every major river valley and tributary in the plains is susceptible at some level to landslide activity.

Figure 1. Western Canadian Sedimentary Basin (after Canadian Society of Western Exploration Geophysicists)



Landslides in the WCSB have formed slopes as flat as five or six degrees. Whereas many of the landslides initiated thousands of years ago, some (perhaps most) continue to creep at rates of millimeters to centimeters per year. Movements at these rates, especially on densely tree-covered slopes, are difficult to detect and often go unrecognized. As such, any sort of infrastructure that is located within or spans such valleys or slopes requires consideration of how to manage the risks associated with landslide activity.

Common landslide mechanisms in the WCSB include deep-seated translational failures along weak bedding planes in shale and glaciolacustrine clay, rotational slides in clay rich till and glaciolacustrine sediments, and earth flows in colluvium. Most of these landslides move at rates ranging from extremely slow to slow according to the velocity classification of Cruden and Varnes (1996) shown in Table 2. Rapid to extremely rapid flow slides occasionally initiate in normally and over-consolidated glaciolacustrine sediments and colluvium containing a high fraction of sand and silt.

Table 2. Landslide velocity classification after Cruden and Varnes (1996)

Velocity class description	Typical velocity
Extremely rapid	>5 m/sec
Very rapid	>3 m/min
Rapid	>1.8 m/hr
Moderate	>13 m/month
Slow	>1.6 m/yr
Very Slow	>16 mm/yr
Extremely Slow	<16 mm/yr

Mansour et al. (2011) compiled examples of damage from slow-moving landslides with velocities typical of prairie landslides and demonstrated that the expected degree of damage to infrastructure can be related to the slide velocity or accumulating displacement. Often minor to no damage is reported for infrastructure impacted by extremely slow landslides unless movements continue to accumulate for a period of decades. Expected damage from very slow landslides can vary widely, however, ranging from increased maintenance costs at the lower end of the range to complete loss of serviceability or infrastructure collapse at the high end of the range. Prairie landslide movement rates vary spatially and temporally in response to river toe erosion, precipitation, forest fires, anthropogenic activity, and other factors. Consequently, economic impacts associated with prairie landslides also vary over space and time, making it challenging to estimate the average magnitude of these impacts.

3 METHODS OF ANALYSIS

The focus of this paper is the economic impact of pre-existing prairie landslides on Canadian infrastructure. Reactivation, acceleration, and ongoing creep movement associated with such landslides may impact infrastructure in a number of ways. Herein we recognize two broad cost categories: 1) direct and indirect cost associated with damage or failure of infrastructure (includes repair costs, safety and environmental impacts, or costs of business interruption and lost productivity) and 2) preventative costs associated with monitoring, maintenance and other proactive management activities for existing infrastructure (includes incremental costs associated with investigation, design and construction of new infrastructure to avoid or mitigate landslide hazards).

Where practical, we have excluded costs associated with other related geotechnical factors such as the stability of engineered slopes in weak soil and rock, bearing capacity failures, rock fall, frost heave and settlement, and surface erosion. Many landslide management programs also address these other geotechnical issues and clear separation of costs associated with prairie landslides and these other factors was not always possible.

The methods used to compile cost estimates were purposefully simplistic, with the objective of obtaining high-level estimates of relative and total costs and highlighting areas where more detailed cost tracking and analysis may be warranted. Given the very approximate nature of the cost estimates, no attempt was made to adjust estimates of historical costs for inflation.

Each of the authors is an experienced landslide practitioner who has focused much of their career on the assessment and management of landslide hazards in western Canada. Many of the authors have or continue to manage industry or government landslide programs for the various infrastructure types that are discussed. Each author used their experience, judgment, and project files, as well as personal communication with other practitioners in similar roles, to prepare the estimates that are presented. Additional detail about data sources, assumptions and limitations are described below.

4 ESTIMATES OF ANNUALIZED ECONOMIC IMPACTS

4.1 Municipal and Residential Infrastructure

Early European exploration and settlement of western Canada used the prairie river system as the primary transportation corridor for goods moving west and east. Settlements were established on the riverbanks, often near the confluence of rivers and creeks. The rivers provided not only a convenient transportation route for goods, but also a secure source of water for the inhabitants.

Over time, certain settlements grew and the infrastructure they contained became more elaborate and widespread. The larger settlements often expanded to occupy both sides of their local river, which in turn doubled the susceptibility of their municipal infrastructure to landslides. Municipalities now represent the densest concentration of infrastructure located adjacent to the prairie river system. Urban areas contain a dense network of underground utilities, surface roadways, drainage outfalls, bridge river crossings, as well as residential and commercial buildings. Collectively, such infrastructure is susceptible to landslide damage. In extreme cases, for instance Regina Beach, Saskatchewan, entire communities reside on deep-seated landslides.

Economic impacts of landslides to municipal infrastructure in the WCSB were estimated, in part, through a brief survey that was sent out to some of the major prairie cities and towns, requesting their annual landslide remediation and monitoring costs for the last number of years. In addition, they were asked to comment on any restrictions they had for development along natural slopes. Data were assembled from survey respondents and project files for Peace River, Edmonton, Calgary, Saskatoon and Winnipeg.

Direct and indirect financial losses associated with landslides include the costs borne by property owners and municipal governments for landslide remediation. In the end, individual landslide remediation budgets reported by the municipalities to the survey was in the order of $1 million to $5 million per year, for an annual aggregate of nearly $12.5 million. Note this figure represents only the monies allocated by the various municipalities on a relatively ongoing basis.

All of the survey respondents reported that they had experienced large, but infrequent landslides in their jurisdictions, remediated using emergency funding from their governing councils. Remediation of these large landslide events often required in excess of $10 million, but given their infrequency, the costs are not reflected in the aggregate figure.

The 2018 Old Fort Landslide that occurred south of Fort St. John, BC in the fall of 2018 is one example of an expensive rare event. A 4.6 million cubic metre rock slide in clay shale triggered a large earth flow that cut off the only road access into the community of Old Fort for a period of nearly 2 months. One home was destroyed by the landslide, and residents of approximately 80 other homes were evacuated. Economic impacts were borne by residents, a gravel pit operator, the local regional district, and at least four provincial agencies (BC Ministry of Transportation and Infrastructure, Emergency Management BC, BC Ministry of Energy, Mines and Petroleum Resources, and BC Ministry of Forests, Lands, Natural Resource Operators and Rural Development). Costs of road reconstruction and landslide monitoring exceeded $1.5 million, and based on communication with various stakeholders we estimate the total direct costs exceeded $10 million.

We added $2 million per year to the reported landslide remediation budgets to account for such infrequent but costly events (assuming an average of one $10 million event every five years within one of the five municipalities), for a total of $14.5 million per year. It is not known what percentage of the total landslide impacts to municipal government infrastructure across the entire region is accounted for by the five large municipalities who responded to the survey, but for this study we assumed it is between 40% and 60%. Based on these assumptions, the total economic impacts likely range between $24 million and $36 million per year.

Generally, the imposition of development restrictions has minimized damages to private property resulting from natural landslides. Costs for any slope remediation that eventually may be required can range from tens of thousands to millions of dollars. Details are not readily available to estimate the total annual cost to property owners across the region, so for this paper we propose they are on the order of 10% of those borne by local governments, or an estimated $2.5 million to $3.5 million per year.

Costs of preventing landslide impacts to communities and municipal infrastructure are even more difficult to estimate. They include costs for geotechnical investigations, incremental design and construction, landslide monitoring programs, and costs associated with land sterilization.

The construction of infrastructure in municipal areas is often influenced by economics and engineering. Land is a valuable commodity in municipalities and there is a shared motivation to maximize the utility and value of real estate. Some of the most valuable and desirable land for residential development in urban areas occurs along the crest of natural river or ravine valleys. The price of individual undeveloped housing lots routinely start at $250,000 and after construction, the total value of these view properties easily ranges from $2.5 million to $10 million. Consequently, there is motivation to develop such land. To help safeguard the residents of these top of bank properties, most jurisdictions have implemented or are planning to implement zoning restrictions and requirements for geotechnical slope stability investigations prior to development. This usually results in the establishment of a setback distance designed to reduce the risk to building occupants should a landslide occur, and to sustain the serviceability of any top of bank structures for their expected lifespan. The cost impact that the restrictions have on developers is difficult to accurately quantify, but for our work we assume they are of similar magnitude to those reported by Hungr (2004) for BC ($10 million to $50 million in 2019 dollars, and ignoring the impact of inflation since 2004).

Ongoing monitoring programs and geotechnical investigations were reported by all five municipalities which responded to the survey. The size of the programs ranged from about $10,000 to a maximum of $100,000 annually. Funding for additional monitoring and investigation was also reported, but only in response to extraordinary one-time landslide events. The total annual monitoring costs and geotechnical investigations of all five reporting municipalities was in the order of $157,000. For this paper we assumed that landslide monitoring costs for all municipal governments across the region are on the order of $0.5 million per year.

Figure 2. Landslides threatening luxury homes on the North Saskatchewan River in southwest Edmonton

4.2 Railways

The WCSB is crossed by Canada's two transcontinental railways, CP and CN, as well as several short line railways. Construction of the Canadian Pacific (CP) railway mainline was completed in 1885. Canadian National (CN) railway formed in 1918 in an amalgamation of several federal and private railway companies. Today, Canada's mainline (Class 1) and short line railways continue to be responsible for moving the largest tonnage of material goods in the Canadian transportation industry. In 2015, for example, the Canadian railway industry moved almost 331.5 million tonnes of freight over more than 63,000 km of track across the country (Statistics Canada 2017). Railways in the WCSB are the foremost mode for transporting industrial chemicals, potash, agricultural products, lumber, automobile and other products for export and domestic consumption.

Railways are generally restricted to operating at limited grades of no more than 2% and consequently follow river systems. As a result, they are exposed to a variety of prairie landslide hazards along valley slopes. Landslides also occur within railway embankments where they cross valleys on fills over lower strength or compressible native soils.

Railways generally utilize one of the following hazard mitigation approaches: avoid the landslide by re-routing the track around the landslide, stabilize the landslide, and/or a combination of these. It has been demonstrated (Hendry et al. 2014) that railways can safely operate over landslides moving at rates up to about 300 mm per year by regularly maintaining the track and having monitoring systems in place to notify them of any unusual movement. Stabilization usually takes the form of surface and subsurface drainage measures, toe berms, shear keys and erosion protection. Generally, measures having a long effective life and minimal maintenance, that do not introduce the potential for sudden failure, are preferred to structural stabilization of landslides. Direct and indirect costs of damage from prairie landslides to the railway industry include the impacts of slow orders, increased frequency of track tamping and track realignment, monitoring and investigation, landslide stabilization for faster-moving slides, business interruption when movement rates temporarily exceed those that can be managed by maintenance activities, and in rare cases, costs of derailments where landslides are a contributing factor. Annualized landslide prevention, repair, track maintenance and business interruption costs for CP and CN are estimated to be on the order of $8 million to $12 million based on a review of data over the past 5 years. Cost associated with rare derailments or lengthy service outages, which can exceed tens of millions of dollars per event, are not included in this estimate, and could be reasonably expected to add a further annual cost of $1 million to $5 million, especially given hazardous materials can be involved.

The railways' costs of research, preventative landslide inspection, monitoring and minor maintenance efforts within the WCSB are estimated at $1 million per year. This includes the railway's in-kind and cash contribution to the Railway Ground Hazard Research Project which has been sponsoring research at the University of Alberta and Queen's University for more than 15 years.

4.3 Transportation Networks

The transportation network in the WCSB is extensive, with rail and road networks providing the main options for movement of people and freight. More than 630,000 km of rural paved and gravel roads exist across Alberta, Saskatchewan, northern British Columbia, and southern Manitoba. Large scale landslides are prominent features along many of the river valleys in the region. In many instances highway corridors unavoidably cross these pervasive and massive landslide complexes. Often the landslide movements consist of creep, leading to operational and maintenance problems and added annual costs. Rarely do such landslides lead to a catastrophic collapse. However, sometimes the rate of movement is such that major repair efforts are required to maintain a safe road system.

Roads that traverse landslide prone valley slopes have a documented history of slope instability. Direct impacts may start with the gradual development of widespread crack systems that affect road safety and result in speed and load restrictions. Crack filling and small-scale patching is performed to maintain the road surface. As the cracks spread and merge the ability of the operations forces to maintain the road become stressed. Large scale pavement patching can be required on an annual basis to maintain the road surface. Over many years some pavement structures thicken to more than a metre to accommodate ground movement and settlement. Occasionally, the amount, or rate, of landslide movement becomes excessive and operations forces are not able to maintain the road so extensive intervention is required.

If one lane of a road is affected by a slide there may be an option to divert traffic onto temporary on-site detours until permanent repairs can be undertaken. If all lanes of traffic are lost there may be requirements for off-site detours, as the affected road would likely be barricaded for many months during repairs. Off-site detours in some areas of the WCSB can be several hundred kilometres in extreme cases, which increases road user costs, may disrupt school bus routes, high and heavy load corridors, major freight corridors and have other indirect costs. Utility costs to raise overhead power lines to accommodate a detoured high load corridor can be significant in-direct costs.

New road alignments requiring valley crossing and landslide avoidance might involve deep cuts and high fills with consequent high capital costs. For example, a proposed realignment of the Alberta Hwy 2 south Dunvegan Hill alignment required about 12M m^3 of excess fill along a new alignment that would avoid seven known landslide zones along the existing highway, at a cost approaching $100 million. Given the above, most jurisdictions struggle to maintain alignments and deal with landslide costs as necessary along their corridors.

Grapel and Skirrow (2012) provide a discussion of the challenges in planning highway alignments through landslide terrain. Existing alignments are often realigned onto more stable portions of the valley slope adjacent to the existing alignment to improve the stability of the right-of-way but not to necessarily completely avoid the hazard. This option may be effective or provide temporary improvement to the roadway until the landslide retrogresses to the realigned road way again. Drainage measures that are complementary to other repair methods may be effective but require periodic maintenance. Repair methods such as very large toe berms and slope flattening options have been used successfully. As most repair options seek to confine the work area within the existing right-of-way the use of large diameter bored cast-in-place piles, usually in combination with tie-back anchors is a costly, but often economical repair method. These methods are used to augment the marginal stability of bridge head-slope fills resting on WCSB shale, where placement of the fill might destabilize the slope (Ruban, A.F. et. al. 2004)

For this study the authors contacted several provincial highway agencies to obtain estimates of landslide repair costs related to WCSB-based slides over the past 10 years. Queries regarding annual investigation and monitoring costs were included. Based on the data we determined that annual capital expenditures were about $16 million to $22 million in Alberta, Saskatchewan, northern BC and southern Manitoba. Note that some project costs can exceed $20 million, which might increase a total annual repair cost to more than $50 million. Furthermore, the costs reported above do not include economic impacts from fuel, vehicle maintenance and loss of productivity associated with poor road conditions, as well as delays and detours during repair and maintenance activities. Several researchers have suggested that these types of indirect costs often exceed direct costs (e.g. Galve et al., 2016).

Most highway agencies have landslide risk management programs that oversee annual landslide inspections, instrumentation programs and site investigations. Annual costs for this preventative work are about $2 million to $4 million within the WCSB.

4.4 Oil and Gas Production

Like municipal and transportation infrastructure, oil and gas production within the WCSB are exposed to prairie landslide hazards. Typically, the location of the subsurface resource drives the location of the surface infrastructure, so avoidance is not always an option. As with other types of development there are access roads, pipelines, structures and machinery that have different tolerances to ground movement. Thus, when these facilities interface with landslide terrain similar suites of preventive and responsive controls can be utilized.

One specific difference with oil and gas development is the drilling of very deep and expensive wells to either extract or inject fluids into the subsurface. We are aware of numerous well bores, as well as some processing facilities, that are situated on deep-seated landslides. These landslides can pose incremental costs for development, operation, and closure. Although we are aware of well bores that have sheared in deep seated landslides (e.g. Mansour et al. 2011), specific data on frequency and cost of these failures could not be obtained for this paper. But as a reference, oil and gas well costs can range between $1 million or less for relatively shallow conventional wells, to $5 to $10 million for deeper horizontal wells in shale formations requiring more extensive well development. This would also include some allowance for access and well site facilities, which can be quite variable.

In lieu of having any direct input on the number of wells lost per year, we have included a $5 million per year cost impact for conventional oil and gas production, assuming the loss of one $5 million well per year. It is expected that the actual cost impact could be significantly larger, because loss of one well per year is likely low, it does not include lost production and it also does not consider areas that are sterilized from production because of landslide risks (proactive economic impacts). We also note that unconventional *in situ* extraction operations, employing various steam injection methodologies (such as Steam Assisted Gravity Drainage, or SAGD), would have higher valued assets at risk from landslide impacts, and are not considered in this paper.

A specific sector of the oil and gas industry in the WCSB that has a unique set of challenges with respect to landslides are the surface mines in the Athabasca Oilsands region. Most of the active or planned surface mines in this region either require access across or encroach upon river and creek valleys containing landslides that must be considered in design, construction, operation and closure. One published example is the occurrence of a landslide in the planned footprint of Suncor's Pond 8A across Wood Creek valley (Treen et al., 1998). This is an example of an existing landslide encountered within the planned footprint for a large tailings dam that then had to be investigated, removed and a shear key constructed prior to completing the dam construction. Other infrequent, but costly facility impacts from landslides are related to river water intakes that are at times located within slide prone terrain along the Athabasca River, and traverse slopes with access roads and intake lines. The two instances we have knowledge of with river water intakes were mitigated in advance of operation, and therefore would be considered preventative. We suggest that the long-term average costs for preventative measures to control slide risk as part of surface mine facility design is in the range of $5 million per year, and that the unplanned cost of damage and repair to infrastructure would be in the range of $1 million per year.

4.5 Pipelines

The oil and gas industry operates several hundred thousand kilometres of pipeline across the WCSB, some of which passes through large, slow moving landslides. If slow landslide movements go undetected for too long, or if landslides accelerate in response to river erosion or rainfall, they can cause pipeline leaks.

Landslides have historically caused about three or four pipeline failures per year in western Canada, which accounts for a relatively small proportion of the total number of leaks. But the costs can be high, ranging from a few hundred thousand dollars to more than $100 million in direct damages, environmental cleanup costs, and lost production. Based on events we are aware of over the past decade, we calculate the average total economic impact of pipeline leaks or damage caused by landslides is about $40 million to $60 million per year.

The risks to pipelines posed by landslides are well-recognized, and the industry's approach to management is continually improving. Aerial photographs, satellite imagery and high-resolution topography are routinely adopted to create inventories of landslide features crossed by pipelines. Risk-based approaches are applied to prioritize visual inspections and other actions taken by landslide specialists. At higher-risk sites, geotechnical investigations are carried out to understand the soil, rock and water conditions and to install instrumentation for slope and pipeline monitoring. Techniques are being developed to monitor slope movements using LiDAR and satellite imagery. Special instruments are run through pipelines to detect deformation caused by ground movement. When hazardous conditions are identified, operators expose their pipelines to relieve strains, or re-locate their pipelines to avoid the landslide hazards. The enormous volumes of information generated and consumed by these management activities are stored in maps and databases, and are made accessible to pipeline operators using web-based tools such as BGC's Cambio™ software. Pipeline failure rates are dropping as a result of these efforts, but we believe these preventative measures cost the pipeline industry at least an additional $150 to $220 million per year.

The pipeline industry incurs other costs associated with landslides that are more difficult to quantify, but include items such as additional effort that goes into routing, design and construction of new pipelines to avoid and mitigate landslide hazards, and the incremental costs for regulatory oversight. We suspect these could amount to another $15 to $25 million per year.

The sum of the estimated economic impacts of prairie landslides to the pipeline industry in direct and indirect costs is estimated to range from about $205 to $305 million per year.

4.6 Other Economic Impacts

Several other industries within the WCSB are also affected by prairie landslides and absorb costs associated with damage and prevention. Examples include hydropower dams and power transmission and distribution infrastructure, irrigation and flood control dams, loss of productive farmland, and loss of productive forest land, fishery resources and incremental development and maintenance cost for forest resource roads crossing landslides. No attempt has been made to estimate the annualized cost for these industries.

4.7 Summary of Estimated Costs

Estimated prairie landslide damage and prevention costs described above are summarized in Table 3. The estimates indicate that the total annual cost for both damage and prevention for the sectors and infrastructure types considered might range from $281 to $450 million.

Table 3. Estimated economic impact of prairie landslides in the WCSB

Sector	Estimated Annualized Losses ($ million/year)	
	Direct Damage	Prevention
Municipal and Residential	26.5 to 39.5	0.5
Railways	9 to 17	1
Provincial Transportation[1]	16 to 22	2 to 4
Oil and Gas Production	10	1
Pipelines	40 to 60	165 to 245
Subtotal	101.5 to 148.5	169.5 to 251.5
Residential land sterilization[2]		10 to 50
Total	101.5 to 148.5	179.5 to 301.5

1. Exclusive of costs borne by private industry and the public associated with road conditions and closures
2. In absence of data for the WCSB, assume cost is comparable to the estimate for BC by Hungr (2004)

5 DISCUSSION

Although the basis for our estimates of economic impacts of prairie landslides in the WCSB is constrained (and in part, because of this) the results yield several interesting points for discussion.

The total estimates of economic losses reported in Table 3 are subject to considerable uncertainty, but do not account for costs to all infrastructure and asset types and are expected to represent a lower-bound estimate. Never-the-less, the total estimated costs associated with Prairie landslides in the WCSB are more than three times those estimated by Hungr (2004) for the mountainous and more densely-populated province of British Columbia, and may exceed those estimated by NRCan (2019) for the entire country!

Many larger government agencies and private companies affected by landslides have an annual budget for landslide remediation, maintenance and monitoring, but data on costs are often lacking, poorly organized and difficult to compile. Annual budgets are often only established to address typical minimum or average landslide impacts, with attempts made to secure emergency funding when infrequent costly events occur. Cost data from responsible agencies are sometimes available for direct damages to municipal and highway infrastructure, but the indirect economic impacts associated with loss of productivity and other costs borne by the public or other stakeholders often appear to have not been estimated or collected.

It appears that current landslide management practice within the WCSB is largely reactive in nature, although this may be an artefact of the data limitations and methods used to prepare the cost estimates. With the exception of the pipeline industry, it appears that annualized costs associated with landslide damage exceed the costs of prevention by a factor of 10 or more. Costs of land sterilization from residential development might also exceed annual municipal and residential landslide damage costs, but data are not available to make this determination.

Pipeline infrastructure appears to be exposed to higher levels of landslide risk than the other infrastructure types examined, but the pipeline industry also appears to be more proactive to investing in preventative measures than others. It is interesting to speculate why this is so. Perhaps it is because the consequences of a pipeline failure caused by a landslide (in terms of business interruption and repair costs, and damage to reputation) are most directly realized by the pipeline operator. Or perhaps industry regulation and pipeline integrity management practice has required better tracking of landslide hazards, consequences and management efforts compared to other industries in the WCSB.

Based on the challenges we faced in attempting to estimate the economic impacts of landslides, we encourage all those impacted by landslides to collaborate on the assembly of more comprehensive data of the direct and indirect financial costs of landslides. Estimates of loss support the need for and value of more proactive landslide management.

Because prairie landslides within the WCSB can impact highway and railway infrastructure, hydropower facilities, communities, productive farmland and other cultural and natural assets, there is value in sharing more information regarding landslide hazards and risks across all industries. The landslide hazards cross provincial boundaries and impact many sectors of the Canadian economy. Transportation of dangerous goods using infrastructure that crosses prairie landslides has the potential to impact safety and the environment, and especially municipal water supply. Yet federal support for landslide management initiatives in the prairie provinces is modest. We believe an argument could be made that additional investment in national landslide inventory and susceptibility mapping, better access to high-resolution topographic data acquired through LiDAR survey, and regional satellite-based InSAR monitoring would improve the efficiency and effectiveness of landslide risk management across many sectors and could be of considerable benefit to all Canadians.

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