Landslide Dam Failures:
Historical Examples and Modelling Considerations

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Failures of landslide dams have resulted in thousands of fatalities worldwide. A review of historical incidents and an assessment of contemporary risks can improve readiness and public safety in the future. This paper highlights historical landslide dam incidents in Australia, New Zealand, and worldwide as case studies, including some that failed catastrophically and others that were stabilised in place.

While landslide dam failures have not resulted in loss of life in Australia, water bodies have formed behind landslide dams, and both landslides and at least one dam failure have resulted in fatalities across Australia. Risk assessments to ascertain the potential consequences of landslide dam failures are warranted in areas with high susceptibility to landslides. In particular, the placement of waste rock dumps adjacent to waterways represents an increasing risk of landslide dam formation in the Australian mining sector.

New Zealand's 2016 Kaikoura Earthquake resulted in the formation of over 200 earthquake-induced natural dams on New Zealand's South Island. The potential failure of some of these landslide dams continues to represent a threat to the downstream environment and population while also providing the international science community with valuable calibration data.

The potential consequences of a landslide dam failure may require immediate assessment after the landslide. Using improved techniques in data acquisition and modelling such as drone-based LiDAR acquisition and cloud-based hydraulic modelling, engineers, hydraulic modellers and emergency services personnel can more quickly and accurately predict upstream and downstream inundation extents. This paper summarises the approach used by various jurisdictions following the Kaikoura Earthquake. Helicopter surveys were undertaken immediately after the earthquake, and lessons learnt during the emergency response and monitoring efforts can be applied to future international incidents to ensure that terrain data, catchment hydrology and other necessary GIS data are readily accessible to modellers prior to an event.

Of particular importance to dam engineers and emergency managers is the formation of landslide dams upstream or downstream of constructed dams, with the potential inundation of upstream outlet works or successive, cascading failures in the downstream zone of impact. In high-risk areas, the potential for landslide formation within reservoir catchments should be assessed and captured in dam failure scenarios due to the potential formation of extremely large seiche waves.

The geotechnical uncertainties associated with the formation and composition of landslide dams result in a high degree of uncertainty associated with the results of emergency modelling of landslide dam failure scenarios. Worst-case assumptions in modelling parameters may be initially required to allow conservative flood inundation and arrival time estimates while additional data are acquired for more detailed simulations with longer computational time requirements. Sensitivity analyses are recommended over the full range of dam break modelling coefficients to provide upper bounds on inundation levels and lower bounds on arrival times.

In addition to the valuable data gained in the Kaikoura Earthquake, improvements in hydraulic modelling techniques and the increasing availability of detailed terrain data and hydrological records allows rapid assessment of potential consequences that can serve to prevent loss of life and guide the adoption of mitigation measures for existing and future landslide dams.

Introduction

The East Branch of Australia's Barwon River was blocked by a landslide in Victoria in 1952. The top 26 metres of the landslide dam breached after heavy rains the following year. Fortunately, the downstream flood wave did not result in any fatalities, and the remaining material is now considered to be stable. The water body that has formed behind the remaining embankment is now known as Lake Elizabeth (Figure 1), which serves as a recreational area and a destination for local eco-tours. While Lake Elizabeth is a benign example of the potential for the formation and failure of landslide dams in Australia, other worldwide examples show tragic loss of life and substantial impacts to property and the environment in similar situations.

The 2016 Kaikoura Earthquake in New Zealand caused thousands of landslides, including over 150 landslide dams that have been mapped along watercourses. Monitoring of these dams is providing the international science community with valuable data for the assessment of landslide dam failure consequences and mitigation measures. Rapid assessment of both upstream and downstream flood propagation associated with landslide dams may help to prevent similar impacts in the future in Australia, New Zealand, and worldwide.

Figure 1. Lake Elizabeth: Landslide-formed lake on the East Barwon River (Source: Dept. of Parks)

Historical landslide dams

Several published reports have sought to document the consequences of landslide dam failures (Chai, et al 1995, Costa and Schuster 1987). These catalogues are incomplete as many landslide dams have historically gone unnoticed or unreported, and flood waves resulting from landslide dam failures have not necessarily been attributed to the breach as a source. Despite the incompleteness of any list, the scenarios that have been documented illustrate the extreme hazard presented by landslide dams.

The largest floods on earth – including the Missoula and Bonneville floods that formed massive canyons in North America – have been caused by the failure of natural dams. Natural dams include not just landslide dams, but ice dams, moraine dams, volcanic dams, and alluvial fan blockages as well. This paper focusses on landslide dams only, including slides that mobilise rock, soil, mud, and debris.

Geological evidence confirms a colossal landslide on China's Yellow River dating back to about 1920 BCE. The breach of this landslide approximately one year later was so catastrophic that it is thought to be the source of numerous Great Flood stories that appear in Chinese mythology. No fatality estimates are available for this event, but another landslide dam failure in China is believed to have been the most catastrophic in terms of loss of life: Although the records are somewhat sparse, some sources have estimated that over 100,000 people were killed by the flood wave that resulted from the 1786 failure of a landslide dam on China's Dadu River. This catastrophic impact rivals the number of deaths from the worst constructed dam breach, which also occurred in China as a result of a cascading series of dam failures during Typhoon Nina in 1975 – and for which the death toll exceeds the combined total of all other recorded dam failure-related deaths worldwide. The next most deadly landslide dam failure likewise occurred in China, when the 1933 Diexi earthquake triggered landslides throughout the Min River catchment. One of the resulting landslides formed a dam across the Min River, and over 2,500 fatalities occurred when the natural dam failed.

When landslide dams fail near a constructed dam, the flood or debris wave from the landslide dam failure can potentially send a tsunami or seiche wave across the reservoir and exceed the capacity of the dam. Fortunately, this type of failure is a relatively rare occurrence, but one that warrants special consideration and risk assessment due to the potentially extreme consequences. The case of Vajont Dam in Italy illustrates the severe risk: A 1959 landslide into the reservoir displaced 50 million cubic metres of water that spilled over the dam in a 250-metre high wave that took the lives of 2,000 downstream villagers. Although it may be argued that this is not considered a dam failure because the dam remained intact following the incident, the dam failed to contain the stored water, and the landslide itself was caused by the rising water level in the reservoir; similar effects could occur if large flood or debris waves from a landslide dam failure entered a reservoir.

The consequences of dam failure – for both natural and constructed dams – are not just measured in terms of immediate fatalities, but also in the resulting displacement of populations, economic impacts, and outbreaks of famine and disease that have historically pushed the number of actual dam failure casualties into the millions. In any case, the consequences can be massive in scale. Figure 2 shows a recent example of a lake forming behind a landslide in Nepal. Figure 3 shows an example of the impacts of a downstream flood wave after the recent failure of a landslide dam in Tibet.

Figure 2. Landslide dam formed in 2014 on Nepal's Sunkoshi River (Source: Kathmandu Post)

Figure 3. Downstream impacts of 2016 landslide dam failure on Tibet's Bhote Kishi River (Himalayan Times)

Landslide dams are far more numerous than constructed dams, and the failure of landslide dams could potentially have much larger consequences than constructed dams due to their sheer size. The deepest lake on New Zealand's North Island, Lake Waikaremoana, was formed by a landslide dam that has since been sealed. As another extreme example, the Usoi earthquake in Tajikstan caused a rock avalanche that dammed the Murgab River in 1911 and formed Lake Sarez. While a stable outlet eventually formed across the landslide, the 570-metre height of the natural dam far exceeds the height of any constructed dam, and failure of the landslide dam would have catastrophic consequences in the absence of early warnings.

It should be noted that some of the largest landslide dam breaches, both in terms of the volume of water released and in the height of the dam, have resulted in very few fatalities due to early warning and evacuation of the at-risk population. The 1967 failure of a 175-metre high landslide dam on the Yalong River in China, for example, caused no fatalities thanks to early warnings issued to residents in the downstream flood path.

Because lake levels typically rise very slowly relative to downstream flood levels, the upstream impacts of a landslide dam are typically less catastrophic in terms of fatalities. In some cases, however, entire population centres can be destroyed by the formation of a lake behind a landslide dam. The town of Diexi in central China, for instance, slid into the lake formed by an earthquake-induced landslide dam, leaving only a single survivor out of a village population of 770.

As another example, when a landslide blocked the Spanish Fork River in the United States in 1983, the town of Thistle, Utah was inundated by the reservoir that formed upstream of the dam (Figure 4). A tunnel was eventually excavated through the hillside to prevent overtopping and failure of the landslide dam, but water levels and siltation in the new lake turned Thistle into a ghost town.

Figure 4. Residence in the former town of Thistle, Utah, inundated by a landslide dam (Source: USGS)

Australian examples

Landslide dams such as Lake Elizabeth have formed and breached in Australia without fatalities; however, there have been fatal landslides and at least one fatal dam failure that highlight the importance of considering the risks of landslide dam formation and failure along vulnerable watercourses.

Australian landslides

Earthquakes exceeding magnitude 7.0 have historically occurred approximately every 100 years in Australia. Given the relatively low seismic risks, earthquake-induced landslides are likewise relatively rare. Most Australian landslides have resulted from saturated soils. Leiba (2011) documented 114 landslides across Australia between 1842 and 2011 that resulted in at least 138 fatalities. The Thredbo landslide in New South Wales caused the largest single loss of life when two ski lodges were swept away by a landslide, killing 18 occupants.

Australian dam failures

The most prominent Australian dam failure occurred in Tasmania in 1929. The Briseis Tin Company had constructed the Cascade Dam to provide water supply for their operations. After 500 mm of rain fell in one day, the dam overtopped and failed (Figure 5) unleashing a 6-metre high wall of water that carved a 30-metre deep channel in the downstream valley and carried floodwater and debris through the town of Derby. Fourteen lives were lost in the flood.

Figure 5. Remains of the Cascade Dam, with ground stripped to bed rock by the flood wave (Source: E. Barsham)

Although the risk of a landslide dam formation and subsequent failure is relatively low in Australia, the occurrence of both fatal landslides and fatal dam failures in Australia highlights the potential consequences of a catastrophic event. The growing number of tailings dams and waste rock dumps across Australia may represent an increased threat of landslide dams. Many Australian tailings dams are constructed along tributaries of larger watercourses. Tailings dam failures have been known to deposit material in downstream channels, forming dams that can impound water and breach catastrophically.

Waste rock landforms represent the largest landforms in many catchments draining to mining areas across Australia. Waste rock landforms typically comprise uncharacterised material and are generally left at the angle of repose prior to rehabilitation for mine closure. Where non-rehabilitated waste rock landforms are located immediately adjacent to watercourses, a slope failure could potentially cause the formation of a landslide dam that impounds water.

New Zealand examples

Historical examples

When the United States Geological Survey (USGS) catalogued 184 worldwide landslide dams (Costa and Schuster 1987) only a single example from New Zealand was included, in which the 1929 Buller earthquake caused landslides that formed 11 landslide-dammed lakes. The extreme case of Lake Waikaremoana was not included because it occurred over 2,000 years ago. Recent monitoring has shown that New Zealand is tremendously underrepresented in these previous studies due to a lack of observation data. In reality, thousands of landslide dams have formed across New Zealand, generally in response to earthquakes.

2016 Kaikoura Earthquake

A Magnitude 7.8 earthquake with an epicentre near Kaikoura on the South Island of New Zealand struck on 14 November 2016. The earthquake triggered thousands of landslides, including over 200 landslide dams that blocked watercourses in the region. Using helicopter-based reconnaissance, GPS positioning, and GIS classification, a team of scientists and consultants undertook a systematic effort to identify and rate landslide dams. In partnership with USGS and Geotechnical Extreme Events Reconnaissance (GEER) teams, local authorities selected 12 high-hazard dams for daily monitoring.

The dams were prioritised for detailed investigation according to a risk matrix, with assessments based on RTK GPS and terrestrial laser scanning along with numerical simulations of rapid-failure debris flow scenarios (Dellow and Massey 2017). Some of the landslides breached within one day of the earthquake while others breached during heavy rainfall associated with Cyclone Debbie approximately five months after formation. Still others continue to be monitored for potential signs of imminent failure. The observed failure of several landslide dams provided calibration data for modelling efforts. The initial modelling efforts required conservative assumptions that in some cases – as shown by the subsequent measured data – significantly overestimated hazards and risks.

Figure 6 shows the location of mapped landslides generated by the Kaikoura 2016 earthquake. Figure 7 shows the largest of the observed landslide dams, which blocked the Hapuku River. Figure 8 shows the landslide immediately following the 2016 earthquake while Figure 9 shows the landslide dam breach formation after overtopping in April 2017.

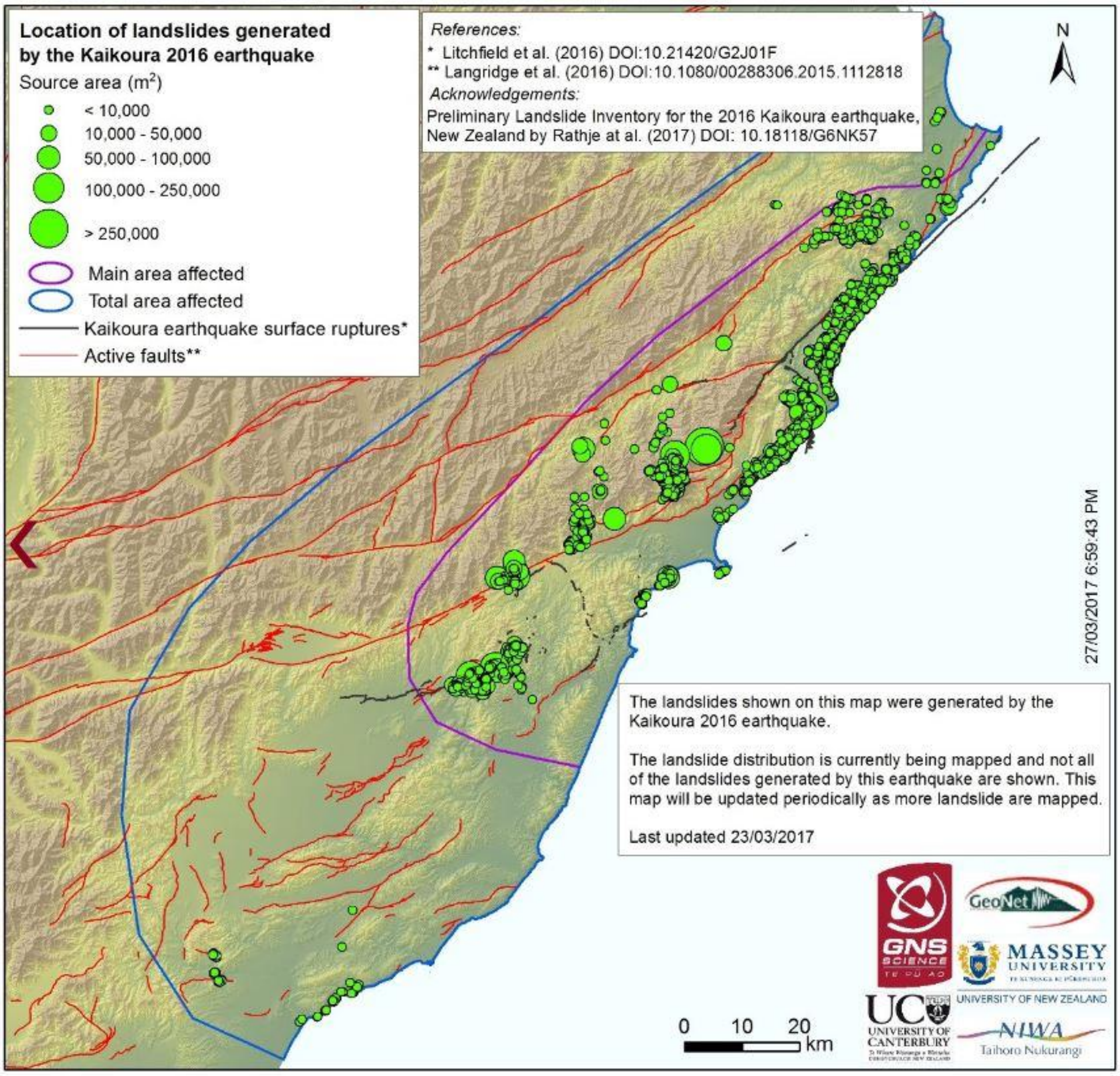

Figure 6. Landslides mapped in Canterbury, 2016 (Source: GeoNet)

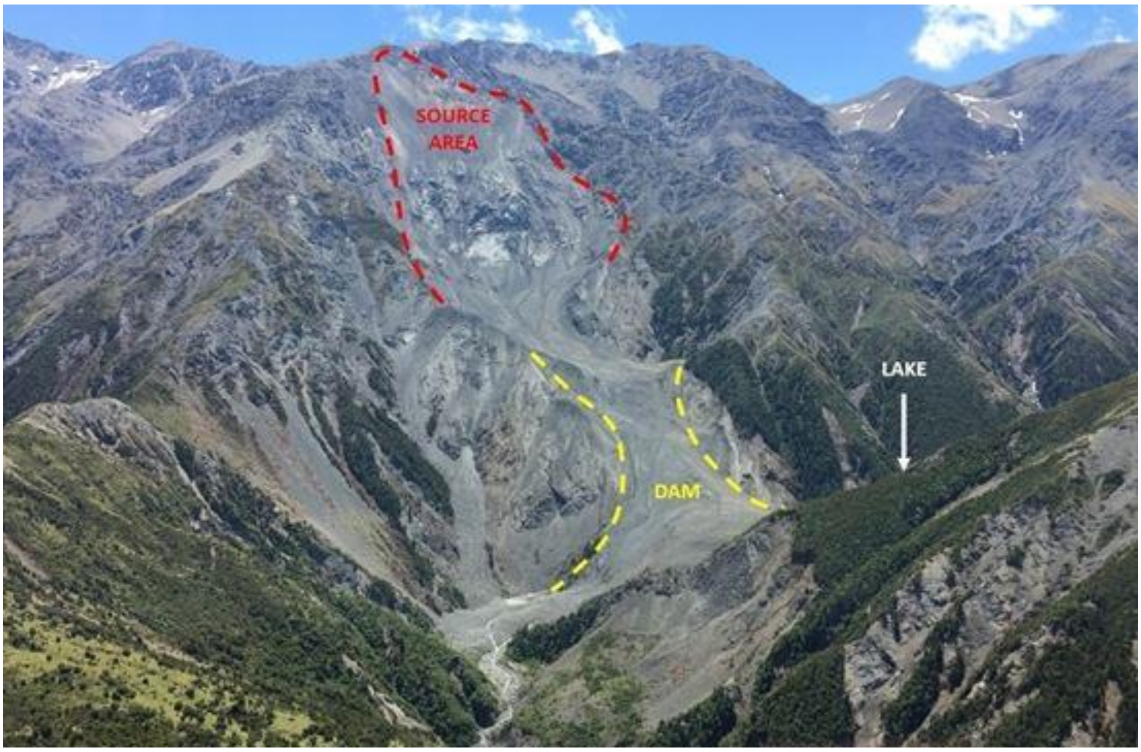

Figure 7. Hapuku Landslide Dam, 2016 (Source: GeoNet)

Figure 8. Hapuku River landslide dam, 2016 (Source: GNS Science)

Figure 9. Breach formation from overtopping of the Hapuku River landslide dam, 2017 (Source: GNS Science)

Computational options

Of the 73 landslide dam failures documented by the USGS, 27% failed the first day, and almost half failed within the first week (USGS 1987). As indicated by these timeframes, predictions of impacts can be required with extreme urgency. In the immediate aftermath of the formation of a landslide dam, decisions regarding evacuation must therefore often be made without the support of detailed hydraulic modelling.

Given recent advances in both hardware and software capacity – coupled with the increasing availability of LiDAR data and telemetered hydrological data – upstream and downstream inundation maps can be prepared relatively quickly following the identification of a landslide dam, provided catchment hydrology and the original watercourse terrain data are readily available. The assigned computational parameters, however, need to be fairly conservative in order to capture the high level of uncertainties inherent in the composition of landslide material, potential failure mechanisms, breach formation time, and other variables.

Decisions on mitigation measures, such as attempts to stabilise the dam in place, excavate diversion channels or tunnels, or even using explosives to blast a spillway, can be greatly aided by simulation results that can help predict critical levels in the upstream lake. Because some landslide dams have failed as a result of aftershocks from the original earthquake, any efforts to stabilise, modify, or remove a landslide dam are extremely hazardous, and improved simulations can assist in preventing loss of life in the event of a catastrophe.

As an upper bound for the magnitude of the downstream flood wave, assigning dam breach model parameters with short breach formation times may be warranted. Typically, the shortest breach formation times occur in concrete arch dams and similar structures; however, this provides a conservative estimate for any landslide dam material. In reality, some landslide dams fail very slowly or may retain stability when overtopped. Likewise, allowing the simulated lake level behind the dam to fill with an initial pool level at the dam crest elevation provides a conservative estimate of the maximum flood wave. In reality, the inflow can take days or weeks to fill the dam behind a landslide; in some cases, overtopping never occurs because of subsurface flow paths. Failure paths can form along subsurface conduits, and failure may occur without the structure having been overtopped; however, even when a landslide dam is overtopped, there have been numerous cases where the armouring process in the breach channel provides adequate protection against further erosion and scour; some landslide dam spillways stabilise for months or even years, even when simulations indicate imminent failure.

Envelope equations in landslide dam breach literature, such as those provided by Evans (2006), may be used to predict outflow hydrographs from a dam breach; however, the resulting impacts would still be subject to the limitations of the downstream inundation mapping; recommended approaches for dam breach models, such as using the full Saint-Venant equation rather than simplified forms, would apply to landslide dam breach models as well. One important parameter in two-dimensional flood modelling, particularly for simulations of a dam failure flood wave, is the Courant number, which relates modelled velocities to grid sizes and computational time steps. In essence, adherence to Courant number stability criteria recommends that computations occur at least at every computational grid. In highly dynamic situations such as a dam breach, where extremely high velocities are encountered, very small time steps are typically required for model stability, substantially increasing the model run time. Decreasing the computational time while maintaining model stability may require the use of larger computational grid sizes; however, this can decrease the accuracy of results, particularly in the vicinity of the dam. The use of variable time steps may improve run times; however, a reliable dam breach model with appropriate grid sizes and computational intervals can often take days to run, even using powerful computers. Given the time requirements to generate meaningful estimates, the development of initial, coarse models may thus be required, subject to later refinement.

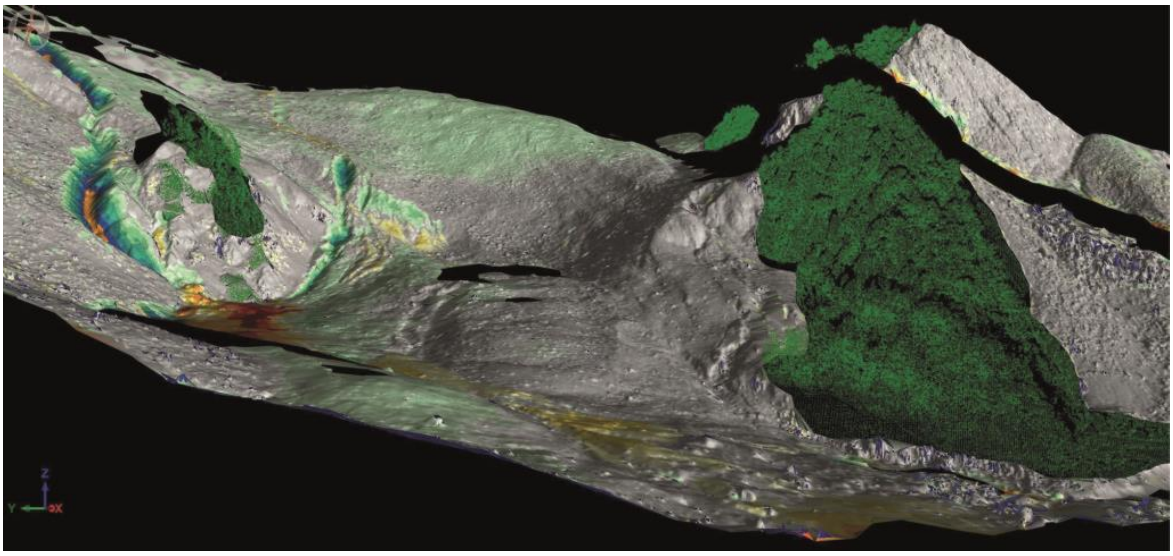

Figure 10. Terrestrial Laser Scan Change Model, 2016 (Source: GNS Science)

As demonstrated by comparisons between modelled and observed breaching of the Kaikoura landslide dams, the initial models typically overestimate the potential impacts quite significantly. The initially conservative simulation results may be used to notify emergency managers for additional preparation prior to evacuation orders while more detailed assessments are performed.

Conclusions

This paper summarises the results of a literature review of pertinent studies covering landslide dams. A review of historical incidents and an assessment of potential incidents can improve readiness and public safety in the future.

The systematic reconnaissance following the Kaikoura earthquake provided data that showed the frequency of landslide dams to be much larger than previously indicated by published landslide dam lists. Using drone-based LiDAR data, improved techniques in 2D flood modelling, and other advances in hardware and software, engineers, hydraulic modellers and emergency services can more quickly and accurately predict inundation extents associated with landslide dam failure scenarios. The geotechnical uncertainties associated with landslide dams require worst-case assumptions in modelling parameters in order to allow conservative flood inundation estimates.

While Australian examples of landslide dams have historically been relatively harmless, landslide dams have formed and breached in Australia. The increasing number and size of manmade landforms adjacent to waterways constitutes a potential risk that warrants further assessment in terms of the potential formation of dams created by slope failures. Potential formation of landslide dams upstream and downstream of existing or planned constructed dams should be taken into account in risk management procedures.

The ongoing monitoring and calibration data provided by the Kaikoura landslide dams provide the international science community with valuable data for assessing potential failure mechanisms and predicting impacts. Should any Australian or New Zealand landslide dams form in the future, rapid computational assessment techniques are available to make conservative predictions of impacts in the short term, with detailed predictions following in the long term. Rapid assessment, however, requires advance preparation of catchment hydrology and watercourse terrain data. Advance coordination between modellers and emergency services regarding GIS data availability and modelling capabilities would allow additional preparation for emergency events involving river blockages.

In earthquake-prone areas, the occurrence of an earthquake often triggers reconnaissance efforts. In Australia, however, landslides are typically caused by saturated soils rather than earthquakes, making the timing of reconnaissance efforts less predictable and the area less focussed. For systems that are gauged with telemetered data, reporting procedures could be programmed to provide immediate notification concerning sudden drops in water levels that may indicate upstream impoundment and trigger further investigations. Landslide dam formation may go unnoticed in ungauged catchments; however, should there be a future failure of a landslide dam in Australia, actively collecting data regarding the downstream flow path and other observations may assist future calibration efforts.

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