

# RCEM 2019: ANALYZING TOPOGRAPHIC TIMESERIES

## GEOMORPHIC CHANGE DETECTION

[gcd.riverscapes.xyz](http://gcd.riverscapes.xyz)

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**NORTH  
ARROW**  
RESEARCH



**Utah State University**  
ECOGEO MORPHOLOGY & TOPOGRAPHIC  
ANALYSIS LABORATORY



THE UNIVERSITY OF  
**WAIKATO**  
*Te Whare Wānanga o Waikato*

# WHO ARE THESE GUYS?

## Philip Bailey

Principal, North Arrow Research

- Geospatial software architect
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## James Brasington

Chair of River Science, University of Waikato

- Fluvial Geomorphology and Remote Sensing
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## Joe Wheaton

Assoc. Prof. Watershed Science, Utah State Uni.

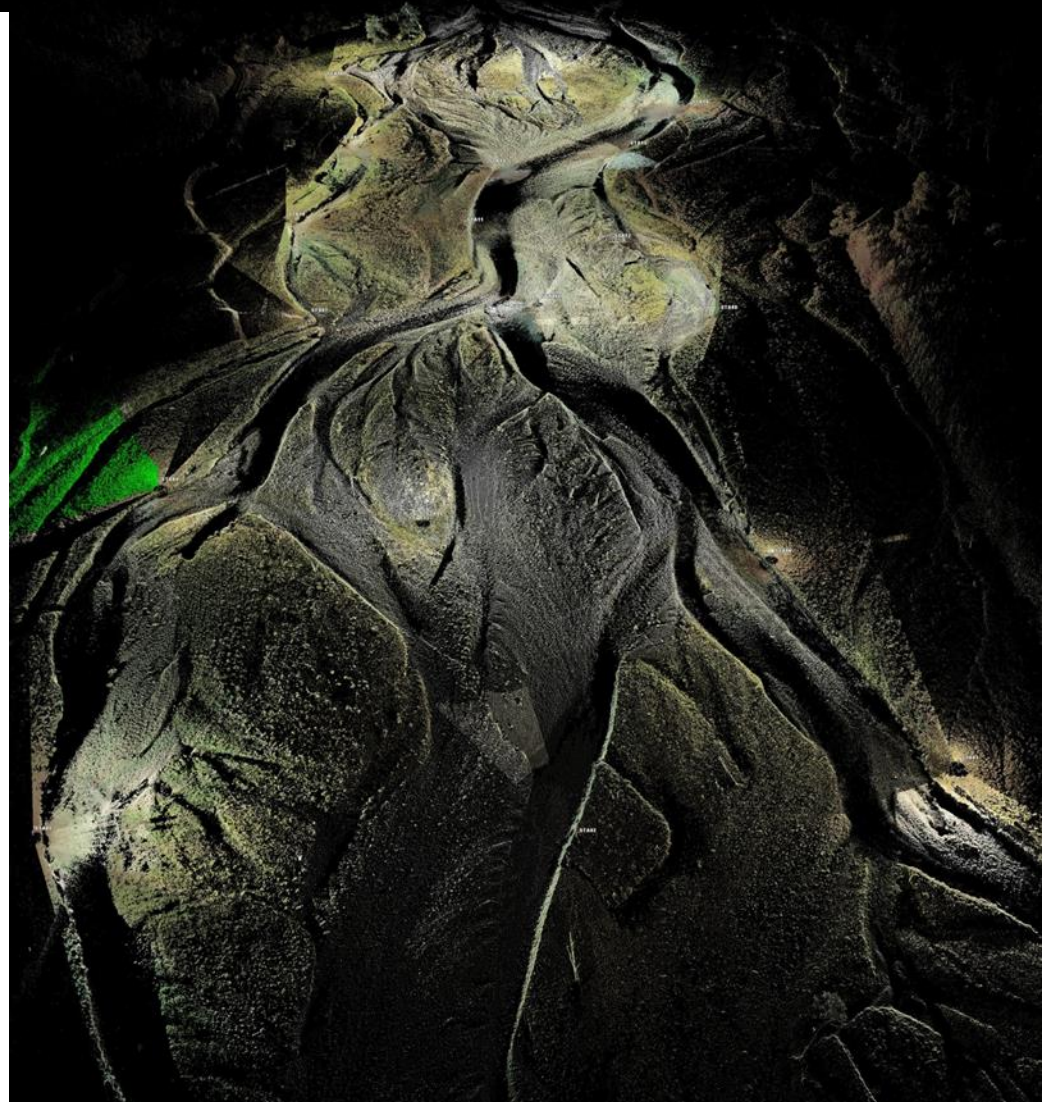
- Fluvial Geomorphology and River Restoration
- [Joe.wheaton@usu.edu](mailto:Joe.wheaton@usu.edu)



# WHAT ARE WE DOING HERE?

## *4D Geomorphology ...*

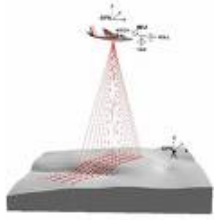
1. Data rich geomorphology
2. Topographic data and modelling
3. DEM differencing
4. *GCD Framework*
5. Quantifying river response



TLS POINT CLOUD – RIVER FESHIE, SCOTLAND



# HIGH RESOLUTION TOPOGRAPHY



Explosion of survey methods to acquire high-resolution topography

## Aerial & Satellite Remote Sensing

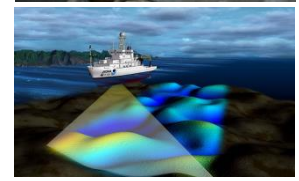
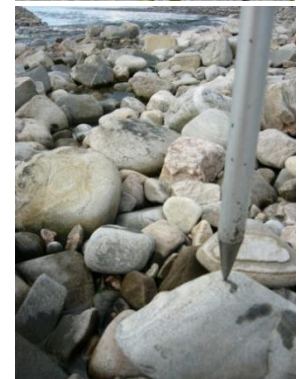
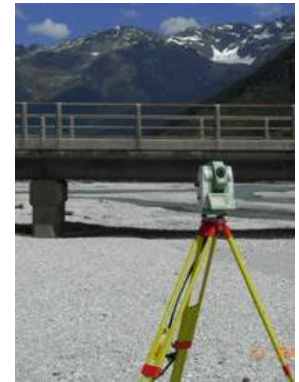
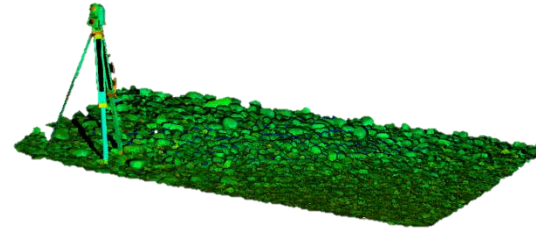
- Lidar
- Stereo Photogrammetry/SFM

## Ground-Based Surveys

- Total Station
- GNSS (GPS)
- Terrestrial Laser Scanning

## Bathymetry

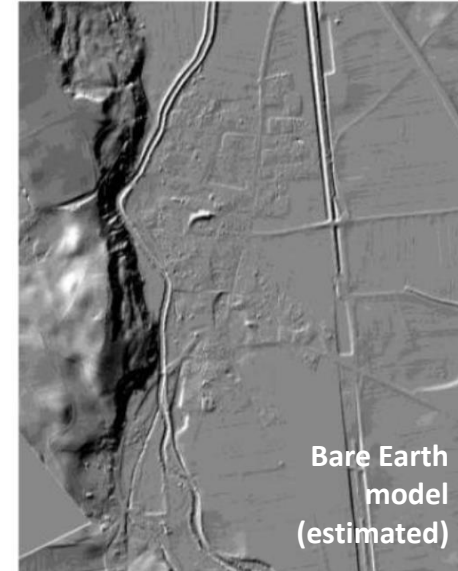
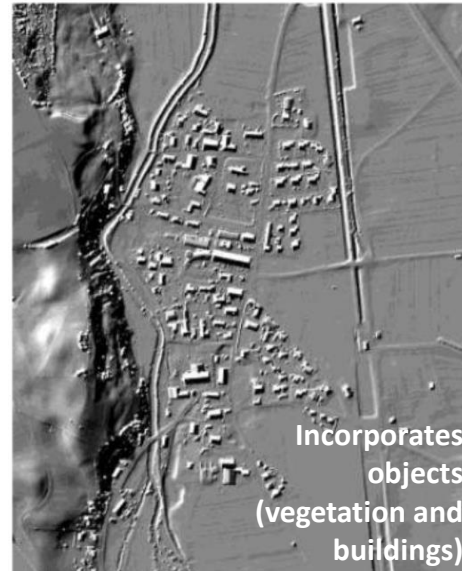
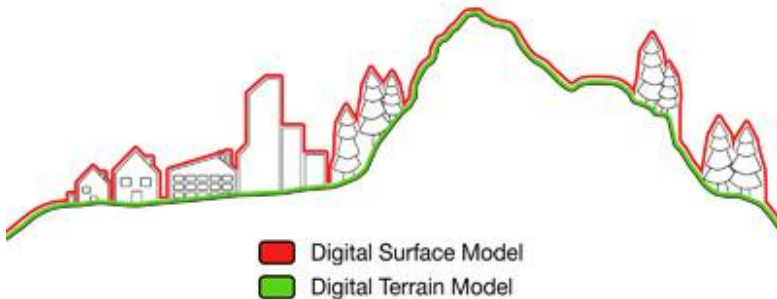
- Single/Multibeam Sonar
- Optical reflectance



# ELEVATION MODELS — DEMs, DTMs & DSMs



What are we representing in a DEM?



Terminology ... (still ambiguous)

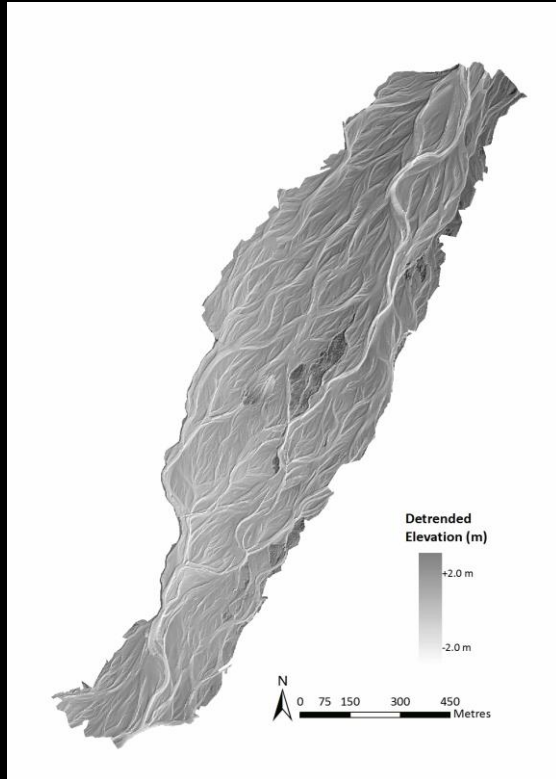
DEM = generic term?

DTM = Digital terrain model (bare earth)

DSM = Digital surface model

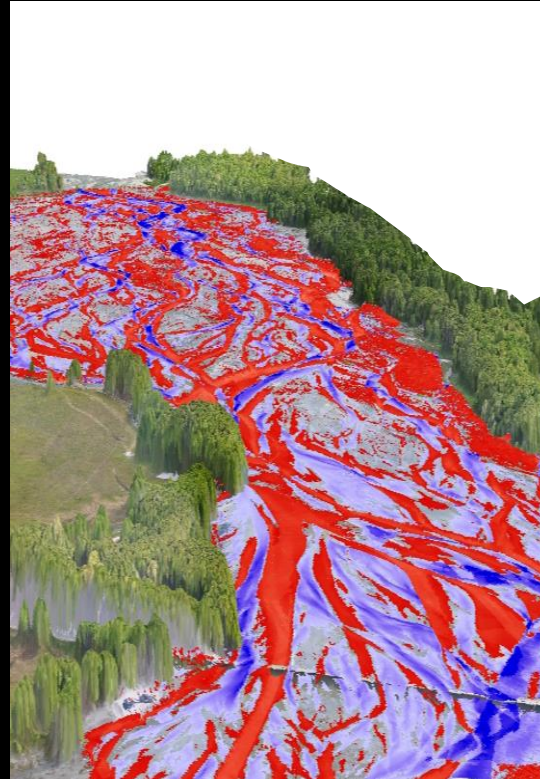
DHM = DSM-DTM

# APPLICATIONS OF TERRAIN DATA



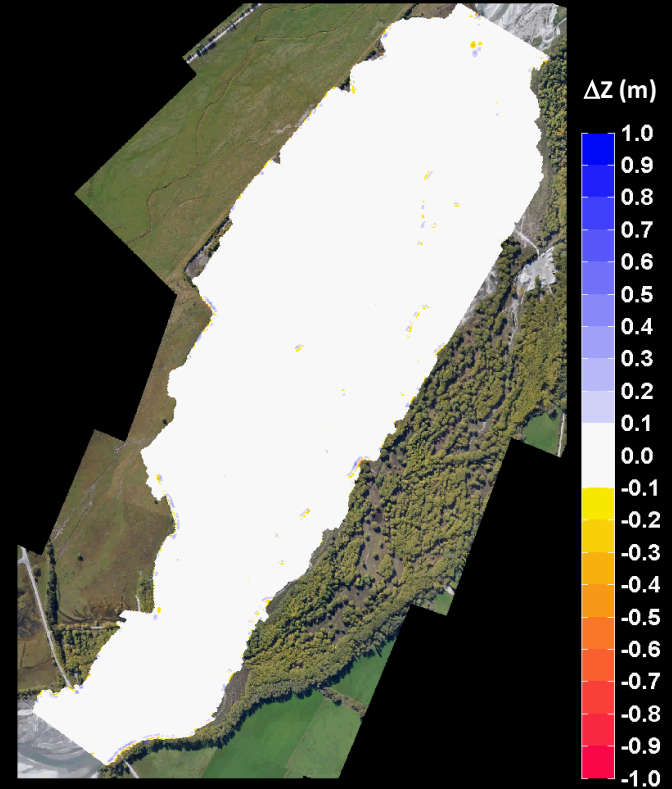
## MORPHOLOGY

(FORM AND STRUCTURE)



## CHANGE

(CHANGE AND BUDGETS)



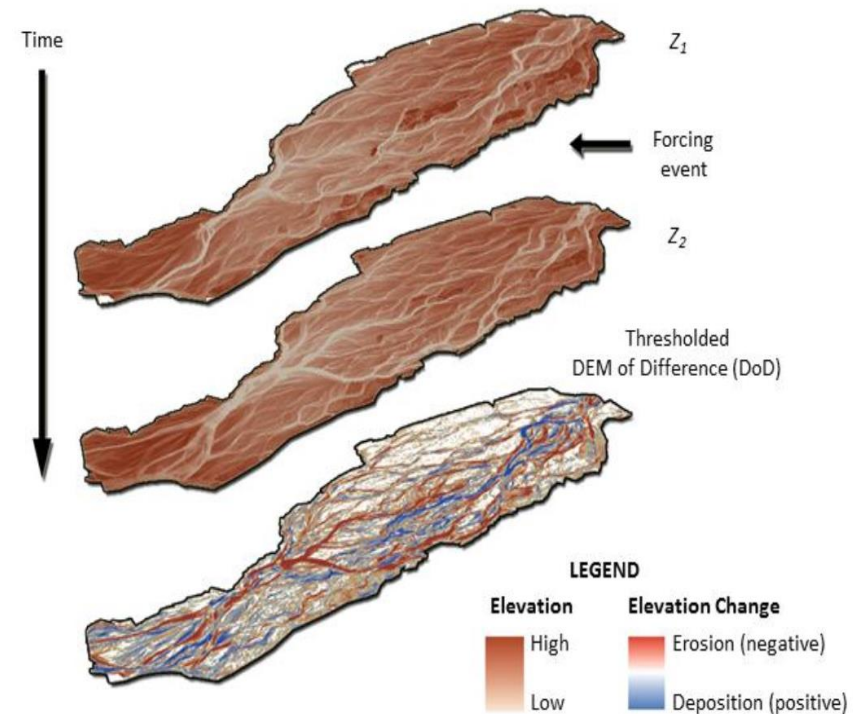
## MODELLING

(RATES AND FORCES)



# QUANTIFYING GEOMORPHIC CHANGE

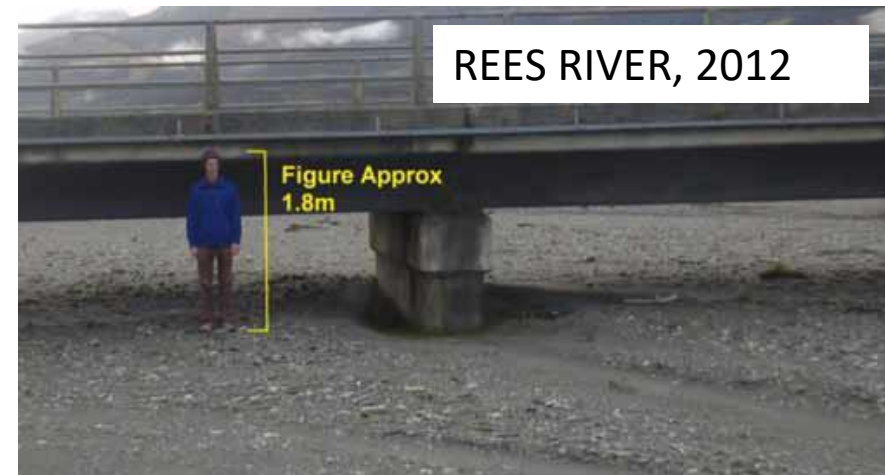
- Improvements in the acquisition and modelling of topography increasingly enable the development of timeseries of topographic models
- Insights into landscape change (kinematics) and the forcing processes and rates of adjustment (dynamics)
- **Reduces the bias associated with measurements based on low frequency, cross-section sampling**



Brasington et al., 2000 (ESPL); 2003 (Geomorp);  
Lane et al., 2003 (ESPL)  
Pasalacqua et al., 2015 (ESR)  
Wheaton et al., 2010 (ESPL); 2013 (JGR-ES)

# POTENTIAL APPLICATIONS

- Understand pattern, magnitude & processes of landscape change
- Support quantification of hazards e.g., flood capacity, soil erosion, fault displacement; and predict impacts (asset risk, navigation)
- Resource management (e.g., sustainable gravel extraction, consent monitoring)
- Assess effectiveness of interventions/restoration activities
- Implications for co-varying phenomena (e.g. ecology)



CHANGING BED LEVEL, REES RIVER, NZ



# NOT JUST RIVERS ...

Geomorphological field	Application	Geomatics technology	Monitoring duration	Survey frequency	Approximate spatial extent	Reference
Coasts	Estuary change	Bathymetric charts (lead lines and echo sounding)	150 years	Half-century	217 km <sup>2</sup>	van der Wal <i>et al.</i> (2002)
	Estuary change induced by earthquakes	Airborne LiDAR	5 months	Start and end of monitoring	5 km <sup>2</sup>	Measures <i>et al.</i> (2011)
	Beach changes after a hurricane	Airborne LiDAR	Event	Pre- and post-event	40 km long coastline	Zhang <i>et al.</i> (2005)
	Cliff and gully erosion	Airborne LiDAR	6 years	Start and end of monitoring	77 km long coastline	Young and Ashford (2006)
	Cliff erosion	TLS	16 months	Monthly	0.1 km <sup>2</sup>	Rosser <i>et al.</i> (2005)
	Cliff erosion	TLS	1 year	Start and end of monitoring	0.005 km <sup>2</sup>	Hobbs <i>et al.</i> (2010)
	Cliff erosion	Oblique terrestrial imagery, SIM and MultiView Stereo	1 year	7 surveys during 1 year	0.05 km long coastline	James <i>et al.</i> (2012)
Fluvial reworking of sediment stores	Talus cone erosion	TLS	3 months	Start and end of monitoring	0.009 km <sup>2</sup>	Morche <i>et al.</i> (2008)
	Cut / fill of gully and alluvial fan	Kinematic GPS	32 months	3 - 5 months	0.5 km <sup>2</sup>	Fuller and Marden (2010)
Glaciology	Glacier surface elevation change	Aerial photogrammetry	1 year	Start and end of monitoring	6.3 km <sup>2</sup>	Hubbard <i>et al.</i> (2000)
	Glacier surface elevation change	Aerial photogrammetry and cartographic data	18 years	Start and end of monitoring	5.5 km <sup>2</sup>	Rippin <i>et al.</i> (2003)
	Rockglacier movement	TLS	8 years	1 month - 3 years	0.04 km <sup>2</sup>	Avian <i>et al.</i> (2009)
	Glacier surface elevation change	Aerial photogrammetry and airborne LiDAR	2 years	Start and end of monitoring	6 km <sup>2</sup>	Barrand <i>et al.</i> (2009)
	Debris covered glacier margins	Airborne LiDAR	4 years	Start and end of monitoring	0.5 km <sup>2</sup>	Abemmann <i>et al.</i> (2010)
	Permafrost affected bedrock and glacier ice	Aerial photogrammetry and airborne LiDAR	51 years	2 - 22 years	6.5 km <sup>2</sup>	Fischer <i>et al.</i> (2011)
	Forefield sediment redistribution	Airborne LiDAR	2 years	Start and end of monitoring	2 km <sup>2</sup>	Irvine-Fynn <i>et al.</i> (2011)
	Proglacial and braidplain change	Airborne LiDAR and TLS	2 years	1 day - 1 year	1.5 km <sup>2</sup>	Carnivick <i>et al.</i> (2012)
	Glacier surface elevation change	TLS	5 days	Daily	0.05 km <sup>2</sup>	Nield <i>et al.</i> (2012)
	Glacier surface elevation change	TLS	5 days	Daily	0.05 km <sup>2</sup>	Nield <i>et al.</i> (2012)
Mass movements	Mudflow	Cartographic data	45 years	1 - 16 years	1.2 km <sup>2</sup>	van Westen and Lulle Getahun (2003)
	Landslide	Kinematic GPS	18 months	7 - 11 months	0.04 km <sup>2</sup>	Mora <i>et al.</i> (2003)
	Earthquake triggered landslide and river erosion of deposit	Aerial photogrammetry and airborne LiDAR	14 years	1 - 11 years	6 km <sup>2</sup>	Chen <i>et al.</i> (2006)
	Rockfall and slope failure (coast)	TLS	32 months	Monthly	0.1 km <sup>2</sup>	Rosser <i>et al.</i> (2007)
	Rockfall and slope failure (deglaciated terrain)	TLS	1 year	1 day - 6 months	0.06 km <sup>2</sup>	Oppikofer <i>et al.</i> (2008)
	Landslide (deep seated, Tertiary sediments)	Aerial photogrammetry and airborne LiDAR	50 years	6 - 21 years	0.8 km <sup>2</sup>	Dewitte <i>et al.</i> (2008)
	Rockslide (ford)	TLS	2 years	Annual	0.6 km <sup>2</sup>	Oppikofer <i>et al.</i> (2009)
	Landslide (slope undercut by river)	TLS	18 months	2 - 6 months	0.01 km <sup>2</sup>	Prokop and Panholzer (2009)
	Rockfall from landslide scar	TLS	10 months	2 - 8 months	0.004 km <sup>2</sup>	Abellán <i>et al.</i> (2010)
	Debris flow and flood	Airborne LiDAR	Event	Pre- and post-event	0.4 km <sup>2</sup>	Bull <i>et al.</i> (2010)
	Earthflow (soil and weathered bedrock)	Airborne LiDAR	4 years	Start and end of monitoring	0.06 km <sup>2</sup>	DeLong <i>et al.</i> (2012)
	Deformation due to surface rupture	Airborne LiDAR	Event	Pre- and post-event	50 km long multi-fault	
	Landslide	Aerial photogrammetry	18 years	3 - 10 years	7 km <sup>2</sup>	Fabris and Pesci (2005)
	Slope evolution during an eruption	Aerial photogrammetry	4 years	8 days - 14 months	1 km <sup>2</sup>	Baldi <i>et al.</i> (2008)
	Summit morphological change due to eruptive processes and deformation	Airborne LiDAR and aerial photogrammetry	21 years	2 - 12 years	7 km <sup>2</sup>	Neri <i>et al.</i> (2008)
Volcanology	Lava dome growth	Oblique terrestrial imagery	17 months	24-48 hours	1 km <sup>2</sup>	Major <i>et al.</i> (2009)
	Lava flow dynamics	Airborne LiDAR	2 days	15 minute intervals	28 km <sup>2</sup>	Favalli <i>et al.</i> (2010)
	Growth and deformation of a scoria cones	Airborne LiDAR	4 years	Annual	2 km <sup>2</sup>	Fornaciai <i>et al.</i> (2010)
	Lahar	Airborne LiDAR	Event	Pre- and post-event	62 km long river	Procter <i>et al.</i> (2010)
	Crater wall collapse	TLS	4 years	17 - 32 months	9 km <sup>2</sup>	Pesci <i>et al.</i> (2011)

Williams, 2012 review in the newly revised and online version of ‘Geomorphological Techniques’ manual by the British Society for Geomorphology

[British Society for Geomorphology Techniques Paper](#)

# A SIMPLE SUBTRACTION PROBLEM?

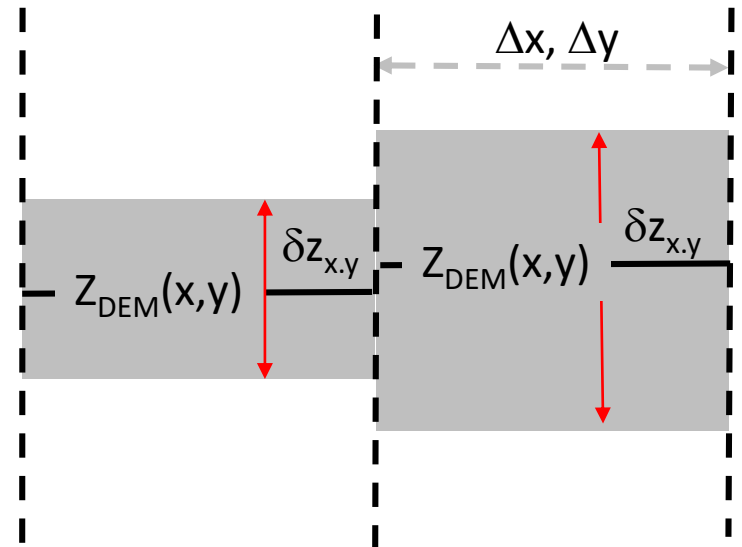
A DEM is a model of topography that will always be in error

$$\sim Z_{\text{DEM}}(x,y) \sim Z_{\mu}(x,y)$$

So, it is useful to consider that a DEM is associated with a given model of error

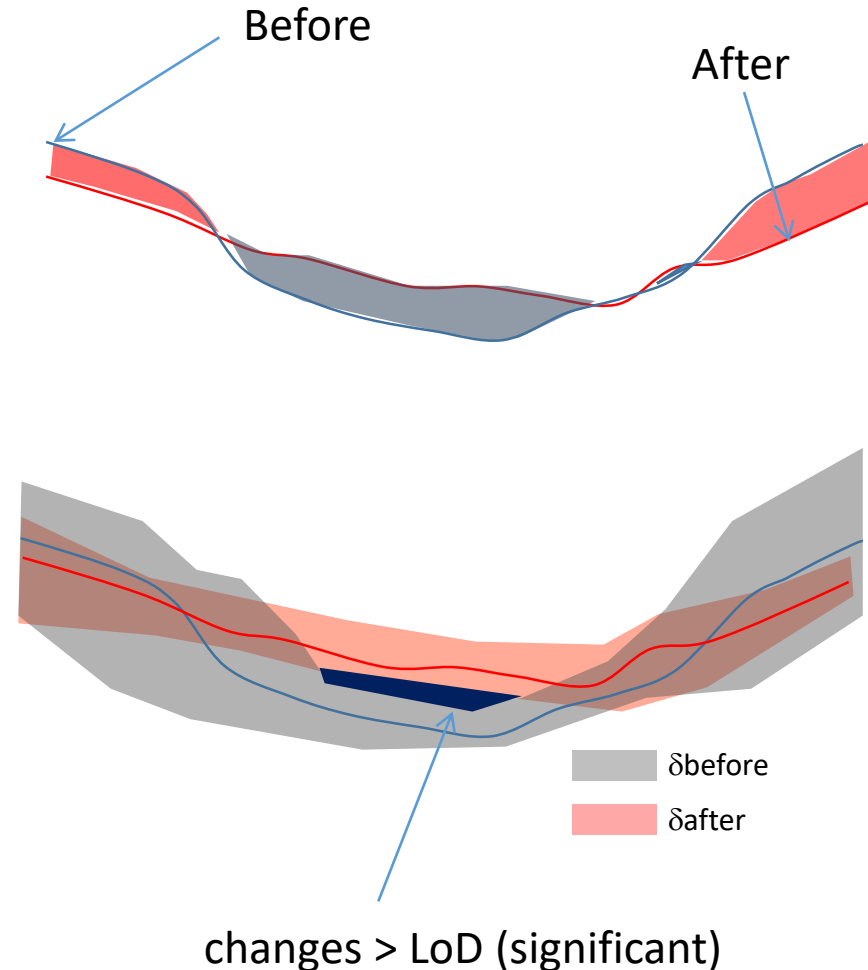
$$Z(x,y) = Z_{\text{DEM}}(x,y) + \delta(z)$$

Where,  $\delta(z)$  can be  $f(x,y)$



# NOT QUITE SIMPLE SUBTRACTION

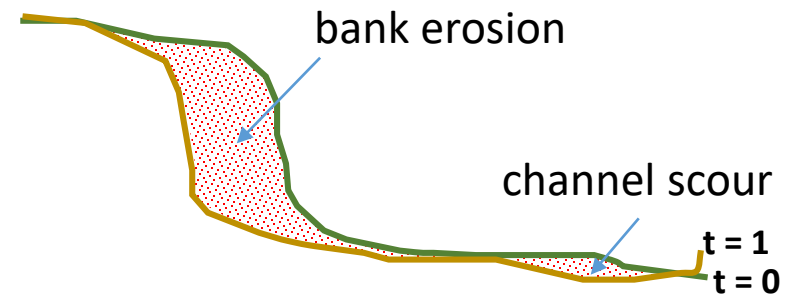
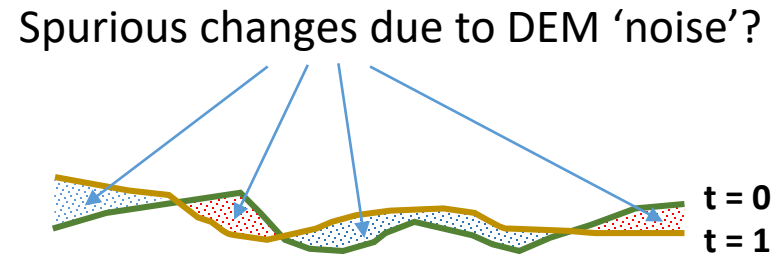
- **DEM of difference (DoD)** combines errors in **both** input models (DEMs)
- Propagation of errors from DEMs into the DoD can be estimated using the standard theory of errors (see Taylor, 1972)
- For functions,  $A = B + C$  or  $A = B - C$
- $$\delta_A = \sqrt{(\delta_B)^2 + (\delta_C)^2}$$
- $\delta_A$  is the propagated error in the DoD
- $\delta_B$  is the error in the before DEM
- $\delta_C$  is the error in the after DEM
- Define a 'minimum Limit of Detection' (LoD) to separate spurious changes from 'significant' variability





# MANAGING UNCERTAINTY

- Need to separate change due to **processes** (erosion, deposition, deformation and interventions) from those due to **errors**
- Distinguish the **signal** of topographic change **from the noise** of the DEM
- **Key issue**: fluvial systems are generally rather flat and changes are rather small, but often widespread.
- **We need**: (1) accurate and precise DEMs; and (2) methods to identify changes that are significant

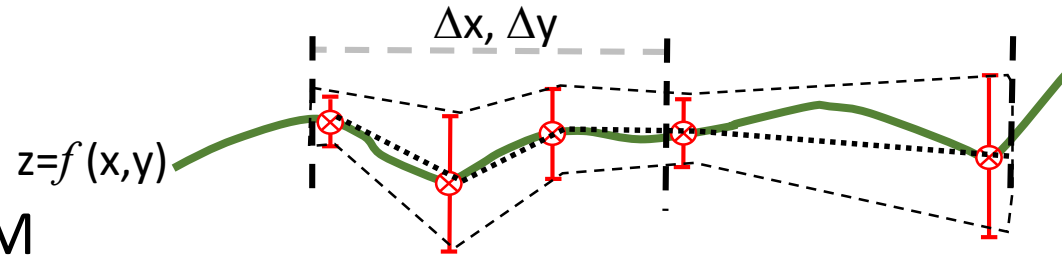


ERRORS INDIVIDUALLY MAY BE SMALL  
BUT INCORPORATING THEM ACROSS  
LARGE AREAS CAN LEAD TO VERY  
LARGE VOLUMETRIC BIAS

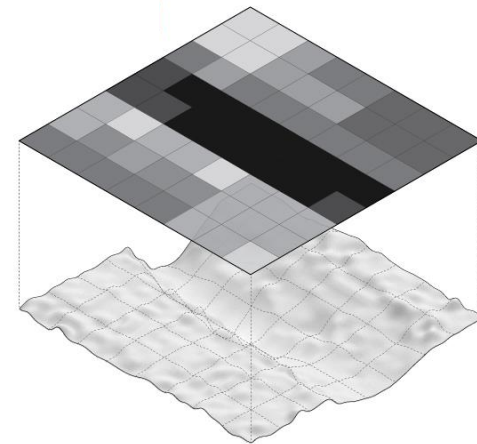
# UNDERSTANDING DEM ERRORS

Sources of error and uncertainty:

1. Variability below the DEM resolution?
2. Survey errors and sampling density?
3. Interpolation and generalization?



DESPITE THIS ... DEMs ... 1 VALUE OF Z PER CELL



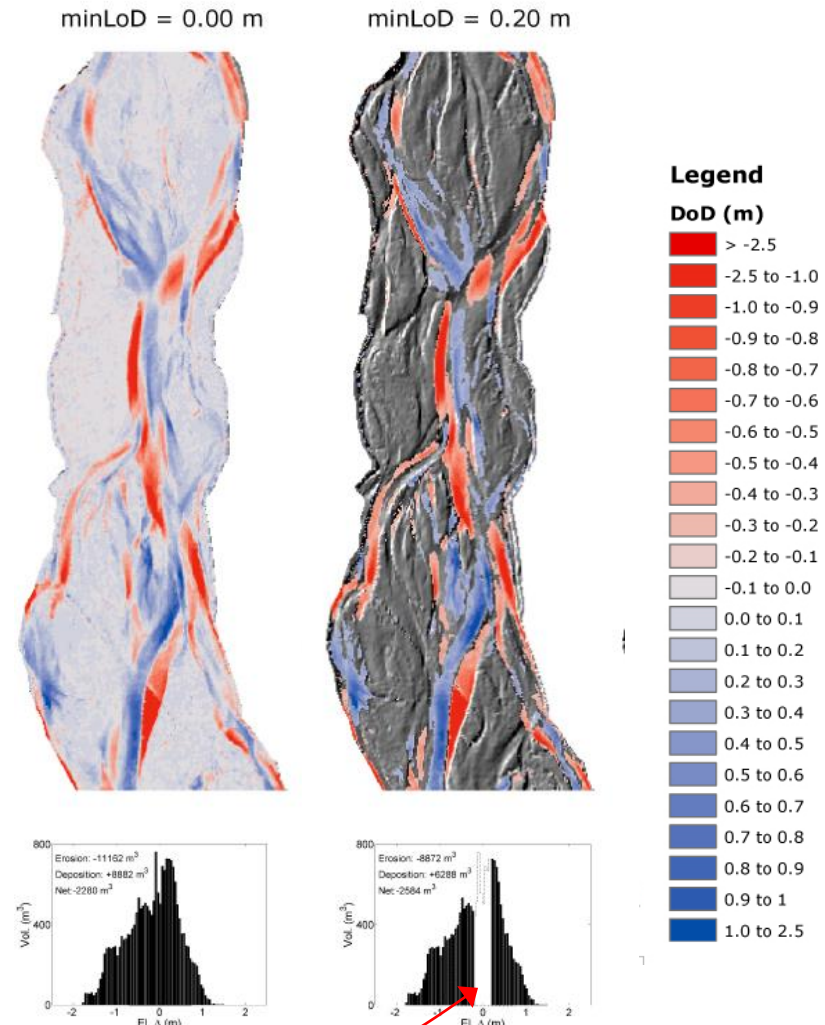
So, even where  $Z_{\text{new}} = Z_{\text{old}}$   
... unlikely that  $Z_{\text{DEM new}} = Z_{\text{DEM old}}$

# LEVEL OF DETECTABLE CHANGE

- Classical approach is to specify a *minimum level of detection* ( $_{\min}\text{LoD}$ ) to identify changes above a given magnitude

i.e., significant where  $\Delta z > x$

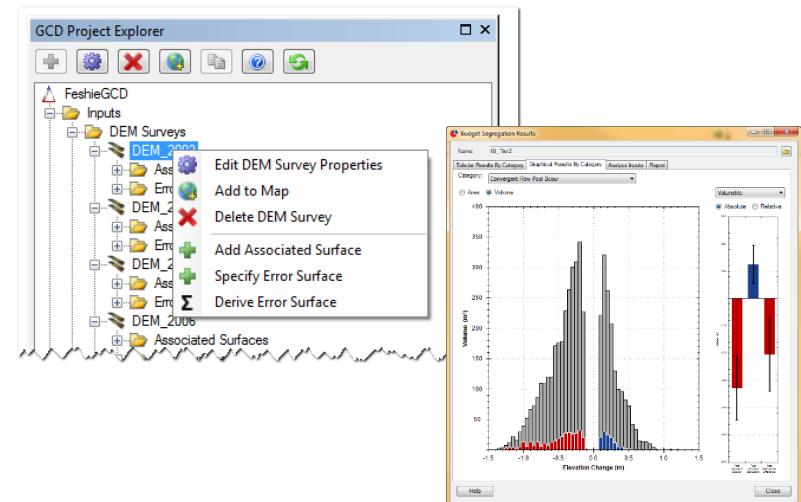
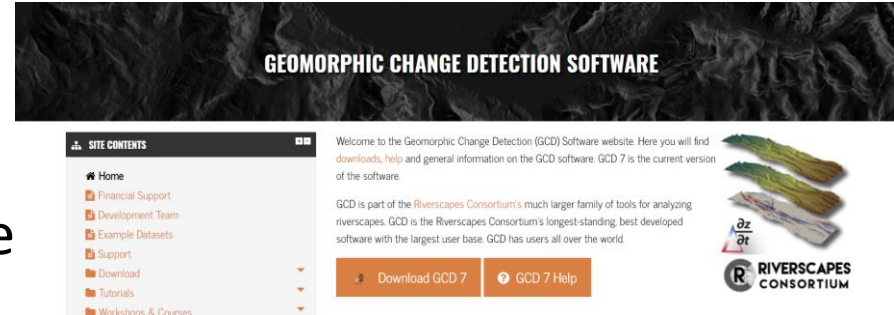
- Where  $x$  defines a magnitude above the scale of DEM noise
- Ignore changes below the threshold ...





# GCD SOFTWARE

- Geomorphic Change Detection Software
- Add-in for ArcGIS and standalone
- 10 years development programme with Joe Wheaton (USU), Philip Bailey (NAR)
- Used now by wide range of regional councils across NZ, the UK EA, SEPA, US Army Corp Engineers, USGS & practitioners and researchers worldwide



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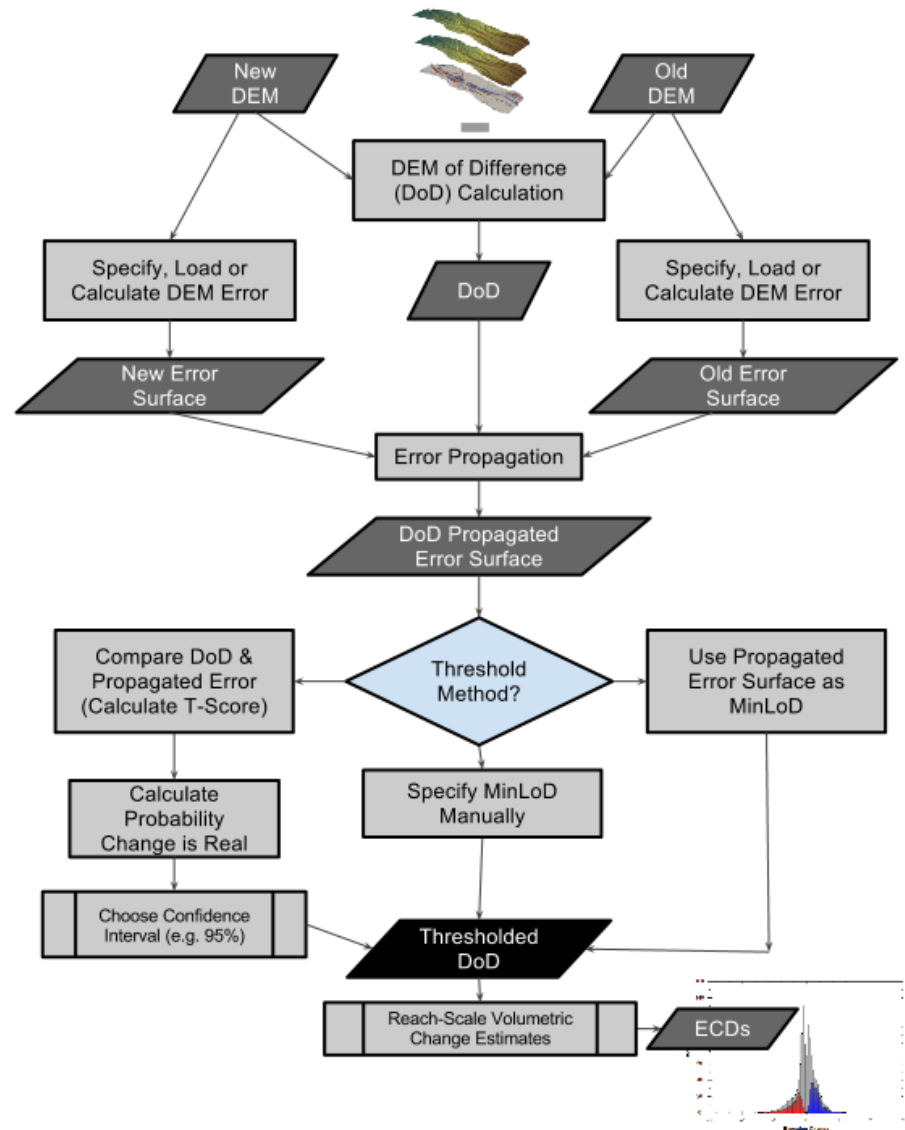
# GOALS OF GCD

Define a **standard of practice** for DEM based change detection

- Key aims:
  - Methods to help **represent** and **model DEM errors**
  - Workflows to **threshold change detections**
  - Tools to support analysis of **point cloud datasets** (ToPCAT)
  - Facilitate the **reproducibility of results**
  - Create standard methods for **reporting and visualizing results**  
(incorporated into reports, publications, maps)
  - Tools to **curate project data** (make it retrievable, interpretable and transportable)

# WORKFLOWS

- Multiple approaches to quantifying change
- Tools to derive error models
- Methods to represent errors spatially
- Tools for data management
- Visualization and communication of results





# EMERGING OPPORTUNITIES

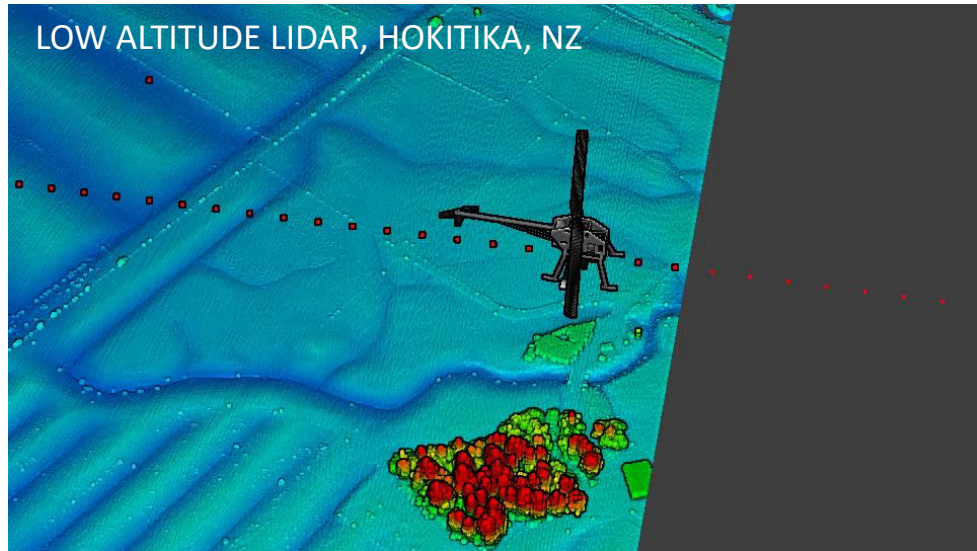
- Emerging 'cheap' data acquisition methods
- SfM, UAV lidar, Mobile TLS, automated TLS etc.
- High frequency monitoring
  - Temporally
    - Before/after floods
    - Monitoring for compliance
  - Spatially
    - Surface facies models
    - Vegetation modelling



SfM MODEL OF THE RIO CINCA, SPAIN



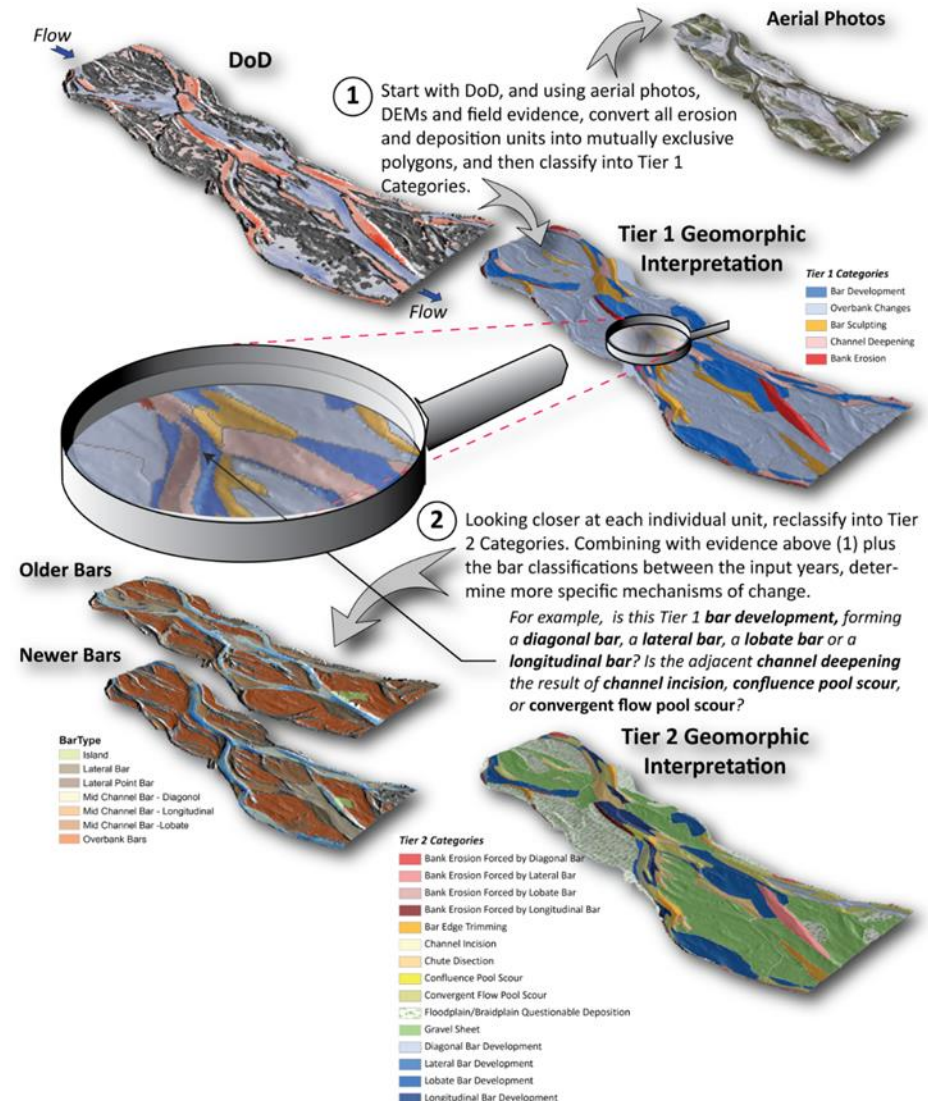
LOW ALTITUDE LIDAR, HOKITIKA, NZ



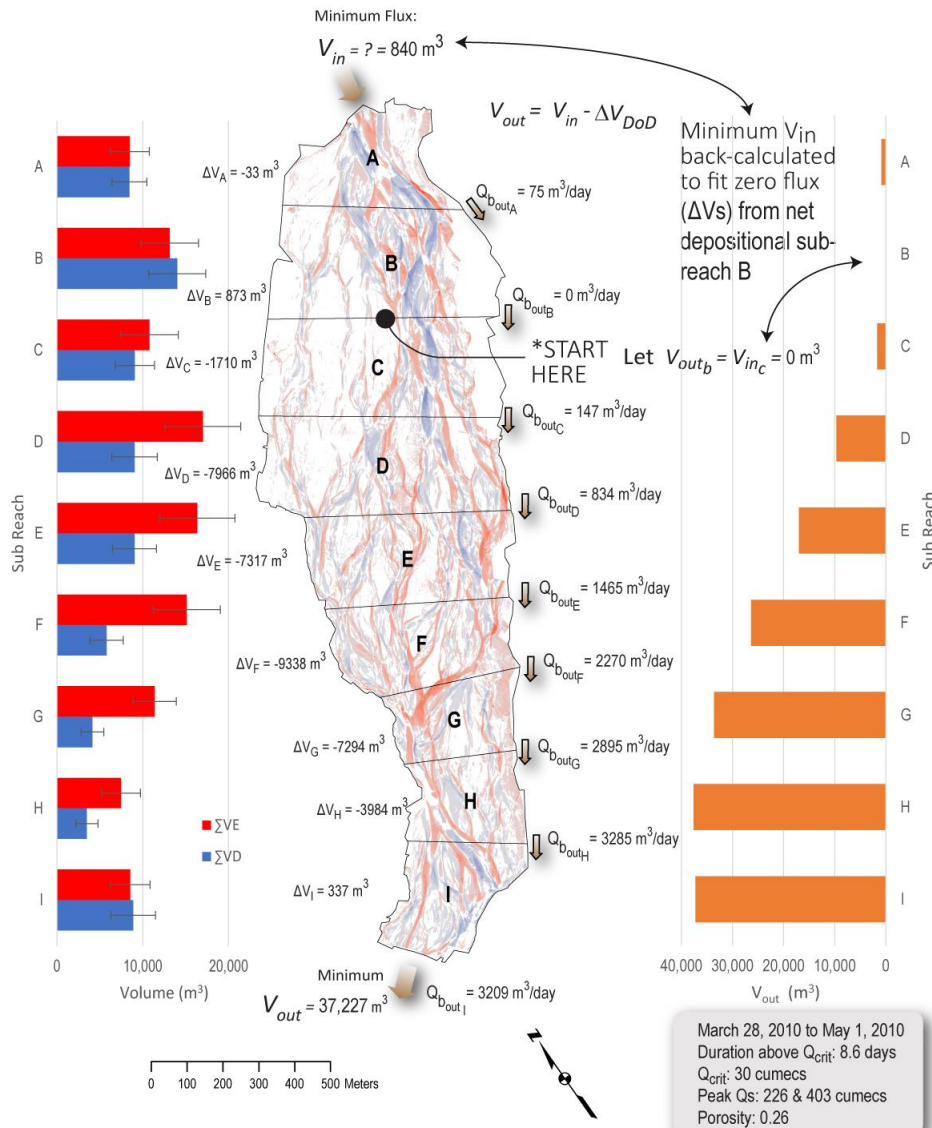
# DATA INTERROGATION

## 1) FACILITATE INTERPRETATION

- **Classify and quantify morphological changes**
  - e.g., Fluvial processes vs anthropogenic processes
- **Spatial 'segmentation' of morphological change**
  - Longitudinal analysis of changes
- **Change relative to reference**
  - i.e., available storage
- **Sensitivity analysis**
  - Evaluate the robustness of the results obtained



# DERIVATIVE PRODUCTS



## 2) SEDIMENT TRANSPORT RATE

Reach-scale sediment budget

Dissect reach into units

Know or estimate a region of zero-flux and solve the longitudinal budget enabling spatial estimation of  $Q$ s

Quantification of gravel yield

# COMMUNICATE RESULTS

## 3) COMMUNICATION OF RESULTS

- Appropriate metrics
- Visualization of results
- Communication of uncertainty
- Automated / tailored reports

Attribute	Raw	Thresholded DoD Estimate:		
AREAL:				
Total Area of Erosion (m²)	57,347	21,304		
Total Area of Deposition (m²)	57,513	21,065		
Total Area of Detectable Change (m²)	NA	42,369		
Total Area of Interest (m²)	114,860	NA		
Percent of Area of Interest with Detectable Change	NA	37%		
VOLUMETRIC:			± Error Volume	% Error
Total Volume of Erosion (m³)	9,284	7,422 ±	1,536	21%
Total Volume of Deposition (m³)	11,772	10,006 ±	1,519	15%
Total Volume of Difference (m³)	21,056	17,429 ±	3,055	18%
Total Net Volume Difference (m³)	2,489	2,584 ±	2,160	84%
VERTICAL AVERAGES:			± Error Thickness	% Error
Average Depth of Erosion (m)	0.16	0.35 ±	0.07	21%
Average Depth of Deposition (m)	0.20	0.48 ±	0.07	15%
Average Total Thickness of Difference (m) for Area of Interest	0.18	0.15 ±	0.03	18%
Average Net Thickness Difference (m) for Area of Interest	0.02	0.02 ±	0.02	84%
Average Total Thickness of Difference (m) for Area With Detectable Change	NA	0.41 ±	0.07	18%
Average Net Thickness Difference (m) for Area with Detectable Change	NA	0.06 ±	0.05	84%
PERCENTAGES (BY VOLUME)				
Percent Erosion	44%	43%		
Percent Deposition	56%	57%		
Percent Imbalance (departure from equilibrium)	6%	7%		
Net to Total Volume Ratio	12%	15%		

# TRANSPARENT WORKFLOWS


## 4) TRANSPARENCY

- Embed QA of process and QC of results
- Metadata
- Database structure
- Established formats of i/o and data exchange

Specify GCD DEM Survey

Name:

Original Raster

Original raster:  

Top:  Rows:  Columns:

Left:  Right:  Width:  Height:

Bottom:  Cell resolution:

GCD DEM Survey

Change Detection Results

Project raster path: Name:

Top:

Left:

Bottom:

New Survey

DEM:  Old Survey

Error:  DEM:

Error:

Uncertainty Analysis Method

Type:  Propagated Error

Threshold:  Propagated error:

Probabilistic Uncertainty Properties

Confidence level:

Bayesian:

Probability raster:

Erosion spatial coherence raster:

Deposition spatial coherence raster:

Conditional probability raster:

Posterior probability raster:

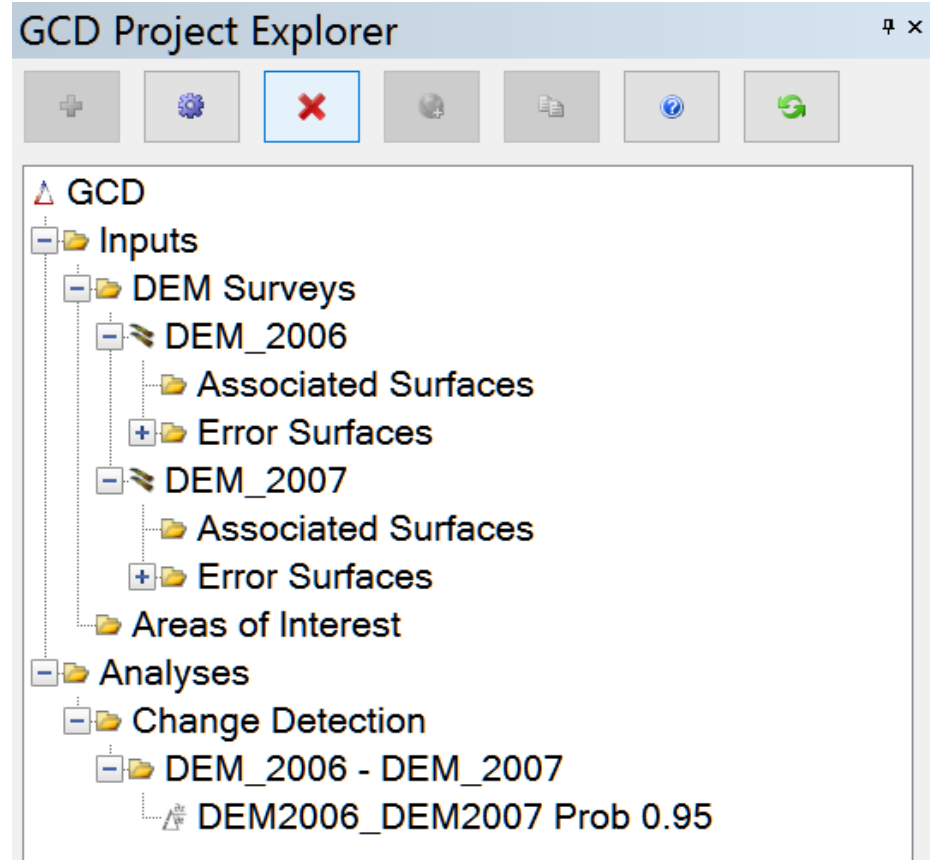
Help Close



# DATA SHARING

## 5) SHARING

- Portability of data analyses between users
- Understanding between team members – analysts and project managers
- Established formats to exchanging results with stakeholders



# WORKSHOP STRUCTURE

**Chalk and talk ... your feedback is encouraged!**

## **1. Digital Elevation Modelling**

- DEM generation

## **2. DEM Differencing**

- Thresholding, the GCD software

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## **3. GCD software functionality**

- Errors, masks, sections, automation, data products

## **4. Modelling river response**

- Case studies

