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Considerations for Addressing Climate Change Impacts on Pipeline Geohazards

IPG 2025

Bogota

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Jaime Aristizabal Sean Sullivan

The inputs of the following organizations are duly noted:

Clim Systems Pacific Climate Impacts Consortium

SLR Stantec Repath Thurber

IPC and IPG references

A DYNAMICALLY EVOLVING TECHNICAL SPACE…

Terrain Mapping	Geohazard Responses to Climate Change Mechanisms	Climate Change Modelling **Projections**	Pipeline Integrity Response to **Projected** Climate Change Induced Geohazards	Climate Change Related Pipeline Integrity Intervention Business Decisions
Identify localized terrain sensitivity to climate change	What is the impact of the various climate change mechanisms to the various geohazards	The projected changes to different climatic events for different climate change scenarios	Integrating scenario-based projected pipeline integrity responses to the cumulative current condition towards intervention thresholds	Optimizing the extent and timing of prudent investment in **proactive** integrity management

The areas with the most sensitive terrain and the most significantly adverse projected climate changes would be projected to respond most frequently and severely (geohazards) in the future

When and how much adaptation investment for climate change resilience?

High Climate Change Vulnerability Index (CCVI)

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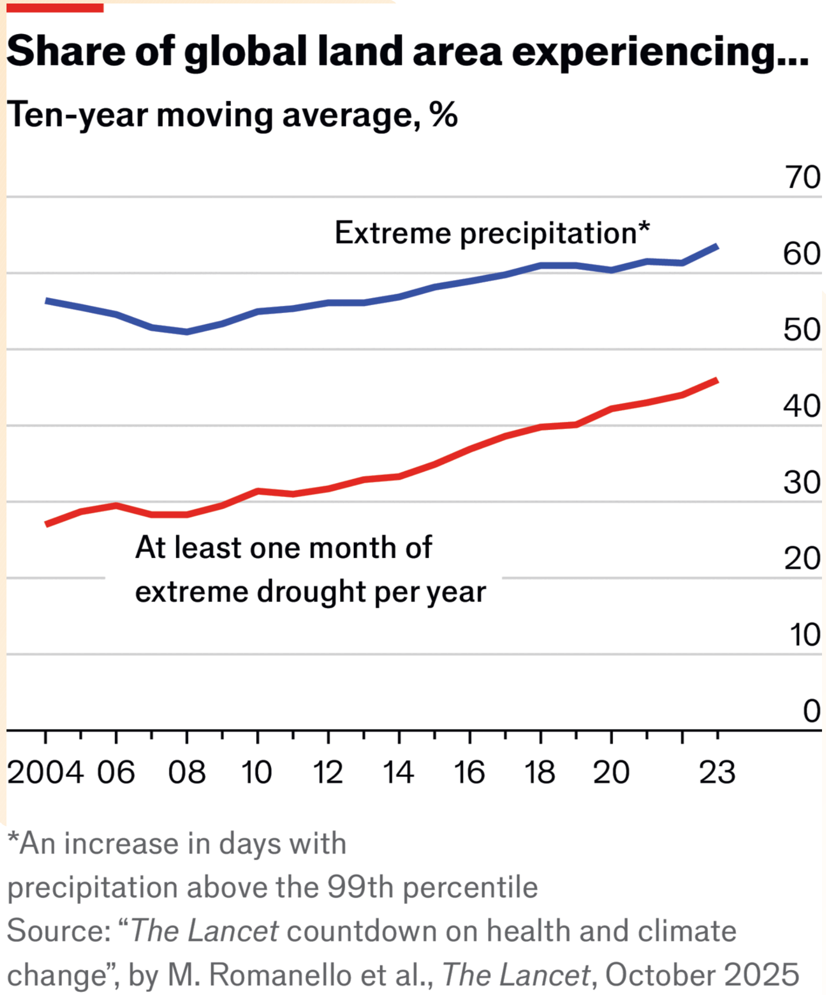
Outline

1. Climate change observations and models
2. Climate change impacts on Geohazards
3. Sub-set of technical management approaches
4. State-of-practice business response

Trends of Extreme Precipitation & Drought



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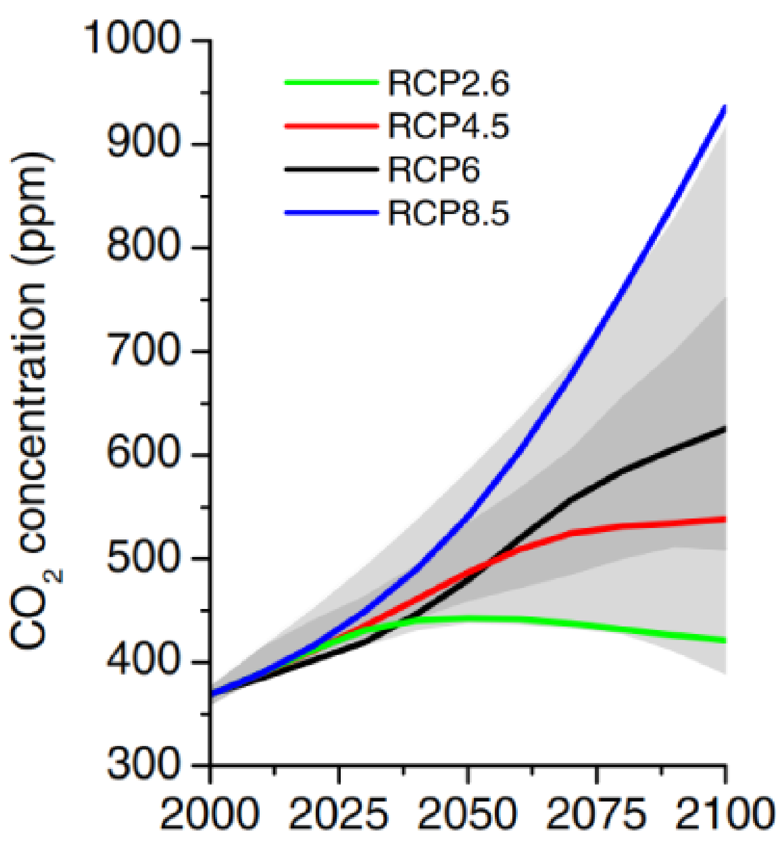
Climate Change Scenarios & Predictions



Scenarios - Representative Concentration Pathways (RCP):

- An RCP is a greenhouse gas concentration trajectory
- RCP 2.6 assumes that global annual GHG emissions peak between 2010–2020
- RCP 8.5, emissions continue to rise throughout the 21st century

The present CO_2 release rate is unprecedented in the last 66 million years!

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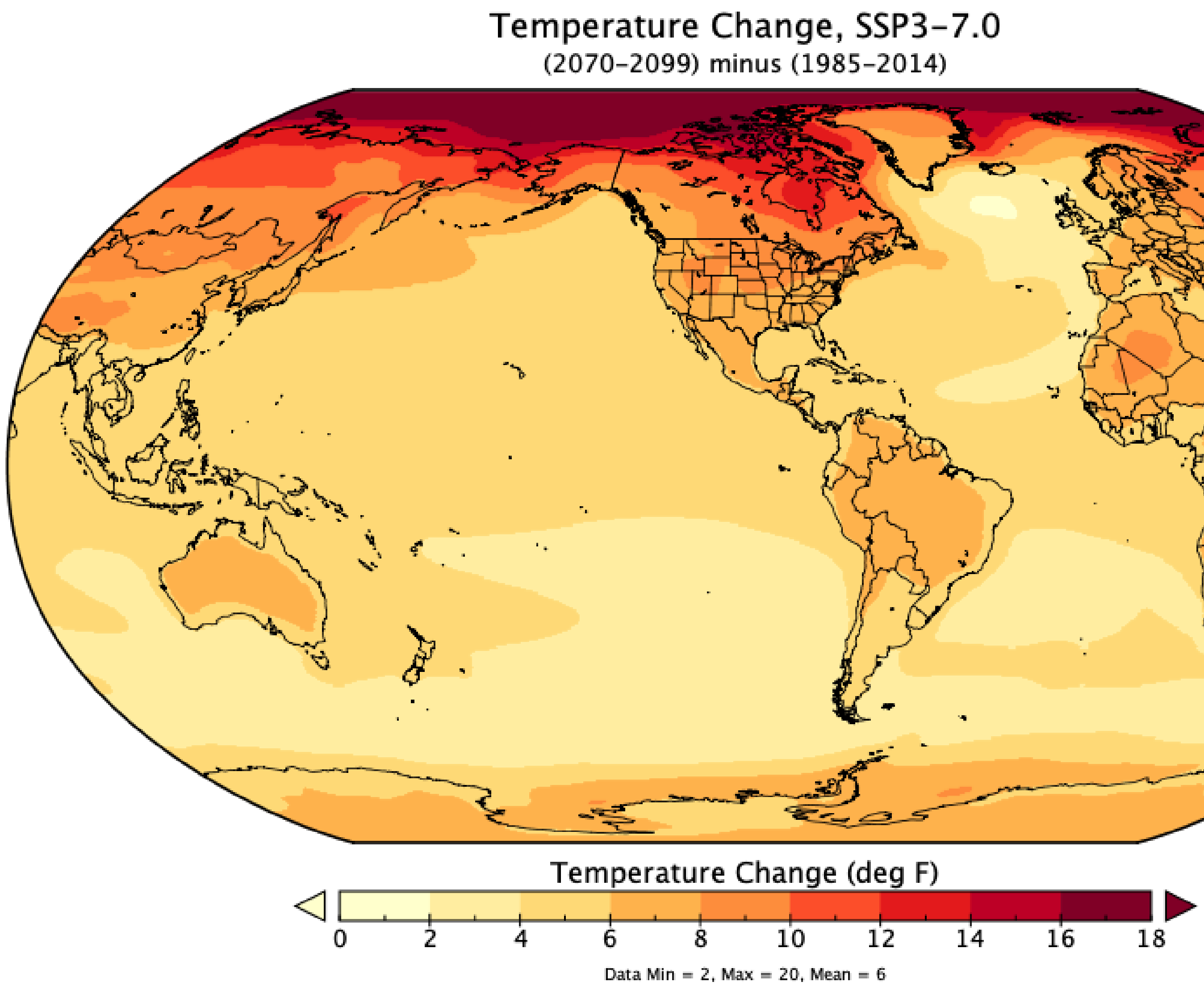
Future Global Temperature Change



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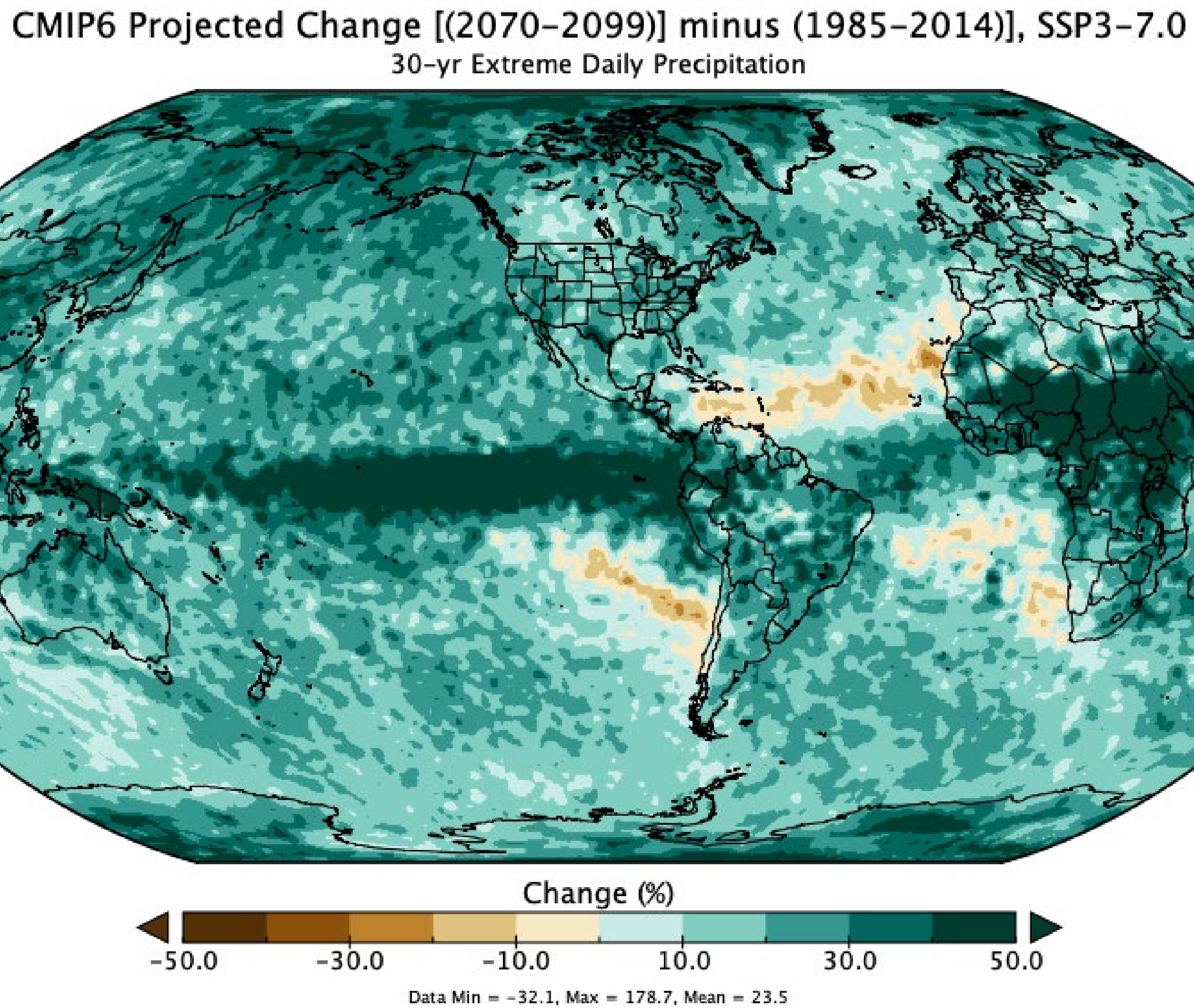
Extreme Precipitation



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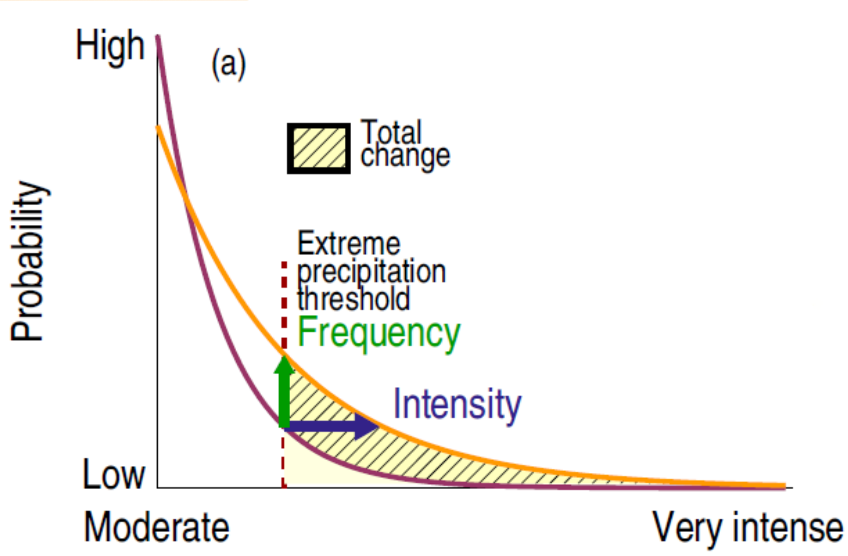
Global Extreme Weather Trends

IPCC (2021) and related studies indicate a predicted trend of increasing frequency and intensity of extreme precipitation events with increasing global temperature

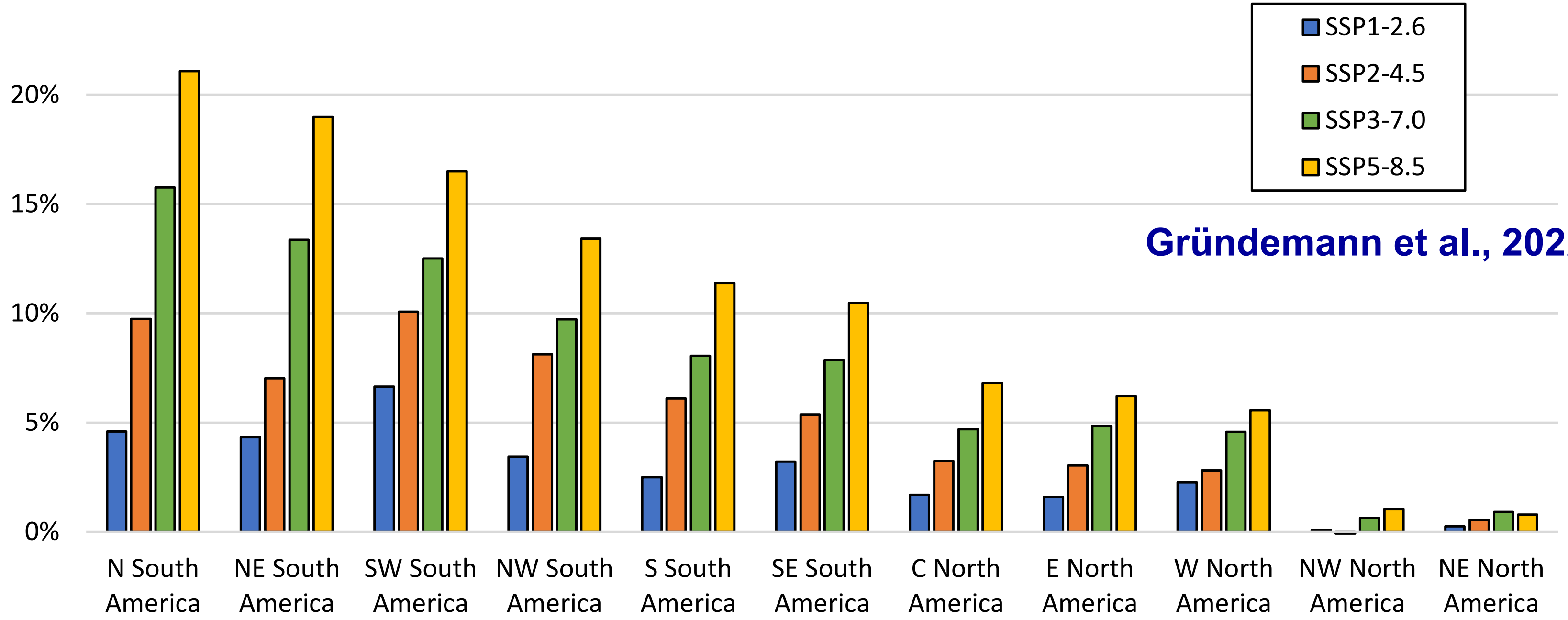
Global observations and climate modelling forecast widespread intensification of short-duration precipitation in warmer climates and in some North American regions already experiencing more intense and frequent precipitation extremes



Myhre et al., 2019

Projected Change in Event Magnitude

Forecast change in 100-year extreme precipitation event magnitude relative to change in 1-year event magnitude (2071-2100) for four emissions scenarios



Gründemann et al., 2022

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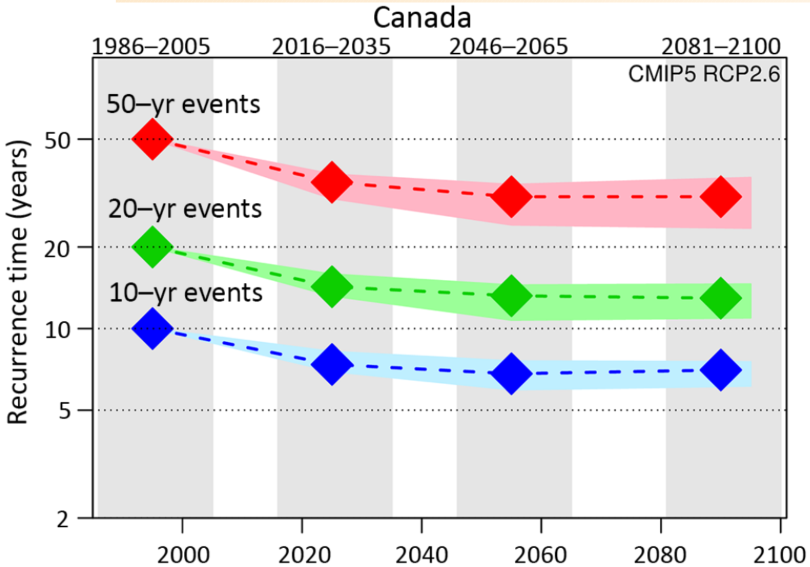
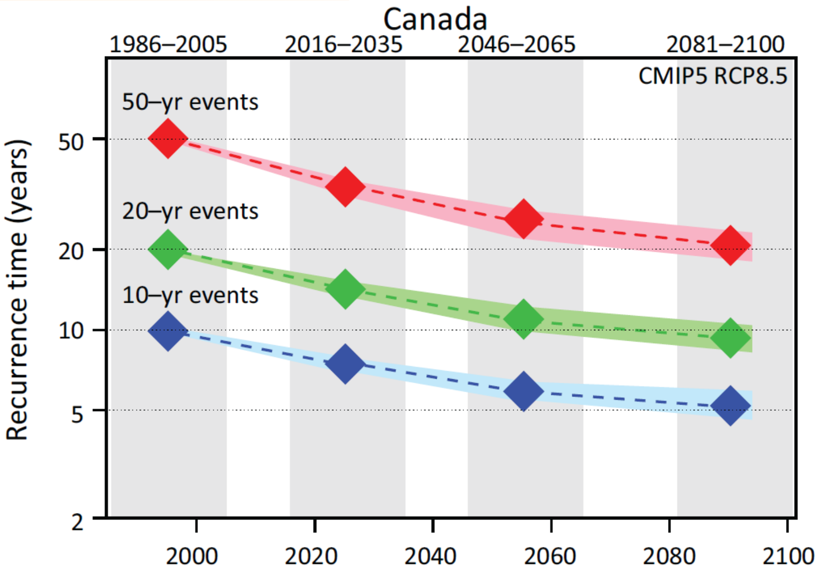
Projected Change in Event Frequency

Projected change in recurrence time for extreme precipitation events in Canada based on CMIP5 GCM results for two emissions scenarios





Canadian Standards Association, 2019

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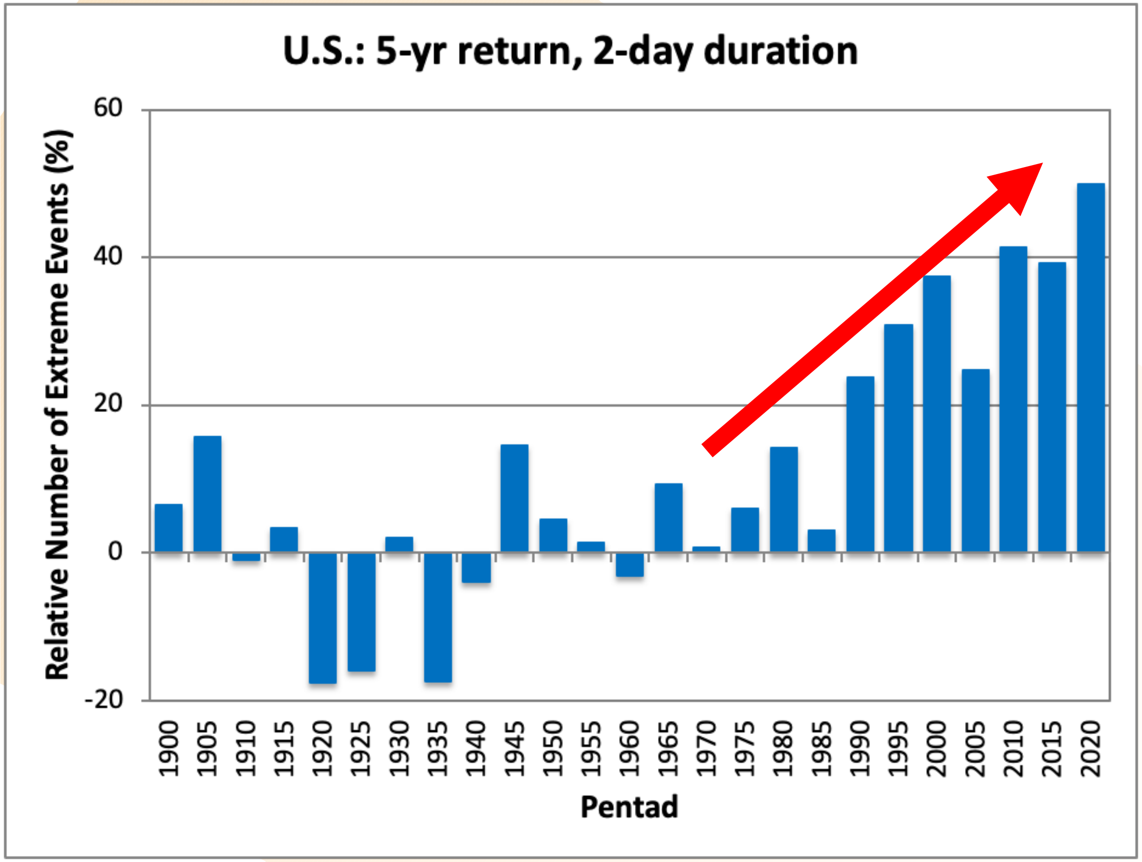
NOAA: U.S. Extreme Precipitation Trends

- Large increases in national average extreme precipitation frequency
- Increases concentrated in eastern half of the U.S.; small trends in the west
- Globally, there are many more observing stations exhibiting increases than decreases in extreme precipitation

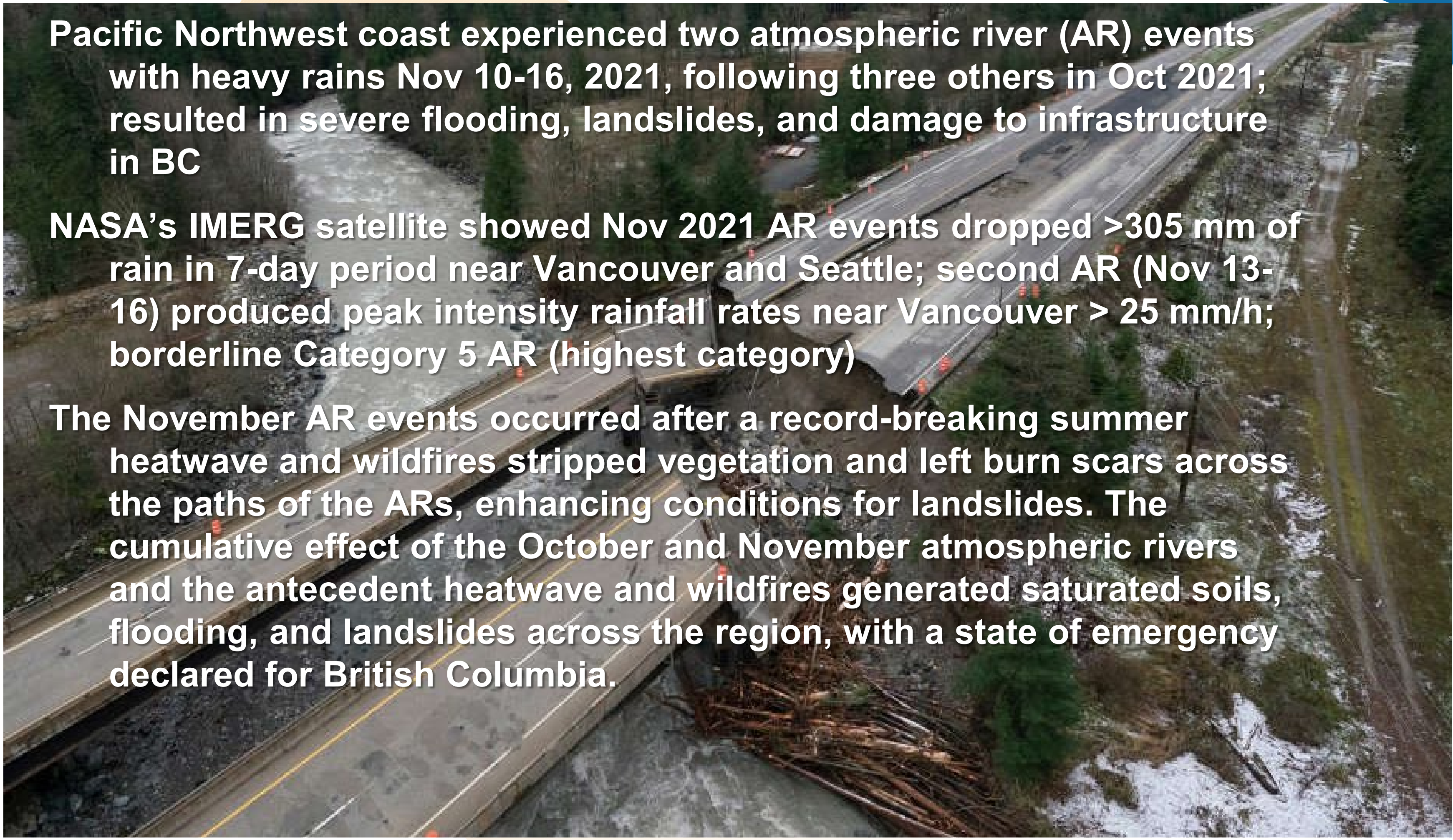
NOAA

NOAA: U.S. Extreme Precipitation Historical Trends



NOAA

Atmospheric River Events – British Columbia



- Pacific Northwest coast experienced two atmospheric river (AR) events with heavy rains Nov 10-16, 2021, following three others in Oct 2021; resulted in severe flooding, landslides, and damage to infrastructure in BC
- NASA's IMERG satellite showed Nov 2021 AR events dropped >305 mm of rain in 7-day period near Vancouver and Seattle; second AR (Nov 13-16) produced peak intensity rainfall rates near Vancouver > 25 mm/h; borderline Category 5 AR (highest category)
- The November AR events occurred after a record-breaking summer heatwave and wildfires stripped vegetation and left burn scars across the paths of the ARs, enhancing conditions for landslides. The cumulative effect of the October and November atmospheric rivers and the antecedent heatwave and wildfires generated saturated soils, flooding, and landslides across the region, with a state of emergency declared for British Columbia.

Pipeline Geohazards Impacts – Brazil

Impacts vary by location and physiographic setting; Central and South America prone to El Niño–Southern Oscillation-driven fluctuations in rainfall amounts

Record-breaking rainfall of 684 mm in 11 hours in February 2023 impacted the OSBAT oil pipeline in São Paulo, Brazil [38]

Guimarães Neto et al., 2023

Observed & Anticipated Geohazards Triggers & Consequences

Increasing Triggers:

- Wildfires
- Extreme precipitation events
- Instabilities due to cascading mechanisms in cases of post-fire extreme precipitation
- Instabilities due to shifts in precipitation patters/seasons

Increasing Consequences:

- Water course bank erosion
- Larger and more frequent landslides
- Rock avalanche from alpine permafrost sources
- Debris flow fas are primary areas of interest

Progressive versus Episodic Geohazards

Progressive Geohazards – occur gradually, cumulative time-dependent

- Identify, monitor and intervene when necessary

Episodic Geohazards – occur suddenly, event-driven

- Identify, assess and intervene if necessary

Geohazard Category	Progressive Time-dependent	Episodic
Geotechnical	- Creeping Slope - Settlement	- Debris Flows - Rockfall - Seismic - Sinkholes
Hydrotechnical	- Bank Erosion - Scour	- Avulsion - Outburst Floods

Inter-related climate change impacts between time-dependent and episodic slope instabilities

Climate Change Mechanism	Time-dependent Slope Instability	Episodic Slope Instability
Increased total annual rainfall	Gradual increase in groundwater and pore pressure over time o	Higher rainfall intensity and/or duration may cross thresholds causing sudden failure
Prolonged wet seasons	Time-dependent loss of shear strength over cumulative period	Successive storms in short intervals may produce an episodic failure
Extreme rainfall event (atmospheric rivers, tropical remnants	Prior saturation conditions amplify effect of each event	One large-footprint extreme storm episode may trigger tens of landslides

Wildfires Impacts on Geohazards

- **Hydrotechnical**
  - Increased runoff
    - Reduced infiltration
    - Reduced evapotranspiration
    - Reduced interception
  - Increased debris/sediment loading
  - Increased risk of major avulsions due to debris jams
- **Geotechnical**
  - Increased risk of shallow landslides
  - Increased instances of debris flows on steep slopes

Impacts due to wildfires are significant immediately after the event but diminish over time (to ~5 years)

Rainfall-Ground Movement Correlations for Pipeline Integrity Context

Given the general rainfall triggering effect on ground movement, various reported correlations and models may be applied to support forecasting pipeline integrity interventions for unstable slopes. Reported methods include:

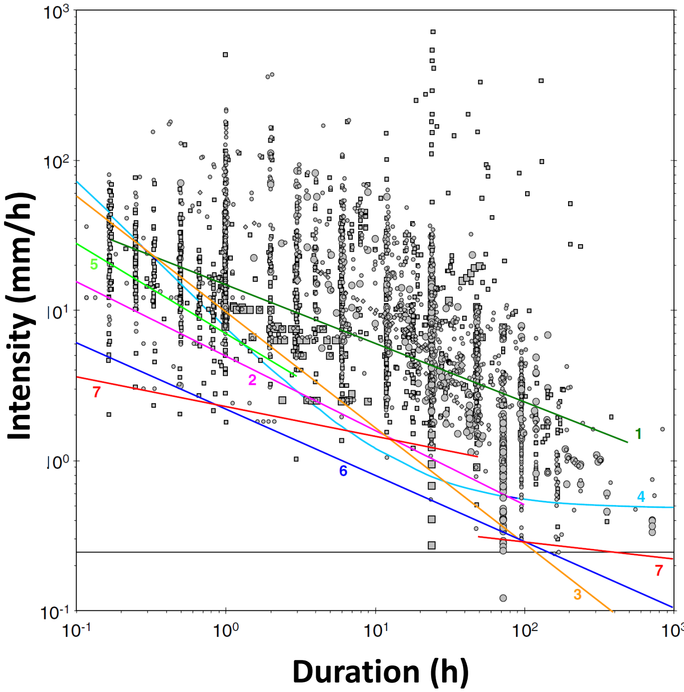
1. **Generalized empirical correlations** – not explicitly linked to geology or site-specific conditions

2. Predictive mechanistic models – attempt to match physics of movement to predict future behaviour

3. **Phenomenological models** – use historical measurements to predict future behavior

Generalized Rainfall-Induced Landslide Initiation

- Empirical relations linking data on rainfall intensity-duration-frequency (IDF), cumulative rainfall, antecedent rainfall, and other metrics to slope instability observations used in various climatic regions with mixed success
- Database of 125 rainfall threshold equations for initiation of various types of landslides available at http://rainfallthresholds.irpi.cnr.it
- Not universal; require consideration of factors such as geology, annual rainfall, antecedent rainfall, and others; limit equilibrium models introduce physics but require relation between rainfall and GWT (pore pressure)



Global rainfall IDF thresholds for shallow slope instability

(Guzzetti et al., 2008)

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Generalized Empirical Correlations

Regional correlations between shallow landslides and rainfall have been developed based on observations from different climatic regions.

Guzzetti et al. (2008) lists eight published global intensity-duration (ID) thresholds and six normalized ID thresholds. These thresholds represent a minimum level below which landslides do not occur based on a global database of 2626 rainfall events that resulted in shallow landslides and debris flows.

Single threshold is given by:

$$I = 2.20\ D^{-0.44} \qquad\qquad 0.1 < D < 1000$$

I – rainfall intensity (mm/hr)   D – rainfall duration (hours)

http://rainfallthresholds.irpi.cnr.it

Generalized Empirical Correlations

Benefit

- Provides a starting point for estimating potential ground movement initiation

Limitations

- These relations provide a generalized global threshold for shallow landslide initiation, and may or may not be suitable for site-specific landslide forecasting (i.e. low correlation factors)

Phenomenological Example - Simonette River, Alberta

Rainfall-ground movement relation

$$G_s(r,t) = 3.57 + 0.042 \cdot r_{(t-1)} + 0.018 \cdot r_{(t-2)}$$

where G_s is ground movement in mm, $r_{(t\text{-}1)}$ and $r_{(t\text{-}2)}$ are total monthly rainfall in mm for two months immediately preceding month of interest

Predicts ongoing creep independent of rainfall but could be modified to include a minimum rainfall amount to trigger ground movement

Refinements possible using newer technologies; means of linking projected future changes in site-specific monthly rainfall to changes in ground movement and pipe strain induced by ground movement

Stantec

Mapping, Predicting & Simulating Debris Flow Hazards:

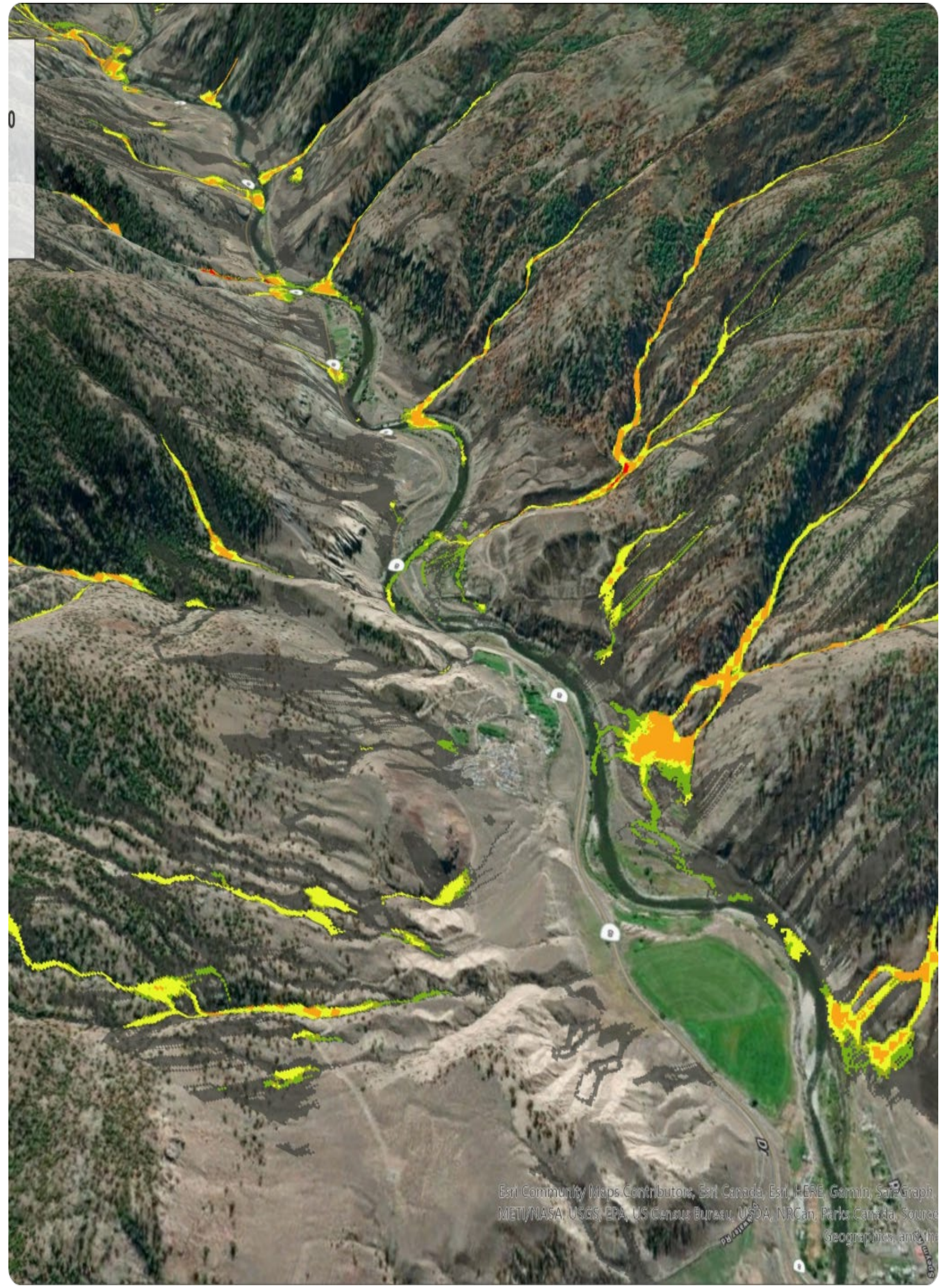
Probability of Occurrence

Susceptibility

Runout

Magnitude

Intensity



Climate Change Vulnerability Assessment (Trans Mountain)

THURBER

Divide the corridor into physiographic regions with similar geography and climate

Identify the key geohazard processes that contribute to pipeline threat in each region

Identify the key climate parameters influencing these geohazards, including weighting

Use public tools to collect baseline and future estimates for the various climate parameters

Estimate future hazard likelihood using weighted climate parameter changes

$$CF = (CV_1 \times RW_1) + (CV_2 \times RW_2) + (CV_3 \times RW_3)$$

CF – Climate Factor

CV – Climate Variable (% change)

RW – Relative Weighting (sum of $RW_X = 1$)

Table 4-2. Summary of climate adjustment factors (CF) by physiographic region.

Physiographic Region	Associated (2041-2070) Climate Factor Increase/Decrease			
	Fluvial Hazards	Debris Flows/Floods	Shallow Landslides	Deep-Seated Landslides
Alberta Plains	1.03	-	-	1.15
Foothills	1.06	1.07	-	1.12
Cordilleran Mountains	1.10	1.14	1.20	-
Interior Plateau	1.02	1.11	-	1.12
Coast Mountains	1.16	1.21	1.17	-
Fraser Valley	1.11	-	-	-

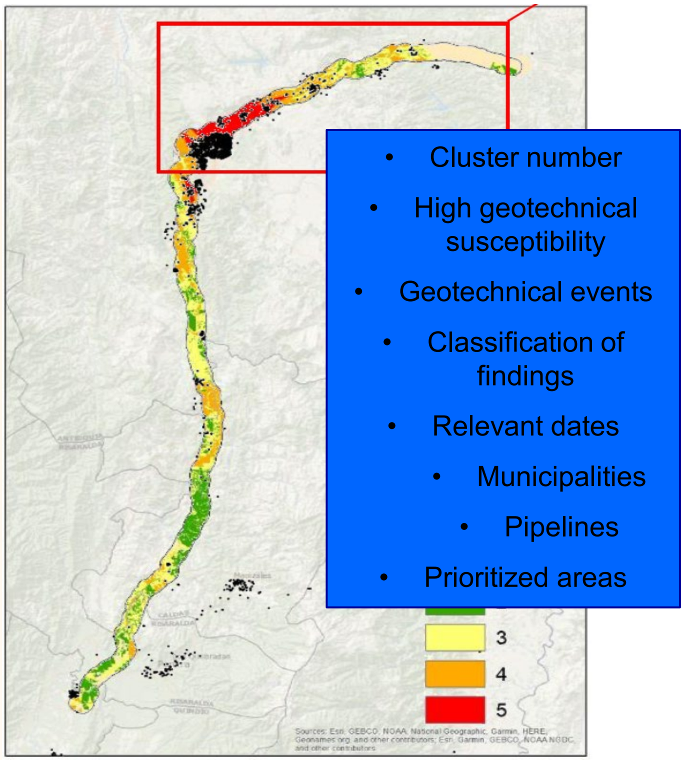
Note: Numbers presented above are randomly produced and not the results of the referenced project.

Climate Change Vulnerability Use Cases (Trans Mountain)

- The climate factors can be used to interpret changes to specific hazard types within each of the physiographic areas
  - How might climate change impact the progression of slow-moving landslides in the Interior Plateau?
    - Anticipated to increase our hazard exposure by 12% in 2041 – 2070, compared to today
  - How might climate change impact the frequency of debris flows along the right-of-way in the Coquihalla Valley?
    - Anticipated to increase our hazard exposure by 21% in 2041 – 2070, compared to today
- Can be applied broadly across our entire geohazard inventory to calculate the increased hazard exposure for the entire pipeline for the purposes of risk assessments and reporting
- For sites with otherwise similar threat, can be used to prioritize mitigation projects in areas where future climate impacts are more likely

Geological & Microclimatic Zonation (CENIT)

- Integrating AI with geotechnical susceptibility models, adaptive zoning identifies locations prone to rainfall-induced landslides, guiding timely inspections and integrity management interventions
- Zonation of pipeline right-of-way on basis of microclimatic conditions, surficial geology, bedrock geology, topography, and other attributes delineates polygons along a route for categorization of susceptibility
- Several **CENIT** IPG papers illustrate zonation for iterative geohazard and risk assessment; susceptibility zoning for geohazards of hydroclimatic origin using supervised learning clustering techniques and algorithms to generate adaptive zoning guided by model data and expert knowledge on interaction of pipeline, soils, and climatic conditions



CENIT (2023)

Geological & Microclimatic Zonation (CENIT)

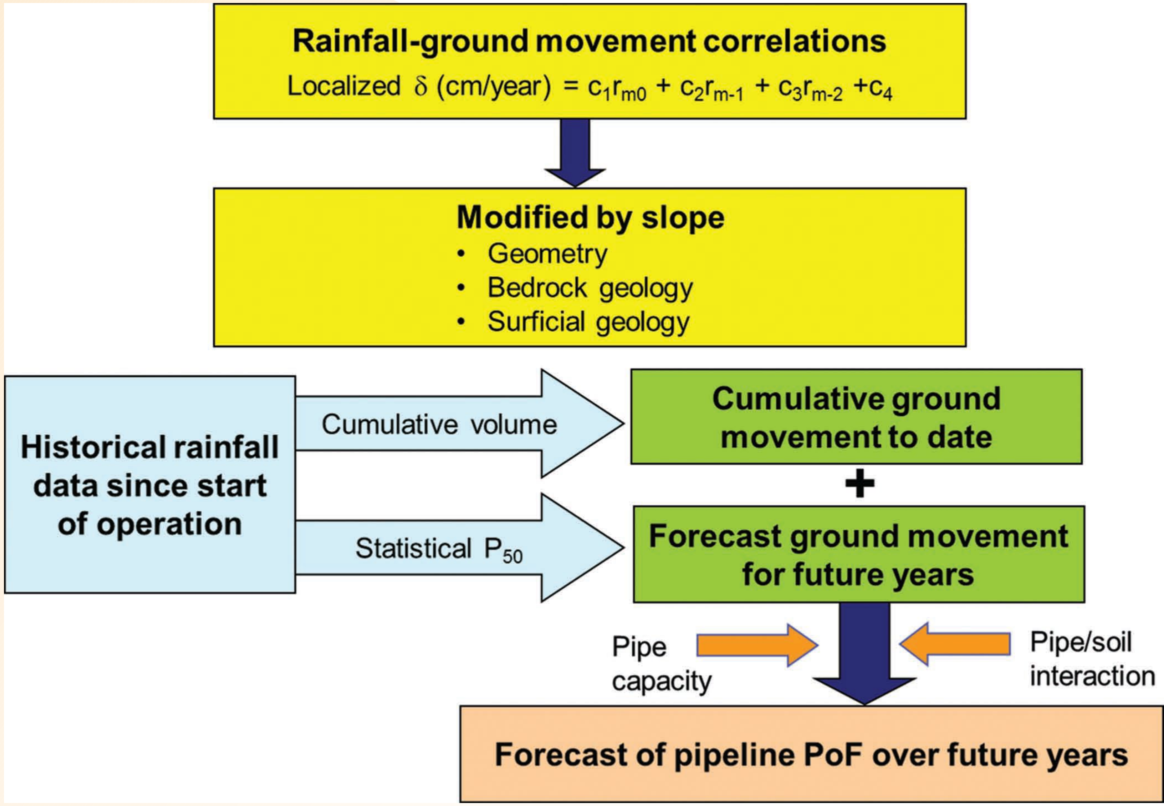
Process supported by 510 measurement points including 90 real-time rainfall monitoring points at critical prioritized sites, weather satellite inputs and forecasting models to generate daily weather analysis bulletins.

Predictive capability combines rainfall data from last 24 hours, precipitation trends and a forecast for the upcoming 72 hours

Continuous application updates has refined (focused/reduced) the number of High and Extreme Susceptibility zone

Empirical Pipeline Response Model

- Screening-level empirical **rainfall-ground movement correlation based** approach to predict pipeline factor of safety
- Applied at several sites with deforming slopes



Zhou et al., 2000

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An Emerging Approach for Climate Change Management

Forward-looking risk management

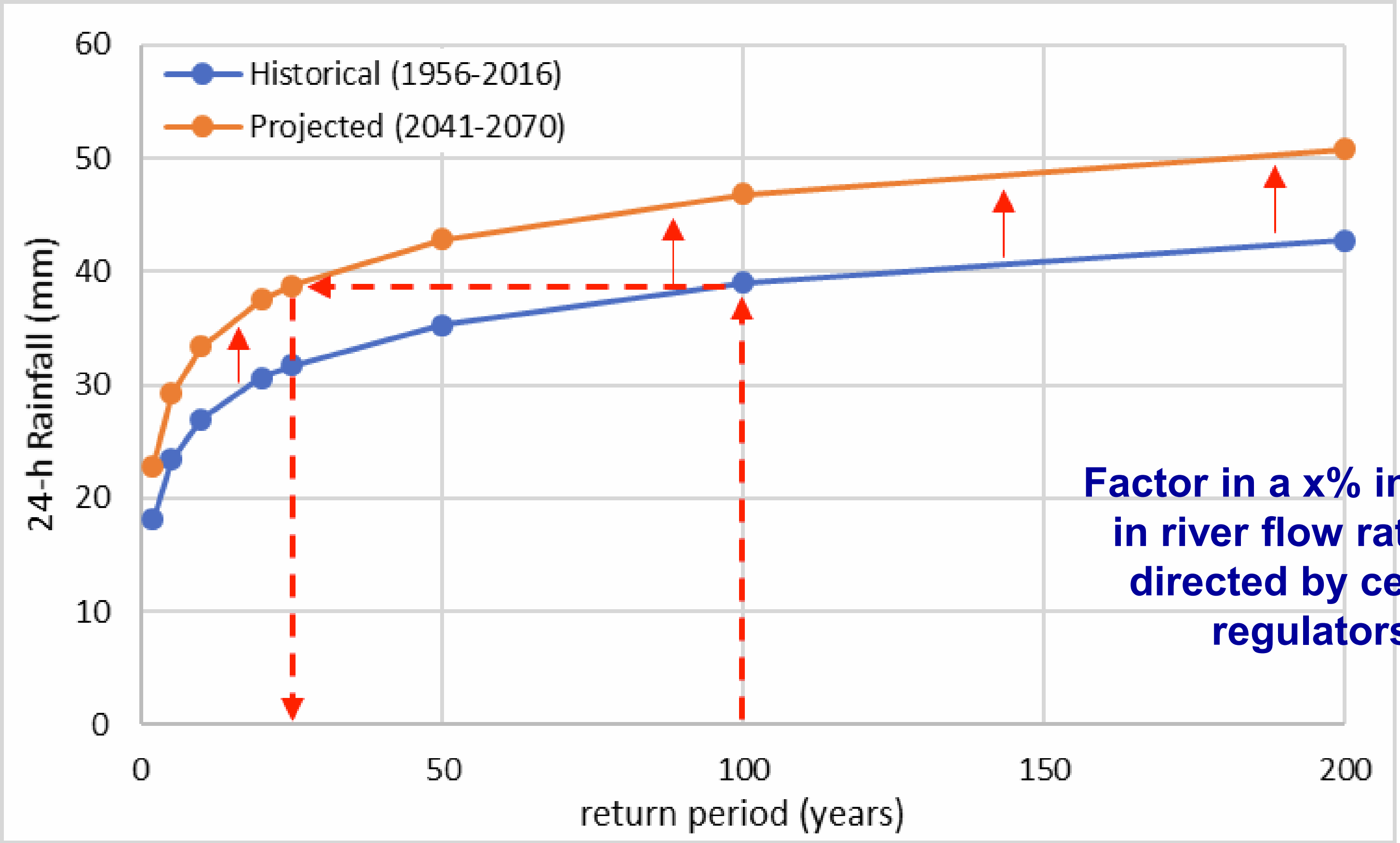
by

Stress-testing under modelled extreme events

for

Resilience planning & adaptation strategies

A General Approach to Address Climate Change



Factor in a x% increase in river flow rates as directed by certain regulators

Source: IPG 2019 Key Note Address by Dr. Mattheis Jakob

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Prioritization of High Consequence Sites

Prioritization of sites for reassessment of geohazard susceptibility and risk should consider previous assessment results to identify areas sensitive to change in extreme precipitation event frequency and/or magnitude

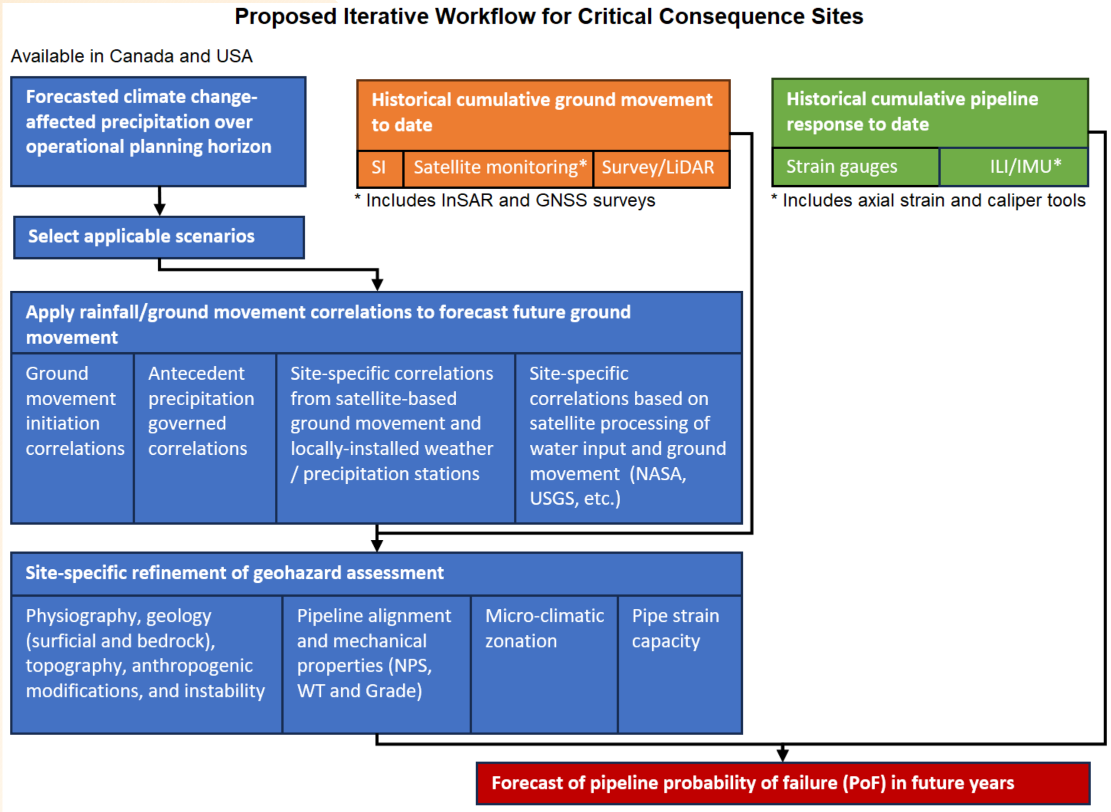
Consider results of any consequence analysis conducted to identify high consequence areas and environmentally sensitive areas (e.g., CSA Z662); susceptible populated and developed areas warrant elevated scrutiny

Previously identified locations of slope movement with known sensitivity to rainfall are potential candidates for reassessment to evaluate implications of possible increased ground movement rate; other sites with conditional instability depending on groundwater level also candidates for re-evaluation

Read et. al. 2024

Proposed Iterative Workflow

- **Follows general methodology used for pipeline geohazard assessment, but incorporates updated projections of future extreme precipitation at critical consequence sites**
- **Connects climate science to pipeline engineering and pipeline integrity management using engineering forward tools**



Read et. al. 2024

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Technical Complexities & Opportunities

Trends in extreme precipitation events are location dependent, can vary significantly from site to site, and can deviate markedly from general global trends described in many publications

Factors affecting projections of extreme precipitation include:

- use of gridded historical climate data versus station data;
- use of GCM-predicted precipitation versus temperature-correlated precipitation;
- updates and progressive improvements to GCMs and their outcomes;
- inherent error related to selection of extreme value function used for analysis (e.g., Gumbel versus Generalized Extreme Value (GEV) distribution);
- adopted GCM bias correction (e.g., PCIC bias correction)

Ongoing improvements in microclimatic and geologic zonation techniques include use of unsupervised and supervised machine learning to identify areas with relatively consistent conditions controlling landslide susceptibility

Practical challenges in operational responses to extreme events

1. Extreme events can impact access as well as assets
2. Resources (materials, equipment, personnel) can be spread thin or completely unavailable
3. Assessing integrity after a precautionary shutdown can be challenging

Such issues need to be considered when preparing emergency response plans or completing exercises

- What are the prerequisites for your plan to be executed?
- What assumptions need to be reframed for emergency preparedness?

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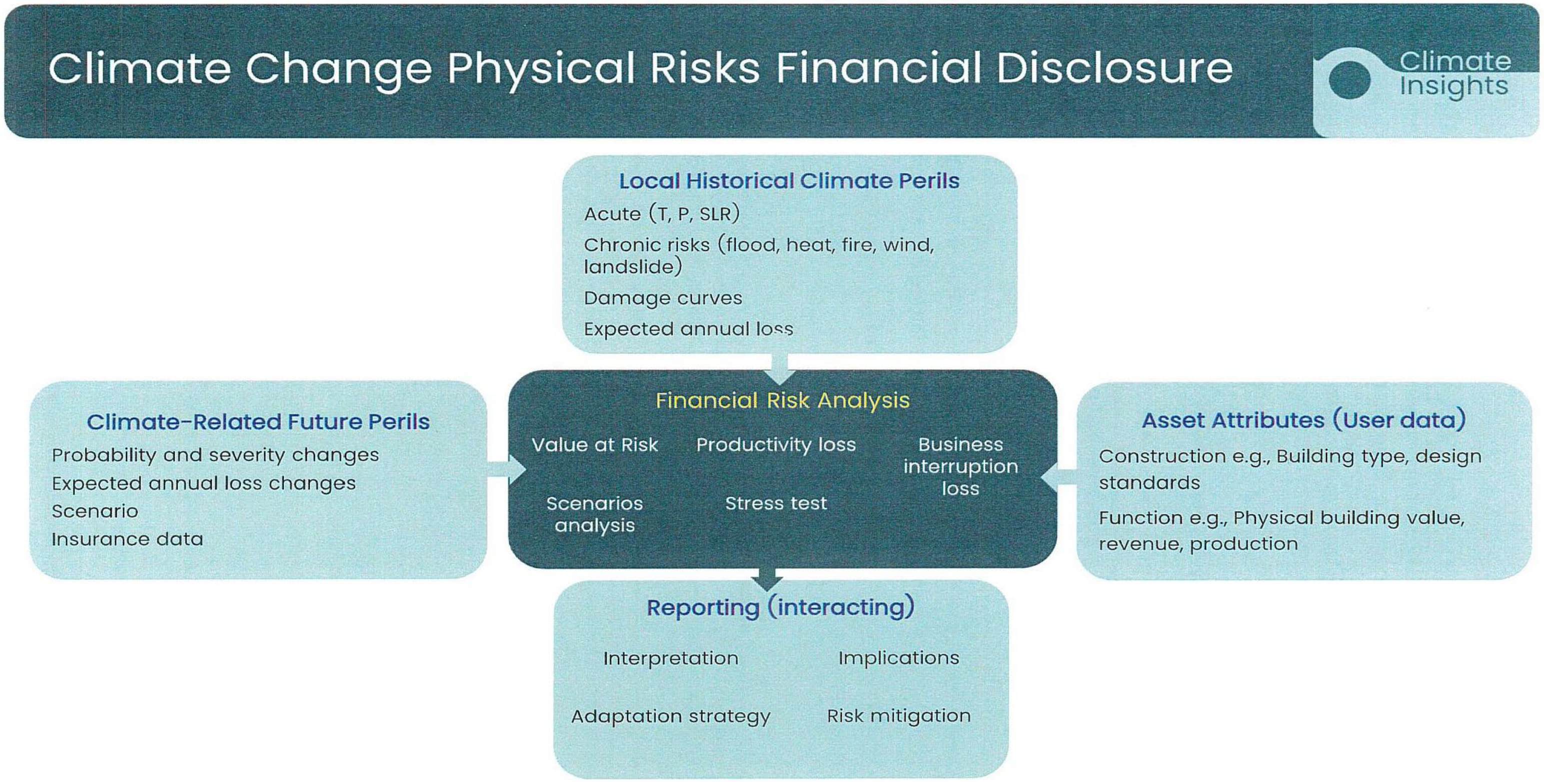
Business Decision Process – Example



Considering a Value at Risk (VaR) perspective
Clim.Systems (2024)

Business Decision Process – Challenges

In evaluating the Rate of Return (RoI), the timing of the pay-off is uncertain.

- The magnitude of the hardening/adaptation benefit depends on how much risk materializes
- Proponents may incorporate co-benefits and value even if a catastrophe doesn't happen
- The forgoing calls for a complex internal discounting finance criteria with near-term benefits easier to justify than long-term adaptation/hardening benefits

An Understandably Cautious State-of-Practice Business Response

Examples of leading pipeline operators' climate resilience management plans KPIs addressing potential asset physical damage include:

- Managing/reducing weather-related outage durations
- Percent of RoW in high wildfire risk areas treated or monitored
- Percent of potential critical unstable areas monitored
- Percent of critical sites above design/potential flood levels
- Percent of assets with completed physical climate risk assessments

Thank You

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