Landslide Hazard Assessment & Mitigation

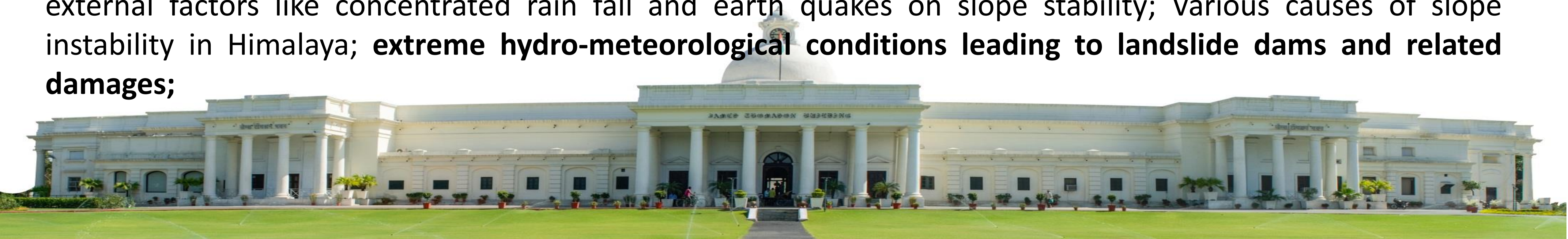
DML – 502 Lecture - 9

Subject Code: DML-502
Course Title: Landslide Hazard Assessment & Mitigation

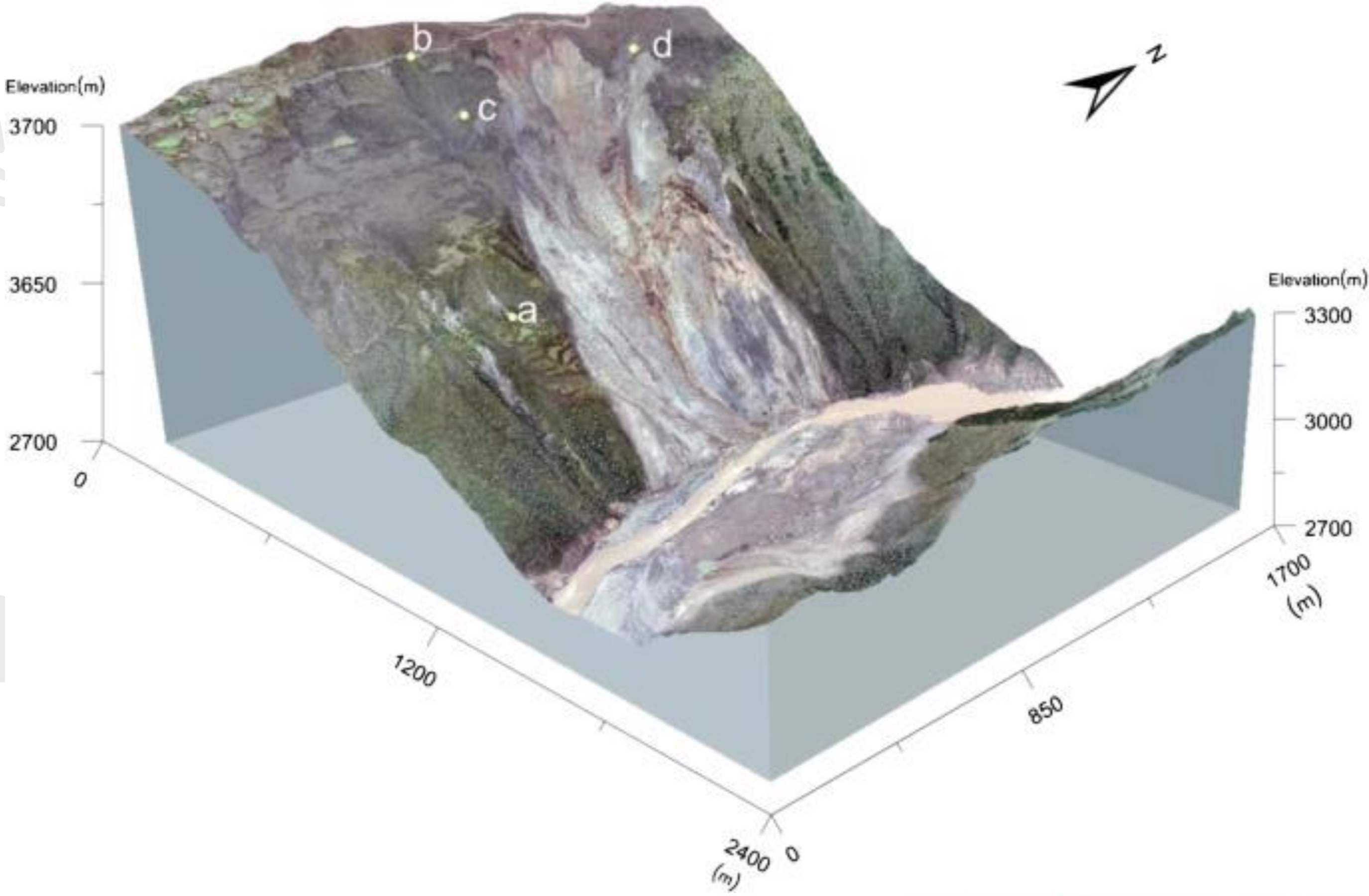
"To understand mapping and hazard assessment techniques of landslides and protection against landslide."

S. No 2

Causative factors of landslides – natural including inherent factors and external factors as well as anthropogenic factors; Impacts of natural causative factors like lithology, structure, slope morphometry, relative relief, hydrogeological conditions and land use and land cover on stability of slopes ; Impacts of external factors like concentrated rain fall and earth quakes on slope stability; Various causes of slope instability in Himalaya; **extreme hydro-meteorological conditions leading to landslide dams and related damages;**



The blocking of river courses by mass movements is very common in mountainous areas with deep and narrow valleys. Landslide dams may pose serious threats to people and their livelihoods downstream in the case of abrupt dam failure.



Costa and Schuster (1988) and Korup (2002) addressed the complex interactions between landslide morphometric characteristics and magnitude, geomorphological parameters of the valley, and hydrological parameters of the river at a given location.

A summary of key papers, reviews and meta-analyses on landslide dams. Modified from Costa and Schuster (1988) and Hermanns et al. (2011b)

Focus	Key references
Previous benchmark reviews	Costa and Schuster (1988); Korup (2002); Korup and Tweed (2007); Evans et al. (2011a)
Papers focus on studying landslide dams formed by different types of landslides and in different materials	Volcanic dams: Capra (2007); Capra (2011); Rockslide and rock avalanche dams: Dufresne et al. (2018); Hermanns et al. (2006); Hermanns et al. (2011a); Hermanns et al. (2011b); Hewitt (2009a); Hewitt (2011) Unconsolidated sediments: Geertsema (1998)
Worldwide landslide dam datasets; event-based landslide dam inventory of the 2008 Wenchuan earthquake; other regional datasets are reviewed in Section 3	Schuster and Costa (1986), 187 cases; Costa and Schuster (1991), 463 cases; Ermini and Casagli (2003), 350 cases; Peng and Zhang (2012), 1239 cases Strom and Abdrakhmatov (2018), 190 cases Fan et al. (2012a); Fan et al. (2012b); Fan et al. (2012c), 828 cases from the Wenchuan earthquake
Empirical indices predicting landslide dam formation	Swanson et al. (1986), Ermini (2003b), Dal Sasso et al. (2014), Tacconi Stefanelli et al. (2016)
Empirical classification schemes and geomorphic indices for landslide dam stability	Casagli and Ermini (1999); Dal Sasso et al. (2014); Dong et al. (2009); Ermini (2003a); Ermini and Casagli (2003); Korup (2002); Korup (2004); Tacconi Stefanelli et al. (2016)
Landscape implications of landslide dams, including their impacts on valley morphology, sediment transport, fluvial incision etc.	Hewitt (2002); Korup (2005a); Schuster (2006); Korup (2012); Jansen (2006); Korup et al. (2006)

The formation and impact of landslide dams – State of the art

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Terms characterizing landslide dam stability.

Casagli and Ermini (1999)	
Dam not formed*	Includes all the cases of partial blockage, channel deviation, erosion of the landslide toe, in which the formation of a complete dam is prevented.
Collapsed dam	Includes all the cases of a catastrophic dam collapse.
Artificially controlled	Includes all the cases where the remedial works drastically changed the natural evolution of the phenomenon.
Slow erosion	Includes all the lakes extinguished because of slow progressive erosion of the dam without catastrophic events.
Filling	Includes all the lakes extinguished due to progressive filling
Existing	Includes lakes existing at present
Ermini and Casagli (2003)	
Unstable dam	Landslide dam that has undergone erosion or collapse leading to a catastrophic breach, with the subsequent release of the impounded lake waters.
Stable dam:	Landslide dam that has remained stable and has not encountered a catastrophic breach thus still impounding an existent or relict lake.
Korup (2004)	
Stable	The landslide-dammed lake persists for over a decade.
Tacconi Stefanelli et al. (2016)	
Not-formed*	The landslide reached the riverbed, but only a partial damming is realized (no lake formed).
Formed-unstable	Over times that can range from hours to centuries, the dam collapsed or was breached by the river, including the artificially breached or removed landslide dams.
Formed-stable	The blockage is complete with the formation of a dam and a lake, which are still existing or disappeared for sediment filling. The dam could have been overtopped during its life, but no total failure or destructive flooding wave occurred.

Note: *Even though these landslides did not create full river blockages, they are considered by the respective authors, and included herein, since they may still alter the river flow and sediment delivery or form partial blockages, which could be of relevance in risk assessment and is of interest for inventory analyses (i.e. factors relevant to the full dam formation and failure statistics).

Classification

Xuanmei Fan[a], Anja Dufresne[b,*], Srikrishnan Siva Subramanian[a,*], Alexander Strom[c], Reginald Hermanns[d,e], Carlo Tacconi Stefanelli[f], Kenneth Hewitt[g], Ali P. Yunus[a], Stuart Dunning[h], Lucia Capra[i], Marten Geertsema[j], Brendan Miller[j], Nicola Casagli[f], John D. Jansen[a,k], Qiang Xu[a]

Classification scheme of apparent landslide dam stability.

Infilled	Impoundment infilled with sediment (i.e. retained landslide-dammed lake throughout its lifetime) and there is no evidence for any catastrophic breaching during its existence.
Long-term stable	Landslide dam that has remained stable and has not encountered a breach over centuries or longer and thus still impounds an existent or relict lake and no immediate change is expected. However, extreme weather / climatic conditions or other effects (e.g. landsliding into the landslide-dammed lake or unusually high inflow) might cause catastrophic failure.
Long-term eroded dam	Entirely/partially eroded, i.e. did not retain the impoundment lake waters, but released it gradually over a hundred to thousands of years.
Short-term stable	Existing landslide-dammed lake with no sign of partial breaching, however, there is a high threat for catastrophic failure in the near future (days to months) based on the material of the dam and/or geomorphic parameters.
Short-term eroded dam	Entirely/partially eroded, i.e. did not retain the landslide-dammed lake waters, but released it gradually in days to months.
Dam breached	Breached (or partially) with evidence of catastrophic outburst flood(s) – includes internal and external causes for breaching (e.g. seepage erosion or erosion caused by overtopping)

Note: blue categories are dams where no remediation is needed; red categories advice hazard assessment and monitoring.

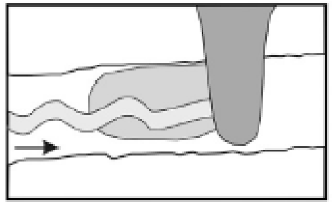
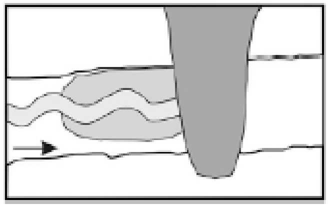
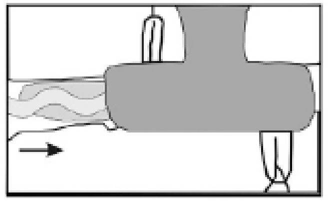
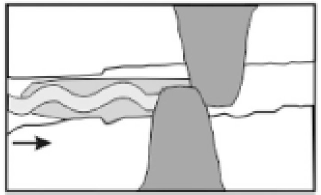
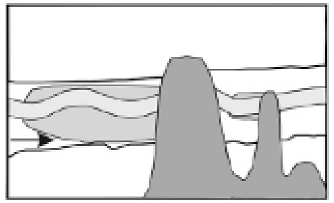
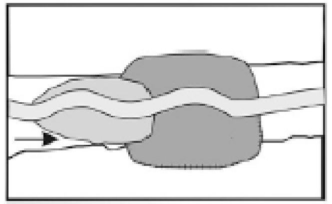
Classification

Legend: Landslide dam

Lake River

Tributary → Flow direction

Geomorphometric landslide dam classifications.

Sketch	Description	Type (Costa and Schuster, 1988)	Type (Hermanns et al., 2011b)
	Small dams relative to the valley size that does not reach the opposite slope	I	II c
	Large dams, but still small compared to the valley dimensions. This is one of the most widespread types, and they are frequently formed by rotational or translational landslides	II	II a
	Very large dams that fill the valley from side to side. The collapsed materials are distributed both upstream and downstream from the release area, at times with a T-shaped deposit. Casagli and Ermini (1999) introduced a distinction in this class, separating the phenomena in which the dam also affects the tributary valleys of the main one (III a) from those in which these are not involved (III b).	III	IV a
	Those very rare dams are formed from the contemporary movement of two landslides detached from opposite sides of the same valley.	IV	II b
	Several dams are formed by multiple tongues of a singular landslide. They are not very common for landslides but may form by glaciers (glacier tongues).	V	III b
	Landslides with sub-channel rupture surfaces.	VI	II d

Classification

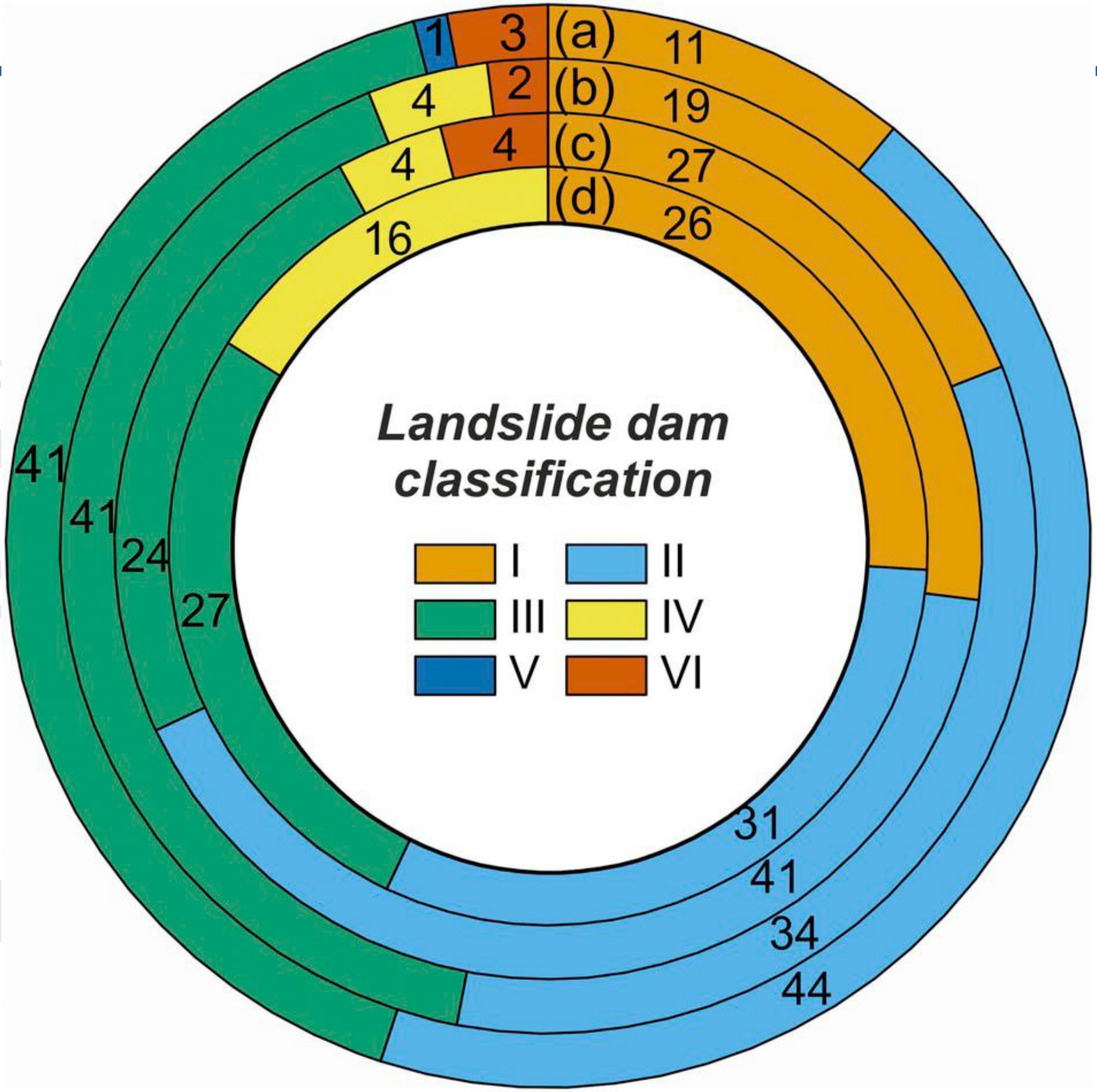
Landslide dam classification (Type I to VI) according to Costa and Schuster (1988) (% of landslide dams in each class) for previous inventories: moving from the outer ring to inner ring:

(a) Worldwide - 225 cases Costa and Schuster (1988);

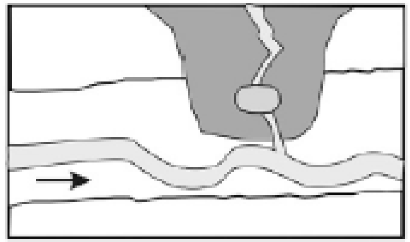
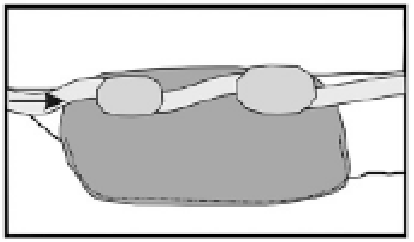
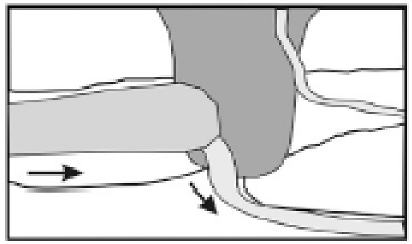
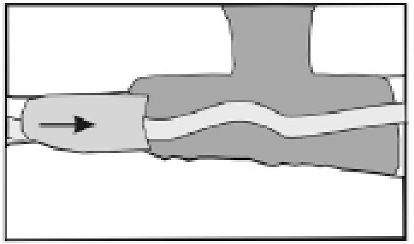
(b) 19 cases by Ermini (2000);

(c) Italy - 300 cases Tacconi Stefanelli et al. (2015);

(d) Cordillera Blanca, Peru- 51 cases Tacconi Stefanelli et al. (2018).

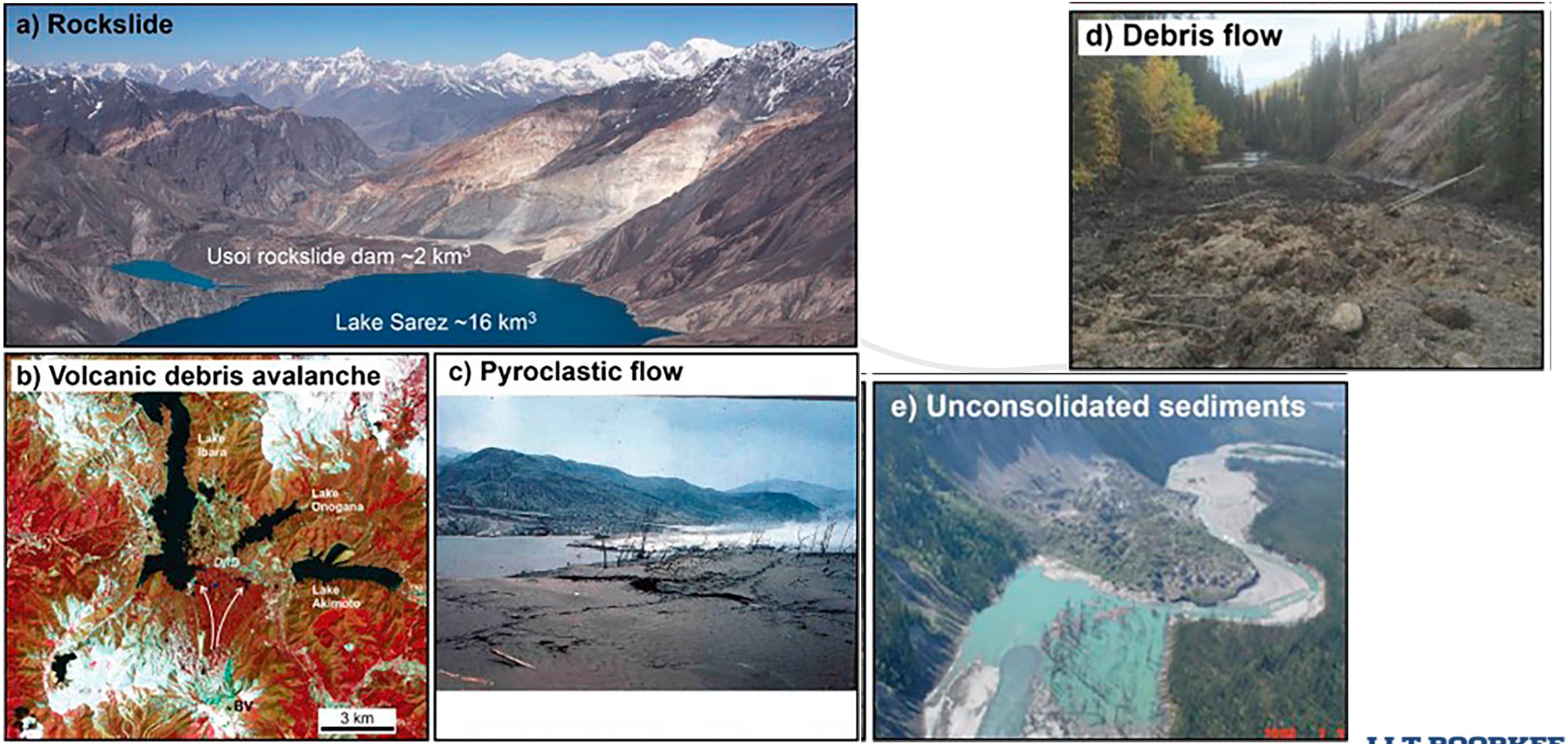


Classification

	Supra-landslide lakes on landslide deposits are frequent on larger rockslide deposits, but can occur on all types of landslides. They are not connected to located within the channel of the dammed river.	-	I
	Sub-type of plan view distribution of multiple landslide dams in a single valley in a line formed by a single landslide. Another type is III b.	-	III a
	Type of a landslide dam affecting water divides; with the landslide deposit depositing directly in the drainage divide.	-	V a
	Single landslide dam having different forms distinguished between a rockslide crossing the valley partially or entirely, a rockslide involving the valley floor, and rockslides which, after impacting the valley bottom, spread in an up- and down valley direction (almost the same as III of Costa and Schuster).	-	II e
-	More complex multi-river geometries, focusing on the morphological relations of the dam in relation to the river valley	-	IV b-e, VII a-b, VIII, IX

Legend: Landslide dam, Lake, River, Tributary, Flow direction

Classification



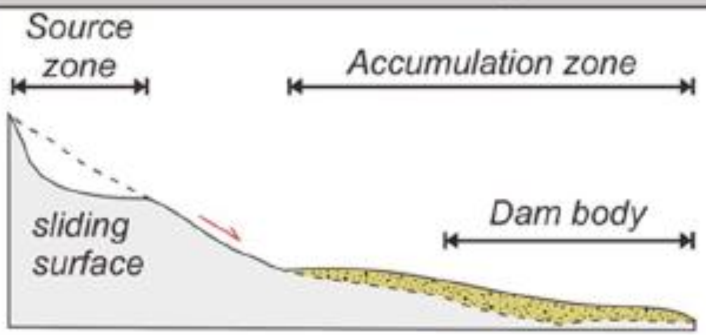
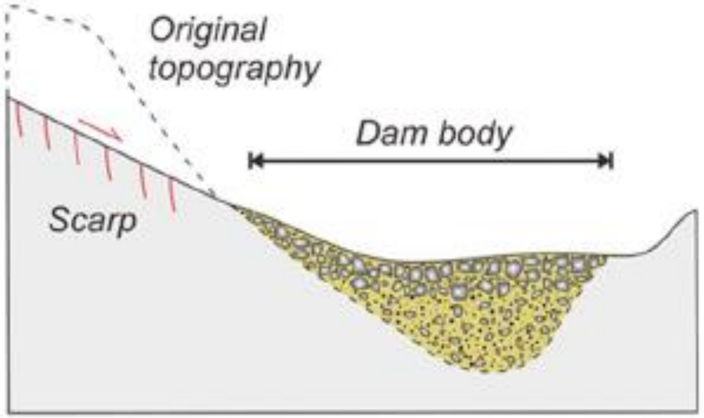
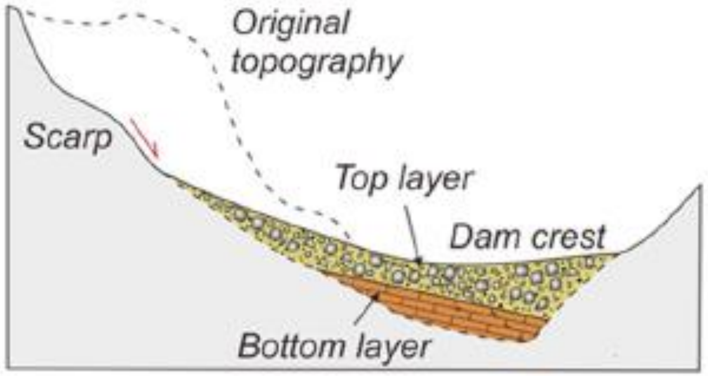
Classification

1. *Dams formed by large rockslides and rock avalanches*
2. *Dams formed by volcanic mass movements*
3. *Dams formed by debris flows*
4. *Dams formed by slides/flows in unconsolidated sediments*
5. *Debris avalanches and complex landslides*

Type of movement	Rock	Soil
Fall	*Rock/ice* fall	*Boulder/debris/silt* fall
Topple	Rock block topple	*Gravel/sand/silt* topple
	Rock flexural topple	
Slide	Rock rotational slide	*Clay/silt* rotational slide
	Rock planar slide	*Clay/silt* planar slide
	Rock wedge slide	*Gravel/sand/debris* slide
	Rock compound slide	*Clay/silt* compound slide
	Rock irregular slide	
Spread	Rock slope spread	*Sand/silt* liquefaction spread
		Sensitive clay spread
Flow	*Rock/ice* avalanche	*Sand/silt/debris* dry flow
		Sand/silt/debris flowslide
		Sensitive clay flowslide
		Debris flow
		Mud flow
		Debris flood
		Debris avalanche
		Earthflow
		Peat flow
Slope deformation	Mountain slope deformation	Soil slope deformation
	Rock slope deformation	Soil creep
		Solifluction

Classification

Landslide dam classification based on dam composition and internal structures (modified from Fan et al., 2017).

Sketches of dam type	Description
	**Sub-type A:** Debris flows, avalanches with long transport paths form landslide dams composed of loose debris. This type of dam has commonly low stability and high erosion sensitivity.
	**Sub-type B:** Dams formed by rock avalanches or rock falls composed of large boulders and blocks. Deposits from rock avalanches have an internal structure formed by highly fragmented debris commonly below a carapace of large blocks.
	**Sub-type C:** Deep-seated rock slides with two-layered internal structure formed by intact strata at the base; fragmented rocks and debris on top.

Dam failure susceptibility

Preliminary landslide dams stability classification matrix combining Costa and Schuster (1988) and Fan et al. (2017) methods. Green is for basically stable, orange for the stable in short time (but unstable in the medium- to long-term), red for unstable in short time.

	Fan et al. (2017)			
Schuster (1988)	Type	Sub-type A	Sub-type B	Sub-type C
	Type I	Small dam blocking valley composed by loose fine materials, formed by debris flows, avalanches, and slides with long long-runout	Small dam blocking valley formed by large boulders and blocks, originated by rock avalanches or rock falls	Small dam blocking valley composed by intact rock strata topped by coarse materials, formed by deep-seated rock slides or avalanches
	Type II	Large dam able to block the valley composed by loose fine materials, formed by debris flows, avalanches, and slides with long long-runout	Large dam able to block the valley formed by large boulders and blocks, originated by rock avalanches or rock falls	Large dam able to block the valley composed by intact rock strata topped by coarse materials, formed by deep-seated rock slides
	Type III	Very large dam that fills the valley composed by loose fine materials, formed by debris flows, avalanches, and slides with long long-runout	Very large dam that fills the valley formed by large boulders and blocks, originated by rock avalanches or rock falls	Very large dam that fills the valley composed by intact rock strata topped by coarse materials, formed by deep-seated rock slides

Worldwide landslide dam database

The formation and impact of landslide dams – State of the art

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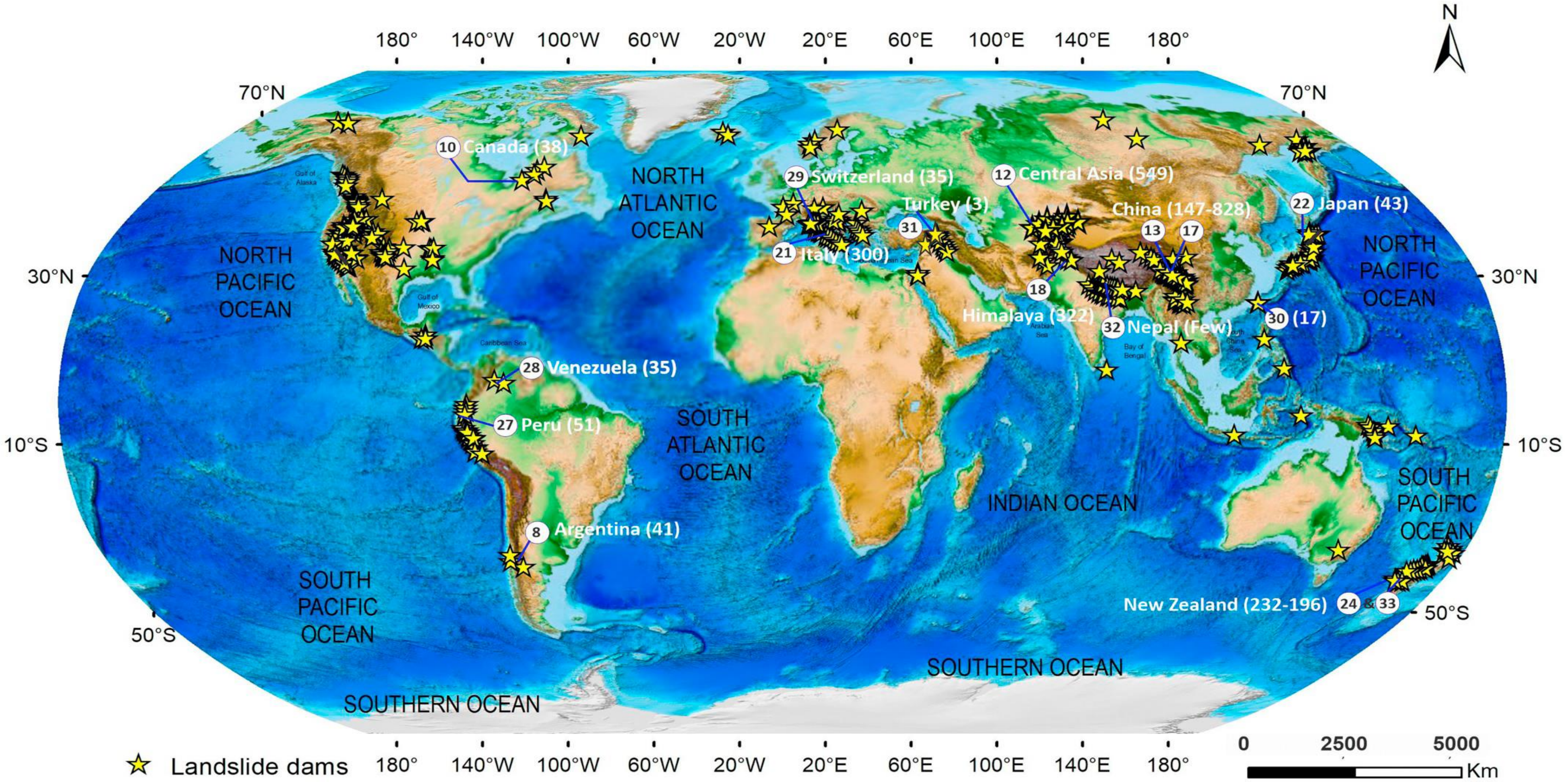

Classification from the database

The formation and impact of landslide dams – State of the art

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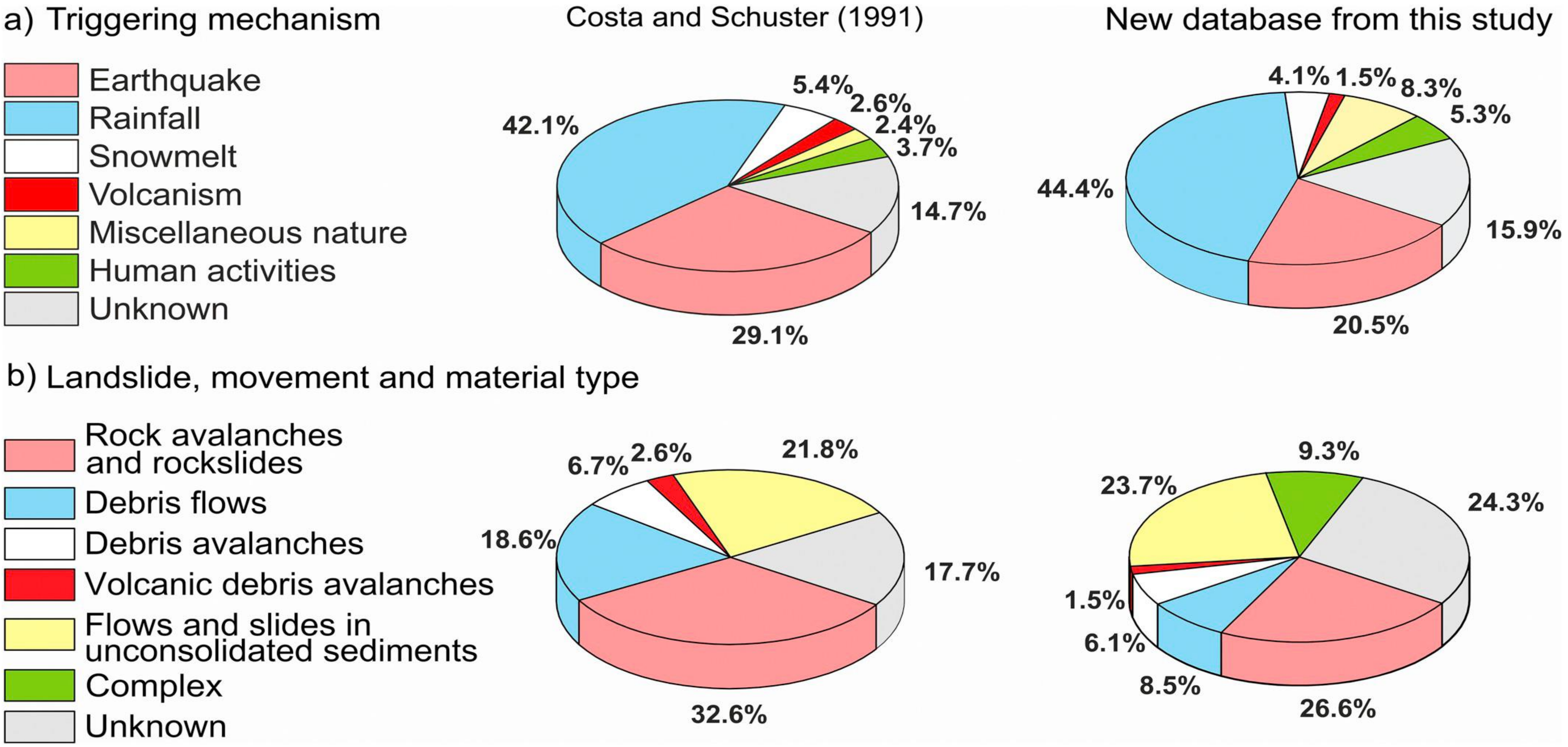

Geometry of landslide dams

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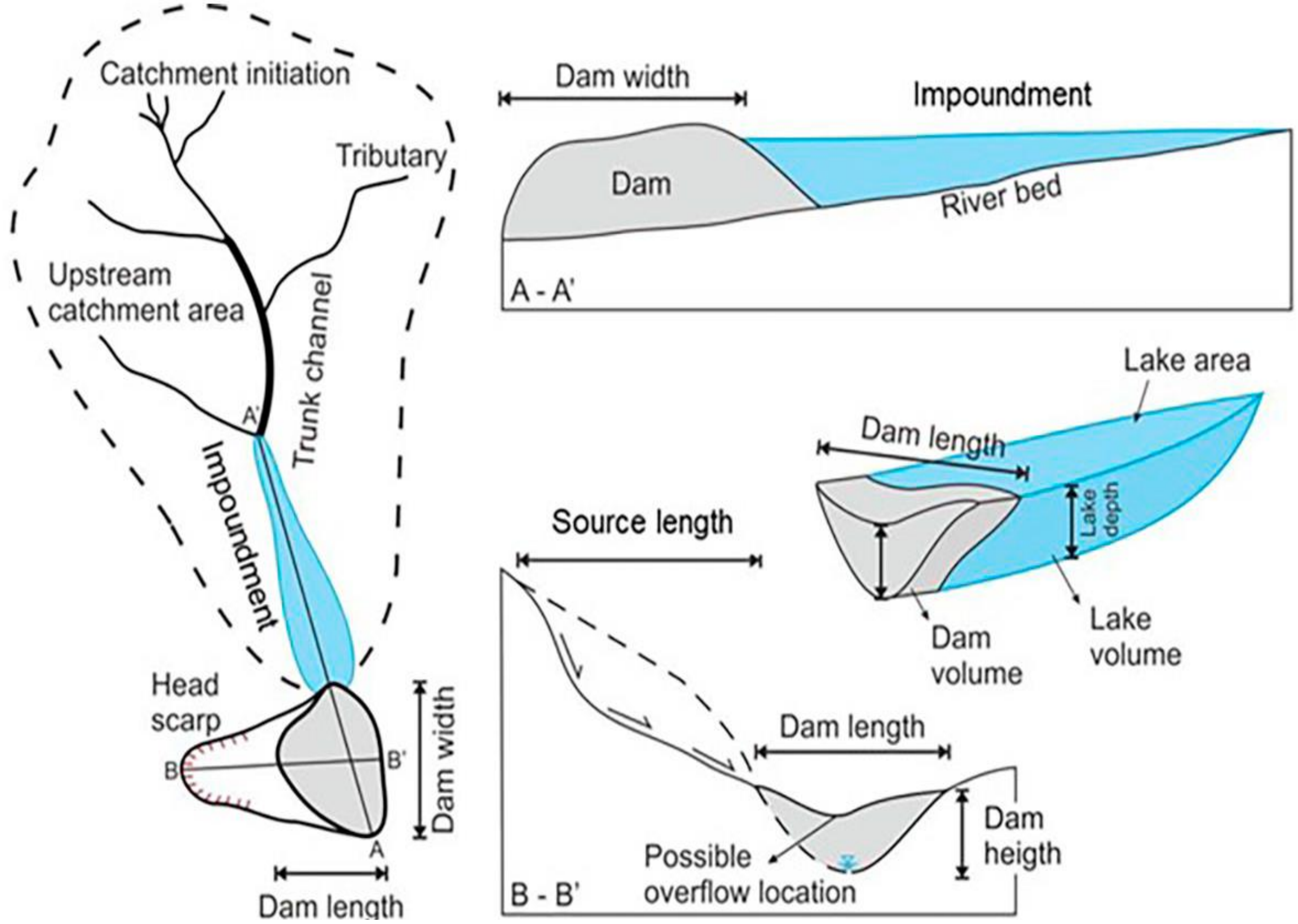

Geomorphic parameters:	
Landslide dam height:	
Height from river bed to overflow point	- H_D
Landslide dam width:	
Maximum width of dam (along valley)	- W_L
Landslide dam volume:	
Approximate volume of dam deposit	- V_D
Landslide volume :	
Approximate volume of landslide deposit	- V_{LS}
Landslide velocity:	
Velocity of landslide during sliding	- V

Density of sliding:	
Density of sliding mass	- p_s
Landslide grain size:	
Grain size of landslide deposits	- D_{30}
Catchment area:	
Area of the catchment having tributaries	- A_c
Water discharge	- Q_p
Slope of channel bed	- S
Valley width	- W_V
Lake volume	- V_L

Stability Indices

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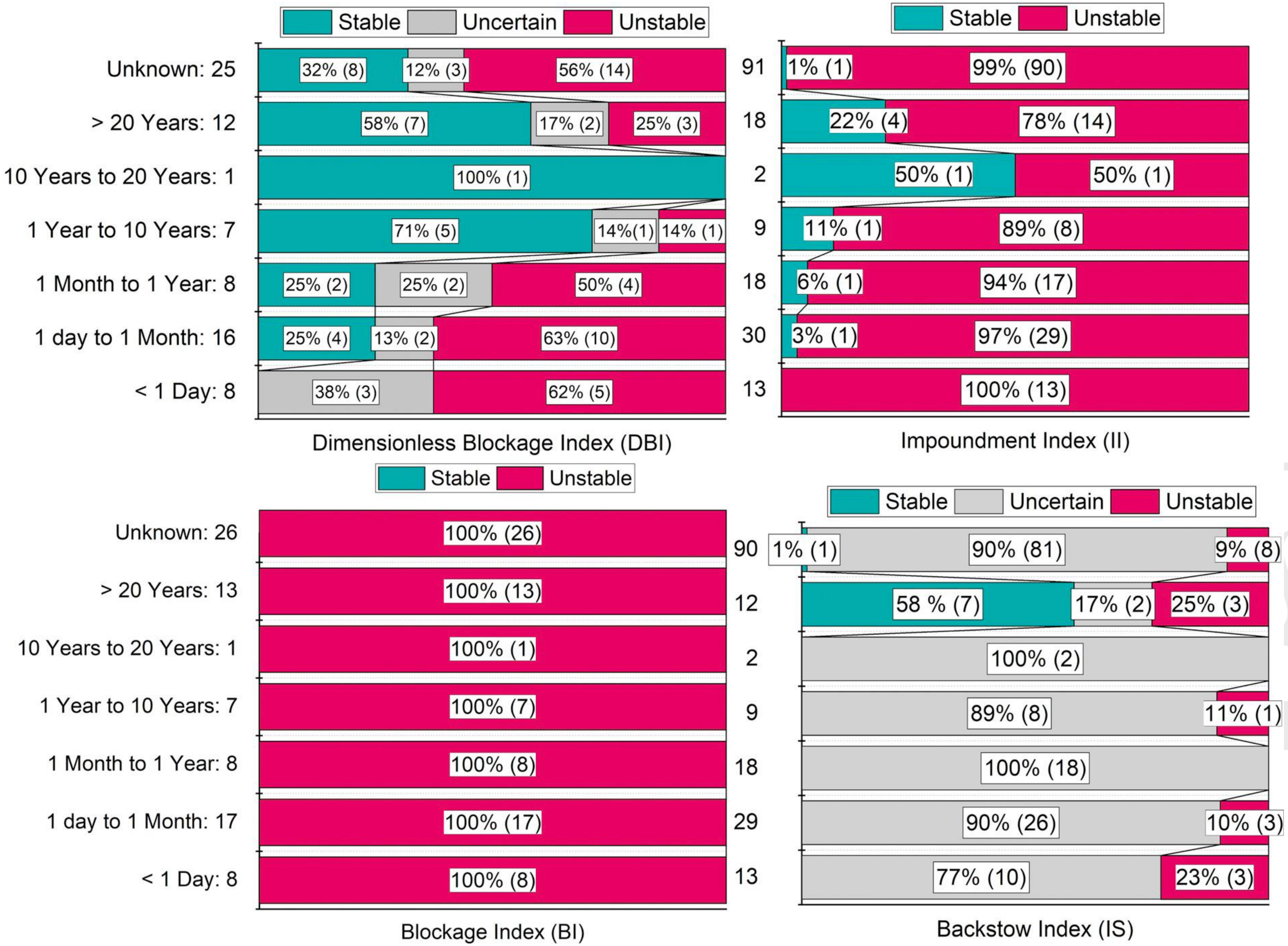

Geomorphic stability indices, categorizing stable and unstable landslide dams verified against longevity for available cases from our new worldwide database. Key to read figure: numbers after longevity denote the number of data-available cases. Read left to right, i.e. for Dimensionless Blockage Index, for > 20 years longevity, 58 % cases are predicted stable, 17% cases are uncertain and 25% cases are falsely predicted as unstable.

Timescale of landslide dams

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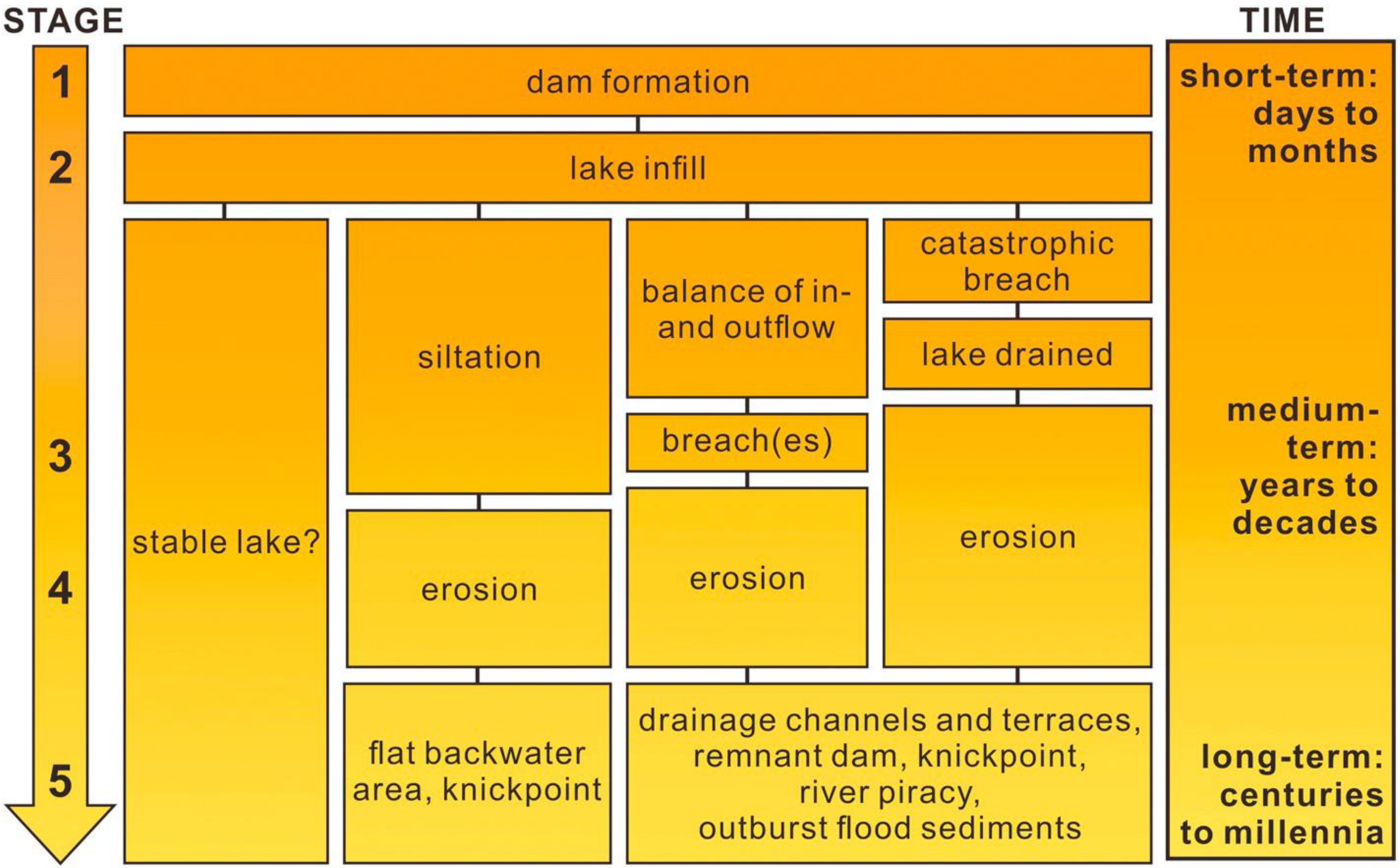

Timescale of landslide dams

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Stages in the evolution of a landslide-interrupted river, identifying characteristic features and how they combine to underpin a land systems approach described below (modified after Hewitt, 2002; Korup, 2005a; Korup, 2005b).

Stage	Main development	Typical landforms and deposits
Stage 1: Landslide dam formation	Landslide emplacement and creation of a dam	Landslide debris lobes, hummocks, pressure ridges, furrows, 'brandung'; rudaceous or fragmented deposits
Stage 2: Lake impoundment	Aggradation and constructional landforms upstream of dam, submergence/inundation of upstream areas, lake sedimentation, reduction of discharge, changes in flow regime, decrease in upstream gradient.	*Axial*, fluvio-lacustrine flats, multi-channel (braided, anastomosing) streams; delta(s) and fan deltas, cross-bedded scour and fill, scattered swamp deposits; redistribution of fine-grained sediment by valley winds and dust storms; dune fields, loess, stream piracy *Valley side and tributaries*; talus, colluvium, sediment fans, debris flow cones, disturbed confluence environments. *On-landslide*; knickpoints, megaclasts, ponds, loess.
Stage 3: Erosional interruption	Overtopping or piping, outburst flood, excavation, trenching and removal of the impoundment complex, changes in channel morphology, downstream sedimentation	Spillway across the dam, segmented fans, trenched valley fill, discontinuous erosion terraces; migrating knickpoints in valley fill, alluvial flats. Reworked and mixed sediments
Stage 4: Superimposed interruption	Incision into the pre-landslide floor, an exhumation of buried valley fill & channels, increasingly scattered, smaller remnants of impoundment complex, increased flood frequency	Strath terraces superimposed (epigenetic) gorges, pothole swarms 'defended' landforms, outwash fan
Stage 5: 'Shadow' interruption	Channels and straths superimposed in bedrock; minor depositional Remnants in sheltered locations, remnant irregularities in river thalwegs	Exhumed, pre-landslide valley floor sediments, epigenetic gorges Migrating knickpoints in bedrock

Longevity vs Type

The formation and impact of landslide dams – State of the art

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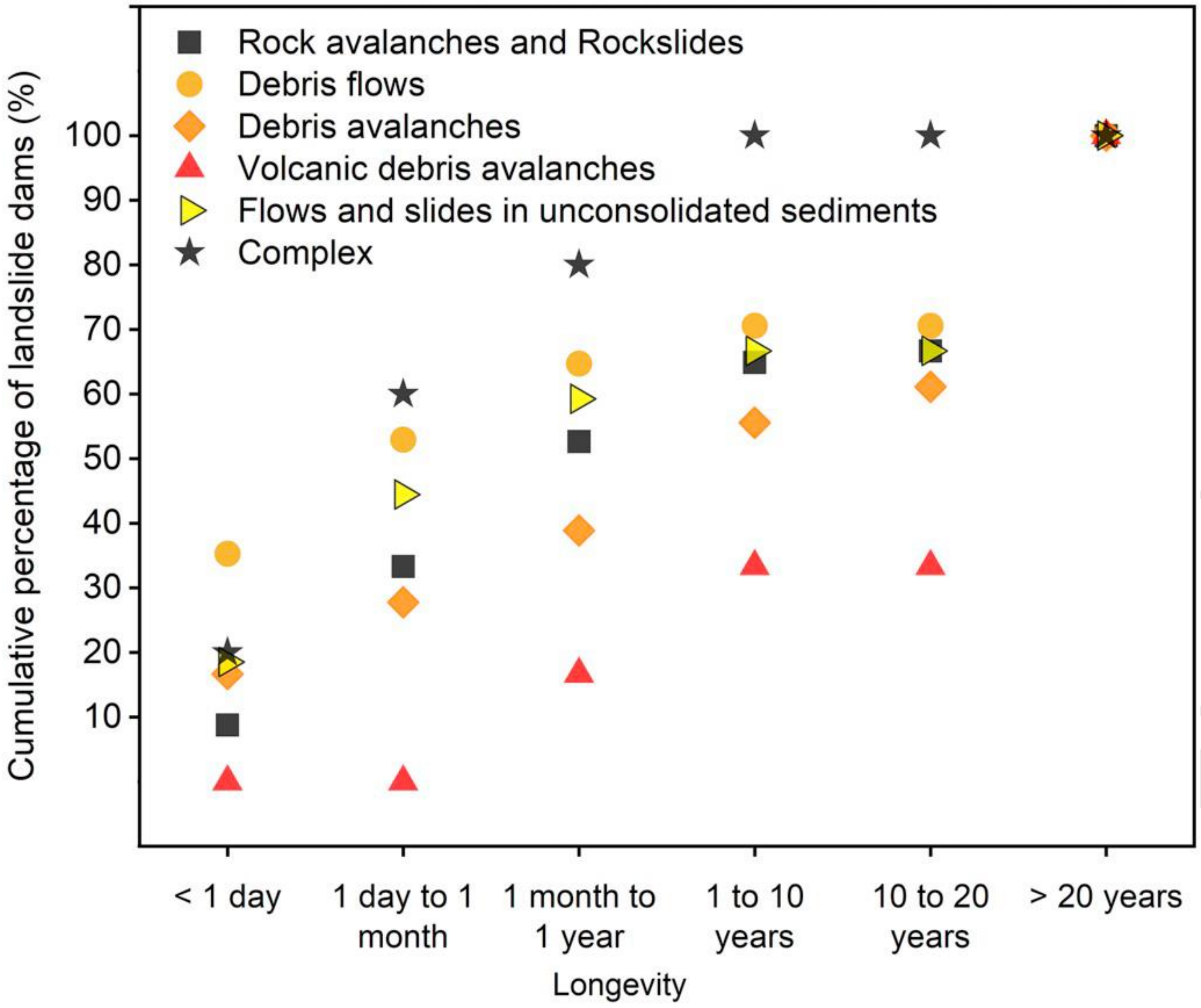

- The longevity of landslide dams relative to landslide type according to our database.
- Landslide dams for which material type is unknown are not shown.
- The sooner cumulative percentage marches towards 100 %, the lesser the longevity of the landslide dam.

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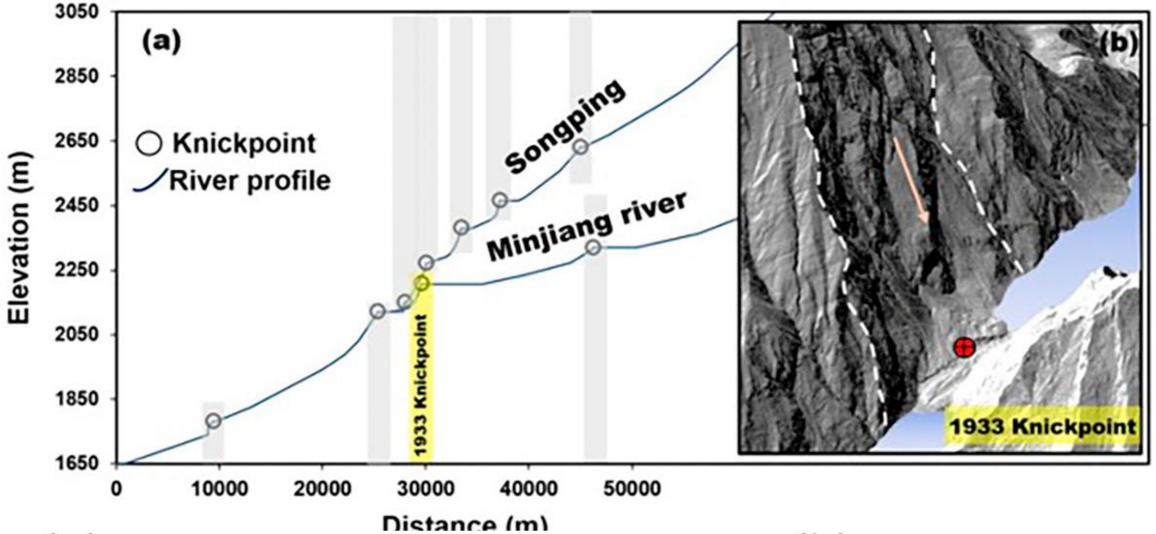
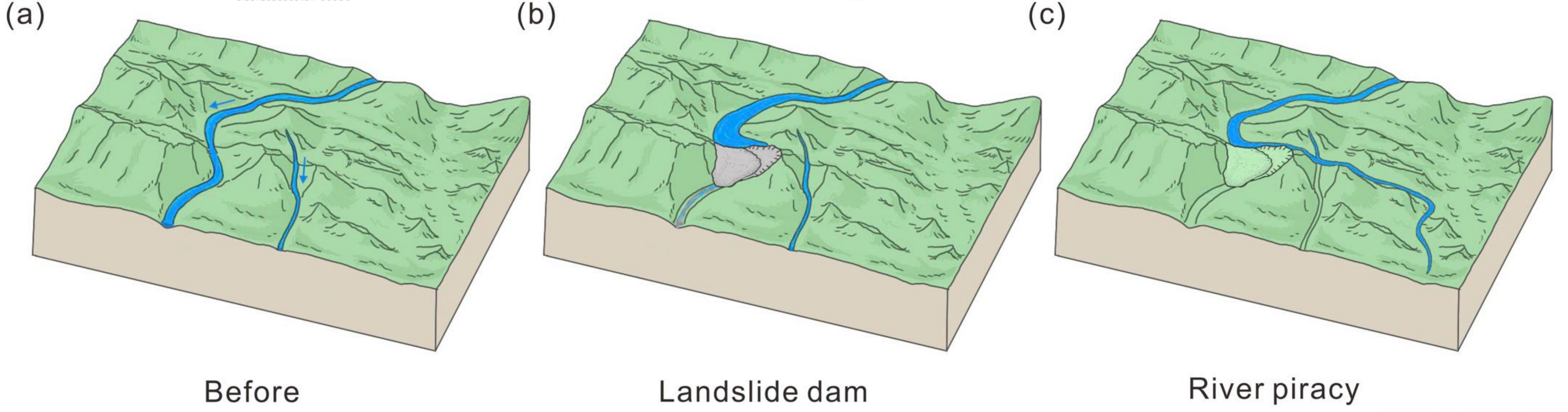
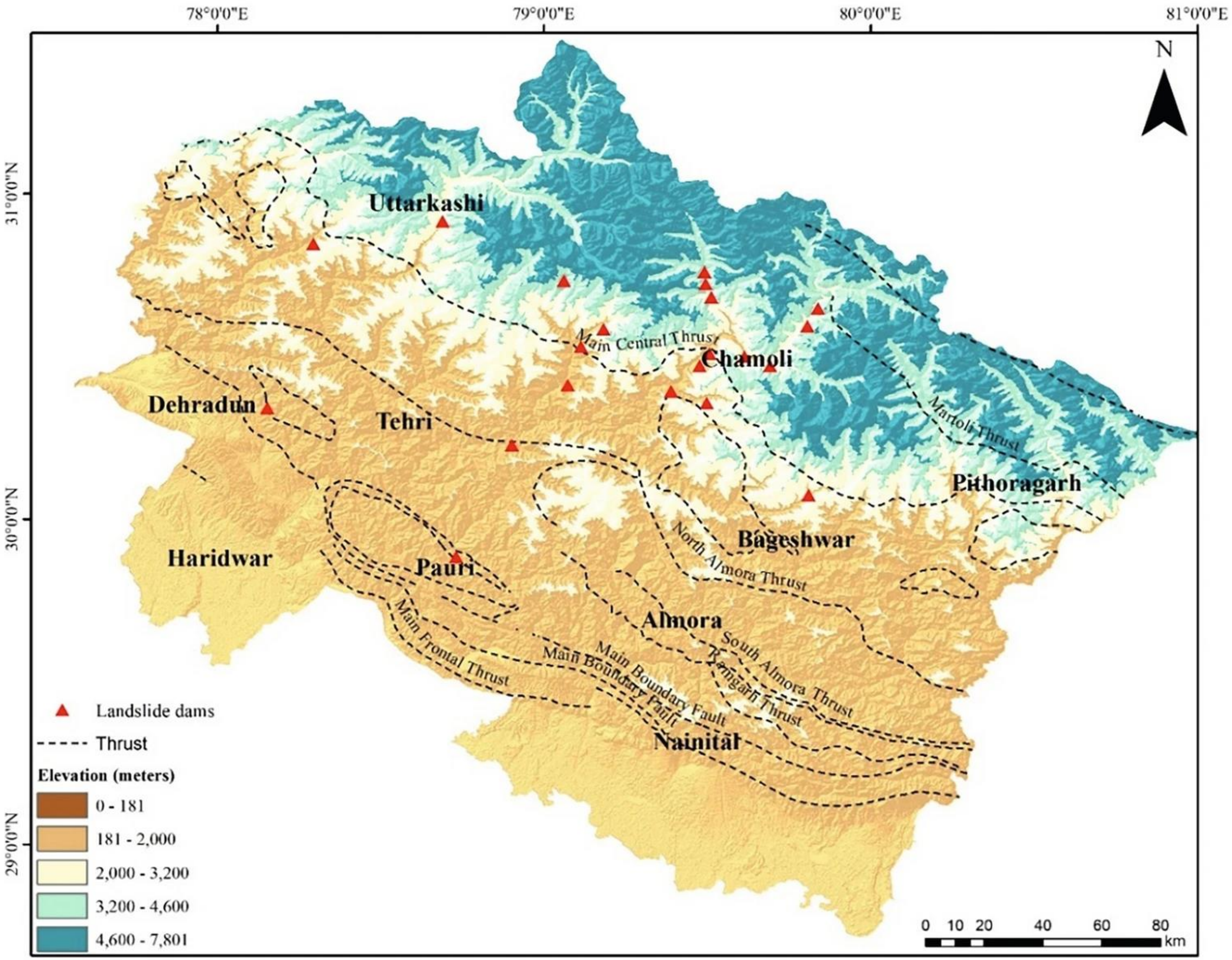


- Multiple knickpoints identified using ‘knickpointfinder’
- Schematic representation of river piracy caused by a landslide dam.



Landslide dams in Uttarakhand, India



The northwestern Indian Himalayas (Jammu & Kashmir, Ladakh, Himachal Pradesh, and Uttarakhand) are particularly susceptible to landslides and landslide dams due to weak, sheared bedrock and confined river valleys.

Map of Uttarakhand, India, showing tectonic thrusts and landslide dam locations

Landslide dams in Uttarakhand, India

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From: Landslide Dam Studies in Uttarakhand, India: Past, Present and Future

Year	Month	River	District	Landslide type	Breach	Triggered by	References
1857		Mandakini	Rudraprayag		3 days		Parkash (2015)
1868		Alaknanda	Chamoli		Temporary		Rautela and Pande (2005)
1893		Alaknanda	Chamoli	Rock fall	Temporary	Rainfall	Pandey and Mishra (2015)
1893	October	Alaknanda	Chamoli	Rock fall/slide	1st in 1894, >75 years		Rana et al. (2013)
1930		Alaknanda	Chamoli	Debris flow	Temporary		Khanduri (2021), Prakesh (2014)
1951	September	Eastern Nayar River	Pauri	Debris flow	Temporary		Khanduri (2021), Prakesh (2014)
1957		Dhauliganga	Chamoli	Avalanche	Filled with debris		Khanduri (2021), Prakesh (2014)
1968	May	Rishiganga	Chamoli	Debris slide	1970		Pandey and Mishra (2015)
1969	September	Alaknanda	Rudraprayag	Rock fall/slide	Temporary	Rainfall	Gulia (2007), Khanduri (2021)
1970	July	Dhak Nala	Chamoli	Debris flow	Temporary		Khanduri (2021)
1970	July	Alaknanda	Chamoli	Debris slide	Temporary		Rautela and Pande (2005)
1970	July	Alaknanda and Dhauliganga	Chamoli	Avalanche	Temporary	Rainfall	Khanduri (2021)
1970	July	Patal Ganga	Chamoli	Debris flow	Temporary		Pandey and Mishra (2015)
1971	August	Kanoldiya Gad, Bhagirathi	Uttarkashi	Debris slide	Temporary		Pandey and Mishra (2015)
1978		Kanoldiya Gad, Bhagirathi	Uttarkashi	Debris slide	Temporary		Pandey and Mishra (2015)
1979	April	Alaknanda	Chamoli	Avalanche	Temporary		Khanduri (2021)
1979	August	Kyunja Gad	Rudraprayag	Debris flow	Temporary		Khanduri (2021)
1998	August	Mandakini	Rudraprayag	Rockslide/fall	12 hours	Rainfall	Khanduri (2021)
1998	August	Kali	Pithoragarh	Rock fall-debris flow	1 day	Rainfall	Paul et al. (2000)
2001	August	Yamuna	Uttarkashi	Debris slide	Temporary	Rainfall	Parkash (2015)
2013	June	Madhyamaheshwar	Rudraprayag	Rock/debris slide	Temporary	Rainfall and flood	Khanduri et al. (2018)
2018	March	Baura Gad, Pindar River tributary	Bageshwar	Debris slide	Still dammed	Reactivated	Khanduri (2018)
2018	August	Song river	Tehri	Rockslide/fall	7 hours		Khanduri (2021)

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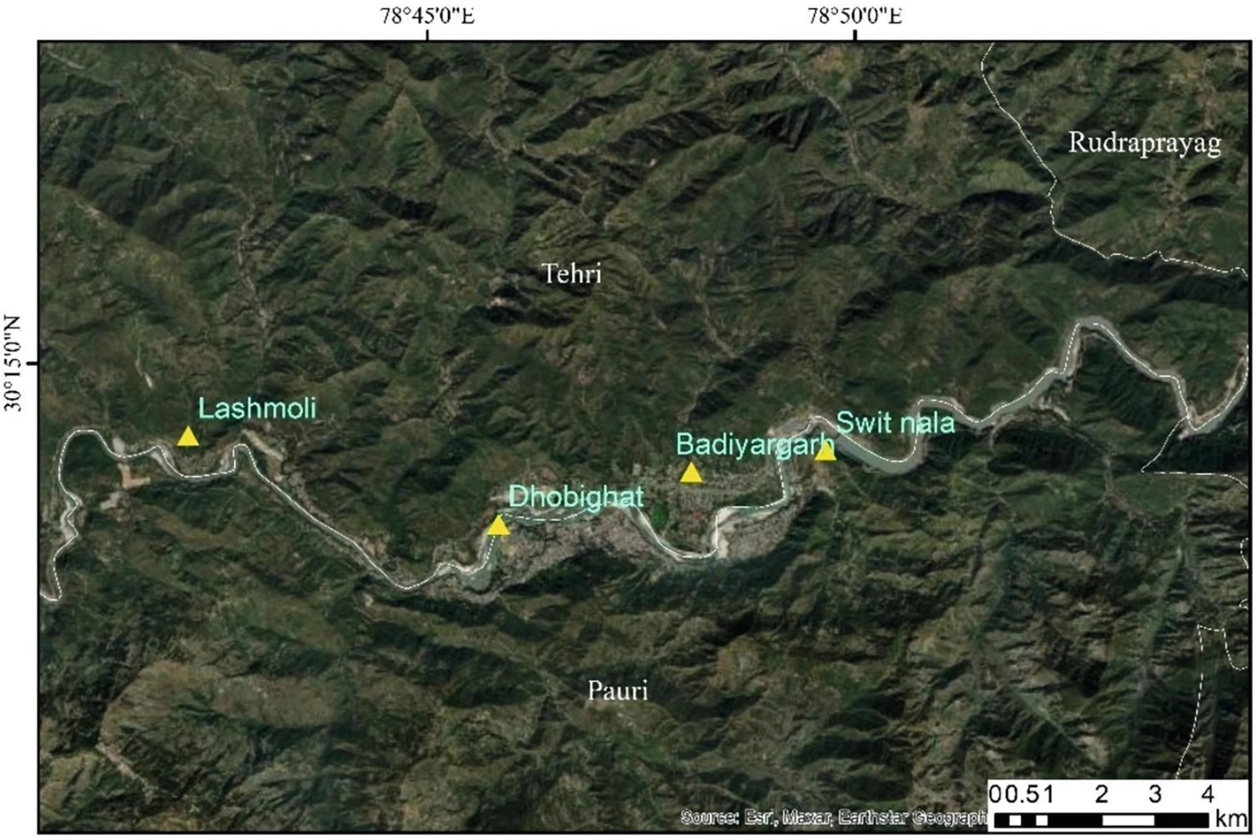
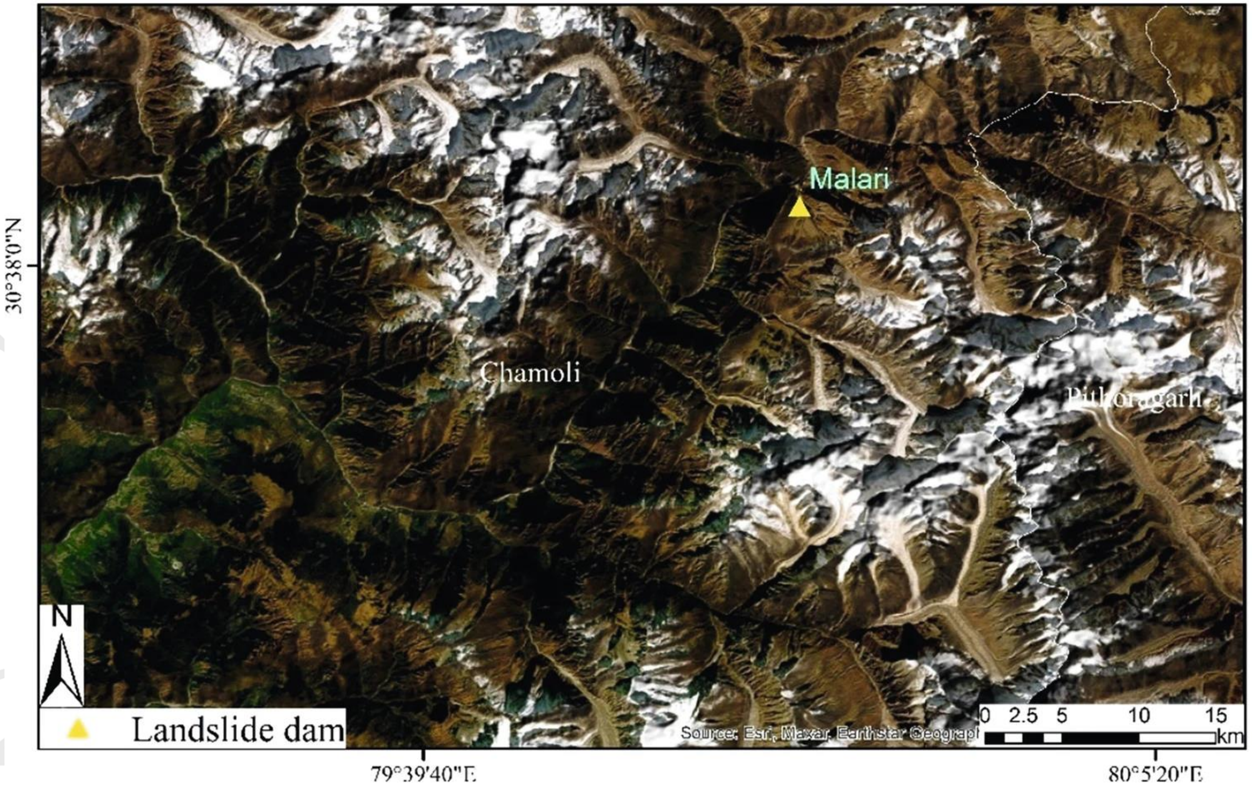


Map showing paleolakes of Alaknanda Valley, Uttarakhand, India



Map showing spatial distribution of paleolakes of Malari, Uttarakhand, India

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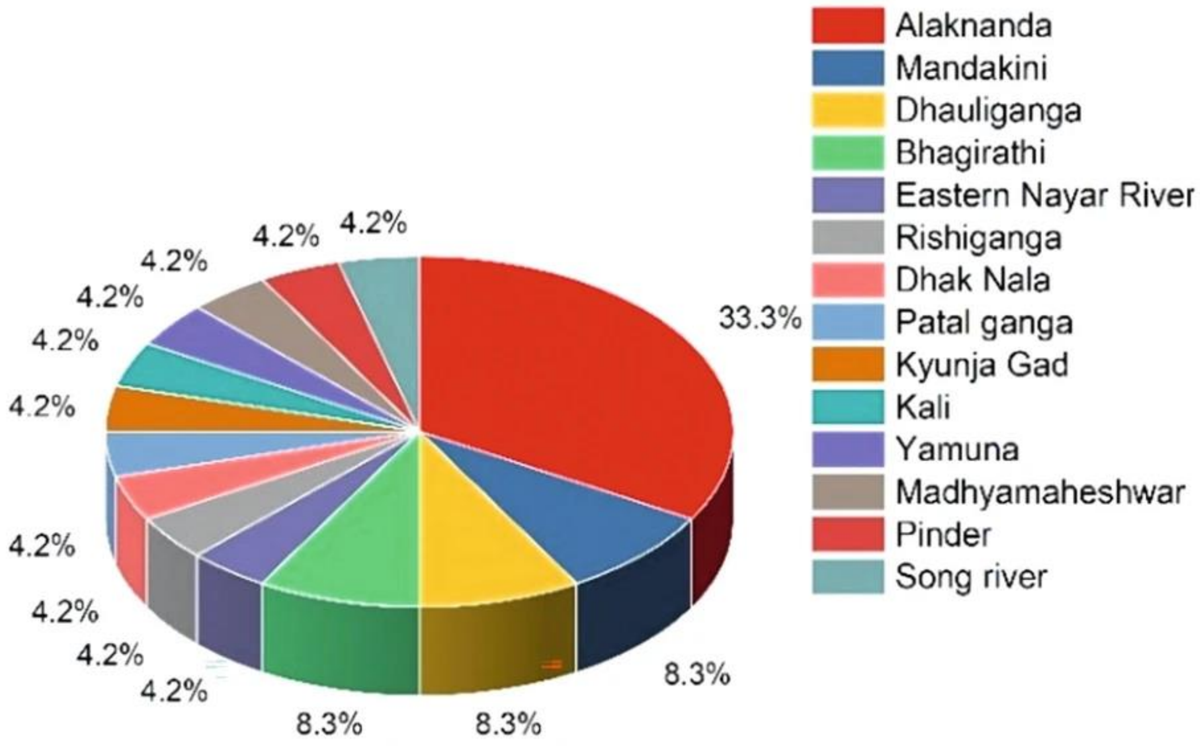
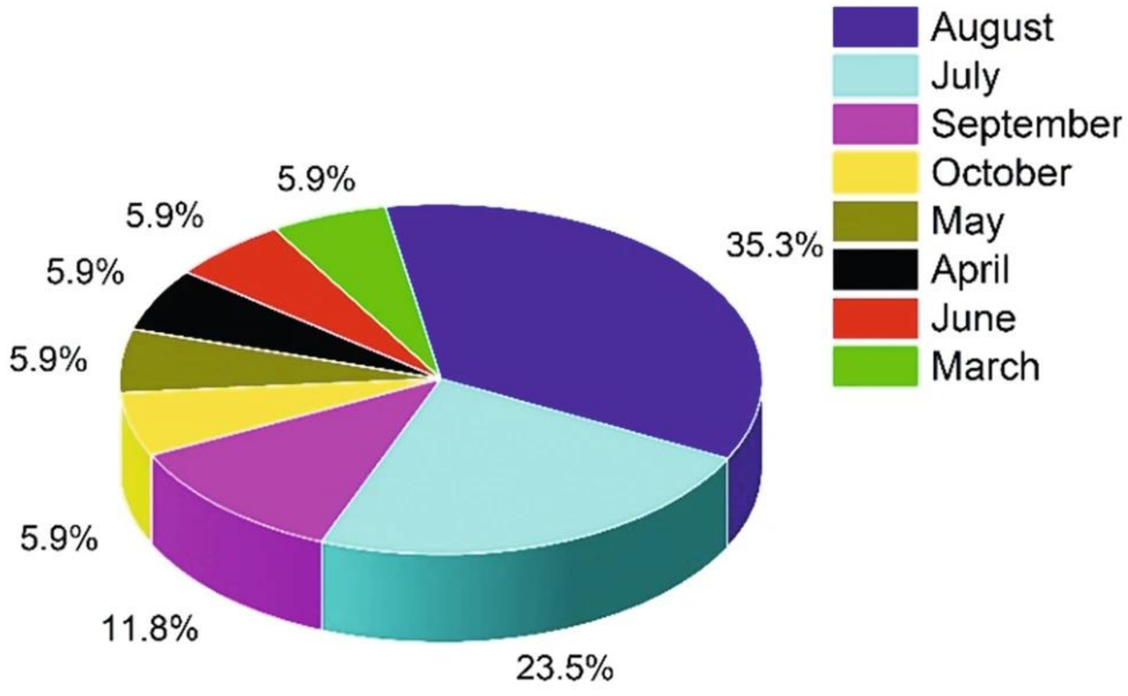


Graph showing percentage of rivers affected by landslide dams in Uttarakhand, India



Graph showing percentage of months affected by landslide dams in Uttarakhand, India

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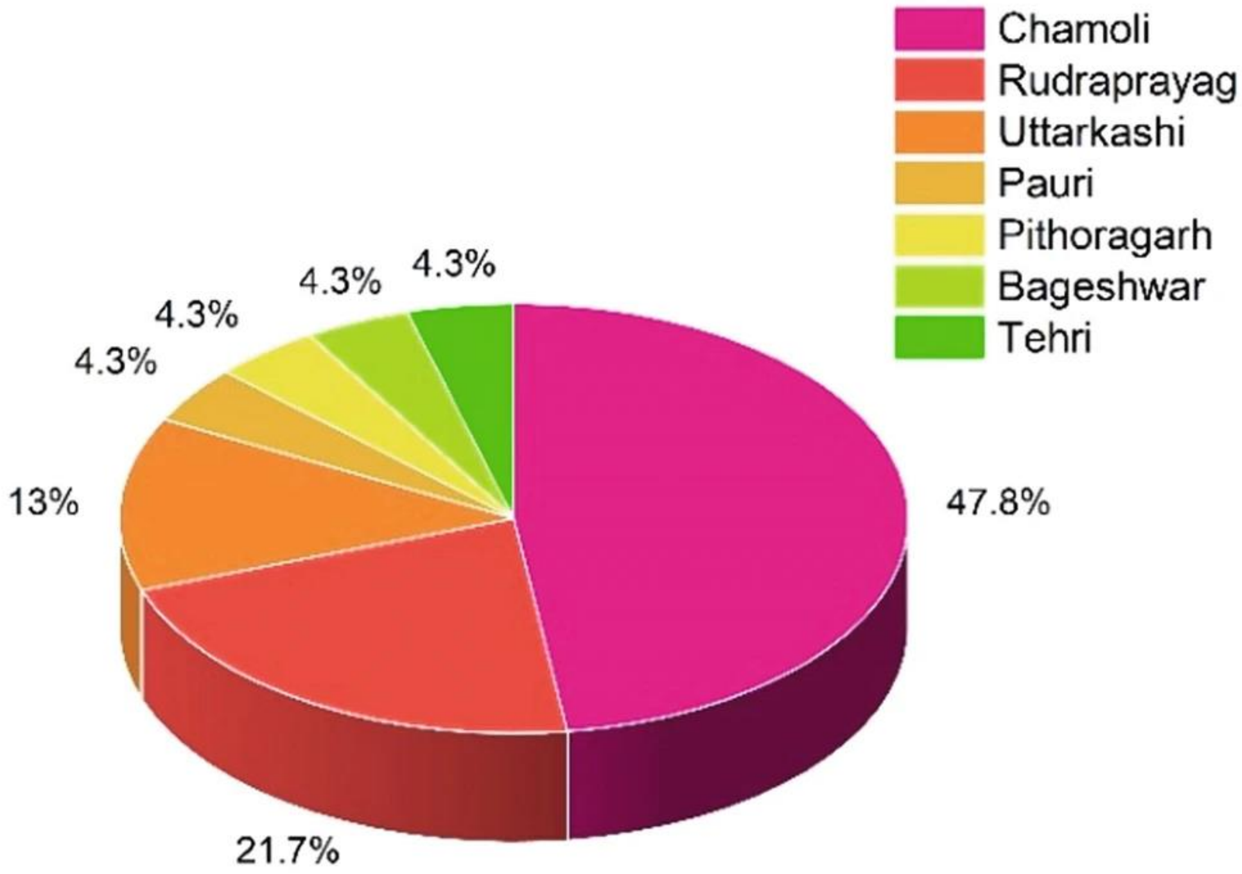
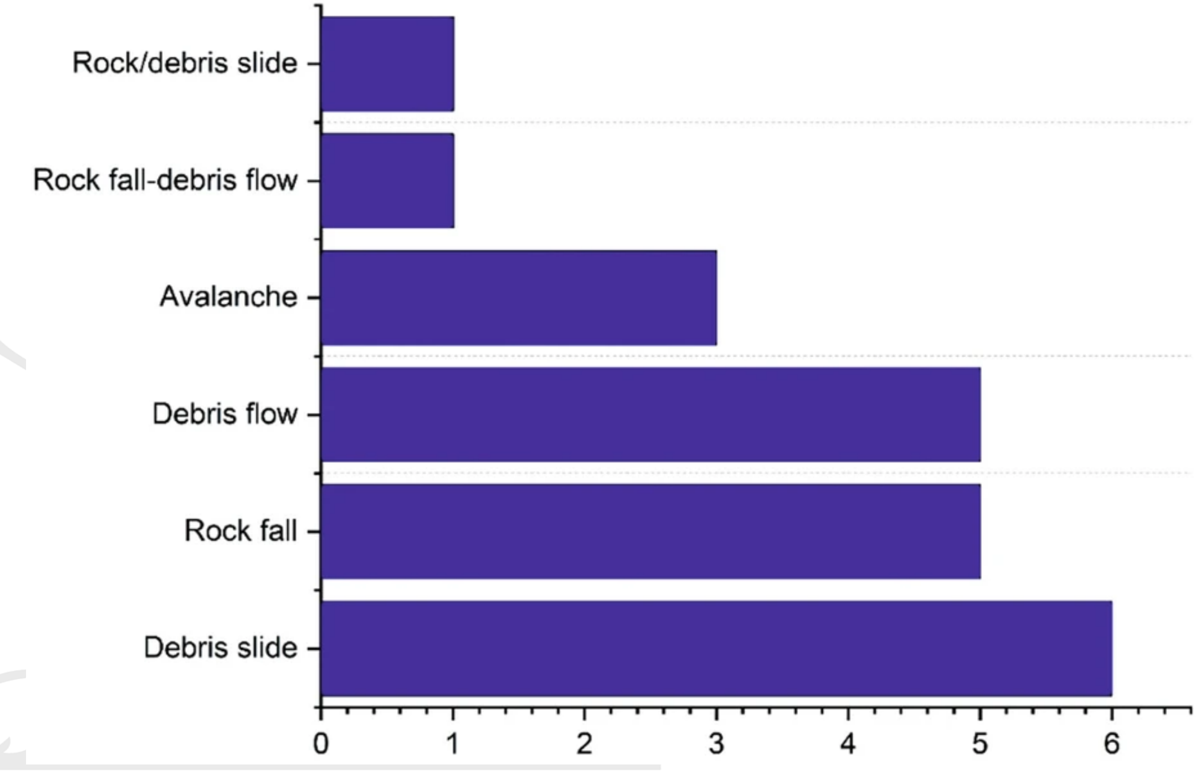


Graph showing percentage of districts of Uttarakhand, India affected by landslide dams



Graph of landslide types that caused landslide dams in Uttarakhand, India

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- Due to the evident climate change, landslide dams in the Higher Himalayas are common. The presence of debris material makes the landslide dam unstable, which may breach within a few hours or days.
- However, rock fall/slide-type landslides form stable landslide dams, which, when breached, cause major floods in the state.
- The 1970 megaflood of Alaknanda was one such example.
- In the present scenario, the Alaknanda River and the Chamoli district of Uttarakhand are most susceptible to damming.
- Analysis reveals debris slides as the most common landslide type, with a notable concentration of landslide dams occurring in August. Globally, landslide dam studies have evolved with time, and different geomorphic indices, geomorphometric parameters, and machine learning algorithms have been utilized to study the stability of landslide dams.
- The Himalayan region is complex in its own way.
- Therefore, developing such indices and numerical models specific to the region is necessary to assess and monitor the dam's formation and stability to reduce risk.

Thank you very much for your kind attention and time!

Question time