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New Zealand's National Landslide Database

Abstract A New Zealand Landslide Database has been developed to hold all of New Zealand's landslide data and provide factual data for use in landslide hazard and risk assessment, including a probabilistic landslide hazard model for New Zealand, which is currently being developed by GNS Science. Design of a national Landslide Database for New Zealand required consideration of existing landslide data stored in a variety of digital formats and future data yet to be collected. Pre-existing landslide datasets were developed and populated with data reflecting the needs of the landslide or hazard project, and the database structures of the time. Bringing these data into a single database required a new structure capable of containing landslide information at a variety of scales and accuracy, with many different attributes. A unified data model was developed to enable the landslide database to be a repository for New Zealand landslides, irrespective of scale and method of capture. Along with landslide locations, the database may contain information on the timing of landslide events, the type of landslide, the triggering event, volume and area data, and impacts (consequences) for each landslide when this information is available. Information from contributing datasets include a variety of sources including aerial photograph interpretation, field reconnaissance and media accounts. There are currently 22,575 landslide records in the database that include point locations, polygons of landslide source and deposit areas, and linear landslide features. Access to all landslide data is provided with a web application accessible via the Internet. This web application has been developed in-house and is based on open-source software such as the underlying relational database (PostGIS) and the map generating Web Map Server (GeoServer). Future work is to develop automated data-upload routines and mobile applications to allow people to report landslides, adopting a consistent framework.

Keywords Landslides · Landslide database · New Zealand

Introduction

Landslides play an important role in the evolution of landscapes, but they can be hazardous to people and economies. In order to quantify the risks posed by landslide hazards to society, knowledge of where, when and why landslides occur is vital. In New Zealand, landslides occur frequently but because of the low population density, especially in the hilly and mountainous terrain, there are relatively few deaths compared to countries where mountainous terrain is more heavily populated (Page 2015). Since 1843, there have been at least 600 deaths (Page 2015; Z. Bruce, pers. comm. 30 June 2016) from landslides in New Zealand (compared with 458 from earthquakes) and a lower estimate of the national annual cost associated with landslides is NZ $250–$300 M/year (Page 2015) (0.1–0.12% GDP). These figures are regarded as a minimum because of the incomplete nature of landslide data and reporting. Indirect costs associated with landslides such as economic losses due to road closures and loss of ecosystem services (Dominati et al. 2014) not only are harder to quantify but also impose significant costs to businesses and communities and are included in these totals (Page 2015). For example, the closure of State Highway 3 through the Manawatu Gorge, a major transport link, for 33 days in 2011, cost road users in excess of NZ $2 M (due to lost productivity, extra fuel and time costs) (Page 2015). Topsoil loss associated with landsliding causes soil degradation and pasture productivity losses that may not be regained within human timescales (Lambert et al. 1984; Rosser and Ross 2011), as well as causing adverse impacts in downstream water bodies, leading to river sedimentation (increased flooding hazard), degradation of riverine habitats and loss of water quality. Dominati et al. (2014) estimated the immediate cost of lost ecosystem services from topsoil loss due to landslides triggered by the 2011 Hawke's Bay storm to be NZ $10 M. However, if the on-going ecosystem services costs calculated for the following 20 years are taken into account, the net cost may reach NZ $146 M (Dominati et al. 2014).

Landslide inventories underpin landslide hazard and risk assessments. The accuracy of landslide hazard and subsequently risk assessments is directly related to the quality of the underpinning data and typically increases with the length (of time) and quality of the landslide records used (Glade and Crozier 1996). Landslide hazard assessments are greatly enhanced if they include information on the magnitude, encompassing the distribution (number and location), type, density, size and impacts of landslides, and temporal frequency of past landslide events (Aleotti and Chowdhury 1999; Glade and Crozier 1996). The on-going capture of landslide records provides the magnitude and temporal frequency of landslide activity and its relationship with terrain types and individual triggering events (Glade and Crozier 1996), and this increases the reliability of landslide hazard assessment.

The importance of landslide inventories was highlighted at the Fifth International Landslide Symposium in 1988, where it was proposed to develop a World Landslide Inventory (Cruden and Brown 1992) to aid the United Nations in understanding the distribution of landslides and their causal factors. This was considered essential for the implementation of mitigation strategies and to plan for future landslide events (Cruden and Brown 1992). At that time, several countries had already established national and regional landslide inventories, and a recent (July 2015) Google search revealed that as many as 46 countries have now established landslide databases. Most European countries have landslide databases (Van Den Eeckhaut and Hervas 2012), and recent efforts to compile landslide databases have been undertaken in Malaysia (Murakami et al. 2014) and Nicaragua (Devoli et al. 2007).

Great Britain (Foster et al. 2012) and Australia (Mazengarb et al. 2010; Chowdhury and Flentje 1998) have recently developed digital landslide databases to aid others in identifying the hazards and risks posed by landslides to society and to provide guidance for landuse planners to recognise areas where landslides are likely to occur and to protect against their consequences (Foster et al. 2012). In Hong Kong, a GIS-based landslide database has been developed (Dai and Lee 2002), which links landslide temporal frequency to the physical parameters contributing to initiation, and includes a multiple-regression model for predicting slope instability. In the USA, the USGS has a landslide inventory pilot project (http://landslides.usgs.gov/research/inventory/) that provides an online framework and tools for displaying and analysing digital landslide spatial data. NASA is also compiling a global database of rainfall-induced landslide events for use in its landslide hazard forecasting tool (Kirschbaum et al. 2010), using satellite-imagery-based landslide hazard assessment. The USGS landslide inventory is being used to test and improve the forecasting model.

This paper describes the development of the New Zealand Landslide Database (NZLD). The various historical and on-going data sources for the database are described, along with the specific data that are recorded. The database design is outlined, including its structure, the metadata used, technical specifications and data dissemination via a website (http://data.gns.cri.nz/landslides).

Data sources for the New Zealand Landslide Database

In New Zealand, landslide data are collected by many different agencies. The databases are populated with data intended to meet the needs of the collecting agency, and therefore, the data structures tend to be different and incompatible, making transfer and comparison of data difficult. Conceptual work on developing a centralised and consistent database began at GNS Science in 2002 (Dellow et al. 2003; Glassey et al. 2002).

This current landside database was initially developed through the GeoNet project (www.geonet.org.nz), New Zealand's geological hazard monitoring system. The NZLD is a source of landslide information for New Zealand, and it currently contains 22,575 records (Fig. 1). The New Zealand Landslide Database is now available online at http://data.gns.cri.nz/landslides.

The landslide database combines a number of existing landslide datasets held by GNS Science. Data held by other agencies will be added as it becomes available. The landslide database is comprised of two groups of data: (a) historical landslide data and (b) data collected from on-going landslide mapping, monitoring and research. The main data sources are listed in Table 1 and outlined briefly below. The number of records derived from each of the data sources is listed in Table 2.

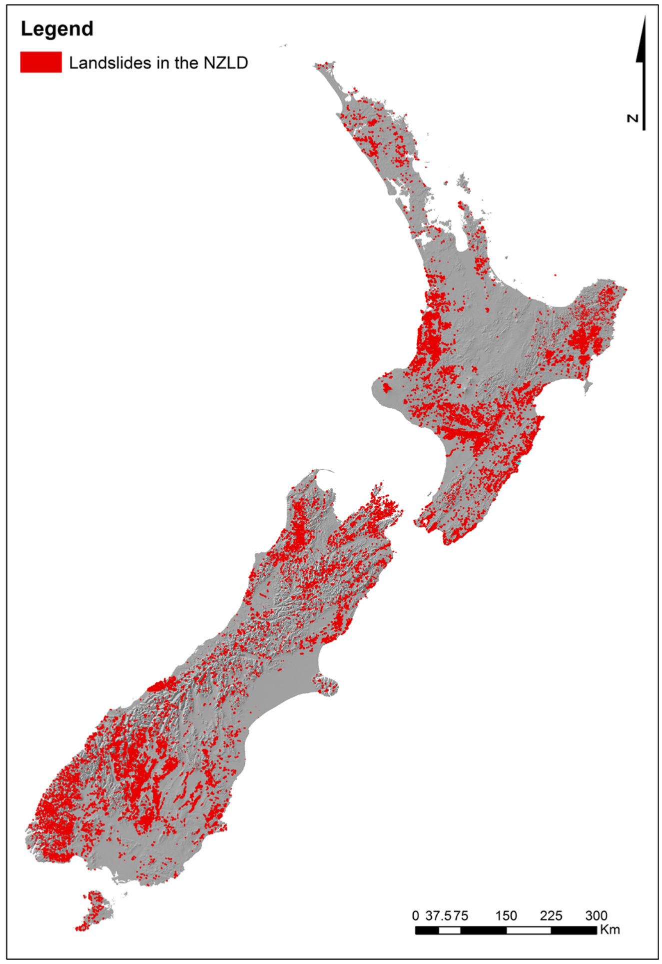

Fig. 1 Areal distribution of landslide data currently held in the New Zealand Landslide Database

Large landslide dataset A GIS-based landslide dataset was first developed by GNS Science in the 1990's using data from a large landslide mapping project. The large landslide mapping project began in 1993 with the objective to catalogue all landslides in New Zealand with volumes greater than 10^5 m^3. Attributes include area, volume, landslide type, activity, causal factors and environmental effects. Landslides were plotted on 1:50,000 topographic maps (NZMS 260 map series), digitised and stored in a spatial database (Glassey et al. 2002). The mapping comprised landslide features plotted by hand onto 1:50,000 NZMS260 topographic maps from air-photo interpretation. Initially, this was restricted to large landslides, but subsequently, some smaller landslides, down to ~10,000 m^2, were recorded on the topographic sheets. The spatial data plotted on the maps includes landslide features (outline "scar", head scarp, source area and debris) and some other geomorphic features associated with landslides and other erosion processes such as hummocky ground, gully erosion, depressions, landslide-dammed lakes. The landslide spatial data in this dataset has an accuracy of ±200 m. Very few records contain information about the age or timing of the landslides (some large historical earthquake-induced landslides were mapped as part of this dataset).

Earthquake-induced landslide dataset The earthquake-induced landslide datasets contain the locations of landslides associated with major earthquakes in New Zealand, at a scale of 1:250,000 (Hancox et al. 1997, 2002). It was developed independently from the Landslide GIS, using different attributes to describe landslides. The Earthquake-induced Landslide maps were prepared using information compiled from a review of New Zealand literature on earthquake-induced landslides and analysis of aerial photos and topographic maps. These landslide distributions, together with other types of environmental effects (e.g. liquefaction and ground cracking), were used by Hancox et al. (2002) to estimate Modified Mercalli (MM) shaking intensities.

These earthquake-induced landslides were initially captured as point coordinate data only, rather than their spatial extent (polygons), although landslide source and deposit areas have been mapped for more recent events, since the 2003 M_w 7.2 Fiordland Earthquake (Hancox et al. 2003, 2014, 2015). The dataset also includes areas of liquefaction and other ground damage sites, shaking intensity contours (isoseismals) and the epicentres of

Table 1 Summary of data sources for the New Zealand Landslide Database

Source	Description	Format	Scale
Large landslide dataset	Data from the Large Landslide database project and NZMS260 mapping (existing)	Mixture of point and polygon data	1:50,000
Earthquake-induced landslides dataset	Locations of earthquake-induced landslides associated with major earthquakes in NZ (existing)	Point data	1: 250,000
QMAP landslides	Generalised landslide data layer from the 1: 250,000 Geology Map of NZ series (existing)	Polygons and linear features	1:250,000
Landslide catalogue	Reported landslides since 1996. Includes newspaper accounts, landslide reports from GeoNet responses, and reports from other sources e.g. New Zealand Transport Agency (NZTA), New Zealand Automobile Association (AA), NIWA, Regional Councils, etc. (on-going)	Point data	Various, accuracy as specified
Site/event specific landslide studies	Detailed data from major storms or earthquakes derived from satellite or aerial photo imagery (on-going)	Point and polygons	>1:5000
Regional/project landslide inventories	A number of GIS-based landslide inventories developed for specific projects e.g. Waipaoa Catchment large landslides (Page and Lukovic 2011) (on-going)	Point and polygons	Various

earthquakes. Only data relevant to landslides have been transferred to the new database. The spatial data in this dataset has frequently been retrieved from historical written accounts. This means that, particularly for many of the smaller landslides, the location is poorly constrained (±2500 m). However, because the landslides are attributed to specific earthquakes, the information on when the landslides occurred is well constrained, usually to within a few minutes of the earthquake.

QMAP landslides QMAP is the 1:250,000 scale Geological Map of New Zealand (http://www.gns.cri.nz), and it originally used the large landslide dataset to form a layer of landslides. The 2nd edition Geological Map of New Zealand was completed in 2012. Additional landslides, not contained in the large landslide dataset, were mapped as part of the revision and compilation of the QMAP series (http://data.gns.cri.nz/geology/) using aerial photo interpretation. Only landslide deposits and headscarps are included in the maps, and only substantial landslide deposits, thicker than 5 m and covering an area greater than 500 × 500 m, are shown (Rattenbury and Heron 1997). The QMAP landslides comprise landslide boundaries including landslide source, deposit and total landslide area (usually referred to as the landslide scar, Cruden and Varnes 1996). It also contains linear features representing head scarps and ground cracks. Mapping was done at 1: 50,000 scale; however, the data are presented at 1: 250,000 scale with some generalisation and simplification with consequent loss of mapped landslide detail (extent/size/characteristics) (Rattenbury and Heron 1997). No information on the date or dates of landslide movement are included in this dataset.

Landslide catalogue In August 1996, a collation of news media accounts of landslides was started by GNS Science and has continued since. As part of GNS Sciences on-going geohazards monitoring through the GeoNet project (www.geonet.org.nz), monthly landslide summaries are produced of all landslides reported by (1) the media, (2) New Zealand Transport Agency (NZTA), (3) New Zealand Automobile Association (AA) (road closures), and (4) GeoNet landslide response activities. Data are mostly point data, due to the nature of source material (media reports). As a consequence, the accuracy with which the landslides are located spatially is variable, ranging from a ±100 m through to ±25 km. However, the date on which the landslide occurred is routinely recorded and in most cases can be constrained to the day of occurrence. The landslide catalogue requires the date and location of a landslide for every record. If additional data about the landslide (size, type) or its impacts (costs to reinstate roads/infrastructure, deaths/injuries, length of time a road is closed) is available, it will be recorded.

Site/event/project specific landslide studies (GeoNet) Detailed information on landslides is collected after major storms and earthquakes as part of on-going geohazard event monitoring through the GeoNet project (www.geonet.org.nz), and as part of research

Table 2 Numbers of records from each of the pre-existing datasets that were combined to form the New Zealand Landslide Database

Data source	Number of records		
	Points	Lines	Polygons
Large landslide dataset		13,964	23,072
Earthquake-induced landslides dataset	1156		653
QMAP landslides		11,461	3804
Landslide catalogue	3448		
Regional/project landslide inventories			1026 (Waipaoa)

and/or commercial projects carried out by GNS Science. A landslide response is undertaken if a landslide/s occurs that causes death or serious injury, has the potential to cause subsequent catastrophic events (such as the breach of a landslide dam), direct damage of greater than NZ$1 million and economic losses of greater than NZ$10 million, threatens public health (such as contaminated water supplies), or provides significant research interest. The purpose of the landslide response is to ensure that potentially important ephemeral information is not lost, and appropriate advice is available to maximise public safety. A GeoNet landslide response will often involve an aerial reconnaissance immediately after the event to document the extent of landsliding (Dellow 2001; McSaveney et al. 2010).

Typically, data are derived from field inspection (for a single landslide) or from satellite or aerial photo imagery when many landslides have been triggered. Local government authorities often contribute to funding the mapping and analysis of landslide distributions from storms affecting their region. Detailed mapping of landslide distributions, usually at scales of <1:10,000, is completed which can then be compared to other GIS datasets to extract other relevant information such as slope, aspect, vegetation, geology and rainfall.

An example of detailed landslide mapping, contained in the database, is illustrated below in Fig. 2. Landslide source areas (scars typically refer to source and debris outline) and debris deposits of different age were delineated on historic aerial photographs and verified in the field. This particular study was undertaken to determine the impact of mass movement erosion on New Zealand's soil carbon monitoring system (Basher et al. 2011).

Other sources of landslide data Other sources of landslide information include data collected by network operators (e.g. NZTA, Kiwirail (railway), Vector (gas and electricity)) and data collected by local authorities as part of their obligations under the Resource Management Act (1991) to collect and provide information on hazards, including landslides. Data collected by network operators is useful to understand the general areas affected by landslides, but due to the specific interests of each network operator, the landslides recorded are usually biased towards particular positions in the landscape (e.g. data from NZTA only provides information specifically for state highways affected by landslides). Data are often hard to obtain, and it is often collected in a manner that is not easily transferred to a database (e.g. "truckloads" of dirt removed from a stretch of road) (Page 2015). Data are often held by contractors working on behalf of the asset owners/managers, who change frequently or do not wish to release the true cost of landslides on their networks.

On-going data collection Data are added to the landslide database on an on-going basis from GeoNet landslide monitoring and reporting, and specific studies. Large event-based datasets, consisting of thousands of landslides, will be loaded into the database (by GNS staff) using a batch-upload routine that requires

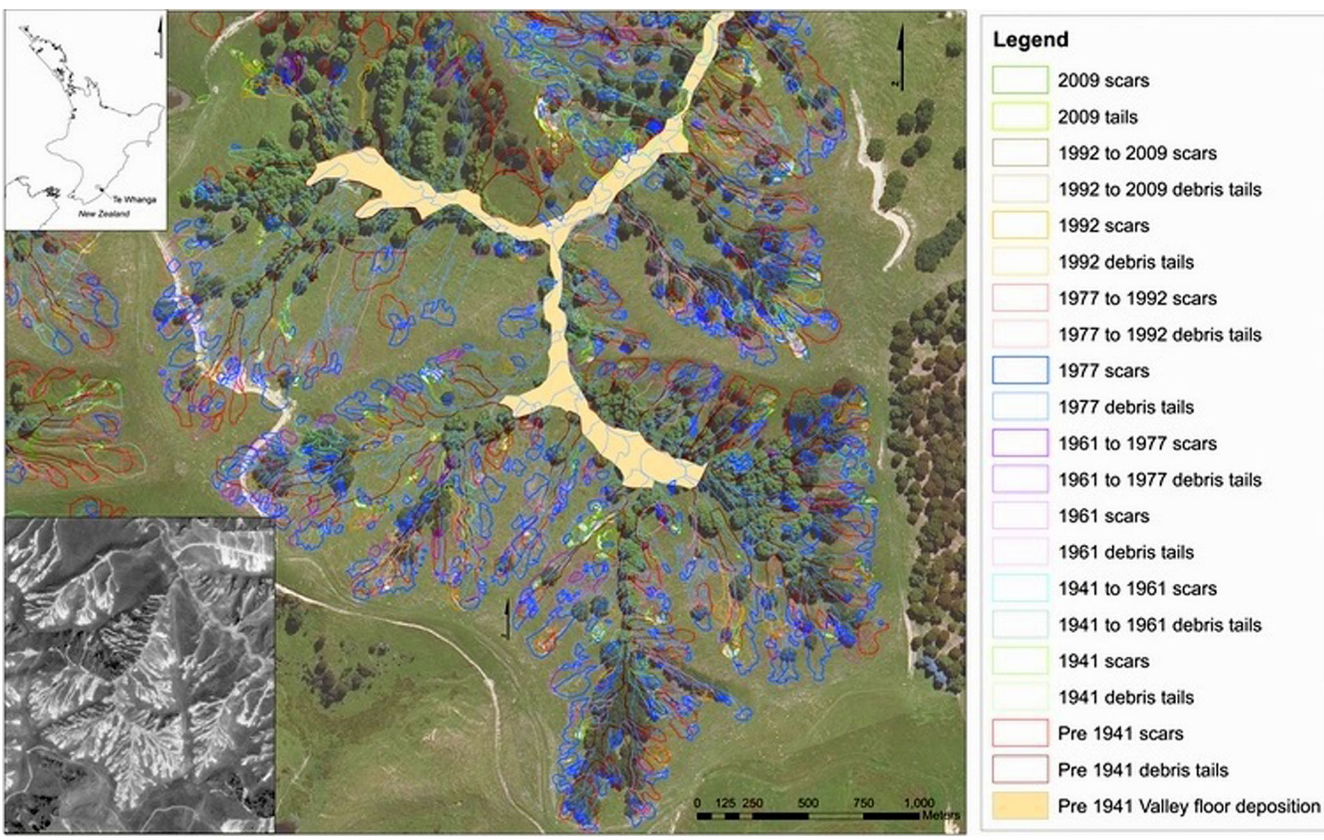

Fig. 2 Distribution of different-aged landslide scars and debris deposits between 1941 and 2009 at Te Whanga Station, Gladstone, Wairarapa (Basher et al. 2011). *Inset* is an aerial photograph of landslides triggered in the same catchment by a storm in 1977

the data format to conform to a predetermined data structure (to map the correct attributes).

New earthquake-induced landslide datasets that will be imported into the database include the recently completed mapping of historical earthquake-induced landslides triggered by the 1929 M_s 7.8 Murchison earthquake (Hancox et al. 2015) and the 1968 M_w 7.1 Inangahua earthquake (Hancox et al. 2014) that contain 6108 and 1400 landslide polygons, respectively. Recent earthquake-induced landslide datasets to be imported include the Canterbury Earthquake Sequence (Massey et al. 2014), Eketahuna (Rosser et al. 2014), Wilberforce (Carey and Rosser 2015), Cook Strait and Lake Grassmere (Van Dissen et al. 2013) earthquakes. A landslide inventory (>10,000 landslides) is currently being mapped for the M7.8 Kaikoura earthquake (Kaiser et al. 2017).

Other datasets include Dunedin City landslides (Glassey and Smith Lyttle 2012) and rainfall-induced landslide datasets from storms affecting Hawke's Bay (Jones et al. 2011) and Kapiti (Page and Rosser 2015).

Summary of landslide data held in the database

The database currently contains 22,575 records, which include 15,678 individual landslides areas (polygons) and 11,903 landslide deposits (Table 3, Fig. 3). There are additional 3174 point locations, with no associated area (polygon). The majority of landslide polygons are for large landslides (>100,000 m^2) (70%), reflecting their data source from the large landslide dataset, and the minimum landslide (polygon) area is 1037 m^2. Each landslide record can have multiple polygon, point and line features mapped, such as the landslide area (encompassing the source and deposit combined), landslide deposit and scarps (Fig. 3), and are linked by a common landslide ID. Landslide polygons each have an associated point that represents the centroid of the landslide area. There are currently 44,471 landslide features in the database (Table 3). As above, several large datasets are awaiting upload which will bring the total number of landslide records to over 200,000. A facility to upload these datasets is in development.

Currently, a large proportion of landslides are not fully attributed e.g. 84% of landslide records have no landslide movement type recorded and 78% have no trigger recorded. This is because the main data source (the large landslide mapping project) mapped prehistoric landslides identified from aerial photo interpretation and consequently have no age or trigger information associated with them. However, 40% of landslides in the database with a recorded trigger (9% of total) were initiated by rainfall, 40% by earthquakes (9% of total) and the remaining 20% are attributed to other triggers (4% of total). These percentages are not thought to be a true reflection of landslides occurring over longer timescales in New Zealand because the more numerous, smaller rainfall-induced landslides are typically under-represented and may represent as much as 90% of landslides. The landslide types represented in the database are shown in Table 4. New entries into the database will be attributed with as much information as is available.

Table 3 Numbers of landslide features held in the landslide database

Landslide feature	No.
Landslide area	15,678
Debris area	11,903
Scarps	14,339
Gully erosion	577
Hummocky ground	1846
Ground cracking	128
Total	44,471

In some instances, the amalgamation of multiple databases has resulted in multiple records for the same landslide. In the situation where the records have a different time-stamp, they may represent multiple movement episodes of the same feature or may just be duplicate records. If the former, then these enable landslide movement to potentially be linked to triggering events, such as rainfall or ground shaking. Alternatively, where multiple landslides have the same time-stamp and the same location, the same landslide will have been captured several times from different datasets. However, the quality of the record may vary in compilation scale and, by inference, accuracy. Obvious duplicates have been removed from the current landslide database; however, multiple records still persist within the original datasets.

Database design and web interface

Database structure

The objectives for developing a single national landslide database were to create a single database allowing the data contained in it to be easily accessed, queried and displayed, and new data to be is easily uploaded. The existing landslide datasets (Table 1) combined in the new database were developed and populated over a period of 25 years, for projects with a variety of objectives. Consequently, the source datasets have different structures and data requirements making transfer and comparison between them a challenge. A unified landslide data model (Fig. 4) has now been developed to enable the new landslide database to be a repository for this old data and for any new data. However, owing to the nature of the source data, the database contains landslide information with a variety of scales, accuracy and attributes.

The NZLD consists of a series of tables and views in a spatial relational database. Spatial information represents the location and shape of landslides and their features. The database has been designed to allow landslide information to be stored as points, lines or polygons. In the database, landslides are stored as single records, with a point representing each landslide location. Each landslide, however, can also have several other spatial features, such as main scarps, debris and source areas. Causes and triggers are recorded and can be queried by referencing a set of tables with standardised values (e.g. earthquake or rainfall for trigger, devegetation for cause).

Data attributes and their metadata

Each of the landslide records can comprise up to 26 attributes, including some or all of the terms and attributes listed in Table 5.

Many more features/attributes are contained in the original source databases (Table 1), but only the fields/features/attributes that we considered to be important were carried across to the new database. All the data in the existing databases are maintained in the original datasets with only relevant landslide data (Table 5)

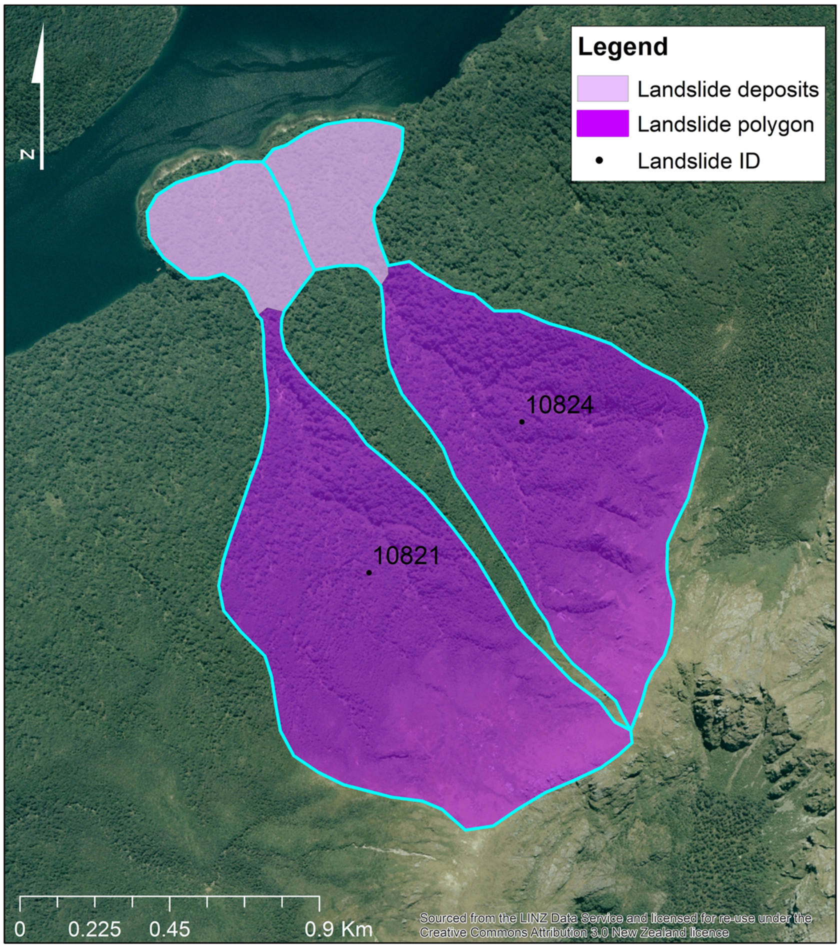

Fig. 3 Example of landslide polygons in the landslide database showing the landslide features recorded in the database. The landslide outline (source area plus deposit) is highlighted (*blue*) and the extent of the deposit is shown in *grey*. The point (showing the landslide ID) is located at the centroid of the landslide outline. All features from the same landslide are linked by a common landslide ID

Table 4 Numbers of different landslide types held in the landslide database

Landslide type	No.
Translational slide	1843
Rotational slide (slump)	504
Flow	230
Complex	153
Fall	147
Avalanche	18
Subsidence	11
Creep	5
Lateral spread	3
Topple	2
Other	1
Unknown	19,658
Total	22,575

mapped to the new database structure (Fig. 3 and Table 5); hence, not all the data from the original databases are visible in the new online version. In situations where the different source databases (Table 1) used different terms to describe similar features and attributes, the process used to describe the transfer between the original and the new databases is documented and provided on the database homepage (http://data.gns.cri.nz/landslides). Information on the original data source for each record is contained in the metadata.

Look up tables and data dictionaries have been developed for each of the attributes. Definitions and nomenclature follow international standards based on Varnes (1978) and Cruden and Varnes (1996), and follow the UNESCO Working Party on the "World Landslide Inventory" (WP/WLI 1990, 1993). An extensive list of attributes was suggested in Glade and Crozier (1996) that should be recorded for a proposed Landslide Database of New Zealand, to facilitate the estimation of landslide hazard. These primary attributes are (1) Landslide Location and (2) Date (time) such that a Frequency-Distribution relationship can be determined. Secondary attributes included (a) associated triggering conditions, (b) causes, (c) type and length of warning, (d)

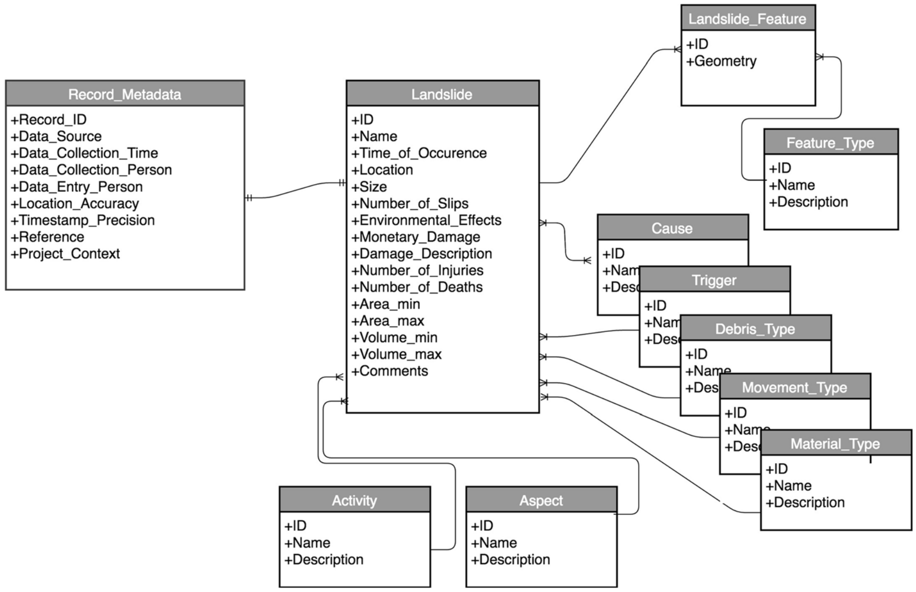

Fig. 4 Database model. Each landslide is represented by a single record in the *Landslide* table and can be related to a number of records in the *Landslide_Feature* table. Landslide records are related to a single record in the *Trigger*, *Debris_Type*, *Movement_Type*, *Material*_Type, *Aspect* and *Activity* tables, respectively, but can have multiple *Cause* records. Each *Landslide* record is associated with a single metadata record. The model shown here has been slightly simplified for better readability

magnitude (volume/area), (e) material type and nature, and (f) length of runout. The majority of attributes suggested by Glade and Crozier (1996) are adopted in the NZLD (listed in Table 5). Other attributes, such as geology, are better extracted by simple GIS analysis. Other attributes, such as nature and length of warning, have not been carried through because these data are rare. The terms and attributes used in the NZLD were also developed by considering those used in other countries such as by the British Geological Survey (Foster et al. 2012), the USGS (http://landslides.usgs.gov/) and Geoscience Australia (Mazengarb et al. 2010) in their respective landslide databases.

Table 5 Terms and attributes recorded for each landslide in the NZLD (if data is available)

Landslide identifiers	**Site descriptors**	**Metadata**
Id	Slope Position	Comments field
Location	Aspect	Data quality information
Location accuracy	Current Vegetation	Source data information
Date/time of occurrence		Bibliographic reference
First known movement date		Certainty
Size class + dimensions		
Landslide morphology	**Hazard and risk data**	**Miscellaneous**
Landslide feature type	Trigger	Survey points
Movement type	Causal factors	
Rate of movement	Age class	
Material type	Activity	
Debris type	Sensitivity	
	Effects/impacts	

Web Interface

The NZLD consists of three technical building blocks: (1) the database, (2) a web map server and (3) a web application. The database itself has been implemented as a spatial relational database and is developed, hosted and maintained by GNS Science. A web application facilitates the user and provides the data management interface. The functionality of the web interface comprises tools for searching for and displaying landslide information in the form of overview tables, attribute pages, charts and map views. The maps displayed are compiled with live data from the database, using the GeoServer software (Fig. 5). The web application can display and allow the user to interact with the map layers. As they are served as a standardised Web Map Service (WMS), they are also available for use outside of the database web application.

Both third-party software components used, the database (PostGIS) and Web Map Server (GeoServer), are open-source, i.e. they do not require a commercial licence. Data collected as part of the GeoNet project are required to be made available to the public free of charge to facilitate research into hazards and assessment of risk. Making the landslide database freely available to the public online via the Internet is intended to facilitate this part of the GeoNet project contract. With the web application being online, the public is able to access, view, search, download and upload landslide data as Excel spreadsheets or GIS shapefiles from anywhere connected to the world wide web.

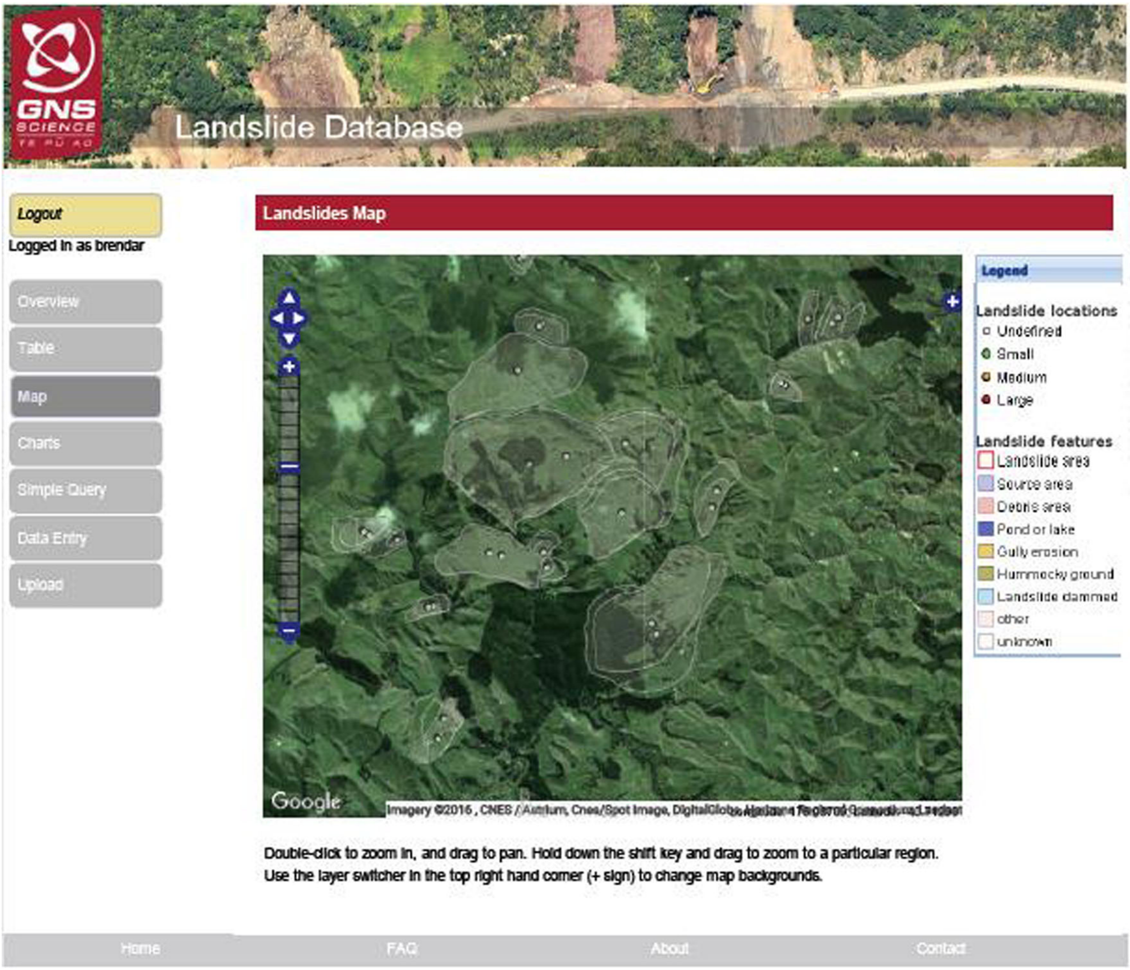

Fig. 5 A screenshot from the NZLD website showing points (centroid of a polygon or a point location of specified accuracy), lines and polygons (representing different parts of a landslide, e.g. source area, deposit)

Limitations of the database

GNS Science has developed and maintains the New Zealand Landslide Database. It has been compiled from several existing landslide databases and is designed to hold data routinely collected for landslides. Along with the location and timing of landslides, the database contains information from investigations of landslides. It stores attributes describing the type of landslide, the triggering event, volume and area data, and damage impacts for each landslide where these are available. The information is collected and summarised from a variety of sources including aerial photograph interpretation, field reconnaissance and media accounts.

This is the first compilation of all mapped landslides in New Zealand in a single database. When displayed on a map, the data readily illustrates the distribution of landslides (and landslide-prone land) in New Zealand (Fig. 1). Storing all of the mapped landslides in New Zealand in a single database has the advantage of allowing better characterisation of landslides in terms of their spatial and temporal distribution in relation to the triggering mechanism, by the type of slope movement, geology, and by the damage or impacts that they cause. This information is helpful to land-use planners, policy makers and network operators in their managing of the landslide hazard and its associated environmental impacts. An example of use of data from the database can be found in Tatard et al. (2010).

The spatial distribution of the landslides in the database (Fig. 1) corresponds areas of steep topography (e.g. the Southern Alps) and areas of landslide prone land underlain by young, poorly consolidated lithologies (e.g. the Taranaki, Manawatu and East Coast regions of the North Island) in New Zealand. However, the distribution of landslides in the database is also influenced by the locations of detailed investigations conducted as part of research programmes (e.g. the Waipaoa catchment (Page and Lukovic 2011) and the Clyde Dam Reservoir Landslide investigations (Gillon 1992)) or in response to significant landslide triggering events (e.g. the Manawatu 2004 storm (Hancox and Wright 2005) and the 2011 Canterbury earthquake sequence (Massey et al. 2014)). There are, however, many gaps in the data, and so caution should be applied when using these data; just because a landslide is not shown at a given location does not mean that a landslide has not occurred.

The quality of the data in the NZLD is dependent on the quality and completeness of data recorded in the source databases. There are many landslide records that only store location information (for example from the large landslide database) with no information on the date of movement, and the type of landslide or triggering event. In contrast, there are some individual landslides (e.g. Taihape) that have been the subject of much research and mitigation work, with detailed records including geomorphic mapping, dates and rates of movement, damage costs and various laboratory test results (Massey 2010). This is also the case for some large triggering events (earthquakes and rainfall). Some triggering events have detailed location and landslide morphology records, whereas others have minimal records associated with them (e.g. storms and earthquakes that occurred early in New Zealands' brief recorded history). The NZLD is intended to be interactive with other GIS datasets e.g. geology (e.g. 1:250,000 QMAP geology), topography (e.g. slope angle, slope height, slope aspect) and triggering events (e.g. earthquakes (epicentre, magnitude, depth, peak ground acceleration, peak ground velocity, peak ground displacement, Modified Mercalli Intensity) and rainfall (intensity, duration, extent).

One of the limitations of the data contained in the landslide database is the variability of the spatial accuracy of landslide points and polygons which has depended on the original method of mapping. Generally, landslide polygons have been recognised from aerial photo interpretation and are accurate at the scale at which they were delineated or portrayed (e.g. the earthquake-induced landslide database at a scale of 1: 250,000). Point location accuracy is highly variable and ranges from sub-metre precision measured by GPS, to reports of road closures from NZTA that could be ±25 km. More recently, better road-closure information has allowed landslides to be better located, but still no information is given on the landslide itself. Development of a mobile application so that the public can report landslides may improve the spatial accuracy of the landslide dataset, along with increasing the number of landslides reported. Legal terms and conditions, covering liability and indemnity for the use of the data contained in the landslide database, have been developed and are appended to all data downloads.

There are also landslides contained in the database that have been mapped using different techniques. For example, landslides from the earthquake induced landslides dataset contain point locations, generally located near the centre of the landslide affected area (source and deposit areas the scar), whereas landslides from the large landslide dataset are mostly polygons, representing the source area, deposit and the whole landslide encompassing both source and deposit areas. Landslides mapped by QMAP often show only the deposit, as the purpose of mapping is to delineate areas of similar lithology. All areas of a single landslide are linked in the database by the landslide ID. A consistent method for mapping, analysing and presenting landslide data is currently being developed at GNS Science to assist the future collection of landslide data in a consistent manner. However, we will continue to add from all sources of landslide data e.g. from media accounts, even where not all information is available.

Case study: movement mechanisms of large, slow-moving, deep-seated landslides

Massey et al. (2016) investigated the role of earthquakes on inducing landslide movement in large, slow-moving, deep-seated landslides formed in Neogene sedimentary rocks. Past researchers have attributed the formation and movement of these types of landslides to strong earthquakes (Crozier et al. 1995). Through high precision movement and piezometric monitoring on the 800,000 m^2 Utiku landslide, which is representative of these large, deep-seated translational block slides in New Zealand, Massey et al. (2016) concluded that earthquake-induced displacements are not the driver of long-term movement on the Utiku landslide and by implication, other similar landslides in New Zealand with low-angle basal slide surfaces, formed in similar materials.

Massey et al. (2016) used the NZLD to characterise the number and types of landslides found in Neogene fine grain sandstone and mudstone terrain that comprises a large proportion of erodible hill country in New Zealand's North Island, by overlaying the large landslides (>2000 m^3) contained in the NZLD onto the QMap geological map of New Zealand (Townsend et al. 2008; Lee et al. 2011). They calculated the proportion of mapped large landslides located in these Neogene sedimentary rock units and characterised the geomorphology of the terrain that these landslides occurred in. The morphology and environmental effects of the large landslides (e.g. landslide dammed or diverted rivers) were used to categorise them into relative age groupings and infer the failure mechanism (rapid and catastrophic vs. slow and episodic movement). Ninety-four per cent of the large landslides in the database were classified by Massey et al. (2016) as being deep-seated, rock planar slides with relatively low-angle slide surfaces characterised by slow episodic movement.

Future directions

Future planned developments for the NZLD include:

- Developing a mobile application for smartphones and tablets that enables both research teams and the public to report landslides and capture data in the field that is transferred directly to the NZLD thus increasing the completeness of the landslide record in the database
- Adding quantitative triggering-event data such as rainfall information and earthquake parameters
- Developing a consistent method for collecting and analysing landslide data that will become the standard for landslide data collection in New Zealand (e.g. differencing pre- and post-event remotely sensed images)
- Linking the NZLD to other databases within or outside of GNS Science holding data relevant to landslides (e.g. geology, topography, photos, lab test results, rainfall data, etc.)

Summary

The database contains information on landslide locations and where available: (1) the timing of landslides and the events that may have triggered them, (2) the type of landslide movement, (3) the volume and area, (4) the source and debris tail, and (5) the impacts caused by the landslide. Where detailed information is available, it has been summarised for each landslide. Information from a variety of sources including aerial photographs (and other remotely sensed data), field reconnaissance and media accounts have been collated and are presented for each landslide along with metadata describing the data sources and quality. There are currently over 22,000 landslide records in the database that include point locations, polygons of landslide source and deposit areas, and linear features. Several large datasets are awaiting upload which will bring the total number of landslide records to over 100,000. Access to the database via the web application is publicly available via the Internet. The underlying software components, i.e. the database (PostGIS) and Web Map Server (GeoServer), are open-source software. The hope is that others will add relevant information to the database as well as downloading the data contained in it.

Learning from the landslide data collection efforts of the last 25 years in New Zealand has shown that there are three key elements to landslide data collection: location, date and impacts. The accuracy with which location can be recorded depends on the data collection method. If the landslide mapping is well-resourced, then high-quality landslide inventories can be created with highly accurate spatial locations. However, for many individual landslides, the only available data is what is reported through various media. Although the data reported through the media is often poorly constrained with respect to location, the date the landslide occurred is well documented along with the impacts (e.g. road closure, building damage, fatalities). The varied ways in which landslide data has been collected in New Zealand is yielding valuable insights into the triggering of landslides and their impacts, both of which are crucial to underpinning quantitative landslide hazard and risk assessments.

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