Conicyt-Chile / NSF-China: Workshop on Water Resources

Water in Chilean Patagonia: Key Resource...and Geohazard

Recent and Ongoing Investigations

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Santiago, Chile, 27th June 2018

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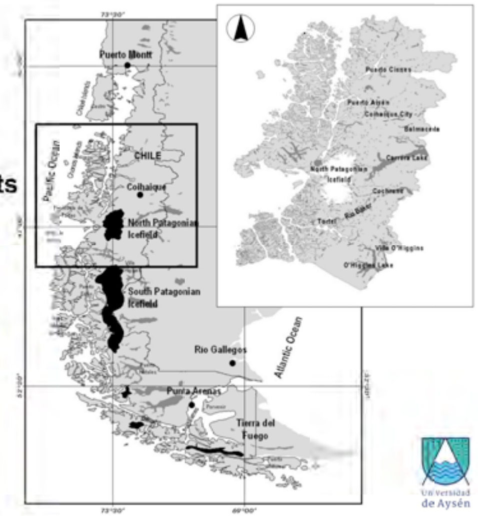
PATAGONIA: Wild, Remote, Extreme…UNIQUE

CHILEAN PATAGONIA

Patagonia:

- very pristine & wild landscape
- endemic biodiversity
- unique ecosystems
- huge physical gradients (yet scarce data)

Key freshwater reserve, Patagonian Icefields



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Baker basin

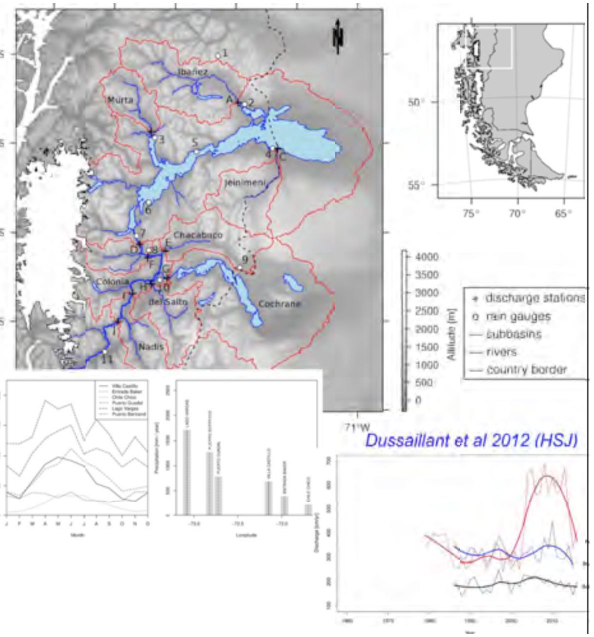
- Basin:

A=27000 km2

Q=1100 m3/s

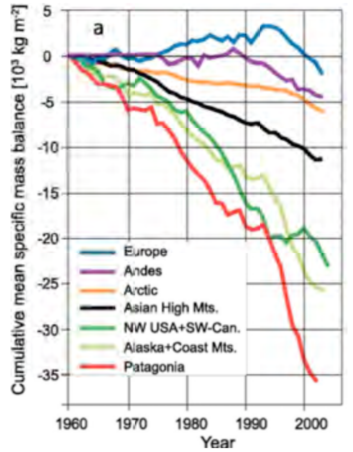
Lake 1900 km2

- Features
  - Steep gradients
  - Seasonality
  - Extreme events



Threats

- Warming
  - glacier shrinkage (Rivera et al 2007)
  - accelerated flow and sediment fluxes in rivers
  - Increased frequency of glacial-lake outburst floods
- Combined hazard factors
  - Tectonic/volcanic activity
  - Slope instability
  - Increased intense rainfall



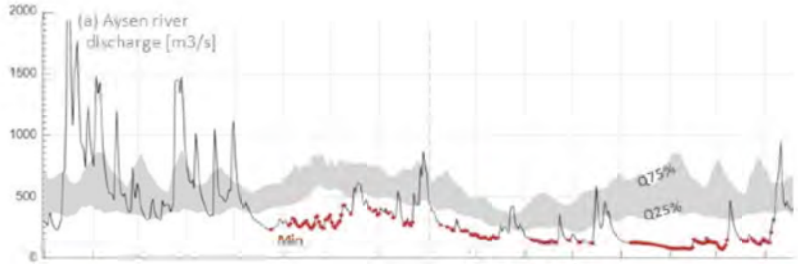
UNEP (2010)
from Dyurgerov & Meier (2005)

Glacier O'Higgins (South Patagonian Icefield SPI)…

(A. Rivera, CECS)

Extreme Events

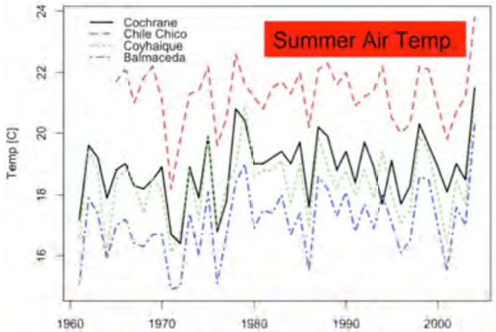
Droughts: reduced seasonal precipitation

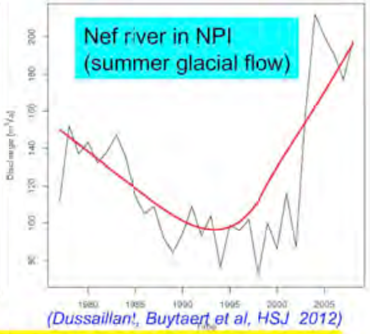


[Garreaud 2017/8]

Floods: intense precipitation events, larger depths; melt & glacial lake outbursts

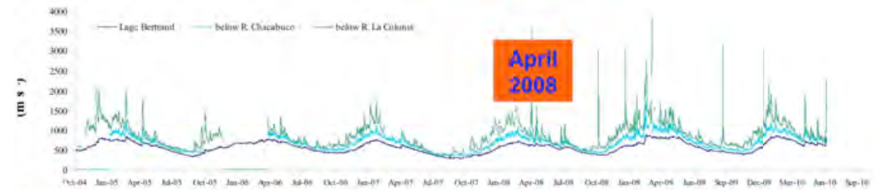
Tortel DGA station
(freq Pdaily in mm)





(Dussaillant, Buytaert et al, HSJ 2012)

HYDRO-CLIMATOLOGY TIPPING POINTS?



Baker regime before new outburst cycle **Baker under new cycle**

(B. Reid)

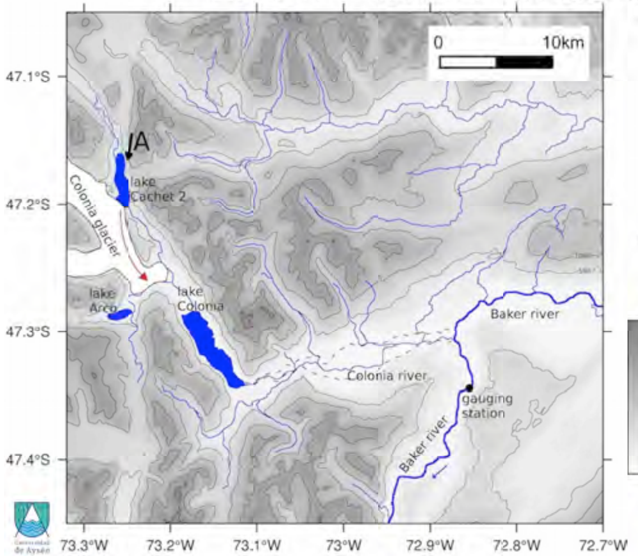
1. Outburst Floods: Baker Basin

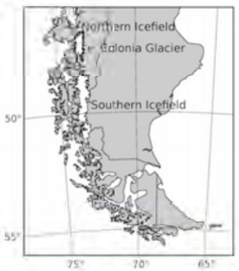
Baker river in summer (Photo: Juan E. Undurraga)

- Baker River Q ~ 1,100 m^3/s, largest in Chile by flow and quite pristine

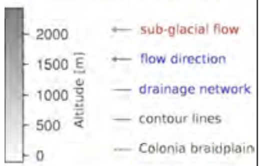
- Outlet of Carrera Lake: 1900 km^2, second largest in South America

Since 2008: >24 Lago Cachet 2 outbursts ~200 million m^3 in 30-60h





(Dussaillant et al. 2010)



Pre-1963: Arco Lake GLOFs (Tanaka 1980)

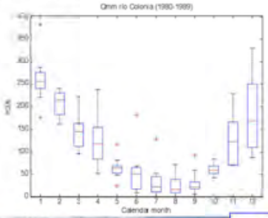
Glacial-Lake Outburst Floods

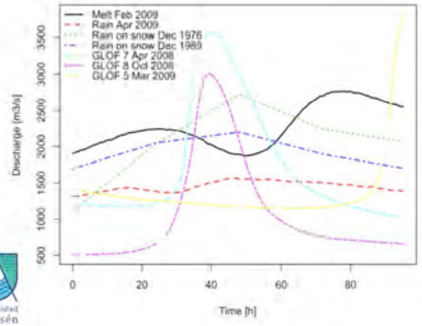
- GLOFs down Colonia River into Baker River (>24 events since April 2008)

***G** lacial*
***L** ake*
***O** utburst*
***F** lood*

Río de la Colonia

- Qmean annual ~110 m3/s
- Qpeak annual ~880 m3/s
- GLOFs: 1000-4000 m3/s, 3-5x Baker flow, backwater flooding





Cachet 2 Lake

- L ~ 5km, W ~ 1km, D~50m
- GLOFs: ~ 200 Hm^3

(J. Lleidich)

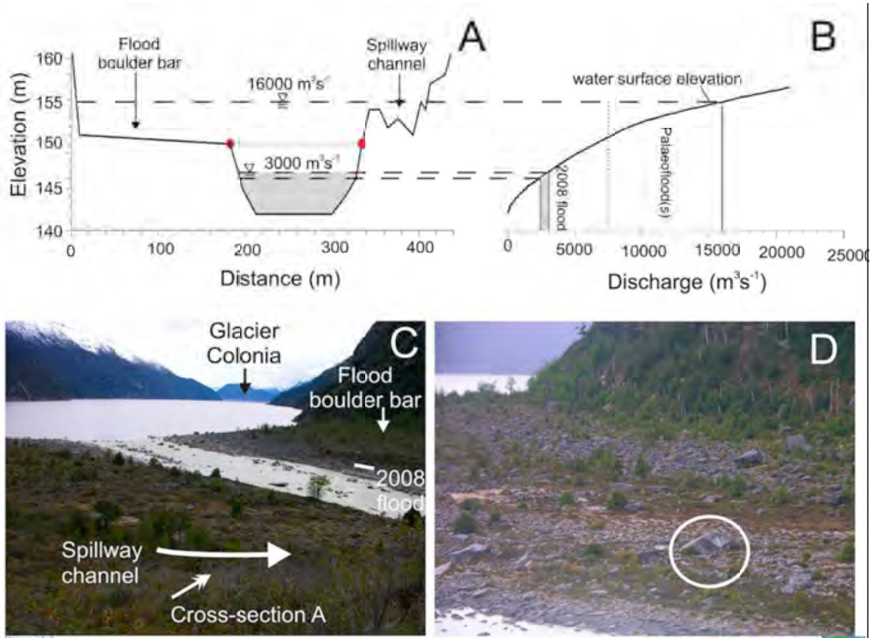
Receding GLOF into Río Baker

Lake Cachet2 emptying…

(A. Rivera, CECS)

Cachet 2 outbursts – impacts

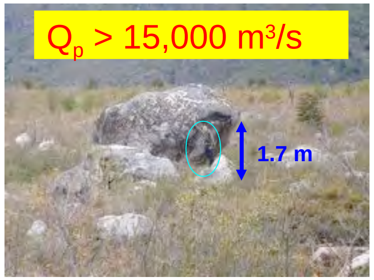
Geomorphological Indicators to identify water levels



(Dussaillant et al 2010)

Palaeofloods

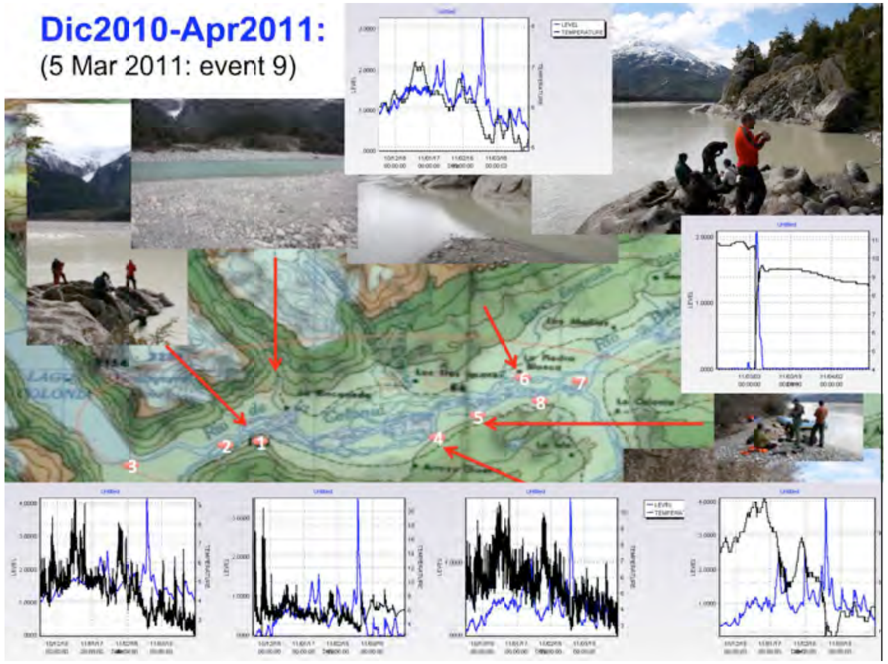
- Colonia Lake outlet
  - palaeo-channel:



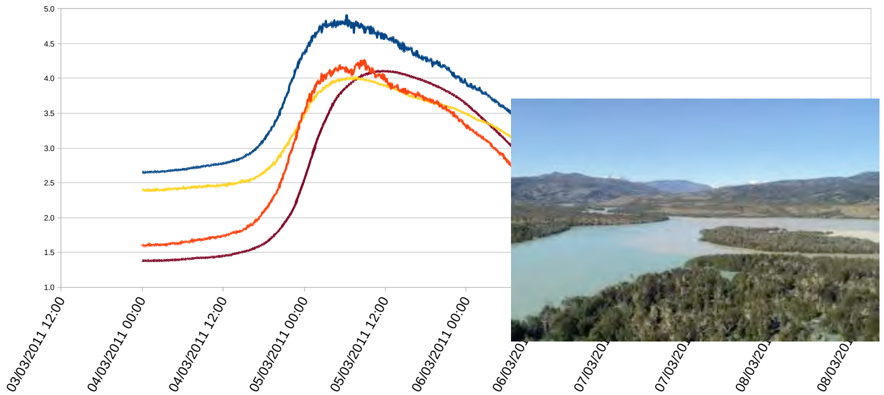
(Benito et al 2014)

- Bakerlonia samples
  - Q > 5000 m3/s (1800 to 1937)
  - Q > 7000 m3/s (1635 to 1677)

Dic2010-Apr2011:
(5 Mar 2011: event 9)



Water level sensors along Río Colonia: GLOF 5 Mar 2011



- 5 Mar 2011: wave 1.6-2.7 m, velocity 0.6-1.6 m/s
- Other outburst flood waves: >4m and >2m/s

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GLOFs: SUMMARY & POTENTIAL IMPLICATIONS

- After 40 years of hiatus (1968-2008), 24+ GLOFs have significantly changed flow & sediment regimes of Colonia & Baker
- This new GLOF cycle is ideal to study extreme floods & effects on floodplain vegetation, braiding & sediment transport
- Initial GLOFs (2008-2010) eroded confluence sediment, while subsequent events (post-2011) accreted sediment
- Implications for flooding risk and planned reservoirs
- Impacts on delta and fjord(s)?

***G** lacial*
***L** ake*
***O** utburst*
***F** lood*

Acknowledgments:
- G Benito, V Thorndycraft, P Carling, W Buytaert, A Russell, B Reid, C Meier
- Equipment: NERC GEF 942 & 965; CIEP
- Data: DGA & SAF - Chile
- Funding: U Greenwich & NRDC funds
- J Tureo, H Soto, settlers & many field assistants from U Concepción & Aysén

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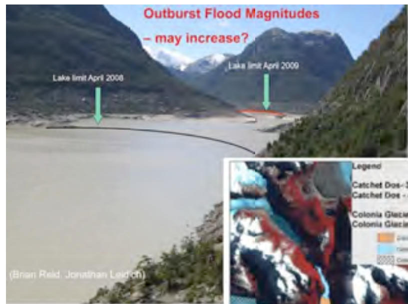
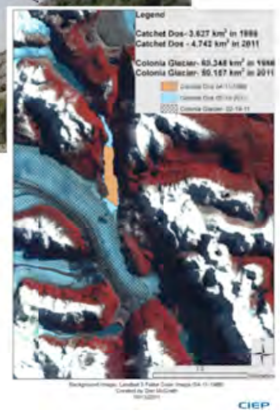
FUTURE: WHAT TO EXPECT?

- Some QUESTIONS:
  1. Outbursts: follow cycle of decaying peak flows? (Tweed & Russell 1999)
  2. Drainage speed: tunnel collapse into open breach? (Walder & Costa 1996)
  3. Drain volume: lake (system) larger? (linked lakes? others?)
  4. Link to volcanism?
  5. Other sites?





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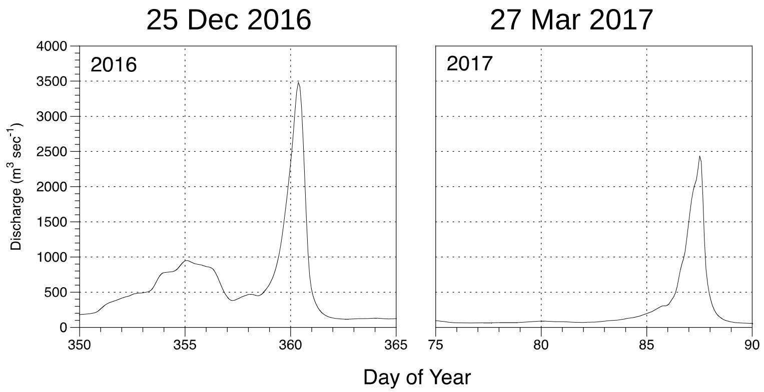
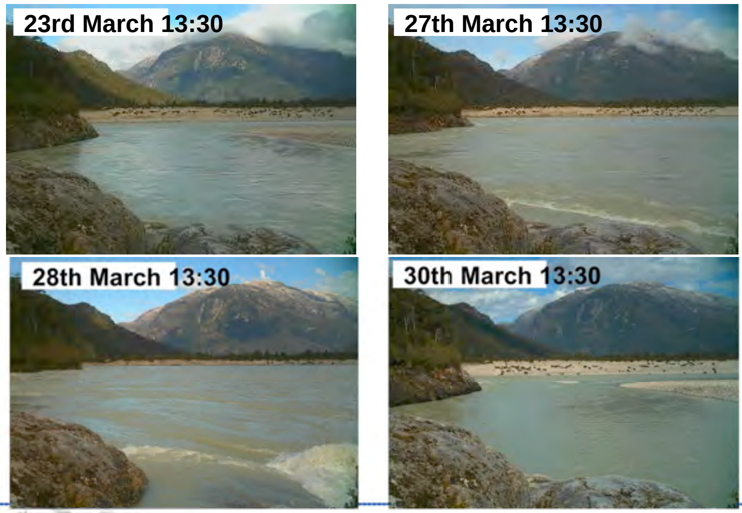
OTHER GLOFs: STEFFEN GLACIER (NPI)

RECENT GLOFs IN STEFFEN GLACIER



GLOF 27 MARCH 2017 STEFFEN GLACIER



March 27th 2017 GLOF
(2nd of season – smaller, with approx 7 m level increase)

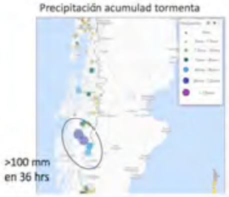
Lake drained
in ~48 hours

Lake area ~11 km^2
(volume ~250 Hm^3)

ESA Sentinel 1 satellite imagery

APRIL 2018 GLOF IN EXPLORADORES GLACIER

- P >100mm in 24h
- High isotherm
- Periglacial lake morraine collapsed
- Impacts:
  - Conaf facilities
  - Flooded road
  - Local economy
  - Social impacts

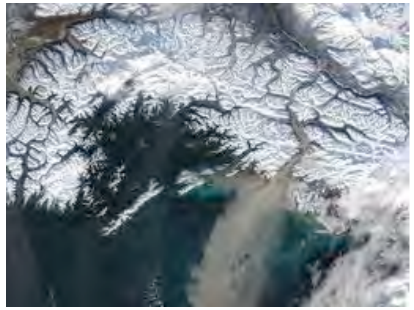


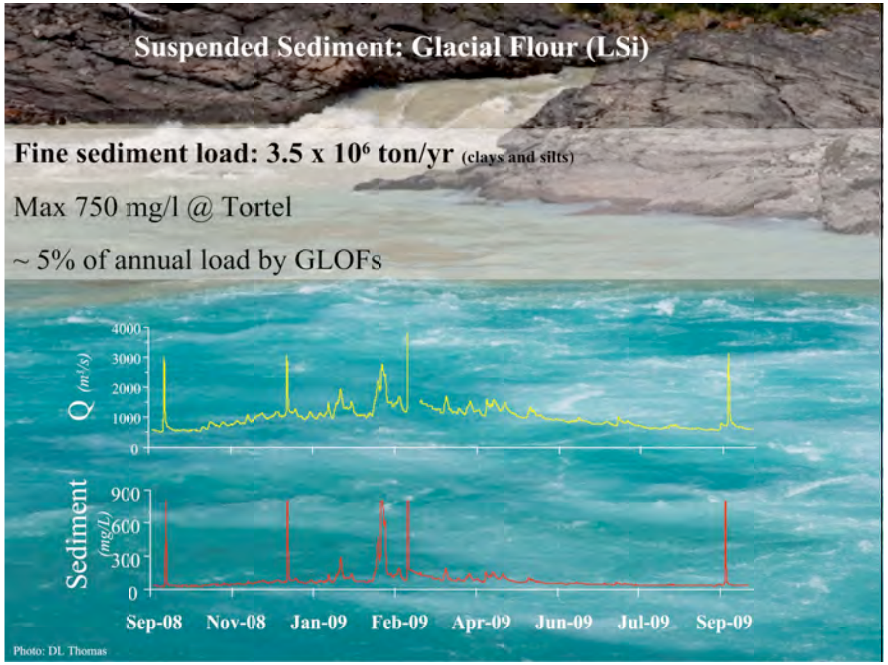
GLOFs are BAD…*or not?*

GLOFs transport water + nutrients/sediment to coastal zones

1996 Icelandic GLOF: 1% of world annual influx to oceans

Patagonia?





OPEN TOPICS TO EXPLORE:

- Sediment waves
- Sediment flux (sensors + surveys)
- Flooding scenarios from cumulative hydrologic & morphologic effects
- Ongoing work on Baker/Colonia: palaeoflood stage indicators + numerical modelling)
- Dendrogeomorphology?
- Other sites e.g. Steffen glacier

Acknowledgments:
- Equipment: NERC GEF 942 & 965; CIEP
- Data: DGA & SAF, Chile
- Funding: U Greenwich & NRDC funds
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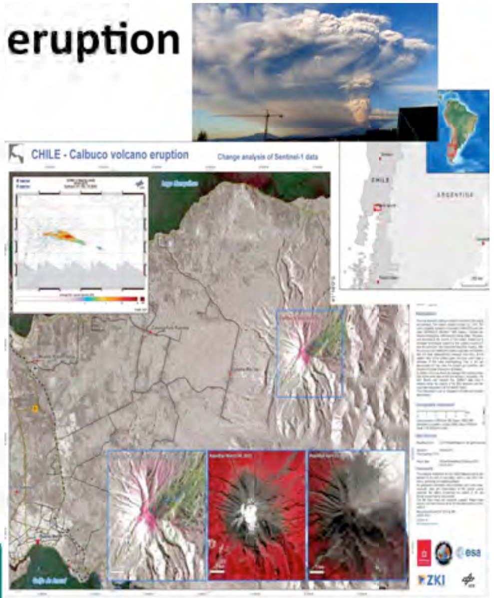
***G** lacial*
***L** ake*
***O** utburst*
***F** lood*

2. Lahars: Calbuco eruption

- Calbuco is a 2015m high, glacier-capped, stratovolcano
- History of large eruptions (1893–95, 1906–7, 1911–12, 1917, 1932, 1945, 1961 & 1972)
- 2015 events:
  - Powerful 90 min eruption at 18:04h on 22 April generated an ash plume >15 km high
  - Eruption 01:00h on 23 April
  - Eruption 13:10h on 30 April
- Pyroclastic flows descended into several river catchments radiating from the volcano

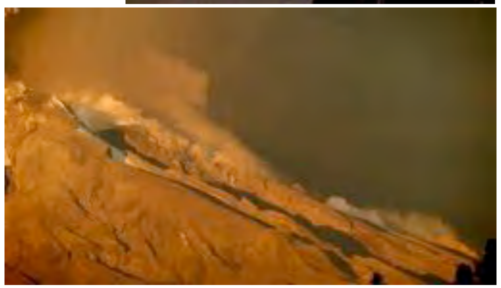


Acknowledgments:
- A Russell, A Rivera
- Data: DOH & Sernageomin - Chile
- Funding: NERC-UK Urgency funds

Lahar down Río Este (S side of Calbuco)

Calbuco volcano lahars

- Lahars travelled distances of up to 14 km, reaching populated areas
- Human consequences:
  - Evacuation of 6500 people
  - 20 km radius exclusion zone
  - Ashfall widespread disruption and damage to property
  - Lahar impacts mainly on S and W flanks
  - Secondary fluvial impacts on N flank of volcano

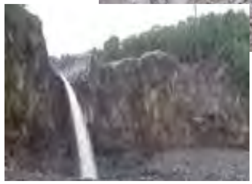


Aims and methods

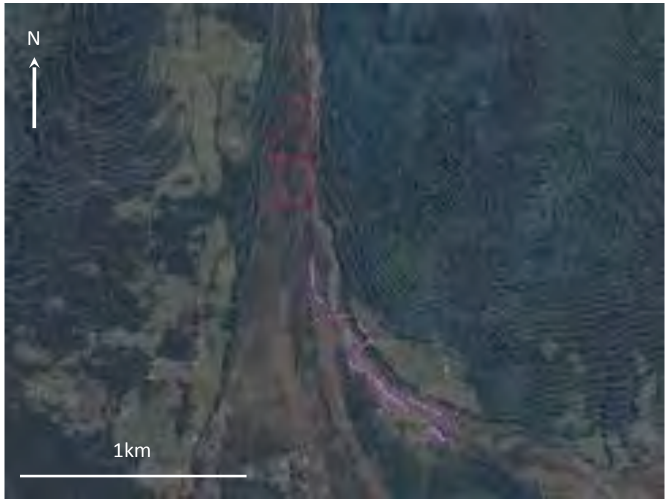
- **Aim:** to determine the causes, dynamics and impacts of lahars generated during the April 2015 volcanic eruption.
- **Methods:**
  - Topo survey of lahar deposits and run-ups (dGPS and TLS)
  - Analysis of sedimentary exposures
  - Grain-size analysis (sieving & sedigraph)
  - Helicopter LiDAR: CECs Airborne Mapping System (CAMS)

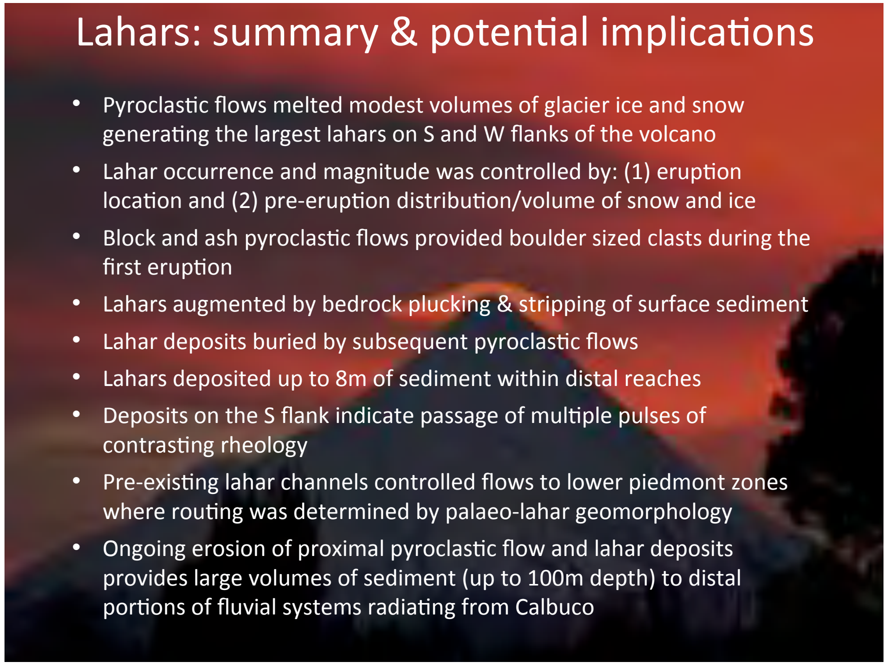
Lahar erosional impacts

- Erosional trimlines
- Streamlined morphologies
- Bedrock plucking
- Superelevation



Depositional impacts: Rio Este





Lahars: summary & potential implications

- Pyroclastic flows melted modest volumes of glacier ice and snow generating the largest lahars on S and W flanks of the volcano
- Lahar occurrence and magnitude was controlled by: (1) eruption location and (2) pre-eruption distribution/volume of snow and ice
- Block and ash pyroclastic flows provided boulder sized clasts during the first eruption
- Lahars augmented by bedrock plucking & stripping of surface sediment
- Lahar deposits buried by subsequent pyroclastic flows
- Lahars deposited up to 8m of sediment within distal reaches
- Deposits on the S flank indicate passage of multiple pulses of contrasting rheology
- Pre-existing lahar channels controlled flows to lower piedmont zones where routing was determined by palaeo-lahar geomorphology
- Ongoing erosion of proximal pyroclastic flow and lahar deposits provides large volumes of sediment (up to 100m depth) to distal portions of fluvial systems radiating from Calbuco

3. Catastrophic Mass Flows (CMFs): Villa Santa Lucía

December 2017 Villa Santa Lucía aluvión (Catastrophic Mass Flow, CMF)

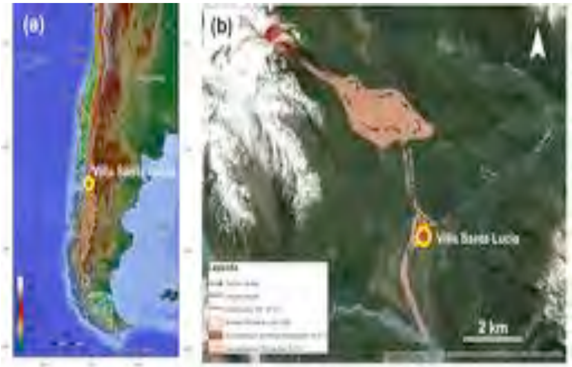


Figure 1 (a) Location of Villa Santa Lucia in Chile. (b) Annotated satellite image showing the landslide location (red) and aluvión / debris flow path (orange) with black arrows indicating the general flow direction. Original image produced by SERNAGEOMIN


EL LLANQUIHUE

LLANQUIHUE • CHILOÉ • PALENA

Aluvión en Villa Santa Lucía deja al menos 4 muertos, 8 lesionados y 18 desaparecidos

(Russell 2018)

Unfolding

CMF 70m deep, 70km/h:
https://www.youtube.com/watch?v=2IJNSAKXdH4
(min 1:22)

When reaching valley, debris fan:
https://www.youtube.com/watch?v=wy631NQjBrw

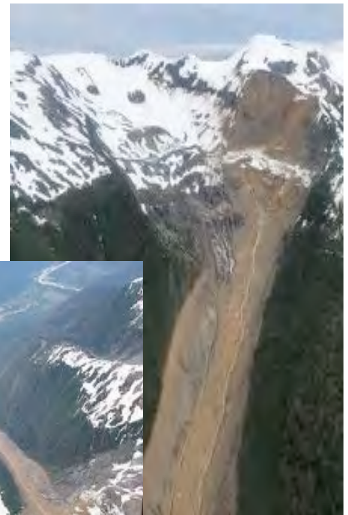
Further impact videos:
https://www.youtube.com/watch?v=TKj448ZTr_8
https://www.youtube.com/watch?v=TE6n91kp5L4

Impacts

- Partial destruction of Villa Santa Lucia
- 18 confirmed fatalities
- 28 houses destroyed
- 79 families evacuated
- Mass flow unit is up to 6m in depth & is still fluid, a factor which is hampering the ongoing recovery efforts.

Interpretation

- Rainfall event of 124 mm in 24h (very rare in this area)
- Elevated 0˚C isotherm (1600 m.a.s.l.)
- Slope failed in uppermost catchment of Burritos River
- Area had shown evidence of previous instability
- High snow accumulation (wettest winter in decade)
- i.e. intense rain on snow
- Failure of $6x10^6$ m^3 also carried water + moraine material of glacial lake (SE of Cordón Yelcho Glacier)
- Saturated soil and trees added to CMF



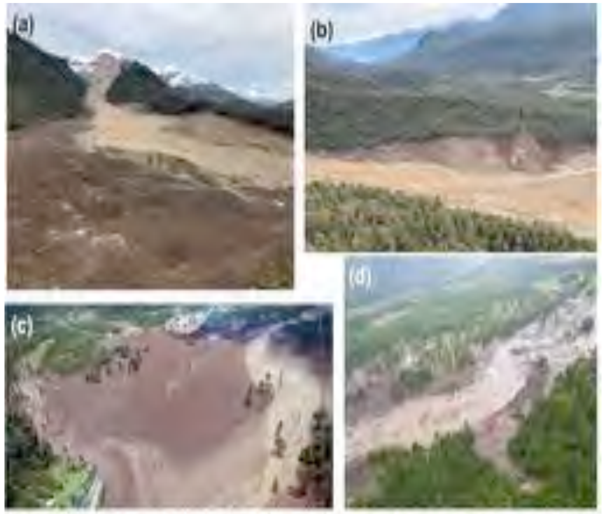


Figure 2 **(a)** Aerial view of the landslide and flow source on the right hand side of the Cordon Yelcho Glacier. Note large areas stripped of forest. **(b)** Distinctive trimlines left by the flow which 'ran-up' hillsides. **(c)** Aerial view of distal piedmont zone where flow has expanded across a pre-existing alluvial fan partially destroying Villa Santa Lucia. **(d)** Aerial view of the Rio Burritos showing major fluvial interaction with the mass flow material. *(Russell 2018)*

Clues about the flow dynamics

(Russell 2018)

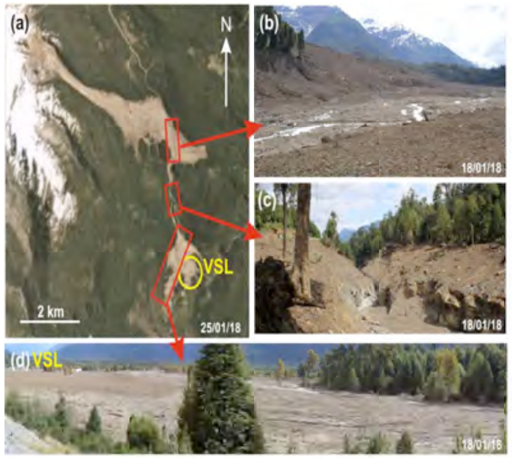


Figure 3 Overview of area impacted by the December 16th, 2017 aluvión. **(a)** Satellite image (25/01/18) shows the highly varied mass flow route down the Rio Burritos in relation to Villa Santa Lucia (VSL) and the location of three distinctive reaches (Fig. 3b-d). **(b)** Upstream of Rio Burritos showing wide river reach characterised by a wandering channel and copious Large Woody Debris (LWD). Note mass flow deposit in foreground and in distance with well-defined super-elevated trimline. **(c)** Downstream view of steep canyonised reach above VSL. Note evidence of flow super-elvation and tree removal. **(d)** View looking downstream of the piedmont zone of the Rio Burritos. Note relatively wide zone of fluvial reworking of mass flow deposit and the presence of copius amounts of LWD.

(Russell 2018)

Epilogue: low-cost monitoring in real time

#PatagoniaSensors @VSL (Jan 2018)

Equipment installed: non-contact hydrometric monitoring station, consisting of: (i) 2 x 100W solar panels; (ii) 1 x 200Ah 12v battery; (iii) Raspberry Pi Model 3 equipped with Arduino header and 3G/GRPS modem on mobile network; (iv) a 12v powered Hikvision IP camera with near-infrared sensing, connected to R-Pi via ethernet cable.

- **Data & projections:**

- Videos of 10s & battery voltage at 5-min intervals (sent to the Amazon S3 cloud)
- Laser scan survey at monitored reach to calculate morphological properties of the cameras field of view e.g. width, wetted area, water surface slope
- Coming soon: (i) river level; (ii) water surface velocities; (iii) estimation of river discharge

Acknowledgments:
• A Russell, M Perks. Data & field support: DOH, Sernageomin, Army - Chile. NERC-UK Innovation fund

Real-time low-cost monitoring for hydro-geomorphological risk reduction in Chile

- **Project aims:**

1. to introduce new state-of-the-art, rapidly-deployed, hydrological monitoring systems to a range of geomorphologically-active test catchments in Chile;
2. to use these data to provide better flood warnings thereby increasing preparedness; and
3. to present a 'low cost' tool kit which can be widely used in low income countries.

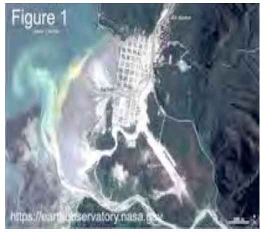
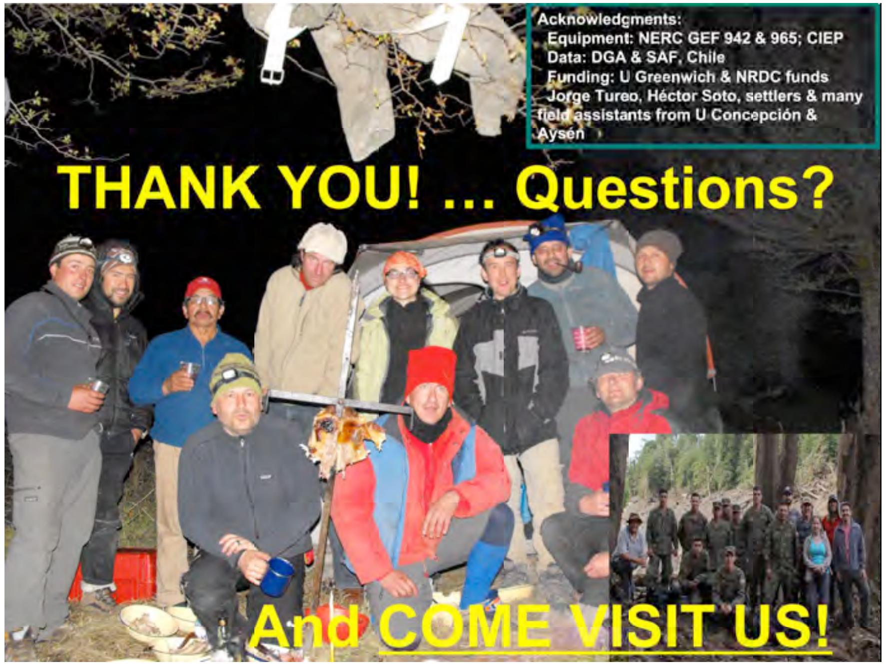


Figure 5: Four of the sites selected for installation of monitoring equipment. (a) Rio Blanco Este: Huenu Huenu Bridge, Calbuco. Photo taken with DOH colleagues in July 2015. (b) Rio Tepu Bridge, Calbuco with DOH directed sediment removal operations in progress. (c) Rio Blanco bridge in Chaiten town. (d) Rio Ryas to the northern flank of Chaiten volcano.

(Russell et al 2017)



Universidad de Aysén - Research Groups

1. Biodiversity & Environmental Change
   - Forestry & Restoration
   - Agroecology
   - Geosciences
2. Biomedicine & Public Health
3. Society & Education in Isolated Territories

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(Claudio Frías)