the close correspondence between peatland initiation and atmospheric methane concentration. At the beginning of the Holocene, 11,500 years ago, there was a sharp rise in atmospheric methane that was contemporaneous with the timeline of peatland expansion in Nichols and Peteet's analysis, providing further support[4,6,13] for the argument that peatland expansion was a key driver of the deglacial atmospheric methane surge.

Nichols and Peteet provide a timely update of the scale of peatlands' capacity for carbon sequestration, which further emphasizes the importance of these ecosystems in the global carbon cycle. The results make the omission of peatlands from many Earth-system models a more urgent issue to be addressed. In addition, peatlands and the carbon they store are increasingly vulnerable to perturbations from climate and land-use change. It is therefore vital to better understand the scale of risks to peatlands in order to address uncertainty over the future direction of the northern peatland carbon stock[14]. ❐

Matthew J. Amesbury[1,2]*, Angela Gallego-Sala[2] and Julie Loisel[3]
[1]Environmental Change Research Unit, University of Helsinki, Helsinki, Finland. [2]Geography, College of Life and Environmental Sciences, University of Exeter, Exeter, UK. [3]Department of Geography, College of Geosciences, Texas A&M University, College Station, TX, USA.
*e-mail: m.j.amesbury@exeter.ac.uk

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NATURAL HAZARDS

Irrigation and the Palu landslides

Wet rice cultivation in the Palu Valley, Indonesia, prepared the ground for the devastating liquefaction-induced landslides that were triggered by the M_w 7.5 earthquake in 2018, suggest two studies of the spatial relationship between landslide morphology and irrigation.

Phil R. Cummins

Human activity can influence earthquake hazard. Artificially filled ground has enhanced earthquake ground motion[1], and the filling of reservoirs and deep injection of waste water have induced earthquakes[2,3]. The moment magnitude (M_w) 7.5 earthquake in Palu, Sulawesi in 2018 has taught us that another — seemingly innocuous — human activity can exacerbate earthquake hazard: irrigation on gentle, alluvial slopes, as is common in many rice-growing areas of Asia. Writing in *Nature Geoscience*, Bradley et al.[4] and Watkinson and Hall[5] have established that the massive and deadly low-angle landslides generated by the Palu earthquake were induced by earthquake-triggered liquefaction, caused by a water table artificially raised by the irrigation system in the Palu Valley.

On 28 September 2018, a M_w 7.5 earthquake ruptured the Palu-Koro Fault, causing a tsunami and massive, liquefaction-induced landslides in the city of Palu. The largest landslides were in the villages of Petobo (Fig. 1), Balaroa, Sidera, Sibulaya and Lolu. In these landslides, a total area of at least 450 ha moved more than 5 m (ref. [4]), including some areas where maximum displacement exceeded 1 km (ref. [5]). The number of deaths due to these massive landslide and liquefaction events may never be known. But it is likely to be several thousand, and to have far exceeded those killed by the tsunami also generated by the earthquake. Because many of the bodies in these areas will never be recovered, villages like Petobo and Balaroa will be designated mass graves with no planned resettlement.

To understand the mechanisms behind this human catastrophe, Bradley and colleagues used pixel correlation of Planet satellite imagery acquired before and after the earthquake. They mapped displacements by up to 15 m associated with long-runout landslides and debris flows along the eastern side of the Palu Valley, opposite the earthquake fault rupture along the valley's western side. (Much larger displacements occurred[5], but are too large to be mapped by pixel correlation.) The mapped displacements abruptly end up-slope at the unlined Gumbasa Aqueduct that had been built by the Dutch colonial government in the early twentieth century. A comparison of the displacement with a detailed map of land use shows a strong correlation between displaced areas, and fields and paddies with little intervening forest.

A map of the strain calculated from the ground movement shows these cultivated areas to have exhibited extensional strain, whereas forested land experienced shortening. These patterns suggest that the most dramatic spreading occurred in irrigated fields that were not interrupted by stretches of forested or urbanized land, whereas forested land had a lower water table that arrested the spreading.

In a parallel study, Watkinson and Hall analysed DigitalGlobe satellite imagery, tracking objects recognizable in both pre- and post-earthquake imagery. They also generated a displacement field for the major landslides on the eastern side of the Palu Valley. Maximum displacements amounted to over 1 km at Petobo and Sidera, observations which suggest that Petobo alone, with a surface area of 140 ha, is the largest lateral spread — ground failure resulting in nearly horizontal flow-like movement — ever documented. Correlation and principal component analyses show that the displacement field was strongly associated with elements of the irrigation system, such as distance to the main conveyance canal, and to irrigation-system turnouts and division boxes, where

Fig. 1 | Destruction by liquefaction, Petobo, Palu. Bradley and colleagues[4] and Watkinson and Hall[5] conclude that the landslides on very gentle slopes were made possible by wet rice cultivation that led to water-saturated soils and liquefaction upon shaking by the M_w 7.5 earthquake. Other regions in Asia could be prone to similar hazards. Credit: Pacific Press Agency / Alamy Stock Photo

infiltration should be high and is expected to raise the water table.

The three main landslides occurred where the slope on the western edge of the main irrigation canal was steepest, exceeding 1.5°. Yet, steeper slopes just above the irrigation network did not fail. These observations, together with those of Bradley and colleagues, confirm that irrigation water in the shallow subsurface exerted the primary control on slope failure by making it susceptible to liquefaction — a loss of cohesion in water-saturated, granular soil that causes it to behave like a fluid.

Liquefaction of the ground was not reported in the accounts of previous earthquakes. For example, an event in 1927, near the time of the Gumbasa Aqueduct's construction, caused extensive damage in Palu but there were no reports of liquefaction[6]. This lack of precedent supports the conclusion of both studies that liquefaction would not have occurred in the absence of the extensive irrigation that is now practised in the Palu Valley. One caveat, though, is that there is a word for liquefaction in the Kaili language of the native ethnic group of Palu: *nalodo* translates as buried under mud, and is thought to describe liquefaction[7].

This type of non-written historical evidence of past disasters is too often ignored. Examples include the 'tsunami stones' in Tohoku, Japan, some placed more than six centuries ago to mark the farthest limit of tsunami inundation, which were largely forgotten prior to the 2011 Tohoku earthquake and tsunami[8]. And the word *smong* signifies a tsunami in the local language of the island of Simeulue off Sumatra; this knowledge saved thousands when tsunamis devastated Sumatran coastal communities in 2004 and 2005[9].

The studies by Bradley et al. and Watkinson and Hall warn that the Palu landslides should serve as a wake-up call that we need to reassess the stability of gentle slopes where irrigation is used in seismically active areas. This applies to Palu, where re-liquefaction may still occur in response to ruptures on the main Palu-Koro Fault south of Palu, or on fault strands directly beneath the Palu Valley[4,10]. The same mechanism may also be cause for concern in other parts of Indonesia as well as in Myanmar and elsewhere.

On the other hand, the anthropogenic nature of this newly recognized hazard may have a silver lining, because it may be mitigated by adjustments in human activity. Reducing or spreading infiltration by using a more distributed system of irrigation canals might help to lower the water table, and breaking up the connectivity of liquefiable layers by staggering land use may reduce the potential for such massive ground failure[4,5]. Such measures should be urgently considered in Palu, before reconstruction locks in the same vulnerability that existed before the 2018 earthquake. ❐

Phil R. Cummins
Research School of Earth Sciences, Australian National University, Canberra, Australian Capital Territory, Australia.
e-mail: phil.cummins@anu.edu.au

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