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Hydrological perspective of landslide dams: a review

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Abstract

Landslide dams, created when rapid mass movements block river channels, are strongly influenced by hydrological conditions of the upstream catchment. The formation and long-term stability of landslide dams are closely linked to hydrological factors such as stream-flow, lake area, water level and precipitation. Conversely, the formation of these dams changes upstream and downstream hydrological regimes such as water storage, sediment transport and flooding risk. Since the previous reviews by Costa and Schuster, (1988) and Korup, (2002), several review articles have focused on the formation and failure mechanism of landslide dams (e.g., Fan et al. 2020; Zheng et al. 2021). These reviews have mainly focused on geomorphological factors of dams and their formation. However, the hydrological processes around and within the landslide dam are crucial for the behavior of landslide dams, the downstream hydrology and potential flash flood risks. Therefore, there is an urgent need to study hydrological processes upstream and within landslide dams in order to better predict landslide dam stability, up- and downstream consequences. Streamflow (inflow and outflow), precipitation and snowmelt, water level, dammed lake area, lake volume, water balance, surface runoff, erosion, sedimentation, and water storage capacity are key factors for assessing the behavior of landslide dams. This review analyzes the current state of knowledge on hydrological processes influencing the evolution, and failure of landslide dams. It further examines the role of remote sensing and modelling techniques in assessing hydrological factors where field data are scarce.

Keywords Landslide dams · Hydrology · Natural dams · Flooding · Catchment management · Dam stability

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1 Introduction

Landslide dams are natural barriers formed when large-scale blockages, such as rock avalanches, landslides, or debris flows obstruct the course of a river (Chen et al. 2021; Fan et al. 2020; N.-X. Shi et al. 2023; Yang et al. 2021; Zheng et al. 2021). The formation of a landslide dam is not an unusual event, inventories show thousands of cases worldwide, but only a fraction have been studied in detail (Costa and Schuster, 1988; Fan et al. 2020). Several recent events, including 2005 Kashmir earthquake, 1999 Chi-Chi earthquake, 2008 Wenchuan earthquake, and 2009 Morakot typhoon in Taiwan, have led to the formation of numerous landslide dams (Dai et al. 2005; Hussain et al. 2009; Lin et al. 2004; Wu et al. 2014). The stability and potential failure of these dams pose significant risks to downstream areas, as a sudden dam failure can lead to catastrophic flooding and widespread destruction. A historical example is the catastrophic failure of a landslide dam on the Daru River in China in 1786, which resulted in a flood extending 1400 km downstream and causing 100,000 fatalities (Dai et al. 2005; Wang et al. 2015). A recent example is the Attabad landslide dam, formed in 2010 in northern Pakistan after a massive slope failure. It blocked the Hunza River, killed 20 people and submerged several villages (Chen et al. 2017; Li et al. 2024a, b, c). These examples highlight the importance of understanding the factors that control the stability, formation and failure of landslide dams.

Costa and Schuster (1988) reported that 50% of the landslide dams fail within 10 days of formation. However, dams can also break long after their formation. Kummer dammed-lake in South Tyrol, Italy, failed after 370 years of formation, resulting in loss of lives and destruction in the city of Merano (Shafieiganjeh et al. 2022). The stability of a landslide dam depends on many interacting factors, including the dam's geometry, volume, and material composition, as well as the physical setting of the valley (Hongchun et al. 2014; Hu et al. 2015; Mahdi 2021; Zhang et al. 2024a, b). Previous research has developed a range of empirical and geomorphological indices to evaluate the stability (Ermini and Casagli 2003; Shi et al. 2023; Tacconi Stefanelli et al. 2015a). Such indices are mostly limited to geomorphologic information, and they do not consider the role of dynamic factors such as hydrological processes. The formation and failure of landslide dams cannot be solely attributed to geological or geomorphological factors.

While substantial progress has been made in understanding geomorphological and mechanical aspects of landslide dam stability, the role of hydrological factors remains underexplored. Rainfall, snowmelt, or glacier melt control the rate at which a dammed lake fills and thus determine the water level exerting pressure on the dam. Hydrological processes also control seepage, piping and erosion which can internally weaken the dam material (Chen et al., 2019). All these factors collectively contribute to pore pressure, water absorption rate, and erosion potential (Peng et al., 2012; Takayama and Imaizumi, 2023; Xue et al., 2021). In addition, extreme meteorological events such as prolonged rainfall or sudden snowmelt can cause increased inflows that exceed the capacity of the dam to safely retain water (Zheng et al. 2021). However, in most studies, hydrology enters only indirectly, often through proxies such as catchment area or rough climate classification. As a result, hydrological processes are generally underrepresented in dam stability assessment. This gap leaves hazard assessments incomplete: it may be possible to estimate the dam's geometry, but without a realistic representation of hydrology, the probability of failure remains highly uncertain. In short, hydrology is a key element determining whether a landslide dam fails

or persists and consequently determines the societal risk both upstream and downstream the dam. Additionally, most landslide dams take place in data scarce regions, such as high mountain regions. In-situ hydrometeorological data are scarce and often fragmented or fundamentally difficult to measure (high mountain snowfall and melt). This complicates the hydrological analysis of the catchments in which the landslide dams have formed.

This situation raises a fundamental question: *can hydrological proxies be improved using new sources of hydrology-related information?* Remote sensing provides opportunities to monitor lake area, lake volume, and sometimes inflow characteristics in ungauged catchments (Abad et al. 2022; Li et al. 2024a, b, c; Zou et al. 2022). Hydrological and hydraulic models, combined with remotely sensed data, can simulate water balance and evaluate different failure scenarios. Moreover, understanding how climate change will affect upstream hydrology through changes in rainfall intensity, snowpack, glaciers, and vegetation cover can help improve the assessment of stability. These developments offer important pathways to explore the dynamic nature of dammed catchments by integrating hydrological information into the evaluation of landslide dam hazards.

The aim of this review is to critically examine how the influence of upstream catchment hydrology on the stability and failure of landslide dams has been investigated so far. Previous reviews have mostly focused on geomorphological, geological, and geotechnical aspects, while the hydrological dimension has remained largely overlooked (Fan et al. 2020; Zheng et al. 2021). Here, we analyze how hydrological factors can be incorporated, either directly or indirectly, into landslide dam research. By comparing these approaches, we identify the main limitations that have hindered a clear understanding of the water-driven processes controlling dam behavior. A literature search conducted using the Scopus database identified 470 records, of which 235 studies were included in this review. These studies were analyzed to examine existing studies about hydrological processes controlling landslide dam formation, evolution, stability, and failure. The review also highlights how recent advances in remote sensing, global reanalysis products, and hydrological modelling can help overcome existing data gaps. Through this synthesis, we aim to outline a clearer hydrological framework for future studies on landslide dam hazards and their response to changing climatic and environmental conditions.

2 Methodology

A comprehensive literature search was conducted using the Scopus database to identify studies related to landslide dams and their hydrological characteristics. A search string including terms such as “landslide dams”, “natural dams”, and “dammed lakes” was developed to capture relevant publications from 2010 onwards (Fig. 1). The search was performed on 23 August 2024 and initially identified 470 records. The retrieved articles were then screened manually based on their relevance to landslide dams, dammed lakes, hydrological processes, stability assessment, monitoring, and failure mechanisms. Following this screening process, 235 studies were identified as highly relevant and were used as the primary literature base for this review. Additional relevant references were obtained through citation tracking of key publications.

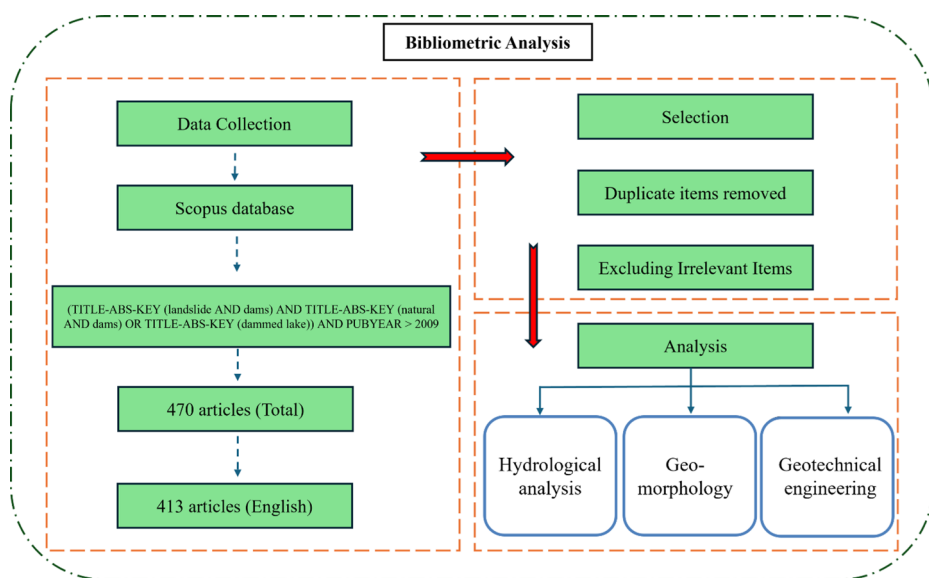


Fig. 1 Literature search and study selection workflow used for identifying and screening publications related to landslide dams and their hydrological characteristics

3 Formation and stability of landslide dams from geomorphologic and geotechnical perspective

Several hydrological and geological processes can combine to create a landslide dam (Fan et al. 2020; Strom et al. 2014). These processes are important in landslide dam formation, most of which appear to take place in fault zones primarily due to tectonic influences. The major triggering factors leading to landslide dam formation are earthquakes and extreme rainfall (Fig. 2a), while other processes such as glacial retreat, snowmelt or volcanic activity are less frequent (Costa and Schuster, 1988; Dai et al. 2005; Ermini and Casagli 2003; Fan et al. 2020; Li et al. 2019). According to a recent study conducted by Fan et al. (2020), a natural dam can be formed by six types of landslide phenomena including (1) rockslides, (2) volcanic mass movements, (3) debris flows, (4) unconsolidated sediments, (5) debris avalanches, (6) complex and transforming landslides (Fig. 2b).

Recently, several studies (Fan et al. 2020; Morgenstern et al. 2024; Shen et al. 2020; Zheng et al. 2021; Wu et al. 2022) have prepared landslide dam inventories by compiling multiple parameters like failure modes, triggering factors and dam volumes. Many of these dams collapse quite fast; 7.3% last less than a day, and 11.2% last up to a month. But some live much longer, and 20.2% of them do so for more than 20 years.

Observed failure modes of landslide dams (Fig. 3) include overtopping (occurring in more than 90% cases), seepage-induced piping and surface erosion, and slope failure (Fig. 3c). Overtopping generally occurs when inflow exceeds the storage capacity of the lake, leading to erosion of the crest and downstream slope. Rapid surface degradation of the dam material after overtopping frequently results in catastrophic failure (Hu et al. 2015; Meng et al. 2025; Zhang et al. 2024a, b). This may occur because of extreme precipitation or snowmelt, and an abrupt rise in river discharge. Piping arises where intense seepage causes

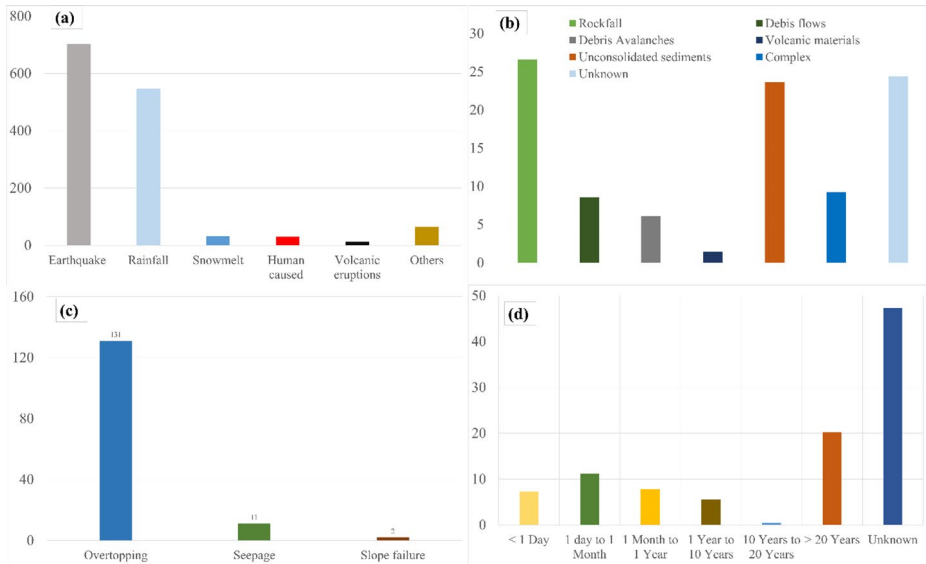


Fig. 2 **a** Triggering factors of landslides that led to the formation of dams (Shen et al. 2020; Zheng et al. 2021), **b** landslide types responsible for dam formation (410 cases) (Fan et al. 2020), **c** types of failures in reported (144 cases) landslide dam failure events (Zheng et al. 2021), **d** life span of landslide dams (410 cases) (Fan et al. 2020)

internal erosion, with water infiltrating preferentially along internal pathways, gradually enlarging them until collapse occurs (Dhungana and Wang 2019; Okeke and Wang 2016). This process is especially dangerous in fine-grained material dams. Surface erosion may result from spillway flow or prolonged seepage through weak zones. Slope failure may involve either upstream or downstream dam face and is caused by pore pressure variations within the dam's body due to rapid water level changes. Each of these mechanisms depends not only on dam's geometry and on the physical properties of the material constituting the dam, but also on hydrological forcing.

Geomorphological research have proposed several empirical indices to evaluate landslide dam stability (Table 1). Swanson et al. (1986) related dam persistence to the ratio between dam volume and catchment size, assuming that the larger dams in smaller catchments are more stable. Casagli and Ermini (1999) emphasized the role of valley width and landslide velocity, suggesting that rapid failures in narrow valleys create more confined and stable dams. Building on these approaches, Ermini and Casagli (2003) proposed a geomorphic index that combines dam height, dam volume, and upstream catchment area. Similar indices and empirical classifications have been proposed by later studies (Chang and Zhang 2010; Takayama and Imaizumi 2023), to provide first-order evaluation of dam stability in the absence of hydrological data. Although such indices are useful, they remain static as they do not consider temporal hydrological variations. To include the influence of water, Tacconi Stefanelli et al. (2016) developed Hydromorphic Dam Stability Index (HDSI) by integrating discharge, fluid density, and gravity. This represents one of the first attempts to bridge the gap between geomorphology and hydrology in dam stability assessment. How-

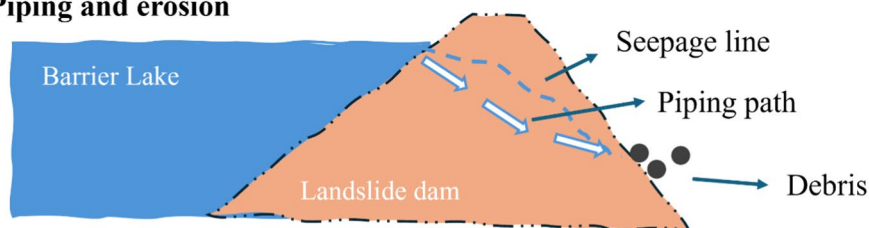
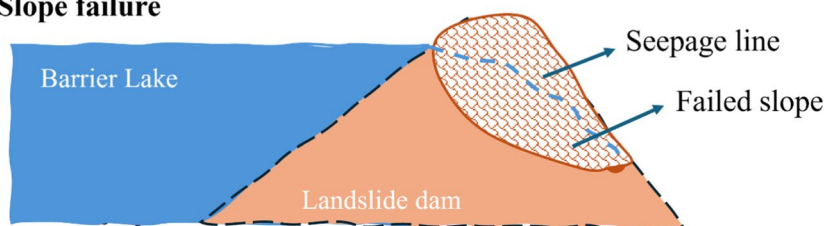
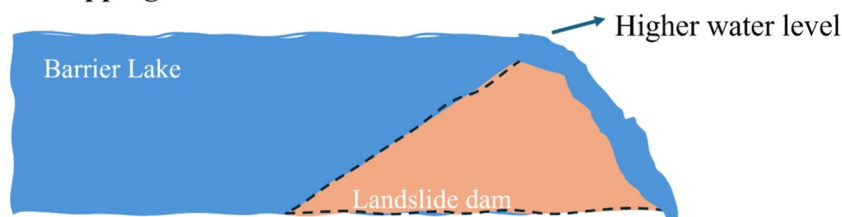
(a) Piping and erosion**(b) Slope failure****(c) Overtopping**

Fig. 3 Schematic representation of failure mechanisms, **a** *Seepage*, occurs when water from barrier lake infiltrates through porous materials of the dam, due to persistent seepage flow internal erosion channels (pipes) develop through the dam body, **b** *Slope failure*, where instability of the dam material causes sliding along a failure surface within the dam body, **c** *Overtopping*, where the rising water level in the lake exceeds the dam crest and the flow over the dam body may initiate downstream breach

ever, geomorphic assessments may suggest that a dam is stable, while it may be vulnerable to failure under extreme hydrological conditions.

Geotechnical research has seen significant advancements to improve landslide dam stability analysis and hazard assessment. Particle size distribution (PSD) has emerged as a key parameter to characterize material properties, affecting dam texture, permeability, and overall stability. Dams formed by rock avalanches often consist of coarse blocky debris with high permeability, which may favor rapid seepage but also reduce the likelihood of overtopping (Dunning et al. 2005; Weidinger 2011). From field surveys, Gorum et al. (2011) observed that landslide dams composed of unconsolidated fine materials have lower stability than those composed of rock boulders, owing to different erosional resistance capacity, dam strength and permeability determined by the composition materials. The degree of sorting, layering, and internal structure of the landslide deposit further affects stability (Zhang et al. 2024a, b). Heterogeneous deposits with weak layers of contrasting permeability are prone to internal erosion and piping (Li et al. 2024a). Mechanical strength and hydraulic conditions also play a role (Kiyota et al. 2011; Wang et al. 2012; Zhang et al. 2024a,

Table 1 Details of some geomorphological empirical indices used to evaluate landslide dam stability

Study	Name	Variables considered	Purpose
Swanson et al. (1986)	Blockage index (BI)	Dam volume, drainage basin area	Relationship between dam size and inflow potential
Casagli and Ermini (1999)	Impoundment index (II)	Landslide volume, lake volume	Empirical stability evaluation
Ermini and Casagli (2003)	Dimensionless blockage index (DBI)	Dam height, dam volume, catchment area	Stability evaluation
Chang and Zhang (2010)	–	Dam volume, lake area, inflow proxies	Classification of dam persistence
Tacconi Stefanelli et al. (2016)	Hydromorphic dam stability index (HDSI)	Discharge, fluid density, gravity	Stability evaluation
Feng et al. (2025)	Dam composition index (DCI)	PSD, grading parameters	Gradation and composition of landslide dam material.
Liao et al. (2022)	Material-based morphological index (MMI)	Grain size distribution, dam volume, height, width	Stability evaluation

b). Cohesion, friction angle, and compaction influence how the dam resists shear failure (Mkilima 2022), while consolidation over time can increase stability.

Efforts have been made to incorporate geotechnical factors into empirical models to predict dam stability, such as logistic regression methods that combine dam geometry and material characteristics, though validation remains limited (Dong et al. 2011; Shi et al. 2023). To improve quantitative assessment, new indices like the Material-based Morphological Index (MMI) have been proposed (Liao et al. 2022), integrating dam geometry, PSD, and impounded water properties for evaluating landslide dam stability. Zhou et al. (2019a, b) applied the discrete element method (DEM) to analyze the particle distribution within landslide dam deposits and observed that a longer sliding path, higher base friction coefficient, and gentler slope gradient increase the heterogeneity of particle arrangement in the dam body. Furthermore, the Dam Composition Index (DCI) has been introduced to systematically quantify the gradation of landslide dam material (Feng et al. 2025). In addition, another dimensionless parameter D^* is proposed by Zhou et al. (2025) to quantify the material distribution. These geotechnical indices face significant limitations due to material data scarcity from heterogeneous natural dams, as material properties have been often considered to be of secondary importance compared to dominant geomorphological controls on dam stability (Shi et al. 2023).

Although geomorphologic and geotechnical indices are useful for a first assessment of landslide dam stability, they do not capture the full picture, as they do not consider the dynamic effects of hydrological processes. As a result, geomorphic assessments may suggest that a dam is stable, while it may be vulnerable to failure under extreme hydrological conditions. This is the case, for example, of the landslide dam of Ram Creek (New Zealand), that was considered stable according to geomorphic indices but failed after a few hours of intense rain (Nash et al., 2008).

4 Upstream catchment hydrology

Hydrology of the upstream catchment plays a major role in the evolution, stability, and potential failure of landslide dams. Inflow from rainfall, snowmelt, glacier melt, or groundwater directly controls the rate at which a lake forms and fills behind the barrier, determining the water loading on the dam (Fig. 4). Unlike geomorphological and geotechnical factors, which are largely static, hydrological processes are dynamic and can change rapidly in response to seasonal conditions. As a result, hydrology is often the triggering force that shifts a landslide dam from a stable to an unstable state.

Although rarely investigated explicitly, the physical link between upstream catchment hydrology and landslide dam stability shows clearly through several studies. Dong et al. (2009) showed the importance of historical peak flow for landslide dam stability assessment through discriminant analysis on a data set of 43 landslide dams in Japan. A similar result was obtained by the same authors with logistic regression (Dong et al. 2011). Cencetti and Di Matteo (2022) showed how a potentially unstable landslide dam in Italy did not fail in a period of high river flows thanks to a pre-existing hydropower by-pass that diverted 80% of the peak flow. With a Bayesian analysis, Frigerio Porta et al. (2020) showed that upstream catchment area, together with dam shape, controls the lifetime of landslide dams. A similar result was obtained by Shi et al. (2023), that pointed out that dam morphology and catchment area are the two major factors affecting dam longevity, while dam material played a

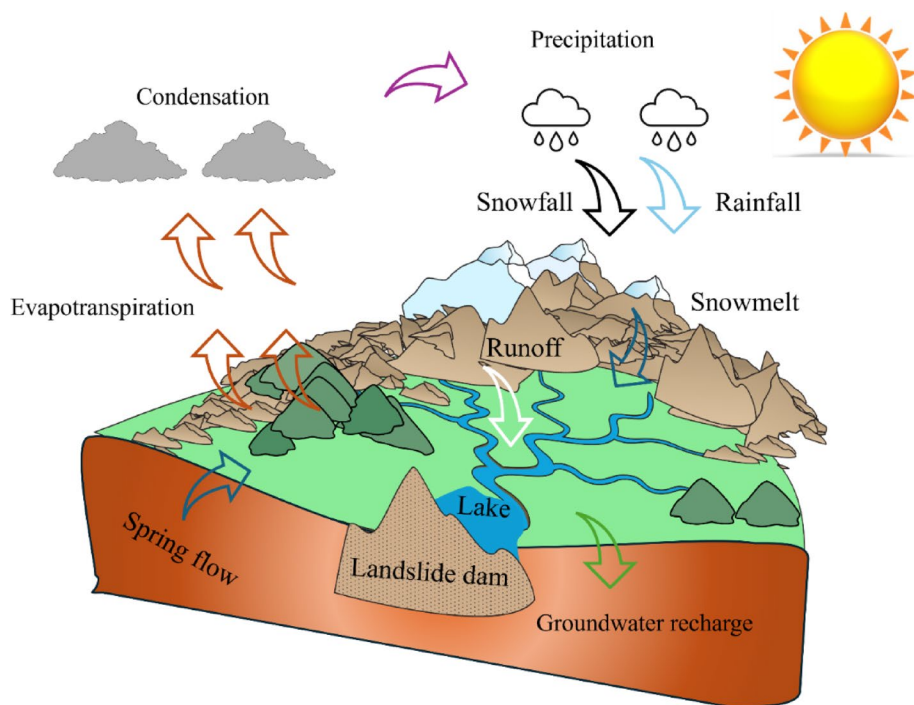


Fig. 4 Schematic representation of hydrological processes in a landslide-dammed catchment. Key hydrological components such as rainfall, snowfall, snowmelt, groundwater recharge, spring flow, surface runoff, and evapotranspiration are shown. These processes interact within the modified catchment system formed due to the landslide-induced blockage of river flow

minor role. Shafieiganjeh et al. (2022) showed that geomorphic indices based on catchment ruggedness predicted the evolution of landslide dams and lakes with little uncertainty. The important role of hydrological factors on landslide dam stability has been recently confirmed by several studies with machine learning and deep learning models (e.g., Huang et al. 2025; Lee et al. 2014). However, availability of field data on river discharge is still limited, and the quantitative evaluation of the effects of inflow conditions on dam failure is still mostly carried out with small scale flume experiments (e.g. Dhungana and Wang 2019; Li et al. 2024b, 2025; Liu et al. 2025; Luo et al. 2025; Niu et al. 2023; Zhou M., 2019a, 2019b) and numerical models (e.g., Hu et al. 2015; Meng et al. 2025; Zhang et al. 2024a, b; Zhong et al. 2020).

All kinds of dam failure mechanisms described in Sect. 3 are activated by high water levels in the lake. Hence, the water balance of upstream catchment is crucial, as surface and subsurface runoff, and evapotranspiration determine the availability of water in the lake. The relationship between inflows and outflows is crucial to maintain a stable water level in the dammed lake. The higher the snowmelt and precipitation, the greater the lake inflow will be. Outflow can occur in several ways like natural spillways and seepage (e.g., Cencetti et al. 2017), and controlled releases (Li et al. 2024a, b, c). Real time monitoring of water storage of the dam is important to have a better understanding of the situation and activating emergency plans.

Recent advancements in remote sensing and hydrology have made it easier to monitor the water balance of dammed catchments (Abad et al. 2022; Li et al. 2024a, b, c; Senay et al. 2011). Landslide dams are often formed in remote mountainous areas where data scarcity is a major issue (Korup and Tweed 2007). Several satellite and reanalysis datasets exist and have proven effective for monitoring ungauged catchments to support water balance analysis (Abatzoglou et al. 2018; Gbetkom et al. 2024; Jamal et al. 2025; Shrestha and Nepal 2019). Satellite imagery can also be used to estimate the surface area and volume of dammed lakes, providing valuable information on storage dynamics. Furthermore, recent developments in radar technologies such as Sentinel-1 (SAR), SWOT, and other satellite altimetry techniques have been introduced (Huang et al. 2024; Le Traon et al. 2025), which can be used to measure the discharge and water surface elevation of dammed lakes. Hydro-meteorological variables can also be accessed and compared through multiple data sources. Some remote sensing products can provide snow fraction and snowmelt data, and datasets are also available on glacier mass balance. Integrating all these technologies can improve water balance assessment in ungauged dammed catchments. Complete details of the available remote sensing products and their potential applications are given in Table 2.

Considering the limited availability of input data required for hydrological modelling of landslide dam catchments, lumped models, such as the Budyko framework (Budyko 1958; Zhang et al. 2008) and GR6J (Perrin et al. 2003; Pushpalatha et al. 2011), can be effectively used to explain the hydrological processes occurring upstream of the dam (Park et al. 2025; Shazil et al. 2025). Reliable hydrological modeling relies on meteorological inputs but in many mountainous catchments ground observations are sparse or completely absent. These inputs can be obtained from both global reanalysis products and General Circulation Models (GCMs). Reanalysis datasets combine observations with numerical weather prediction models, making them suitable for historical and near-real-time hydrological monitoring. In contrast, GCMs simulate future climate conditions and can be used to investigate the impacts of climate change on hydrological regimes. Nevertheless, both datasets are subject

Table 2 Remote sensing datasets and technologies supporting hydrological monitoring of upstream catchments influencing landslide dam formation and stability

Hydrological process	Product	Sensor	Spatial–temporal resolution
Precipitation	GPM, TRMM, ERA5-Land, CHIRPS	Microwave / reanalysis	0.1°–0.25°, 30 min–daily
Evapotranspiration	MOD16, TerraClimate, ERA5-Land	MODIS / multi-source fusion	500 m–0.25°, 8-day–monthly
Soil moisture	SMAP, ASCAT, ESA CCI	Microwave L-band / scatterometer	9–25 km, daily–weekly
Snow cover and melt	MOD10A1 (MODIS), Sentinel-2 MSI, Landsat-8/9 OLI	Optical / NIR	10–500 m, daily–16 days
Glacier melt	ICESat-2, GRACE-FO, Sentinel-1 SAR	Laser altimeter / gravimetry / radar	20–300 m (altimetry), ~300 km (GRACE), 6–30 days
Surface water extent	Sentinel-1/2, Landsat Series	Radar / optical	3–30 m, 6–16 days
Lake volume estimation	Landsat+DEM Integration, Sentinel-2, ICESat-2	Optical+elevation	10–30 m, 10–35 days
Lake water level	ICESat-2, CryoSat-2, Sentinel-3 SRAL, Jason-3	Laser / radar altimeter	~20–300 m footprint, 10–35 days
Catchment runoff	GRACE-FO, ERA5-Land, GLDAS	Gravimetry / reanalysis	0.1°–1°, daily–monthly

to uncertainties related to spatial resolution and topographic complexities, therefore reducing these uncertainties are equally important for increasing the reliability of landslide dam stability predictions.

The Attabad landslide dam in northern Pakistan shows the importance of considering hydrological processes in landslide dam stability. Although the dam was initially considered highly vulnerable due to its size and large catchment, it is still stable after more than 16 years. Along with the spillway excavation, a major factor contributing to dam persistence is the hydrological regime of the upper Karakoram catchment, where precipitation is relatively low and mainly falls as snow. The gradual release of meltwater reduces extreme discharge peaks and limits overtopping potential, clearly showing how upstream catchment hydrology can affect dam stability.

5 Hydrological drivers of dam stability

The hydrologic controls governing landslide dam evolution are case-specific and cannot be generally attributed to a single variable or process. Unlike geomorphological conditions, which remain relatively constant after dam formation, hydrological conditions are highly dynamic and directly influence dam stability and potential failure mechanisms. Their importance depends on the interaction between upstream catchment characteristics, regional climate, dam shape and material, and dominant failure mechanism. In humid catchments, extreme precipitation may increase inflow and trigger overtopping, while in snow-dominated catchments seasonal snow and glacier melt control long term reservoir filling and dam stability. In arid and semi-arid regions, prolonged dam persistence may be favored by limited precipitation, although high discharge peaks may occasionally occur during extreme precipitation events. In the same way, seepage and internal erosion are more important

potential failure mechanisms for permeable dams. This case-dependent behavior explains why landslide dams with similar dimensions and shape may exhibit different lifetimes and failure patterns.

Hydrological factors such as snowmelt, rainfall and river discharge contribute to hydraulic mechanisms like seepage and overtopping (Fig. 4). The hydrology of the upstream catchment controls the amount and timing of water entering the lake that forms behind a landslide dam. The rate at which this water accumulates determines the water level and the pressure acting on the dam body. These factors are directly linked to whether a dam remains stable or fails. However, the role of hydrology has often been simplified in previous studies and treated only through indirect indicators (Huang et al. 2025; Meng et al. 2025; Zhang et al. 2024a, b). Rainfall is the most direct and important factor influencing inflow. Intense or prolonged rainfall events can rapidly increase runoff from the upstream catchment (Dunning et al. 2006; Nash et al., 2008) and raise the lake level to the dam crest. Such conditions may also trigger secondary landslides into the lake, producing waves that overtop the dam (e.g., Hermanns et al. 2004). Despite this, many existing studies only consider average rainfall conditions or use broad climatic categories, which fail to represent short-term extremes that usually cause failure.

Snowmelt and glacier melt also play a critical role, especially in high mountain regions. During warm periods or sudden temperature rises, snow and glacier melt can generate large inflows within a short period. These inflows often occur with a delay after the triggering event, which makes them difficult to predict. In several reported cases, stable dams failed months or even years later due to exceptional meltwater inflows (Evans et al. 2011; Ruiz-Villanueva et al. 2017). Yet, most stability assessments ignore these delayed hydrological effects and treat dam formation and failure as single events.

Catchment size and physical characteristics also influence the hydrological response (Liao et al. 2022). Larger and steeper catchments tend to generate higher runoff peaks, but the relationship is not always linear. Factors such as vegetation, land cover, and soil type affect infiltration and the timing of runoff. Still, many studies use catchment area as the only hydrological parameter, assuming it represents inflow potential. This simplification often leads to uncertainty, since two catchments of similar size may behave very differently depending on their climatic and topographic setting. Existing approaches rarely capture this variability and instead rely on indirect indicators that cannot represent actual inflow or water level fluctuations (Fig. 5).

Recent studies use satellite data to estimate changes in lake area and volume. For example, Li et al. 2024a, b, c; Zou et al. (2022) applied satellite imagery to measure the size and height of landslide dams and to estimate the volume of the dammed lakes. Abad et al. (2022) used Sentinel-2 images in Google Earth Engine to detect and monitor new lakes formed after the Kaikōura earthquake in New Zealand. They found that such methods can quickly map and show how a lake expands or shrinks over time. A recent study by Shen et al. (2020) estimated landslide dam longevity by dividing it into infilling, overflowing, and breaching stages. Regression models based on inflow rate, discharge coefficient, and lake shape coefficient showed that dam longevity is mainly governed by hydrological factors, with rainfall-induced dams exhibiting shorter lifespans due to high inflow and fine-grained material. In another study Zhou et al. 2019a, b; Meng et al. (2025) simulated dam failures using laboratory and numerical models, focusing on how inflow discharge and erosion processes affect the peak of the outburst flood. These studies confirm that the amount and timing of

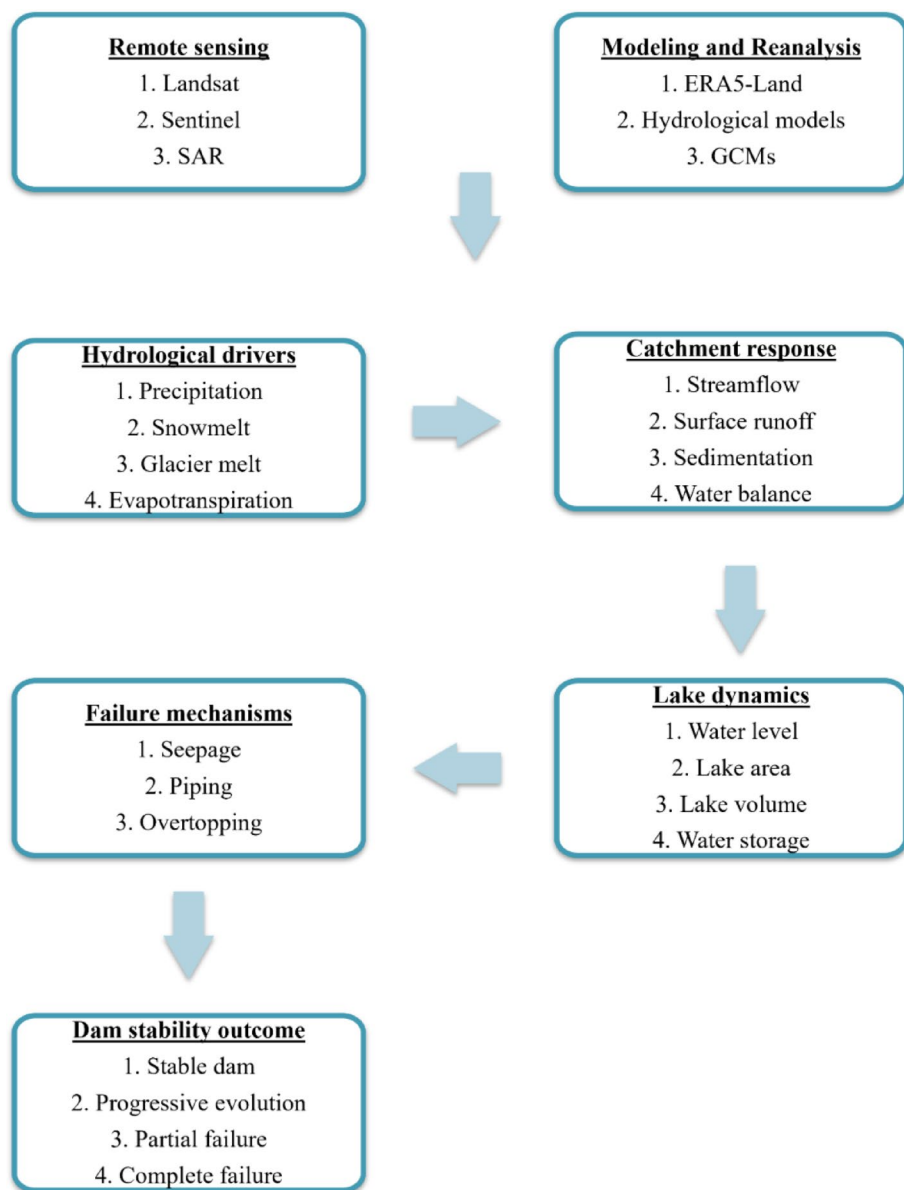


Fig. 5 Conceptual hydrological framework linking climatic drivers, catchment response, lake dynamics, and failure mechanisms controlling landslide dam stability

inflow are critical factors in dam stability. Lee et al. (2014) presented a more data-driven method, using real-time hydrological observations and neural networks to detect abnormal flow changes that may indicate dam formation or failure.

Available literature indicates that no single hydrological parameter or process can reliably help predict landslide dam stability in different environments. Effectiveness of stabil-

ity assessments depends on integrating multiple hydrological variables rather than relying on oversimplified hydrological proxies such as catchment area or average annual rainfall. Recent advances in hydrometeorological remote sensing and data driven approaches provide opportunities to investigate the role of dynamic hydrological variables in landslide dam monitoring (Table 3).

6 Climate change impact on landslide dam stability

Climate change is expected to modify the hydrology of mountain catchments where most landslide dams occur. In many mountainous regions climate change is expected to increase the intensity and frequency of rainfall and snowmelt extremes, leading to increasing landslide occurrence (Bernardie et al. 2021; Clague 2009; Fan et al. 2025; Hürlimann et al. 2022) that can block rivers and also alter the hydrology. These changes will influence inflow magnitude, timing, and the internal moisture conditions that control dam stability. Existing work rarely combines climate projections with hydrology or stability models. Most analyses still use simplified rainfall scenarios. Using downscaled future climate projections with process based hydrological models can quantify how changing water input can alter dammed lakes and failure probabilities.

Climate change can also influence the other factors of water balance like snowmelt, glacier retreat and permafrost degradation. Warming temperatures lead to rapid snowmelts and glacier retreats which can influence runoff timings. Such shifts in timing may result in lake level peaks occurring sooner after dam formation, increasing the risk of early failure. Glacier retreat can also expose new valley walls and debris sources, creating conditions for future landslide dams (Haeberli et al. 2017; Jamal et al. 2025; Korup and Tweed 2007). Meltwater from glaciers may accelerate lake filling or destabilize existing dams through increased seepage. Recent studies show the effects of climate change on landslide susceptibility (e.g., Hürlimann et al. 2022; Roman Quintero et al. 2026).

Vegetation dynamics under changing climate affect runoff and infiltration, with possible influence on landslide occurrence. Increase in vegetation cover may increase evapotranspiration and reduce surface runoff, while deforestation or vegetation loss (due to drought or wildfires) can enhance runoff generation. These changes can alter the timing and volume of inflow to dammed lakes, influencing the probability of overtopping or erosion. However, vegetation responses are spatially variable, and their influence on hydrology is still poorly studied in the context of landslide dams.

Table 3 Relative importance, data availability, and operational relevance of hydrological variables used in landslide dam monitoring and stability assessment.

Hydrological variable	Role	Monitoring priority	Data availability
Water level	Direct control of overtopping	High	Moderate
Streamflow	Controls reservoir filling	High	Moderate
Precipitation	Main hydrological trigger	High	High
Snowmelt/glacier melt	Seasonal inflow control	Medium	Moderate
Lake area/Volume	Indicates reservoir evolution	Medium	High
Sedimentation	Long-term evolution	Low-Medium	Low

Table 4 Failure mechanisms and their potential impacts by climate change

Failure mechanism	Affected hydrological component	Expected climate influence
Overtopping	Extreme rainfall and earlier snowmelt	Higher peak inflow and rapid lake filling
Piping / Seepage	Groundwater, infiltration	Greater internal saturation and erosion
Surface erosion	Discharge variability	Enhanced scour and dam degradation
Long-term persistence	Seasonal water balance	Unpredictable inflow and prolonged wet periods

Climate change acts mainly through hydrological processes that influence existing failure modes. Table 4 shows the potential influence of climate change on failure mechanisms of landslide dams.

7 Conclusions and future recommendations

The importance of hydrological analysis in evaluating the stability of landslide dams is increasingly recognized despite most advancements still fall in geomorphological and geotechnical domains. This review highlights key hydrological processes that play a substantial role in the behavior of landslide dams. There are several limitations in landslide dam research including lack of hydrological data, limitations in real time monitoring, lack of standardization in hydrological modelling and limited use of satellite data. To address these limitations, the present review provides future recommendations to consider hydro-climatological variables, remote sensing techniques for monitoring surface area and water level variations of dammed lakes, integration of physical and machine learning models, conducting field work to collect continuous data for validation purposes and updating landslide dam inventories by adding hydrological information of existing landslide dams. Research on hydrological analysis of landslide dams is critically important for early warning systems and for reducing the impact of disasters following dam failures. While significant progress has been made over the past years in analyzing the characteristics of landslide dams, a comprehensive quantification and relative importance of hydrological factors influencing dam stability and failure processes remains challenging. To understand the role of hydrology on landslide dams the following future recommendations should be considered.

1. Future studies should emphasize monitoring key hydrological parameters like landslide dammed lake area, lake volume, and estimating the inflows and outflows associated with dammed lakes. Continuous assessment of these parameters can provide more accurate and dynamic understanding of dam behavior and trends in water budget. Field measurements should be regularly carried out to monitor the seasonal variations in water level and the impact of extreme precipitation and snowmelt events.
2. Remote sensing techniques can be valuable in assessing the key parameters in data scarce regions. Remote sensing products should be utilized to assess hydrometeorological parameters such as potential evapotranspiration, snowmelt, surface runoff, temperature, precipitation and terrestrial water storage. These parameters are important in calculating water balance of dammed lakes as well as in predicting flooding or drought events. Future climate projections should also be used to evaluate future scenarios and the impact of changing hydrology on landslide dams.

3. The potential of combining Physically based hydrological models with machine learning models should be explored to improve the assessment of river runoff and sediment transport. While physical models provide a comprehensive analysis of natural processes even with limited information, machine learning models, that may help identify complex patterns and forecast the stability and failure mechanisms of landslide dams, require extensive data sets for their training. In any case, machine learning models should include satellite and reanalysis data, geotechnical and geomorphological information along with hydrological parameters to enhance the reliability of results.
4. Current global landslide dam inventories lack hydrological information useful to estimate lake volume, inflows, and outflows. It would be crucial to document this information for old landslide dams. Adding these parameters to global inventories would allow improvement of risk and vulnerability assessment of landslide dams.

While several numerical models have been created to simulate hydrological processes of landslide dams, field data is still crucial to validate the consistency of these models. Fieldwork focused on collecting information on discharge and sediment dynamics, infiltration rates, dam composition and structure should be given top priority in future studies. This data will enable more accurate forecasts and evaluations by numerical models. These models cannot reflect the evolution process efficiently and are also deficient in consideration of the factors underlying landslide dam failure. Significant improvements need to be made to enhance the performance of these numerical models.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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