The 70th Anniversary of the Tangiwai Railway Disaster – A Volcanic Dam Break Story

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ABSTRACT

The Tangiwai Railway Disaster, which occurred on Christmas Eve in 1953, remains the most devastating rail accident in New Zealand's history. Of the 285 persons on board, 151 lost their lives when the train heading from Wellington to Auckland plunged into Whangaehu River shortly after the collapse of the Tangiwai railway bridge. The accident was caused by the break of a natural dam formed eight years earlier by erupted volcanic material and glacial ice, which together held back Mount Ruapehu's crater lake. The resulting lahar, a fast-moving, mud-like flood, swept down the Whangaehu River, destroying the bridge's piers and causing its beams and deck to fall into the river. The efforts of a passerby to warn the oncoming train kept this disaster from becoming even more catastrophic. This article recounts the harrowing tale of the Tangiwai Railway Disaster and delves into the intricate and dynamic geomorphic and hydraulic processes that led to the dam's collapse. It also examines the valuable lessons learned by New Zealand, including the implementation and ongoing refinements of early warning systems and other precautions made after 1953 and prior to the collapse of another volcanic dam and its lahar in March 2007. Furthermore, as this case study focuses on the failure of a natural dam, the article begins with a brief introduction to other types of significant natural dams such as landslide dams, avalanche dams, ice runs, and Glacial Lake Outburst Floods (GLOFs), to raise awareness among readers.

I.INTRODUCTION

1) *Natural Dams*

In natural settings, various mechanisms contribute to the formation of dams. These include landslide dams, glacial ice dams, neoglacial moraine dams, volcanic dams, fluviatile dams, eolian dams, coastal dams, and organic dams. Among them, landslides, glacial ice, and moraine dams pose the greatest threats to both people and property [1, 2]. A brief description of each type is presented below.

Landslides Dams: The most common type of mass movements are rock and debris avalanches, rock and soil slumps and slides, and mud, debris, and earth flows. Heavy rainfall, snowmelts, and earthquakes are common triggers for dam formation. These dams typically have a short lifespan, with approximately 27% failing within a day and 50% failing within 10 days of their formation. Overtopping is the primary cause of failure [1].

Glacial Ice Dams: Glacial ice dams impound water within, beneath, or behind masses of glacial ice. Failures of glacial ice dams occur periodically, with typical return periods ranging from 1 to 10 years. Several failure mechanisms have been observed, including erosion of tunnels under or through the ice, hydrostatic flotation, slow plastic yielding of ice due to hydrostatic pressures, crack propagation under shear stresses from glacier flow and hydrostatic pressure, water overflow erosion, subglacial melting by volcanic heat, and weakening of the ice dam caused by earthquakes. The type of ice that forms the dam impacts the failure mechanism, with warmer temperate glacier dams being less dense and more prone to fractures compared to colder ice dams. Warmer dams tend to drain subglacially or englacially, while colder dams typically drain supraglacially or marginally.

Neoglacial Moraine Dams: Late-neoglacial moraine dams are in steep mountains where the advances and retreats of glaciers leaves behind piles of debris and rocks that create a dam. The term moraine stands for any accumulation of unconsolidated material. These dams are hazardous due to their geological youth, lack of established vegetation, the steep slopes – often exceeding 40 degrees -, and potential instability caused by deteriorating frozen core material. Global warning could have a serious impact on these cores, potentially accelerating and aggravating the instability by loss of frozen material. The most common failure mechanism is overtopping and breaching triggered by waves generated by ice or rock falls or snow or rock avalanches. Other failure mechanisms include melting of frozen core material, piping, and seepage.

Both ice and moraine dams can release large floods known as Glacial Lake Outburst Floods (GLOF). These types of dammed water body are becoming an increasing hazard as ice melt increases with warming global temperatures.

Volcanic Dams: Volcanic dams are natural barriers created by volcanic activity which holds or temporarily restricts the flow of water in existing rivers. They can be formed by the flow of molten lava or by deposition of pyroclastic material and debris. Tephra is the name of any fragmented material produced by a volcanic eruption while pyroclastic material is a mixture of lava blocks, ash and gas. Interestingly, Crater lakes, which often hold larger volumes of water for longer periods of time are not considered volcanic dams [3].

Crater Lakes: A volcanic crater lake is a depression formed by explosive activity or collapse during an eruption. These lakes are filled primarily by precipitation, melted ice and snow, and some groundwater circulation. Water loss from these lakes occurs through evaporation and seepage, and, if the water level reaches the rim, surface overflow.

Several notable examples of crater lakes exist worldwide, such as Crater Lake in Oregon, known for its remarkable depth of 594 m, making it the deepest lake in the United States, and Lake Toba in Indonesia, the largest crater lake globally, measuring 100 km by 30 km with a depth of 505 m [4].

The processes of seepage and overflow may lead to erosion of the rim or tephra barrier and produce a dam break or outburst, releasing a large volume of water and debris, called Lahars. Lahars are also formed by eruptions, by snow and ice melting by the heat produced by the volcano or by rain [5]. Catastrophic failure of the rim of a crater lake due to, say, a large earthquake can also cause an enormous flood.

2) Lahars

Lahars are swiftly flowing mixtures of volcanic ash, rock fragments, water, snow, and ice [5, 6]. These matrix-rich debris flows exhibit a thick slurry consistency, like fresh concrete, with a density ranging from 1795 to 2290 kg/m^3 and sediment accounting for 50 to 75% of the volume. Lahars are more viscous than water and can reach velocities exceeding 69 km/hr or 20 m/s. The highest velocity of lahars yet measured at Ruapehu was 90 km/hr or 24.9 m/s during an eruption on 23 September 1995 (Peter Otway personal communication). The entrainment of sediment in lahar flows leads to increased peak discharge, with bulking factors of 1.8-2.5 observed for past lahars at Mount Ruapehu. The damage inflicted on structures during a lahar event depends on factors such as the depth and velocity of the flow, as well as the design and construction capacity of the structure to withstand the erosive force of sediment-laden flows containing boulders up to 1 m or more in diameter [7,8].

Photo 1 – Mount Ruapehu lahar, following eruption 24 September 1995 by Lloyd Homer (copyright GNS Science)

Photo 2 – Lahar deposits in Whangaehu Valley, Ruapehu, following Ruapehu eruption on the night of Tuesday 25 September 2007 by Vern Manville (copyright GNS Science / EQC)

Photo 3 - Whangaehu River boulders on April 28, 1975, by Brad Scott (copyright GNS Science)

Photo 4- Lahar deposits in Whangaehu Valley, Ruapehu on September 26, 2007, by Vern Manville (Copyright GNS Science / EQC)

3) Mount Ruapehu

At Mount Ruapehu, three types of natural dam formations are observed: a rim composed of effusive and explosive deposits erupted over the last c 1800 years which retains a lake, called Crater Lake or Te Wai ā-moe, within the active crater , glacial ice dams created by glacier fields in older volcanic formations with subglacial and englacial tunnels feeding the Whangaehu and possibly other rivers, and volcanic dams formed by young lava or tephra material or lava blocking the overflow into the Whangaehu River following the 1945 and 1995-96 eruptions respectively.

II.MOUNT RUAPEHU & ITS ERUPTIONS

Mount Ruapehu (2,797 m), located in the North Island of New Zealand, is one of the country's most active volcanoes. It is situated in Tongariro National Park, which is also home to two other active volcanoes, Ngauruhoe (2287 m) and Tongariro (1967 m) [9]. Tongariro National Park was designated as a UNESCO World Heritage site in 1990 and is one of the oldest national parks in the world, established in 1887 [10, 11].

Mount Ruapehu stands out as the only North Island mountain with glaciers [9]. There are several glaciers located around Crater Lake/Te Wai ā-moe and summit area (comprised of three peaks over 2,700 m), and during the summer months, crevasses form around the lake, sometimes leading to ice blocks sliding into the lake, particularly along the cliffed margins [12]. The volcano is a popular tourist attraction, offering two major ski resorts and hiking trails.

As a stratovolcano, also known as a composite volcano, Mount Ruapehu has been formed by layers of lava and tephra (volcanic material) accumulated from past eruptions. It has moderately steep slopes in a conical shape, featuring summit craters the oldest of which are filled by glacial ice and the youngest occupied by the lake [13].

Major eruptions recorded in history happened 50 years apart 1895, 1945 and 1995. Minor eruptions are more frequent, with approximately 60 occurring since 1945 [14]. A comprehensive list of eruptive activity is presented in [15]. Typically, steam burst events occur about 1-5 years apart, phreatic eruptions (steam and rock) about 5-10 years apart and larger and longer phreatomagmatic (molten magma and water) events, like the one of 1995-1996, have occurred every 50 years [11, 16] probably coincidentally. The last typical short-lived event occurred in September 2007.

Volcanic hazards associated with Mount Ruapehu include ashfall, gases, lahars, ballistic projectiles, lava flows, pyroclastic flows, and debris avalanches. It is important to note that volcanic ash is different from the ashes found in fireplaces or left behind by burned paper. Volcanic ash is made of rock fragments, minerals, and volcanic glass, with particle sizes ranging from the size of a grain of sand to as fine as a grain of clay. It is highly abrasive, mildly corrosive, conductive of electricity when wet, and insoluble in water [16, 17].

Typical eruptions from Mount Ruapehu are likely to result in light ashfall, with thicknesses generally less than 50 mm [17]. Ashfall in this range (4.762 mm – 102 mm thick) can have various impacts on daily life, including health issues (eye and lung irritation), infrastructure disruptions (roads, rail, hydropower generation and transmission) environmental problems (contamination of water bodies, damage to crops) [18]. These impacts highlight the importance of preparedness and safety measures when dealing with volcanic ash hazards.

III.CRATER LAKE/ TE WAI Ā-MOE

Situated at the center of the peaks is the Crater Lake, occupying a volcanic crater formed as a result of volcanic activity. This approximately circular depression measures about 500 m in diameter with a depth varying over the decades around 150 m deep. The presence of the lake serves as a steam condenser and somewhat masks the volcanic activity of Mount Ruapehu [19].

The Crater Lake undergoes thermal cycles with the water temperature fluctuating between approximately 15°C and 40°C in a period of 6-12 months; it is usually lukewarm, but during eruptions it may reach boiling point. Historical records indicate that the lake was observed boiling in 1886. On rare occasions, the lake freezes, as reported in 1886 and 1926 [19].

Photo 5 – Mount Ruapehu Crater Lake (Source: GeoNet / Copyright of GNS Science – https://static.geonet.org.nz/info/images/volcano/Ruapehu-Crater-Lake.jpg) – the red arrow indicates the Whangaehu River

The water is very acidic with a pH less than one. It contains sulfur, chloride, and magnesium. The correlation between the sulphates and chlorides can provide valuable insights into the level of the volcano's activity [20, 21]. The color of crater lakes varies markedly according to the temperature and chemistry of the water, and the type and concentration of particles suspended within it.

The refilling of Crater Lake, following eruptions or collapse/break of the tephra dam, depends on a range of factors, including snowfall, rainfall, melting, lake temperature, and volcanic activity including steam input [7, 23].

IV.THE WHANGAEHU RIVER & ITS LAHARS

The Whangaehu River, which translates as "muddy river mouth" or "large body of muddy water" has also been known locally as the Sulphur Stream, owing to its strong sulfur smell. The water of the river carries a high level of sediment, giving it the sensation of swimming in dense saltwater where one can easily float for an extended period.

Occasionally, the river water exhibits a discolored appearance due to its sulfurous origin, appearing yellowish or brownish [6].

Originating from the Lake, the river's outlet is located on the southeast rim – see Photo 5. It flows eastward through a gorge and across an alluvial fan before taking a curve and turning south. After a journey of 160 km from its source, the Whangaehu River finally reaches the Tasman Sea.

Historically the lake had no surface outlet visible. But the fact that the Crater Lake was, and is, fed during the summer months by copious quantities of melt water from the surrounding icefields, and its level normally remains constant for considerable periods, suggested the possibility of a natural outlet for water, apart from seepage into the ground-water system.

From the early 1900s, most authors agreed that the Crater Lake fed the Whangaehu River through a tunnel under the ice fields. O'Shea [12] believed that the major outlet was in the form of an ice tunnel or ice-bridged ravine, often concealed by the extensive overhang of ice walls bordering the lake's southern edge [19]. Glacial recession led to the outlet becoming visible in the 1960s and the last remnant of ice-bridge below the outlet was destroyed during September 1995 early event in the 1995-1996 eruption.

One of the earliest documented lahar events was recorded over 160 years ago by Rev. Richard Taylor on February 13, 1861. Starting at 6 am and lasting approximately 2 hours, the flood swept away the bridge connecting Palmerston North to New Plymouth, approximately 67.6 km downstream of Tangiwai. An eyewitness, a Maori (native indigenous people of New Zealand), described the surface as a thick mass of snow, ice, timber, and debris. At the time, Rev. Richard Taylor speculated that the flood waters originated from the Crater Lake, which turned out to be an accurate guess, considering the mountain had not been climbed until 1877. He noted the water was milky and in fact a diluted sulphuric acid, and surely from a volcanic origin [6].

In January of 1922, Mr. L.M. Lennard first observed the ice caves in the Crater Lake. In 1937, a local guide by the name Roy Sheffield swam in the lake and entered the cave, where he discovered a waterfall feeding into the Whangaehu River [12, 19].

During the 1945 eruption, the existing ice tunnel became blocked (see below). After the eruption ended, the lake slowly refilled a new crater to a level above the pre-eruption level. On December 24, 1953, the dammed water was released over a few hours causing another lahar. This lahar caused the train accident described below.

In the 1995-96 eruptions, a tephra dam ("Tephra Dam") was created from tephra deposited across the lake outlet, the lowest point in the crater rim. After the eruption, the water in the crater rose to levels again significantly higher than before the eruption. Leakage through the dam and earlier through the hard rim was chemically detected in the stream water [23]. The dam failed on 18 March 2007 when the lake was 1.1 m below overtopping. The dam-collapse sequence, captured by a time-lapse camera, involved a series of retrogressing landslides initiated and accelerated by seepage forces and toe scour [24]. 1.3 million cubic meters of lake water was released, 0.5 million cubic metres less than the one from 1953 but the peak lahar discharge at Tangiwai was up to twice as large because of the shorter duration of release [23, 25].

Currently, the Crater Lake maximum water level maintains at the same level established on March 2007, as the water flows over old solid lava on the southeast rim.

V.THE DISASTER – CHRISTMAS EVE 1953

1) *The Dam Break at Crater Lake & its released Lahar*

The tragic events of December 24,1953 can be traced back to the eruption of Mount Ruapehu in 1945. The eruption, a phreatomagmatic event, produced a tholoid (magma dome) to rise in the center of the Crater Lake. The tholoid pushed the warm lake water into the pre-existing cave, enlarging it. Hot water was observed gushing out through the outlet into the Whangaehu River at a rate of 1.4 m^3/s, far exceeding the usual flow rate of 0.06 or 0.08 m^3/s. Apparently the hot water ceased to flow quite quickly. It is believed that lava blocked the cave/outlet at that time. Subsequent explosions excavated the crater again leaving an almost empty 300 m deep crater and a covering of ash and debris over the mountain [19,26].

The lake refilled to a level 6 to 7.5 m higher than the 1945 pre-eruption levels and stabilized in August 1953 [22]. The water level remained stable for four months. Mr. and Mrs. Wood from Auckland visited the lake on the morning of the accident and reported the presence of a cave at the south end of the lake [26].

On 24 December 1953, a stage may have been reached when the volcanic material and the ice wall buttressing it upstream of a temporarily re-forming tunnel could no longer hold back the high volume of lake water. Consequently, the combined rock and ice dam gave way suddenly, and the water above the rock rim rushed out, enlarging the tunnel as it passed [19].

It is believed that while the lake was discharging through the first formed cave – believed to be about 4m to 5 m in diameter [7] -, the water was also seeping around and through the volcanic lava, ash and scoria alongside to form another channel beneath the ice at a lower level. Erosion of this channel may have weakened the volcanic barrier, while cracking movements in the ice above could have triggered a sudden collapse of the ash barrier. An observed ice bridge in the Whangaehu Glacier was likely thin, and when the mass of water from the Crater Lake surged down the channel, the vibrations and pressure may have caused the ice to crack and shatter or a temporary blockage beneath the ice to increase pressure until it gave way [7, 12].

No volcanic activity was recorded, but vibrations were noted about 8:00 pm to 9:00 pm. A local tremor of very small magnitude was recorded at the Chateau Tongariro seismic station, which was uncharacteristic of a local earthquake. [12] The recording time agrees with witness accounts of a roaring sound. [19,26]. It is believed that the vibration was due to the waters bursting through the previously blocked tunnel/outlet.

The lahar is believed to have reached the Tangiwai bridge sometime between 10:10pm and 10:15 pm [26]. It took the wave 2 hours and 15 minutes to travel the 38 km to the Tangiwai bridge at an estimated average flow velocity of 4.7 m/s (16.9 km/hr). The lahar density was calculated by Mr. James Healy to be 1600 kg/m^3 [14]. The lahar at the Tangiwai bridge was a mixture of water, ice, mud, sand, and boulders, some as large as 1.2 m in diameter [26]. The Crater Lake water level dropped 7.9 m, with 6 m of the drop occurring in the first 150 minutes. The flow varied from a maximum peak of 850 m^3/s to 36.7 m^3/s. The last 1.8 m discharged relatively slower [26].

Photo 6 – Mount Ruapehu Crater Lake Outlet after the Tangiwai Disaster on December 28, 1953 (Copyright GNS Science)

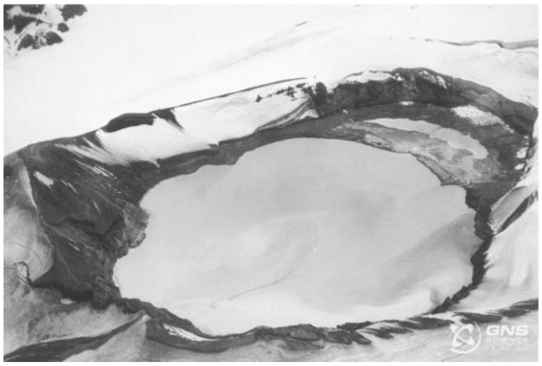

Photo 7 – Mount Ruapehu Crater Lake after Tangiwai on December 28, 1953 (Copyright GNS Science)

Photo 8 – Ruapehu Crater Lake outlet after the Tangiwai disaster on Dec 28, 1953 – the red arrow indicates the breached 1945 lava and tephra/debris layers (Copyright GNS Science)

When the lahar reached the bridge, it is believed to have washed away Pier 4, leading to the collapse of spans 3 and 4 into the river. The water level at the bridge rose by 4.5 to 5.2 m or 6 m allowing for uncertainty [5, 7]. It is believed that span 3 girders were struck by the waves, as the flood water was measured above the elevation of the bottom flange of girder 3. Lateral and diagonal forces on the pier then caused it to fracture at a construction joint, and the upper portion was then forced upwards and sideways. When the lower portion of the pier was relieved of most, if not all, of the vertical forces from above it was swept away by the flood. As a result, the upper portion of the pier and spans 3 and 4 were then unsupported and fell into the raging waters [26, 27].

At 10:22pm, approximately 5 to 10 min after the collapse of the piers, and at the lahar peak, the train arrived at the bridge [26].

2) *The Disaster*

Just moments before the train arrived at the bridge, Cyril Ellis, accompanied by his wife and mother-in-law, was driving from east to west, on the road parallel to the train tracks, now State Highway 49 – the Volcanic Loop Highway. Upon reaching the road bridge, he noticed that it was nearly submerged, with only the handrails visible. When he saw the express train approaching the nearby rail bridge, he realized, even though he didn't check, that the rail bridge couldn't possibly be safe to cross. He took a torch (flashlight) and ran toward the train, jumping the fence on his way. He desperately waved his torch at the driver and conductor, and shouted, but they didn't have time to completely stop the train before reaching the bridge. Later at the inquiry, it was concluded that the emergency brakes were applied at 210 m before the bridge and that dry sand was used to increase wheel traction, creating sparks witnessed by passersbys. The calculated required stopping distance for a train travelling at a speed of 80 km/hr to completely stop was 358 m [6, 27].

The locomotive along with its tender, five second class wagons and one first class wagon fell into the raging waters. Of the 285 persons in the train, 151 lost their lives. Of those 151, only 131 bodies were recovered. Thanks to the heroic efforts of the conductor and Ellis and the actions of brave passerbys and others, a worse disaster was averted.

3) *Christmas Day*

When the sun rose, the full extent of the disaster became apparent. The violence of the raging flood waters was clearly displayed in the river area and banks. The vegetation on the banks was laid flat toward downstream, and there was clay covering everything. The train wagons were spread downstream of the bridge and some were completely destroyed. One wagon, A1920, was carried 2.4 km downstream and is believed to have been catapulted over the road bridge or more likely swept around or between the abutment and the edge of the lahar flood, as the wagon would not have fit underneath the bridge. Some of wagons were severely distorted.

Graham Steward, the photographer present at the scene, described the aftermath in the preface of his book "The Tangiwai Disaster – A Christmas Eve Tragedy" (1972):

> *"What greeted us I will never forget: first, a strange silence – an aerie atmosphere – which hung over and around the disaster scene. Before our eyes was unbelievable destruction, as if a giant Gulliver had flung this mighty railway train of steel into the river. The concrete and steel bridge had been smashed beyond comprehension. Wrecked carriages were scattered unbelievably in all directions. Seats, blankets, suitcases, children's toys, some still wrapped in festive paper, and many personal belongings, all lay half buried in silt and mud wherever one stepped."*

Photo 9 - The scene at the site, looking toward the west - Dec 25, 1953, Mount Ruapehu in the background (Copyright Graham Stewart)

Search parties were organized, and many volunteered. The scene was horrific. Many bodies were stripped of clothing, some were found hanging on the survived vegetation on the top of the banks. Briefcases, gifts, toys, and other items were scattered in the downstream area. The bodies were heavy with the sedimented water. Most victims died by drowning, but the evidence of injuries from the boulders carried by the floodwaters was visible in some deformed bodies.

4) The Board of Inquiry

Following the tragic Tangiwai disaster, a board of inquiry was promptly appointed to investigate the accident. Their main tasks were to find the cause of the accident, whether anybody was responsible for it, and what steps should be taken to prevent similar accidents.

The board went into great depth to investigate and bring forth the details of design, construction, and maintenance of the rail bridge, and into the operations and maintenance of the rail line itself. As part of their investigation, they studied the origin of the flood and characteristics of the Whangaehu River, the damage to the bridge and rational behind its failure.

Regrettably, crucial background information regarding the rail bridge, including as-built plans and construction records, was lost in a fire. The only available documentation consisted of typical plans that were used at the beginning of construction that lacked the final details of the bridge's foundations.

Regarding the cause of the accident, the board concluded that it resulted from the sudden release of a large volume of a mixture of water and ash from the Crater Lake though a subglacial ice tunnel combined with large blocks of ice which collapsed from the glacier above. The flood bulked up with enormous amounts of sand, silt and boulders and was very violent. The flood destroyed the bridge before the train arrived.

With regards to assigning blame for the tragedy, the board concluded that no individual or entity could be held responsible. The bridge had been designed, constructed, and maintained in a reasonable manner, and the trains were operated and maintained properly as well. Damage sustained in a 1925 lahar had been managed and risks from that mitigated.

The board of inquiry recommended the following protective measures to be implemented immediately and kept until effective warning measures could be implemented: installation of a telephone at the bridge, reduction of train speeds over the bridge to 9.6 km/hr and stationing a person at the bridge to signal drivers and prohibit passage until an "all clear" signal was received. This protocol was to remain in effect until alternative and effective warning systems were established.

Overall, the board of inquiry diligently fulfilled its mandate. It thoroughly investigated the incident, provided comprehensive findings, and made valuable recommendations to prevent future disasters, or in terms of modern understanding significantly reduced the risk of future accidents.

VI. LESSONS LEARNED & EVOLUTION OF THE ERUPTION DETECTION SYSTEMS AND THE LAHAR ALERT AND WARNING SYSTEMS

The first warning device

The Board of Inquiry finalized its report in April 1954. By November of the same year, a comprehensive investigation on flood warning systems was conducted, focusing on several types of warning devices. The report aimed to address the operational requirements specific to the local conditions, which included factors such as isolation, extreme climatic changes, prolonged dampness, vulnerability to damage, atmospheric corrosion, and the need for continuous reliability despite extended periods of no operation [27]. The alarm needed to be reliable, have a fail-safe operation, it should always carry a message indicating that “the river is safe”, it should be a closed circuit, the device should break an electrical circuit to activate the alarm, a mechanical fuse that fractures a wire was considered the most reliable option, the power source should be located at or upriver from the detector, or an alternate route should be used for powering the detector separately from the indicating circuit, and the system should be trouble free.

Various types of devices were investigated. The chosen device consisted of a waterproof concrete chamber with fixed probes installed at specific heights through holes in the concrete wall. The device was installed by January 1957 at the Whangaehu River 27 km downstream of the Crater Lake [28]. It provided a 30-minute warning time before the flood reached the rail bridge. Locals in the county council, Civil Defence and Ministry of Works were then to be alerted manually by phone (Bob Norling personal communication.)

Table 1 – Flood warning levels that were set

Level 1	A flood which will occur once or twice each year
Level 2	A flood reaching ½ the height of the 1953 flood
Level 3	A flood reaching ¾ the height of the 1953 flood
Level 4	A flood of the same height as the 1953 flood

Photo 10 - Rail lahar warning system, Whangaehu River, Taupo Volcanic Zone by Lloyd Homer (Copyright: GNS Science)

The 1969 failure & 1975 weakness exposed

In 1969 Mount Ruapehu erupted again, without warning, generating a lahar that failed to register at Level 1. The warning system had failed. Again, in the 1975 another unheralded eruption occurred, releasing a lahar which travelled at an average speed of 25 km/hr, with peak flood velocity estimated to be 43 km/hr and the peak flow 5000 m^3/s. Within 2 or 3 minutes the Whangaehu River rose from normal flow to above the gauge maximum at circa 5 m above normal river level [28, 29]. This time the alarm was successful, but the alarm only alerted the rail station of the incoming flood waters. Apparently there was no warning given to or integration with other stakeholders.

The Lahar Warning System (LWS)

After the 1969 and 1975 eruptions, it became evident that an improved warning system was necessary, particularly for those residing at Whakapapa Village on the slopes of Mount Ruapehu, and especially people in the Whakapapa Ski Area.

In 1984 the Lahar Warning System (LWS) was installed by government departments, the Ministry of Works, Dept of Scientific & Industrial Research (forerunner of GNS Science) and the Department of Lands & Survey (forerunner of DOC). Key parts of the system needed to be placed near the crater so a strong wooden structure (Dome Shelter) the size of a shed with a steel bunker beneath it, was located on Dome Peak overlooking Crater Lake/Te Wai ā-moe. The system would trigger an automatic “Stage 1” alarm at Whakapapa offices when detecting significant differences in seismic signals between the volcano and a remote peak in Tongariro Forest. A “Stage 2” alarm would be sent when Dome Shelter was destroyed as it had been in the 1969 eruption. Keeping it powered and operational was a challenge in the severe alpine environment characterized by rime ice most months and very thick in winter.

The 1995 LWS failure

In September 1995, another eruption occurred, damaging the Dome Shelter and the LWS, and exposing its inadequacy. Like that of a brief lahar generating eruption in 1988, the longer 1995 eruption produced numerous Stage 1 alarms but not a Stage 2 alarm, despite the damage, and a series of lahars, including two through the Whakapapa ski area. Valuable lessons were learned from this near-miss event, including the need to have multiple stations with sensors and more robust detection and communication systems. The system was then re-engineered by GNS Science as the Eruption Detection System (EDS).

The Eruption Detection System (EDS)

The primary purpose of the Eruption Detection System (EDS) was to identify eruptions on Mount Ruapehu and provide skiers in valleys at the Whakapapa Ski Area with timely (within 30 seconds) warnings via sirens and voice message of an approaching lahar, so they could make their way to higher ground and out of danger. This system also ensured that response agencies were promptly notified via SMS, email, and page messages.

Whakapapa Village Lahar Alarm and Warning System (VLAWS)

The VLAWS was designed after the lessons learned from the 1975 and 1995 eruption lahars and the upgraded EDS and was commissioned in 2013. The purpose of the VLAWS is to detect lahars travelling down the Whakapapanui River on the northern flanks of Ruapehu and provide residents, visitors, and businesses in Whakapapa Village with a 20-minute warning via sirens and voice message of an approaching lahar, so they can leave to designated evacuation areas. The system also provided alerts via SMS, email, and page messages to response agencies.

The 1995-96 changes to the Crater Lake/Te Wai ā-moe

After the 1995 eruptions, significant changes were found to have occurred in the Crater Lake rim and upper Whangaehu Valley due to erosion and the accumulation of a thick layer of tephra (ash, scoria, and lava rocks) over the crater area. Parts of the southeastern rim, between Pyramid Peak and the outlet and the spur to the west of the outlet, and the ridge between the Pyramid and J Peak were eroded by cascading lake water and the explosions that occurred during the eruptions. These changes led to a 40% enlargement of the crater lake. Its walls south of the Pyramid thinned and parts of the crater rim were lowered. Such changes brought a concern about the stability of the rim, and size and path for future lahars [7].

Tephra Dam was the name given to the built up of material that blocked the natural outlet to the Whangaehu River. Unlike in 1953, there was no longer an ice tunnel restricting the flow out of the Crater Lake. Therefore, the peak outflow from the lake into the Whangaehu River was expected to be unrestricted and potentially significantly larger than in the 1953 flood [7]. The expectation was that as the Crater Lake started to refill and came close to overflow the Tephra Dam, internal seepage flow was likely to occur through the permeable tephra, which was expected to lead to piping erosion in the tephra layer, weakening it, and leading, eventually to a rapid breach and discharge of the lake into the Whangaehu River. Based on the 1953 precedent, overtopping of the dam, channel erosion and slow lowering of the lake was deemed unlikely [7].

The growing concern with a 1953 repeat event

The concern over the possibility of a repeat of the 1953 event was significant. Following observations after the eruptions in 1995, the NZ Department of Conservation convened a workshop In April 1996. The workshop focused on the changes observed in the Crater Lake and developed a plan to investigate and address these concerns [7]. The plan consisted of two phases: Phase I (1997) included survey and geological/geomorphological mapping, oblique photography, sampling and testing the southeastern rim and stability, and dam break analysis. Phase II (1998) involved a refinement and more in-depth analysis of the hydraulic modelling and inundation studies, with estimation of peak flow depths, and assessment of possible infrastructure and environmental damages.

At the Minister of Conservation’s request in 1997, the New Zealand Department of Conservation (DOC) prepared an Assessment of Environmental Effects (AEE) report to provide mitigation measures to the Minister of Conservation [7, 23]. The AEE process was carried out under a short timeframe dictated by an early forecast that the lake could refill by 2000 at the earliest. A draft assessment was released in October 1998, based on the scientific and technical information compiled, and some consultation with stakeholders. Six categories of options were developed with knowledge of work conducted at crater lakes and similar situations elsewhere around the world, to mitigate the concerns:

1- Allow lahar to occur naturally: develop alarm and response system, improve land use planning but no engineering intervention at crater, etc.
2- Allow lahar to occur but intervene in lahar flood zones to reduce its size and/or confine it.
3- Aim to prevent or reduce a lahar by hardening or perforating tephra barrier e.g., grouting, weir, tunnelling, culvert.

4- Prevent or reduce a lahar by excavating a trench through the 1995-1996 tephra barrier using techniques such as bulldozer, snow groomer, explosives, sluicing.
5- Prevent a lahar and reduce lake volume by excavating trench into underlying lava at the lake outlet.
6- Defer, prevent, or reduce a lahar by other options like siphoning or barrier truss.

Further agency, iwi and public submissions were then sought. The final report was released in mid-1999. Most stakeholders favored option 1 to allow the lahar to occur naturally while developing an alarm and response systems and improving land use planning for the long term [23]. However, a strong minority favoured the short-term option of bulldozing because of perceived risks to life, the local economy and jobs, perceptions that it would be easy to do and that costs would be less, or more constrained, with this option, and an argument that it was better to prevent a lahar than allow it to happen [23].

As it became apparent that the lake was taking longer to fill, further, more robust risk assessments of a narrowing range of residual risks were prepared between 2001 and 2006 for the government and individual agencies. This process was facilitated by DOC initially and from 2001 jointly with the Ministry of Civil Defence and Emergency Management until 2002/2003, when councils assumed responsibility under the Civil Defence and Emergency Management Act 2002. Three Conservation and later other ministers, from successive governments composed of different political parties, were responsible for a series of planning, administrative and funding decisions between 1997 and March 2004. These decisions were made to ensure the risks from the predicted dam-break lahar and future lahars potentially large enough to affect infrastructure on the Whangaehu and Tongariro rivers were understood and mitigated. [This period is further elaborated in 23 and 30].

The Eastern Ruapehu Lahar Alarm and Warning System (ERLAWS)

In May 2000, after reviewing the final AEE and an independent review of it, the Minister of Conservation approved the design and installation of a public lahar alarm system and recommended the drafting up of a contingency plan for warning and response actions by responsible agencies [7].

The alarm system, named the Eastern Ruapehu Lahar Alarm and Warning System (ERLAWS), was installed the summer of 2001/02. It was a best-practice alarm system, which comprised of a network of sensors, acoustic flow monitors (AFMs [31]), dual-pathway telemetry to a base station at Tokaanu power station (Genesis Energy), and near real-time interfaces to pagers, telephones, and the internet. While the geophones and the tripwire across the dam were reliable sensors, the pressure transducers used to help monitor lake level proved to be unreliable for alarming [23].

The goal of the ERLAWS was to provide an early warning (two hours in advance of a lahar reaching Tangiwai) and notify all stakeholders of the impending danger. Its objective was to detect the actual dam break as well as a large lahar coming down the upper Whangaehu valley. A response plan was developed by the local district councils with major support from DOC, the NZ police, the Fire Service and the other agencies and companies involved. This included a succession of exercises as the lake level rose [23]

Infrastructure improvements

Since the Tangiwai disaster of 1953, significant efforts were made to enhance the resilience of vulnerable infrastructure to lahars. By January 6, 1954, a temporary rail bridge replacing the collapsed one was in operation. This temporary bridge was eventually replaced with a permanent bridge in 1957. The highway was rerouted in the 1960s with a new stronger bridge. In 2002-2003, lahar and risk predictions due to the Tephra Dam made specifically for the highway site indicated that, similar to what happened to the rail bridge in 1953, the exposure of the road bridge girders to peak lahar flows would produce overturning load demands far in excess of the bridge’s ability to resist particularly in a scoured bed environment [25, 32]. In response, Transit New Zealand under government direction funded raising of the road bridge by 2 m in 2005 which cost NZ$4 million ($6.4 million in 2023 dollars. This cost can be compared with that of building a replacement bridge which might have been around $40-50 million based on the widely publicized cost of a similar sized, three span bridge just completed on NZ Highway 25A).

To mitigate the risk of distributary flows crossing into the Tongariro catchment and affecting the State Highway 1 bridge and Tongariro River, a 300-m-long bund structure, reaching a height of 4.6 m, was constructed during 2001-2002 [23].

Dome Shelter was replaced by a concrete bunker built in 2011/12 1.4 km away from the center of Crater Lake/Te Wai ā-moe. The shelter was removed in 2017 after confirmation from the seismic detection and communication systems that the data from the new, mains-powered bunker were compatible with the long seismic record from Dome.

Further observational measures

The lake level was closely monitored throughout based on regular surveys and lake level recording transducers. Measurements of the grainsize and permeability of the layers of tephra in the Tephra Dam were used to determine the probability of dam failure by various failure modes at specific lake levels [33] . Specific Warning Levels were agreed, based on these probabilities to provide a more definite warning of the impending lahar and give responsible authorities, transport, and utility agencies more time to plan and initiate an appropriate response.

The March 2007 success story

In March 2007 the tephra dam broke and released the waters from the crater lake, but this time, the warning system worked. The predictions were in very good agreement with the actual lahar [23, 25] especially at Tangiwai (30). The response plan worked very well, no one was hurt, and apart from a small toilet block that was closed off very little damage occurred to infrastructure. The highway and rail bridges were operational within a few hours of closing as part of the response plan. Reflections on land-use planning, risk mitigation, cost-benefits and improved resilience with the long-term approach taken are discussed elsewhere [30]. It is unlikely that the highway bridge would have been raised if Option 4 had been chosen. This would have meant that the bridge, if it had survived the lahar, would have remained exposed to sudden large unheralded eruption lahars.

With the Tephra Dam gone, the water level at the crater lake is now controlled by the outlet into the Whangaehu River. The concerns now, besides the usual eruption generated lahars (and the eruptions itself), would be lahars produced by the collapse of the rim (hard rock) or landslide of parts of the crater rim into the crater lake. Such landslides were part of the scenarios developed before the dam break, but the probability and risks were assessed as low compared to the main dam break process.

The September 2007 lessons

Another eruption occurred without warning on September 25 the same year, a phreatic eruption, which produced a snow rich lahar, which did not trigger either ERLAWS or EDS alarms, even though its peak discharge was approximately 1700 m^3/s. ERLAWS detected the lahar, but the system didn't trigger [23, 30]. This appears due to the low energy transfer to the riverbed as a function of the low bulk density and low collisional interaction in the turbulence-damped water-poor/snow-rich composition lahar flows (V. Manville & S. Cole personal communications). The EDS determined quickly that the eruption was large enough to cause a lahar but the main alarm communication system at Dome was destroyed and the second system (set up after the 1995 near-miss) was too slow to reach the alarm threshold.

Retirement of ERLAWS

After 20 years of service, the Eastern Ruapehu Lahar Alert and Warning System (ERLAWS) was retired in June 2022. ERLAWS was built to mitigate the lahar risk from the tephra dam created by the 1995 and 1996 eruptions of Ruapehu. It successfully detected the lahar caused by the tephra dam's collapse on 18 March 2007. However, with the tephra dam gone, the water level at the crater lake is now controlled by the outlet into the Whangaehu River. One AFM site installed at the Crater Lake dam site to detect the lahar initiation was removed in January 2008, as its main purpose had been achieved. It was partly redundant and further operation was not justified given the environmental and logistic challenges with that site, including false positive alarms caused by storms in the alpine location [23]. By 2022 the technology had become dated. It has been replaced by a new lahar detection and warning system for the Whangaehu River, operated by Genesis Energy and Horizons Regional Council. A lahar detection results in phone alerts being sent automatically to the same stakeholders as for ERLAWS (Nathan Penny HRC, personal communication).

Volcano and lake monitoring

Mount Ruapehu Volcano is monitored by the GNS Science through a program called GeoNet (www.geonet.org.nz). Instrumentation includes seismometers, web cameras, and continuous GNSS stations to record ground deformation. [14, 16]. A supervisory control and data acquisition system (SCADA) monitors the eruption detection data inputs from GeoNet. It sends eruption, all clear, testing, and diagnostic alerts via email and email-to-SMS to emergency response groups and stakeholders.

GNS Science’s monitoring program also measures the temperature and level at the Crater Lake, performs monthly gas and water chemistry analysis, mostly collected manually by staff. GNS Science has recently installed three permanent gas monitoring stations on the northern, eastern and western sides of the volcano. The agency also sets Volcanic Alert Levels (VALs), and issues Volcanic Activity Bulletins via GeoNet [36, 37].

Status of Emergency Management

The National Emergency Management Agency (NEMA) is the legislated agency responsible in the event of a volcanic emergency, and the overall response at Ruapehu is led by the Ruapehu District Council. DOC, through their Initial Response Plan (IRP [34]) takes on an operational lead role within the Tongariro National Park specifically addressing the initial stages after an eruption, or volcanic event. DOC works collaboratively with District Councils, GNS Science, Police, local iwi, and Ruapehu Alpine Lifts in the first instance. The size and scale of the event will often determine if additional support is required. All agencies are represented on the Central Plateau Volcanic Advisory Group which ensures integration of individual agency plans. The IRP [34] for volcanic activity in Tongariro National Park (TNP) is one of two documents used by DOC to guide its approach to volcanic risk management and response. The IRP addresses the initial response to an eruption in the TNP. The Guidelines for DOC Volcanic Risk Management in TNP [35] address the escalation and de-escalation of volcanic unrest and the associated management actions that accompany the changing volcanic climate.

The IRP response is triggered by the activation of the TNP Volcanic Alert Network (TNP VAN) or observations of an eruption. The TNP VAN has continued to build on the systems outlined above with periodic upgrades of components and central processing most recently in 2022. The EDS concept has become expanded and rationalized into detection systems for Ruapehu and Tongariro volcanoes owned and operated by GNS Science. The public messaging system on Whakapapa Ski Area is based at the DOC Visitor Centre at Whakapapa Village and is owned and operated by DOC with operational assistance at the mountain sites by the ski company. VLAWS, also owned and operated by DOC is integrated with and activated by the Ruapehu EDS. It continues to have an outstation beside the ski area at the Skippers Fence, equipped with a tripwire, a cabinet with UHF radio link to the base station at the DOC Visitor Centre at Whakapapa Village and a multicore power and communication cable from the ski area Schuss House. Triggering of the tripwire by breakage (drop in voltage due to tripwire breakage) provides a “confirmation” that a lahar has arrived at this location. Programmable Logic Controllers are now used rather than AFMs using standard industrial automation technology aligned with other stations on the mountain providing better integration with SCADA. Agencies continue to be alerted but paging has become redundant. In summary the TNP VAN includes:

• *The Ruapehu Eruption Detection System (REDS) and Whakapapa Ski Area Lahar Alert and Warning System (WLAWS)*	The REDS detects eruptions from the crater lake using acoustic and seismic sensors. If an eruption is detected, it triggers the WLAWS system, which consist of a siren and a voice message instructing people to move to out of the valley into higher ground.
• *The Whakapapa Village Lahar Alert and Warning System (VLAWS)*	VLAWS uses a tripwire in Skippers Canyon to detect lahars travelling down the Whakapapanui Stream. This system will activate if REDS is activated.
• *The Tongariro Eruption Detection System (TEDS)*	TEDS detects eruptions and communicates like REDS but on Tongariro Volcano including Ngauruhoe and only to GNS and DOC

Based on past eruptions, planning assumes it takes 1-5 minutes for a lahar to reach the top Whakapapa Ski field, 15 minutes to reach the bottom and 25 minutes to reach the Whakapapa Village [34].

Public Safety

The Department of Conservation (DOC) in conjunction with GNS Science, Ruapehu Alpine Lifts Ltd and Ruapehu District Council, has undertaken various initiatives to promote public safety and awareness of the volcano hazards. Educational materials, including posters, have been distributed throughout the Whakapapa Village and Ski Area, as well as material on the web. However, despite these efforts, research involving public tests of the Eruption Detection System in Whakapapa ski area revealed that a persistent minority of up to 20% of individuals remain in lahar paths even one minute after warning broadcasts [38]. Ensuring effective response to the warning system at Mount Ruapehu presents challenges due to the transient nature of ski area visitors and their lack of familiarity with volcanic hazards. Detailed interviews with staff and public, as well as observations during "open" and "blind" exercises serve as important research tools. Risk can never be eliminated entirely.

VII.CONCLUSIONS/EPILOGUE

Natural dams present significant hazards, particularly in the case of Mount Ruapehu, where the complex geomorphology and dynamic nature of its rims, comprised of various layers of lava deposits, eruption debris, ice, and snow, pose unique challenges. The location of this site on top of an active volcano within a much-visited national park and World Heritage site further compounds these challenges.

Although predicting eruptions remains a difficult task, the presence of the Crater Lake provides valuable insights into the volcano's activity and proximity to an eruption. Thus, monitoring the lake is crucial to the monitoring of lahars, and the instrumentation scattered across Mount Ruapehu plays a vital role in providing timely alarms and warnings, especially to those in the most at risk Whakapapa and Tangiwai areas.

Effective emergency response and preparedness plans in place, regularly updated and accompanied by proper training, have proven their effectiveness as demonstrated during the March 2007 event and most recently in 2022 during a period of relatively intense volcanic unrest.

Furthermore, public education is essential, albeit challenging when the target group is continuously changing, as is the case with visitors to the Whakapapa ski areas. While the alarm and warning system will alert individuals within the hazard zone, understanding and heeding the warning is of utmost importance.

Infrastructure, including road and rail bridges, is particularly vulnerable to lahars where they exist. It is imperative to either locate these structures outside the path of destruction or design them to withstand such hazards.

The use of monitoring systems to detect volcano activity and lahar flows are challenging. Volcanos are dynamic, unpredictable, locating and protecting the instrumentation is difficult and can be dangerous to maintenance staff. New generations of technologies offer additional capacity and reliability. Ongoing installation, operation, testing, and maintenance of these systems is critical to protecting the public from the hazards of lahars.

Numerous lessons have been learned since the tragic events of the Christmas Eve in 1953. These lessons have been transformed into action, evolving over the years, culminating in the successful prediction and management of the Tephra Dam break in March 2007. The efforts of the individuals involved encompassed accurate predictions of the event (timing, water level, failure mode, peak flow, and bulking factor), effective monitoring triggering the alarm and warning systems, seamless interagency application of the emergency response plan, and, most importantly, the prevention of loss of life.

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