# Assessing landslide dam hazards in Aotearoa New Zealand: a data driven approach.

**Regine Morgenstern[1], Andrea Wolter[1], Chris Massey[1], Brenda Rosser[1], Simon C. Cox[2] and Biljana Lukovic[1]**

*[1]GNS Science, Lower Hutt, New Zealand*

*[2]GNS Science, Dunedin, New Zealand*

*Email: r.morgenstern@gns.cri.nz*

**Abstract:** Landslide dams form when debris from a landslide blocks the watercourse of a valley and if they fail rapidly, they can pose a significant and catastrophic hazard to downstream life, property and infrastructure. Landslide dams and their remnants occur widely throughout Aotearoa New Zealand, being a function of the maritime climate and active tectonic setting, as well as the high relief and/or steep topography. At least 500 natural dams have formed here in the last few decades, with the 2016 Kaikōura earthquake contributing to the majority (94%). Many of these have been in remote, mountainous terrain; however, their frequency and potential for causing loss or harm should they occur in populated areas and fail rapidly, can have huge consequences. Here we present ongoing work to better understand dam formation potential, stability, breach mechanisms and downstream impacts, by utilizing a combination of techniques and data including a new geospatial database, field-based monitoring, hindcast and forecast modelling and expert judgement based on observations relating to the previous performance of landslide dams.

The recent completion of version 1.0 of the New Zealand Landslide Dam Database presents the compilation of historical and recent efforts to map landslide dams in New Zealand. It includes 1036 dams, each of which have source area, debris trail, dam and lake polygons mapped, where possible, as well as a categorical measure of the data quality. The location of each dam is represented by a point at the upstream end of the dam, and attribute information includes: dimensions and volumes; triggering mechanisms and dates; geological parameters; catchment and valley properties; and breach details. Our data show that most of the recent landslide dams in New Zealand have failed within the first year of their formation, often triggered by the first high intensity or prolonged rainfall – post dam formation – which caused overtopping. The database is being used to further investigate and analyse the formation potential, longevity, and stability of natural dams across the country.

Detailed case studies are also needed to help calibrate these historical regional-scale observations and to provide better spatiotemporal resolution for assessing longevity, failure modes and downstream impacts. Here, we summarize a method for assessing these post-formation, drawing on two detailed monitoring campaigns: the Kaiwhata (rainfall-induced) and Hapuku (earthquake-induced) landslide dams. This includes the following steps: (1) perform initial, desktop breach inundation modelling to determine scale of hazard and impact utilizing empirical dam-breach relationships; (2) collect high-resolution topographic surveys of the dam and downstream floodplain, using both field-based and remote sensing techniques; (3) investigate and identify dam-forming materials; (4) revise breach mechanisms/models using field data to identify dam failure scenarios; (5) revise numerical simulations to more clearly define the likely area of inundation, for each scenario; and (6) overlay dam failure and inundation scenario models on asset maps to identify life, property and infrastructure that are potentially at risk. By following such a method, the impacts posed by landslide dam-breach hazards can be better managed.

**Keywords:** Landslide dam, dam outburst flood hazard, monitoring, rapid response, database, GIS

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GNS Science, New Zealand

# Presentation overview and introduction

## Landslide dams in New Zealand (NZ)

- >500 formed in last few decades
- NZ Landslide Dam Database

## Methods for assessing landslide dams

- **Case studies**: assessing failure modes, longevity and downstream impacts
  - **Kaiwhata** landslide dam
  - **Hapuku** landslide dam

**Brumadinho dam disaster (Brazil) - 25 Jan 2019**
**270 deaths**


A rapid failure and breach event can have devastating impacts on downstream life and critical infrastructure.

# Background – landslide dams in NZ

## NZ Landslide Dam Database (NZLDD)

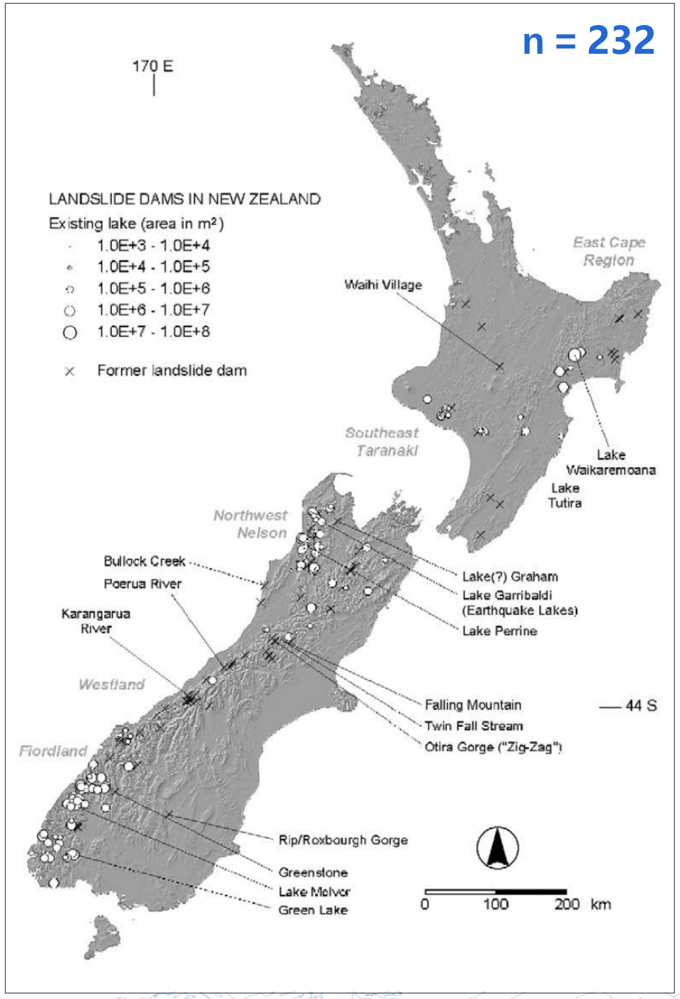
assessing landslide dam formation potential, stability and longevity.

- Significant increase in catalogued landslide dams globally (1434, Shan et al. 2020)
- Contains **1036** dams, with a representative subset of 265
- Includes dams generated during the 2016 Kaikōura earthquake

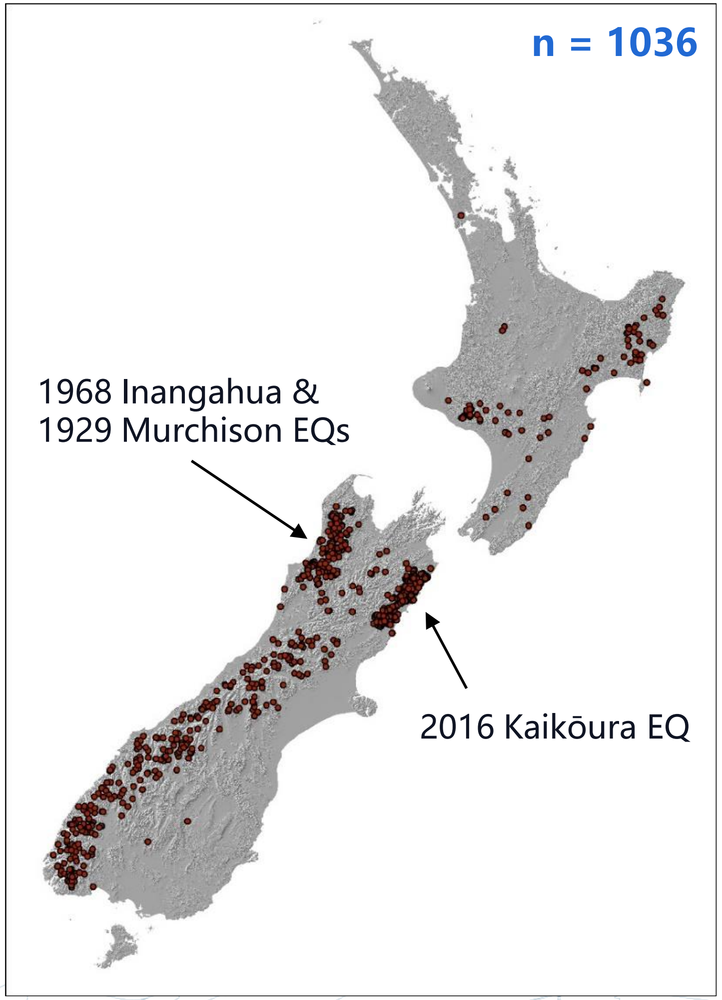
Data (OSF)

Metadata

Early 2000s (Korup 2004)

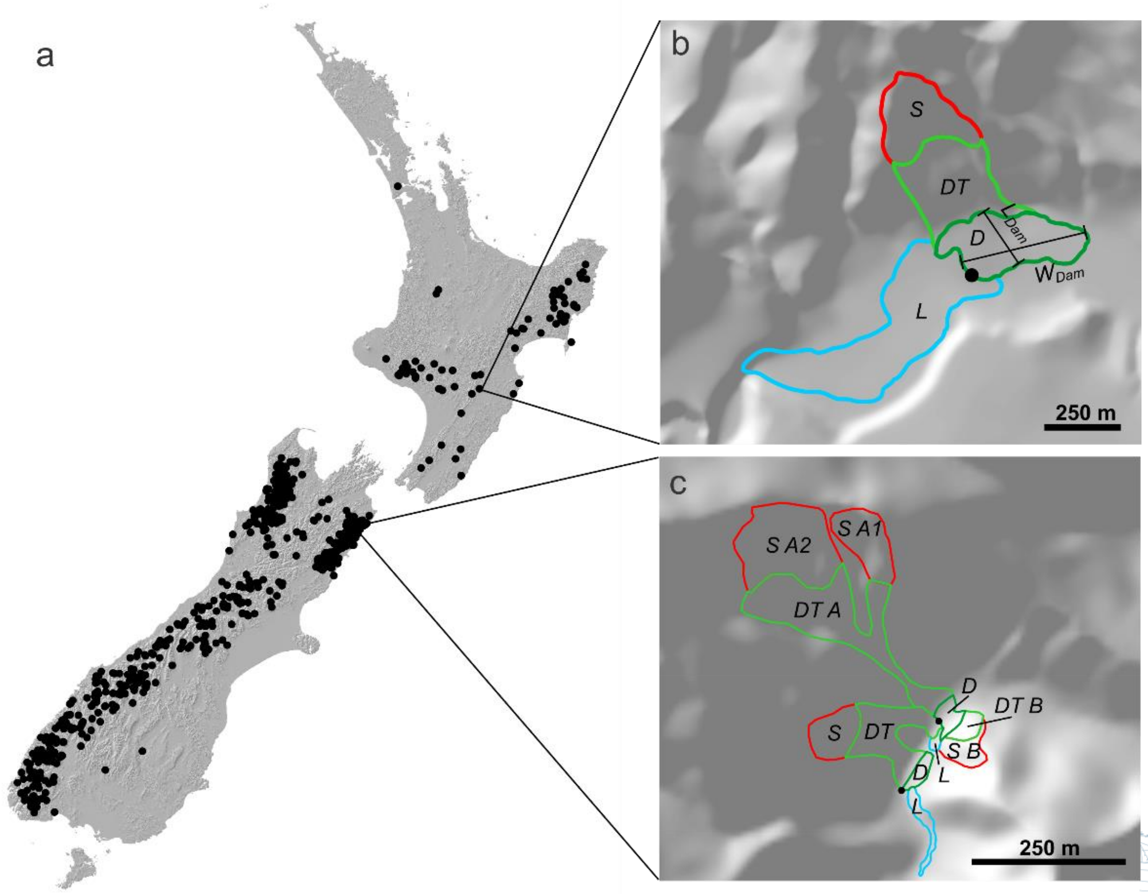



2023 (Morgenstern et al. in press)



# NZLDD - design

- ArcGIS geodatabase
  - 5 feature classes + 1 table
- Site ID that links all components




S: Source
DT: Debris Trail
D: Dam
L: Lake

**Bold** = all dams (where possible)
*Italics* = subset only
All other = ArcPy (where possible)

📖 Morgenstern et al. (in press)

**DamSite (Master Point Feature Class)**

**OBJECTID**
**DamSiteID** (PK)
**SiteID**
**X_Dam**
**Y_Dam**
**Z_Dam**
*H_Dam*
*W_Dam*
*L_Dam*
*V_Dam*
H_LS
R_LS
R_LS_3D
L_LS
H_R_ratio
H_R3D_ratio
H_L_ratio
**A_LS_debris_sum**
**V_LS_debris_sum**
**Material_LS**
**Type_LS**
**Trigger**
**Type_Dam**
*DBI*
Upstream_Catchment_Area
*W_Channel_at_Dam*
Grad_Channel_at_Dam
**DateFormed_Dam**
*FailureMech_Dam*
*Dam_breach*
**Dam_breach_details**
*Dam_Stability*
*Q_at_Failure*
**Confidence**
**Comments**
**References**
**SUBSET**
**MetadataID** (FK)

Dam site-specific info

**QualityRanking (Table)**

**OBJECTID**
**MetadataID** (PK)
**Reference**
**Reference_full**
**Data_Source**
**Mapping_Method**
**QR_Method**
**Completeness**
**QR_Completeness**
**Location_Accuracy**
**Polygon_Accuracy**
**Mapping_Scale**
**QR_Accuracy**
**QR_OVERALL**

Dataset-specific info

**Source (Polygon Feature Class)**

**OBJECTID**
**SourceID** (PK)
**SiteID**
**Source_Geology**
**V_S**
**References**
**SUBSET**
**Shape_Length**
**Shape_Area**

Source-specific info

**DebrisTrail (Polygon Feature Class)**

**OBJECTID**
**DebrisTrailID** (PK)
**SiteID**
**References**
**SUBSET**
**Shape_Length**
**Shape_Area**

Debris trail-specific info

**Dam (Polygon Feature Class)**

**OBJECTID**
**DamID** (PK)
**SiteID**
**Dens_Dam**
**References**
**SUBSET**
**Shape_Length**
**Shape_Area**

Dam-specific info

**Lake (Polygon Feature Class)**

**OBJECTID**
**LakeID** (PK)
**SiteID**
D_Lake
V_Lake
**References**
**SUBSET**
**Shape_Length**
**Shape_Area**

Lake-specific info

PK: primary key; FK: foreign key

# NZLDD

Morgenstern et al. (in press)

## Methods

- Mapping of newly identified dams
- Compilation and re-mapping of previous data

## Statistics

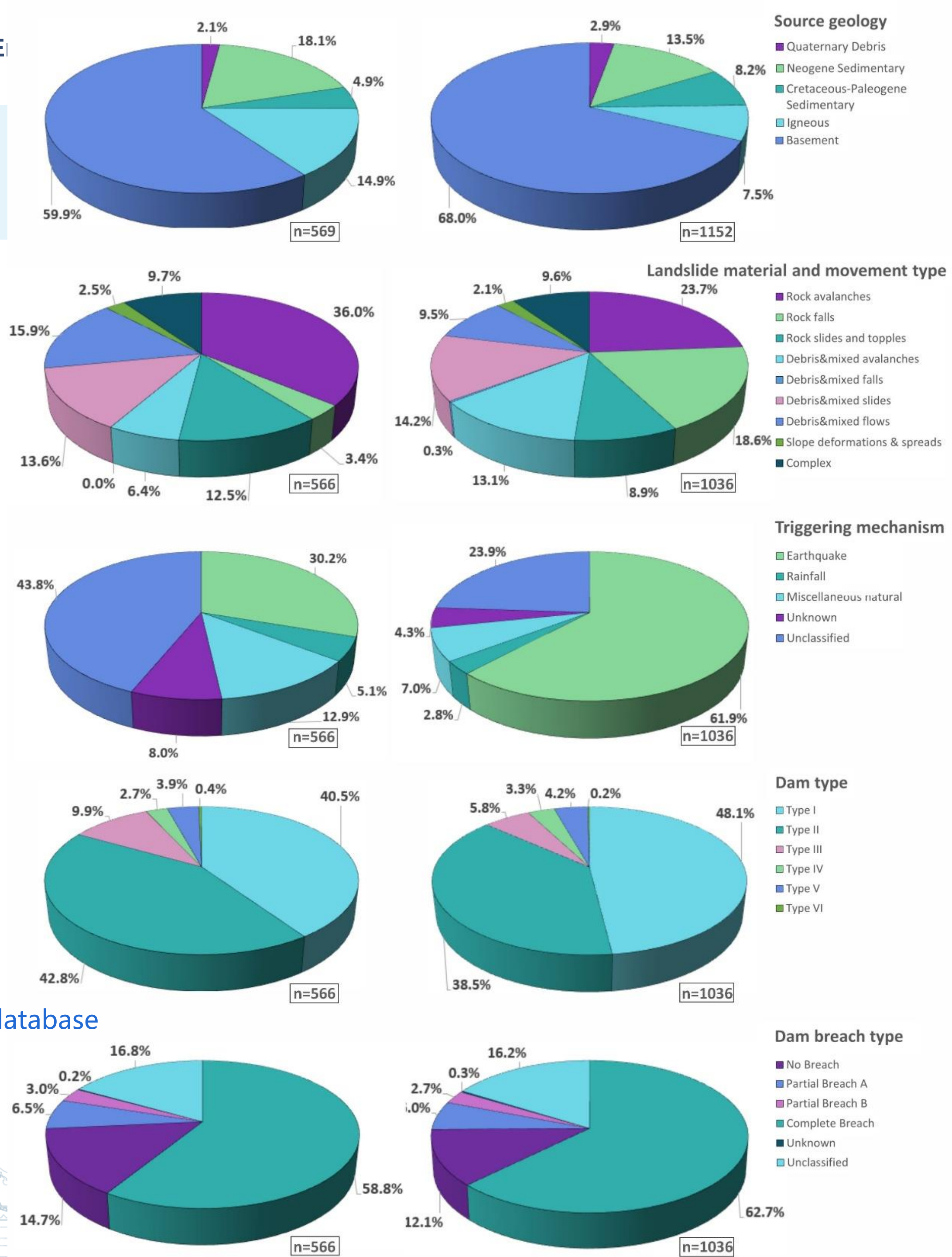
Majority of dams in the database have formed:

- In greywacke basement terrane (60-68%)
- Rock avalanches, falls, slides and topples (51-52%) - Hungr et al. (2014) classification
- From EQ-trigger (30-62%), where classified
- Dam Type I & II (83-87%) - Costa & Schuster (1988)
- Have since breached completely and no longer impound water (59-63%)

Significant dam-forming events

| Event | Type | # dams |
|---|---|---|
| 2020 Gisborne | rainfall | 5 |
| 2016 Kaikōura | earthquake | 470 |
| 2011 Hawkes Bay | rainfall | 3 |
| 2009 Fiordland | earthquake | 3 |
| 2004 Manawatu | rainfall | 5 |
| 2003 Fiordland | earthquake | 10 |
| 1968 Inangahua | earthquake | 40 |
| 1929 Murchison | earthquake | 61 |

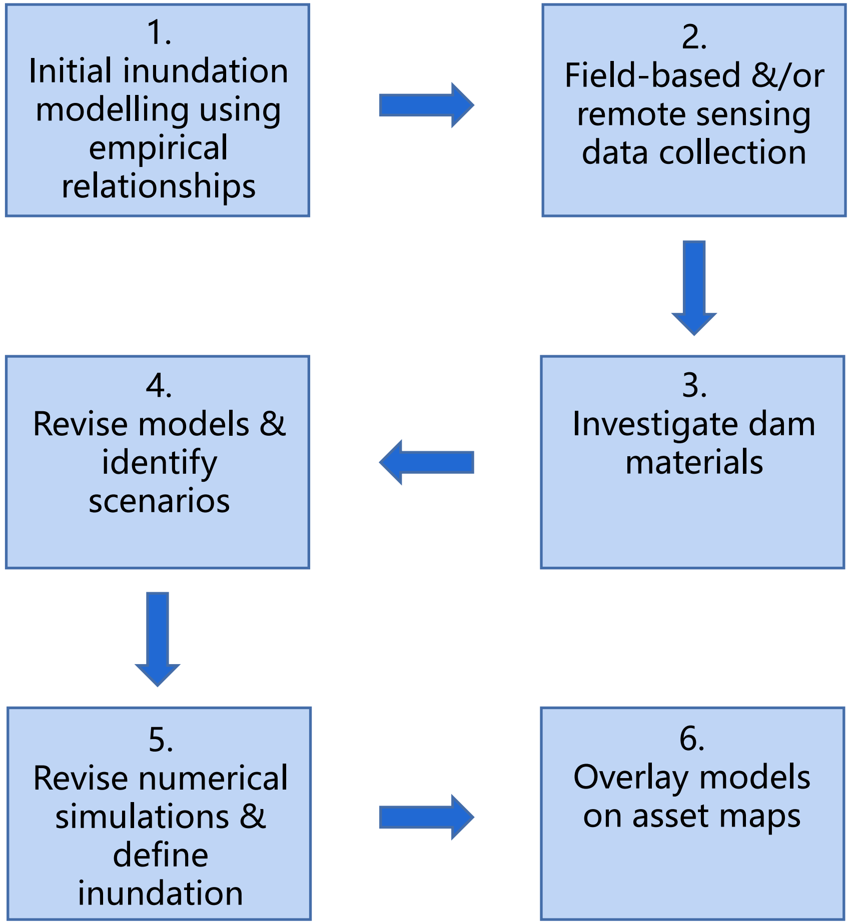
Left: exclude Kaikoura; Right: full database



# Assessing landslide dams in NZ - methods

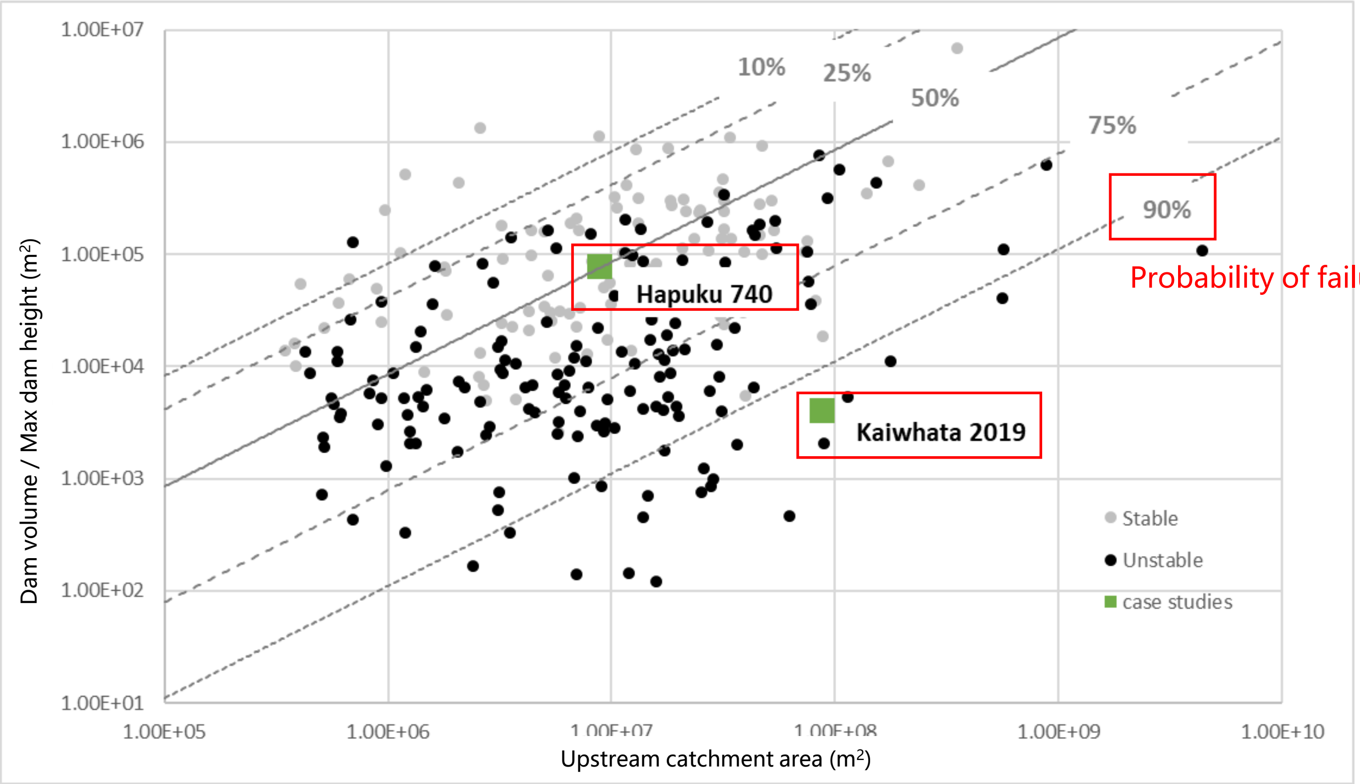
## 6-step approach:

1. Initial desktop modelling to determine scale of hazard and impact
2. Collect high-resolution topographic surveys of the dam and downstream floodplain (RTK, TLS, UAV, LiDAR, lake level, rain gauge, mapping)
3. Investigate and identify dam-forming materials (PSD)
4. Revise breach mechanisms/models using field data to identify dam failure scenarios
5. Revise numerical simulations for each scenario
6. Overlay dam failure and inundation scenario models on asset maps to identify life, property and infrastructure that are potentially at risk




Morgenstern et al. (2021)

# Case study 1: Kaiwhata landslide dam




**Dimensionless Blockage Index (DBI) tool**

Probability of dam failure: regional-scale assessment based on dam geometry and catchment area (stream power)

## Landslide dammed Kaiwhata River 1st June 2020 following heavy rain

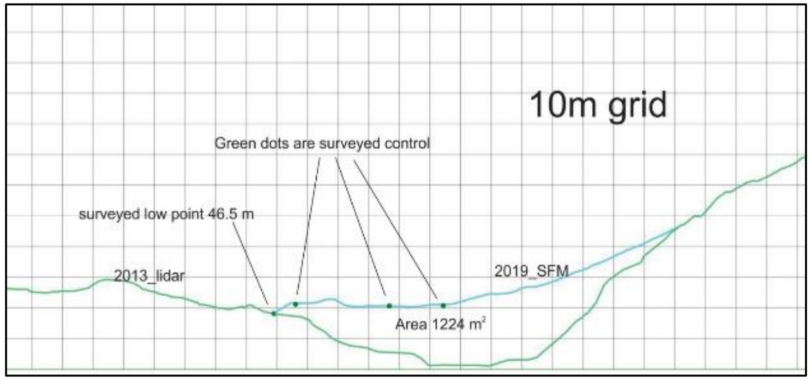
Data collected over 4 weeks – from just after formation to immediately post-failure

# Kaiwhata – event timeline

## June 6th

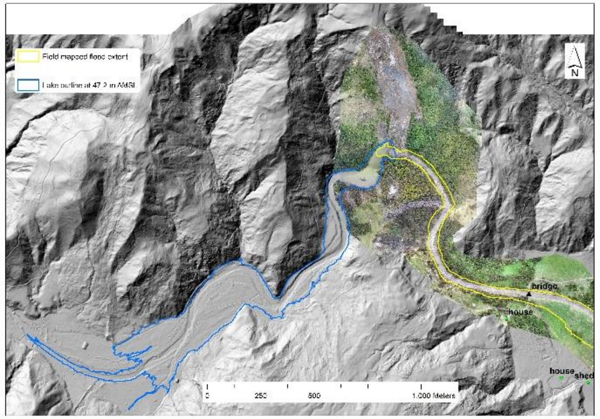
Field data indicated:
- dam height: ~**16 m**
- dam volume: ~**110,000 m³**
- lake volume: **600,000 m³**
- PSD: **D50** was **3 mm** (mudstone with clay + glauconitic sandstone)

Dam cross-section



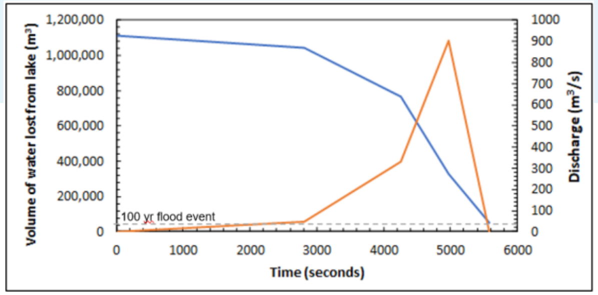

## By June 12th

- **Outflow channel** had formed
- Seepage and slumping observed
- Lake level was still **1.2 m below max**




June 12th

## June 13th



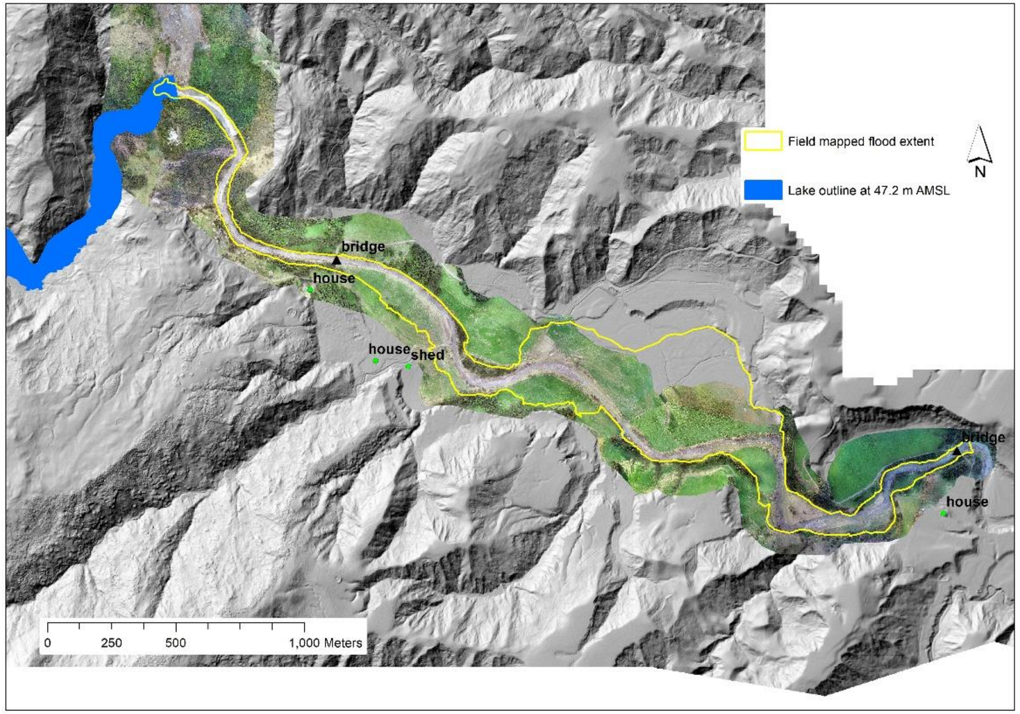

- Dam failed 9.15pm (steady all-day rain)
- Released ~**1 M m³** water in <**1.5 hours**
- Peak discharge: **900 m³/s** (100 yr flood: **15 m³/s**)
- Full breach: due to throughflow and slumping; ultimately via overtopping

June 14th

# Kaiwhata – flood extent

**Trash line surveying** – field mapping of floodplain day after the event

- Entire floodplain inundated with **1-2 m** of water (max **600 m wide** and **6 m depth**)
- Failure occurred in **multiple pulses**
- No one hurt, no buildings or infrastructure damaged



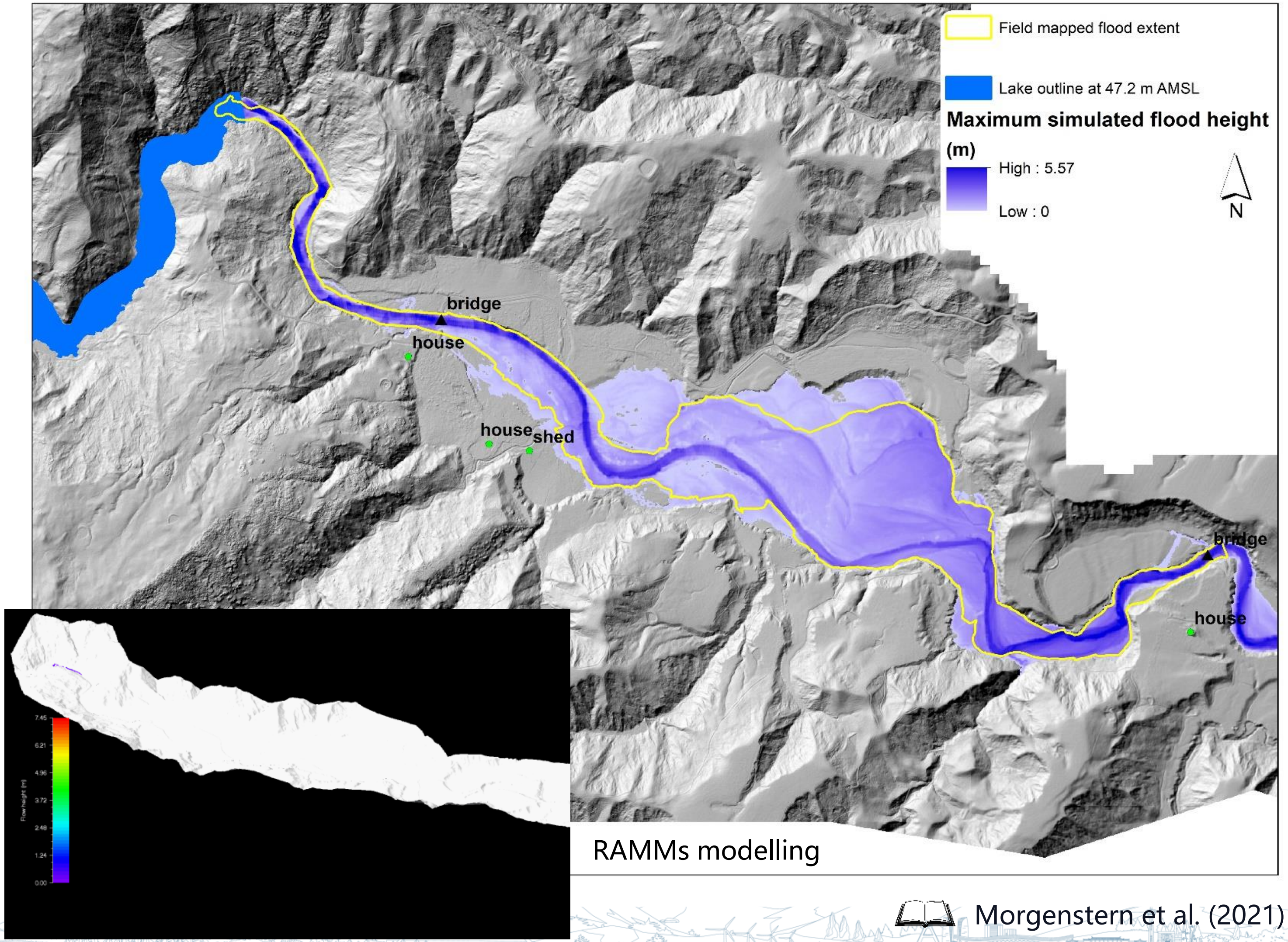

# Kaiwhata – scenario modelling

The breach and inundation models were trained using empirical data

- lake level and volume
- rainfall
- eyewitness accounts
- breach hydrograph
- flood extent

➢ **Back analysis of dam failure** – comparing modelled flood depths and extents with field-mapped depths and extents

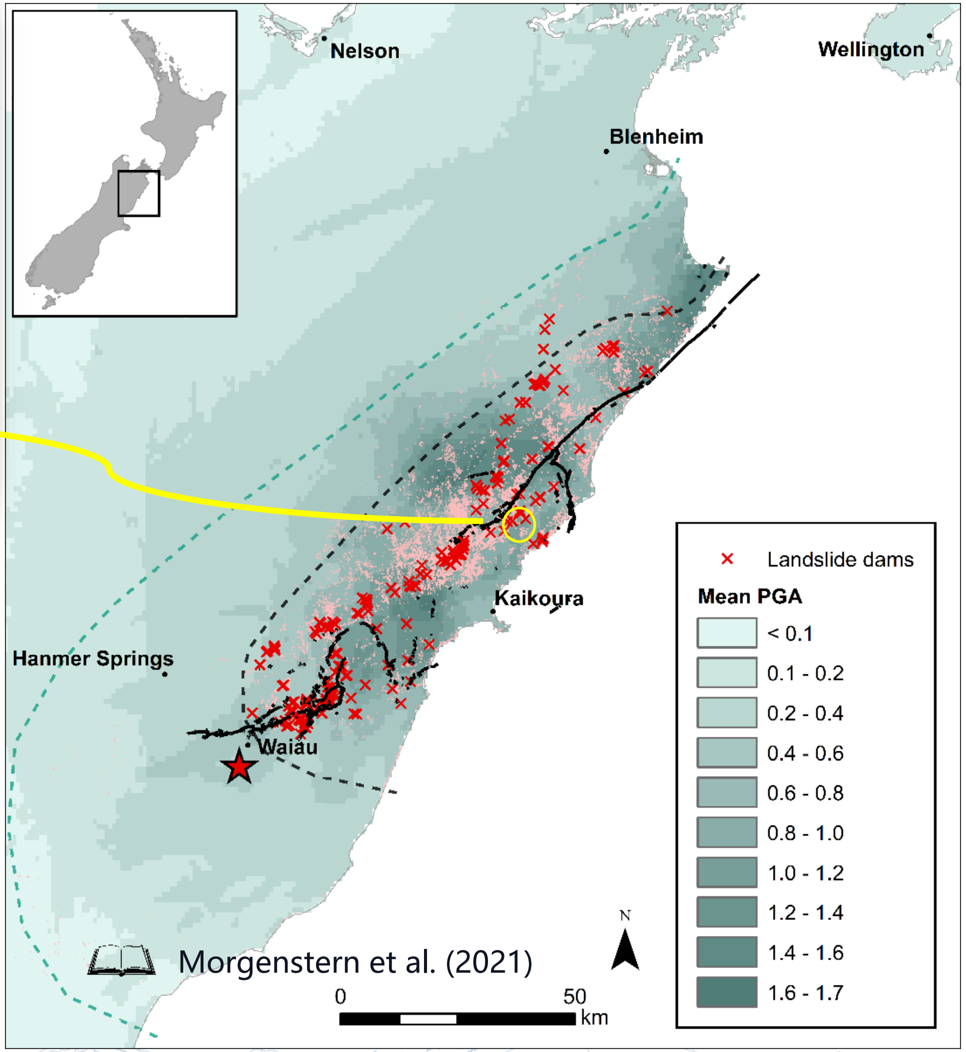
➢ Initial model: overestimated water depths and velocities – importance of **field data** to check input parameters and **verify model results**




Morgenstern et al. (2021)

# Case study 2: Hapuku landslide dam

## $M_w$ 7.8 Kaikōura Earthquake (14 Nov 2016)

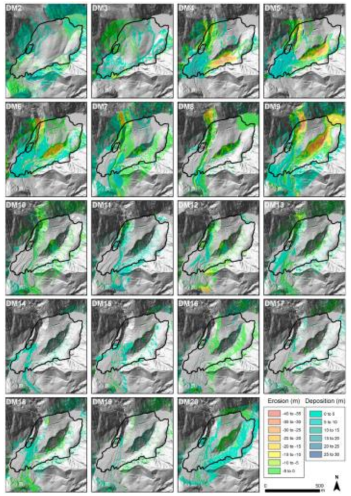




Morgenstern et al. (2021)

- Regional-scale response
- ~30 faults ruptures
- c. 30,000 landslides
- Initial assessment: ~200 landslide dams
- Now mapped: **470 landslide dams** (NZLDD)
- **Life safety risk** and **impact on infrastructure**: stability of these dams (7 in particular) was a major concern
- Hapuku:
  - 9 km upstream of main highway + rail corridor

# Hapuku – event timeline

From 27 data epochs…



Wolter et al. (2022)

### 14th Nov 2016 (T-0)

- 80 m high dam forms with ~1 M m³ lake
- Seepage, piping + headward erosion begins
- PSD: **D50** was **4-30 mm** (greywacke)

### 28th Mar–20th Apr 2017 (T ~4.5 months)

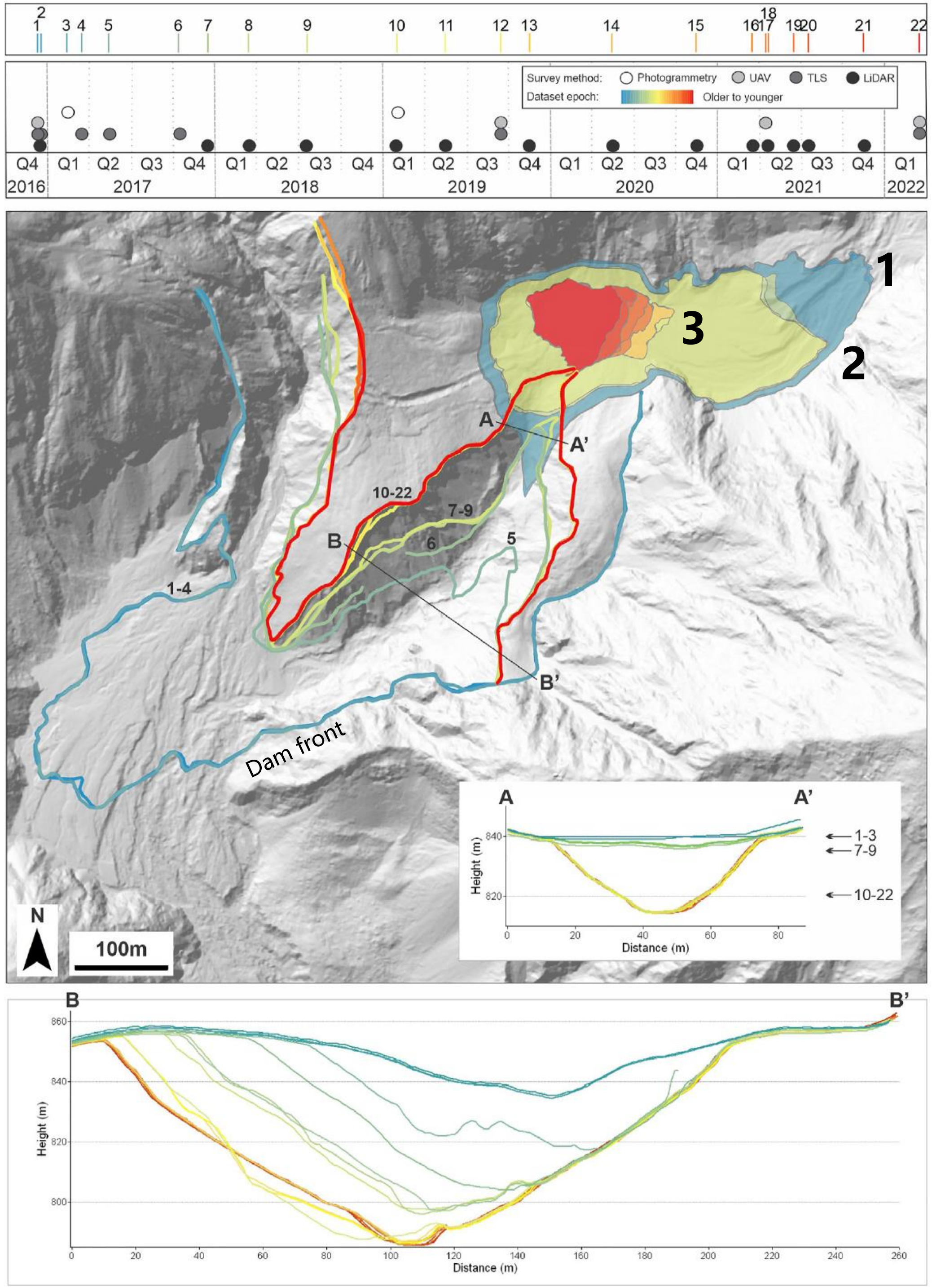
- 1st mod-intensity rainfall event (cyclones)
- Partial breach 1: overtopping + gradual erosion of **~0.4 M m³** , peak discharge of up to **12 m³/s**
- Debris flood **9 km** downstream **40 mins** later

### 12-19th Sep 2017 (T 10 months)

- Partial breach 2
- Not associated with a storm
- Peak discharge of **90 m³/s**

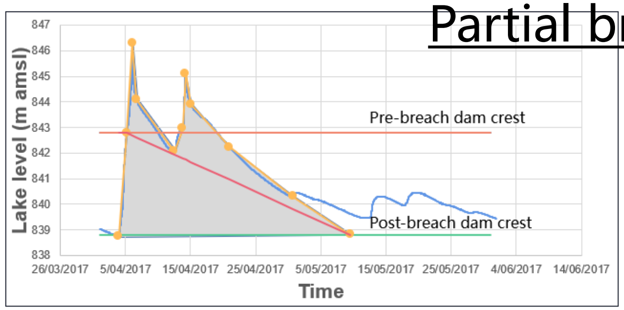
### 17th Nov–3rd Dec 2018 (T 2 years)

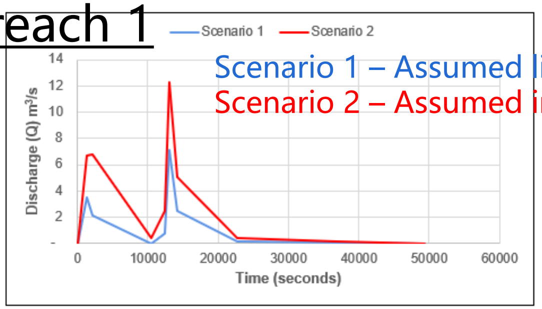
- Partial breach 3: **1.4 M m³** erosion
- Most significant erosion event
- Spring storm following 4 months of dry weather



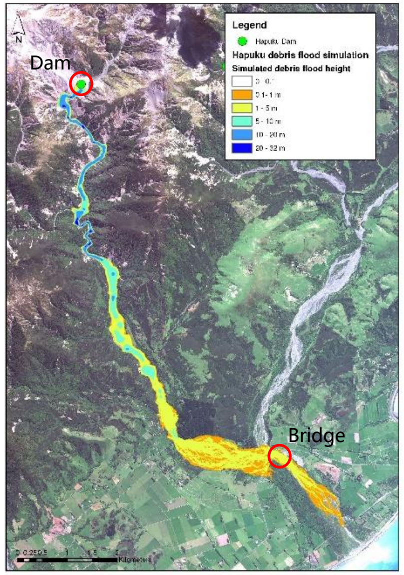
# Hapuku – event timeline

## Partial breach 1




Scenario 1 – Assumed linear channel erosion
Scenario 2 – Assumed instant channel erosion




Partial breach 1
RAMMs modelling

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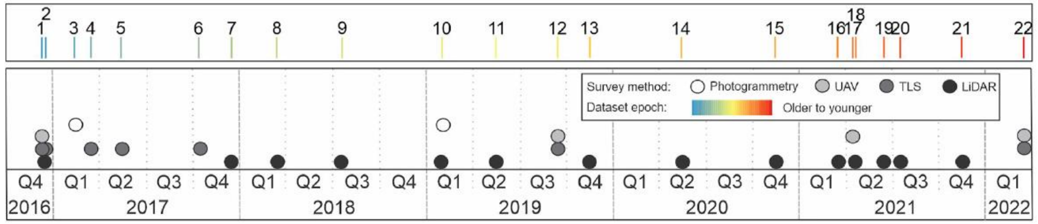
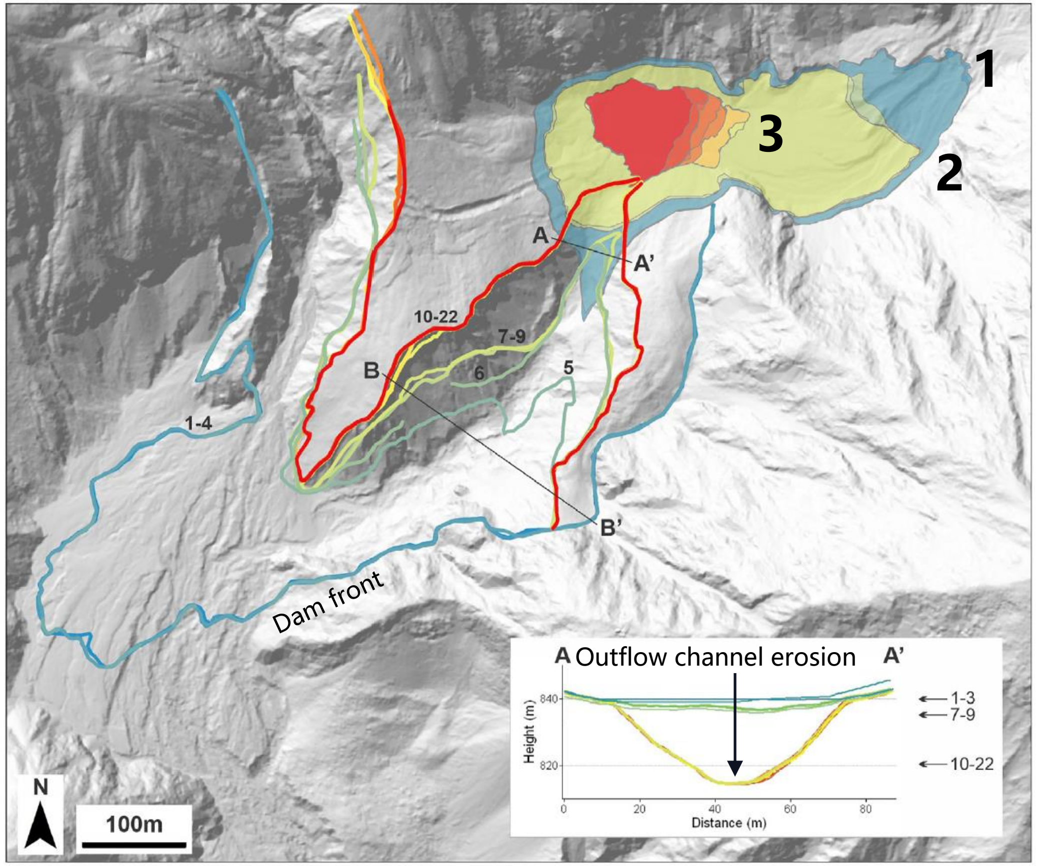
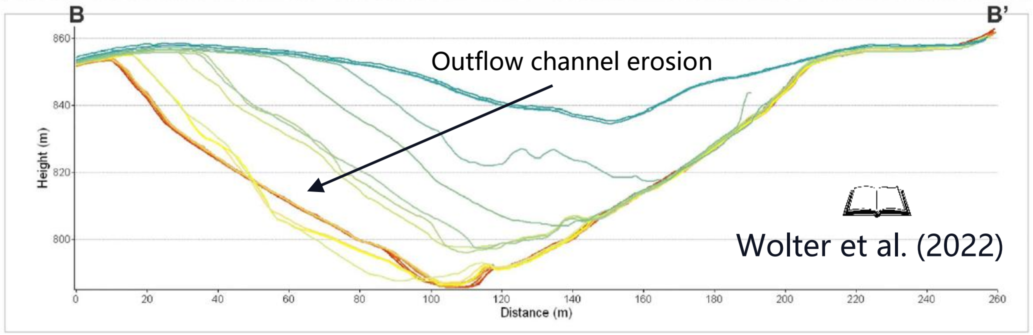


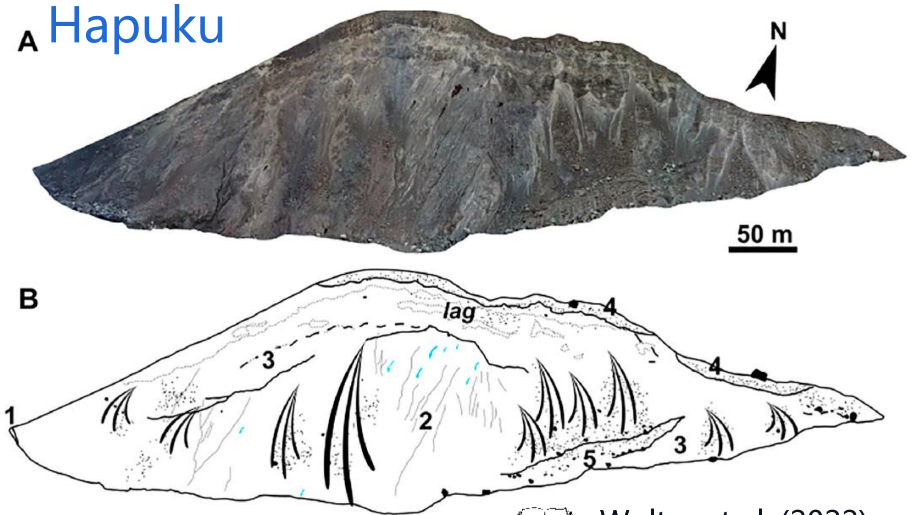




Wolter et al. (2022)

# Kaiwhata vs Hapuku landslide dams

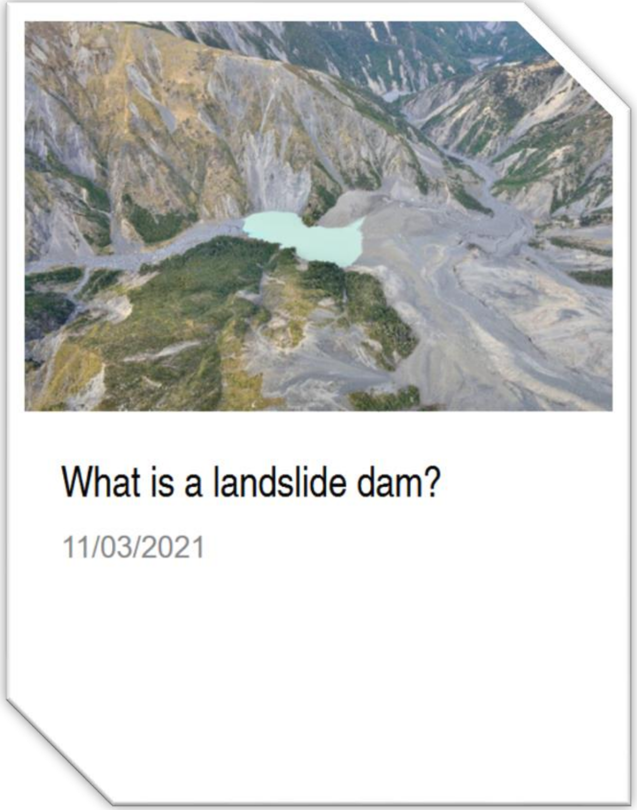
| | Kaiwhata | Hapuku |
|---|---|---|
| **Emplacement mechanism** | Debris avalanche, single event | Rock slide, multiple pulses, highly sheared, debris consolidated post-emplacement |
| **Source material type** | Soft mudstone | Hard greywacke |
| **Source material UCS** | 2 MPa | 100 MPa |
| **Source material age** | Neogene (23-2.6 Ma) | Early Cretaceous (145-100 Ma) |
| **Deposit D50** | 3 mm | 4-30 mm |
| **Lake volume (lowest point on dam crest)** | 1 M $m^3$ | 1.2 M $m^3$ |
| **Peak breach discharge** | 900 $m^3/s$ | 12 $m^3/s$ |
| **Breach type** | Complete, rapid within 1.5 hours, overtopping | Partial, gradual headward erosion over ~1 month, followed by multiple overtopping events |
| **Longevity** | 4 weeks | 4.5 months (partial); 7+ years |
| **Lake status** | Fully evacuated | Remnant lake |



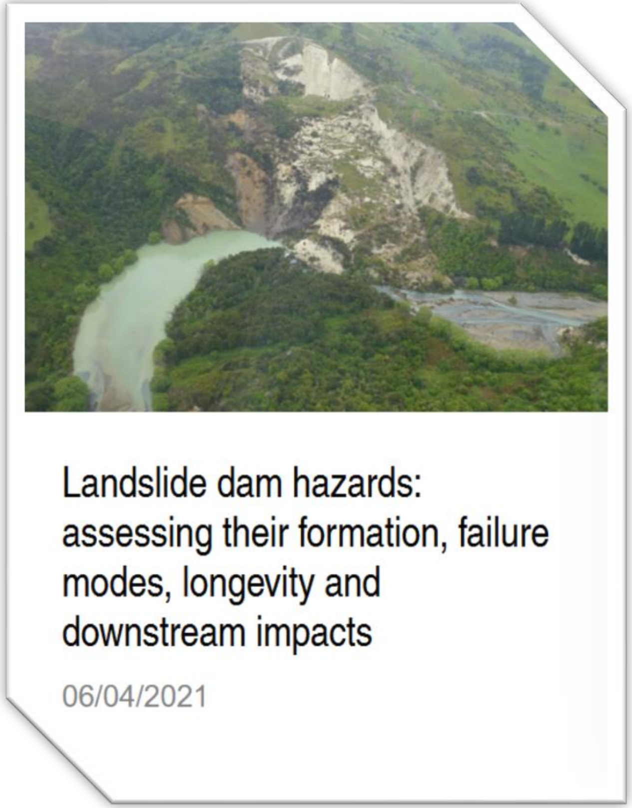

Wolter et al. (2022)

# NZ landslide dams – more information

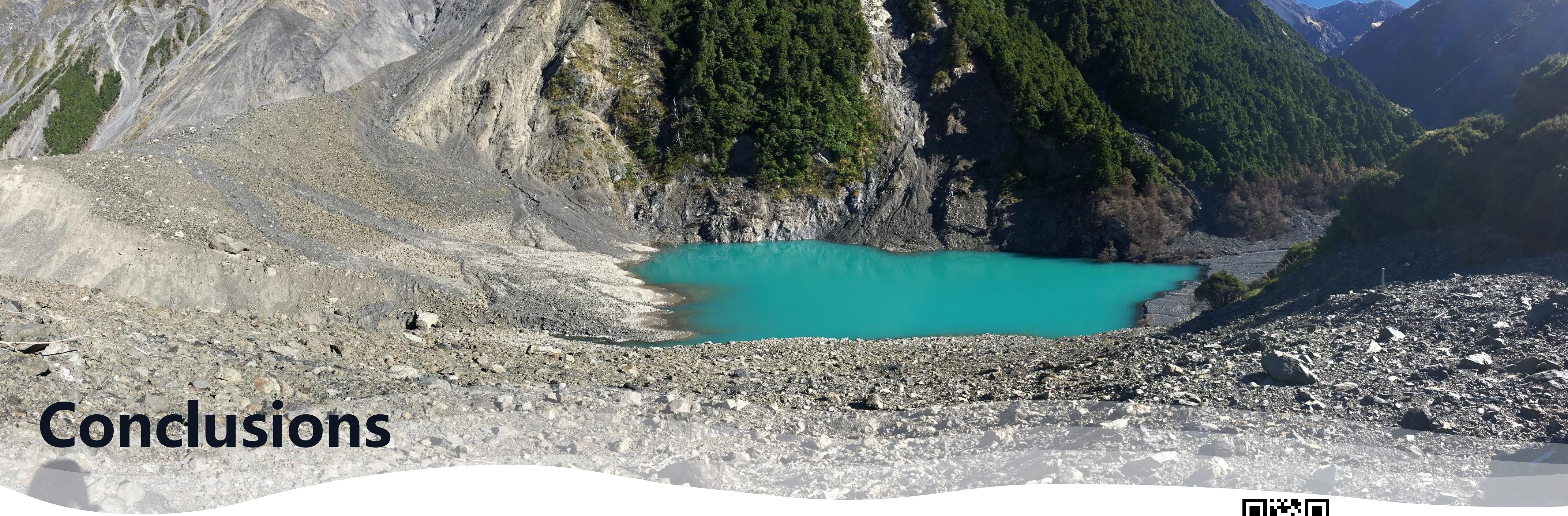
www.slidenz.net








Morgenstern et al. (in press) The New Zealand landslide dam database, v1.0. *Landslides*



# Conclusions

- New **NZLDD** – added to global datasets to assess landslide dam formation potential, stability and longevity
- **High resolution data** and other field data are required to assess landslide dam hazards and monitor and quantify dam evolution. They **show the complexity** of dam breach and evolution processes, which are often oversimplified
- The **three main factors** that contributed to dam stability and longevity are **source material** and **volume, emplacement mechanism** and **catchment characteristics**
- **Empirical data** are used to train, revise and calibrate breach and inundation scenario models to **more accurately inform life safety risk and manage potential impacts** on downstream infrastructure in the event of a rapid dam failure

# Thank you!

r.morgenstern@gns.cri.nz