Dams and Hydropower Schemesin New Zealand

Mohammad Reza Okhovat[1]
1- Senior Structural Engineer, Damwatch Engineering Ltd, Wellington, New Zealand

Email:mohammad.okhovat@damwatch.co.nz

Abstract
This paper provides a brief overview of the dam engineering and hydropower industry in New Zealand. It summarises the dam design and construction practice in the country along with some statistics about current number of the dams and their usage type. The current technical and socio-environmental challenges of the dam engineering and dam safety management in New Zealand are also briefly presented. The challenges are underscored by the recent large seismic events in the country as well as extreme rainfall events associated with the climate change effects. Two main hydropower schemes within the country are also specifically described.
Keywords: Dams, Hydropower, New Zealand.

1. DAMS IN NEW ZEALAND

Dams are critically important to the New Zealand (NZ) economy, being used to store water for municipal water supply, irrigation, hydroelectricity generation, enhancing fisheries, and recreation. Dams are also used for effluent storage, flood management, and mine tailings. Hydroelectricity generation makes up 60% of electricity generation capacity in a country which boasts over 80% generation from renewable sources.

The New Zealand Inventory of Dams (NZID) contains the most up to date information on the 3,284 known dam structures [1]. Recorded dam heights varybetween 0.5m and 118m, although heights are recordedonly for under half of the dams in the inventory. Figures 1 and 2 illustrate how known dams across New Zealand vary historically by construction type and use.

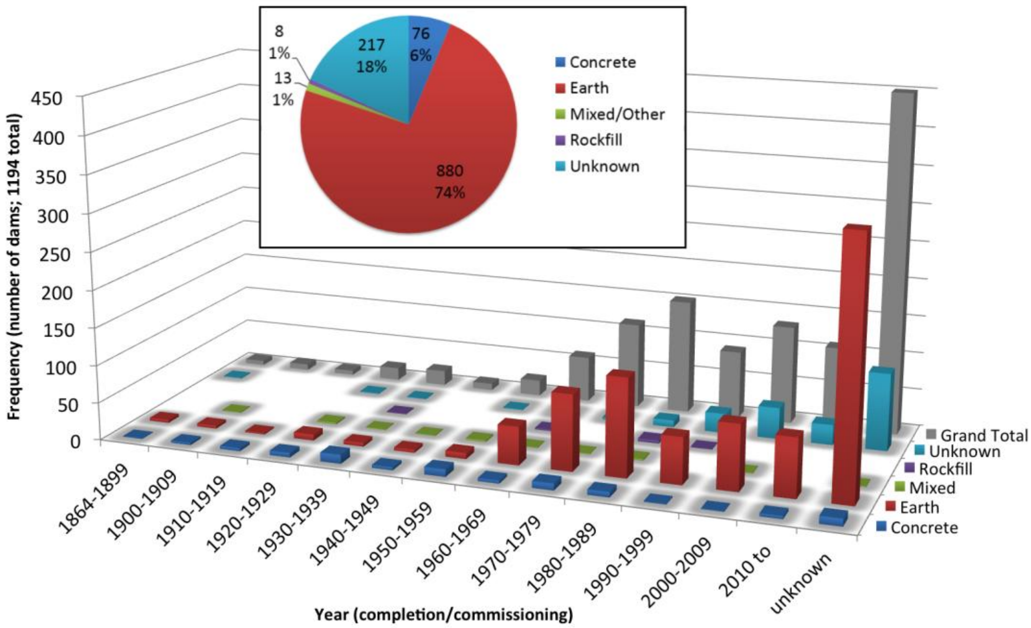

Figure 1. Number of known dams in NZ by construction typeand age [2]

Owners of dams range from public bodies such as regional authorities and territorial local authorities, to private owners such as electricity generators, cooperative irrigation companies and farmers. Of the 3,284 dams in the NZID, there is information available on the owners of around 1,600 dams.

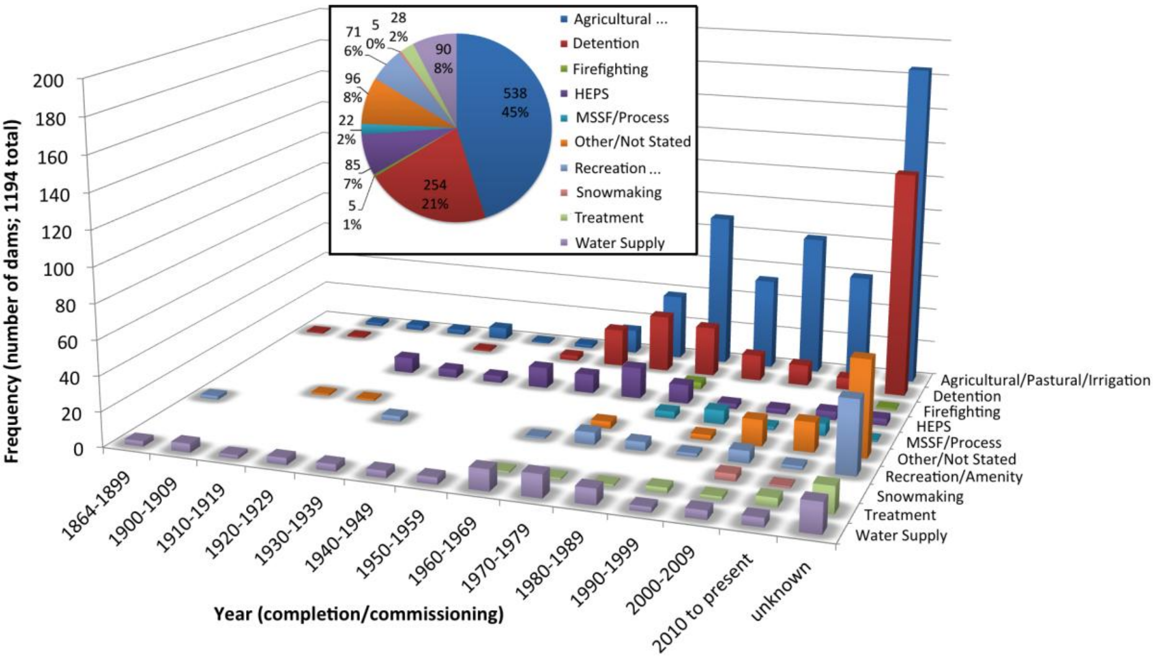

Figure 2. Number of known dams in NZ by primary purposeand age [2]
(Abbreviations: HEPS: Hydro-Electric Power Schemes, MSSF: Mineral Solid Storage Facilities)

2. HYDROPOWER IN NEW ZEALAND

Hydro-electricity produces around 60% of the country's total electricity supply [3]. The total installed capacity of hydro-power generation was about 5,500MW by the end of 2017 (refer Figure 3 below). Hydro-electricity was primarily developed by the New Zealand Government after a nationwide survey of potential resources in the early 1900s. Design of major hydro-power stations was commonly undertaken by Government agencies with construction either by Government workforce or private contractors.

The six largest hydro-schemes,which account for 90% of national hydro generation capacity in the country, are the Waikaremoana, Tongariro, Waikato, Waitaki, Manapouri, and Clutha schemes. The continued operation of hydro-electricbaseloadwill be crucial in meeting the carbon emission and renewable electricity goals set by the NZ Government.

Most of the hydro generation in NZ is owned by five large generators, three of which are 51% government owned. No large hydro development is under construction or contemplated.

Since 2014, electricity demand has flattened off and is now steady at about 45,000 GWh/year [4]. Load growth is expected to increase in the futureand with no large hydro development in sight, the new demand is likely to be largely addressed by developing other types of renewable energy sources, particularly wind energy.

INSTALLED CAPACITY BY FUEL TYPE AT YEAR END (MW AND % OF TOTAL)

	Hydro		Geothermal		Wind		Biogas		Gas		Coal		Diesel		Cogeneration		TOTAL
2017	5,484	58.0%	982	10.4%	689	7.3%	37	0.39%	1,157	12.2%	500	5.3%	169	1.80%	437	4.6%	9,455
2016	5,473	57.8%	1,023	10.8%	690	7.3%	33	0.39%	1,150	12.2%	500	5.3%	170	1.80%	431	4.5%	9,470
2015	5,471	57.8%	1,023	10.8%	689	7.3%	37	0.39%	1,152	12.2%	500	5.3%	170	1.80%	431	4.5%	9,473
2014	5,468	54.7%	1,021	10.2%	682	6.8%	35	0.35%	1,550	15.5%	500	5.0%	170	1.70%	571	5.7%	9,997
2013	5,455	55.6%	897	9.1%	621	6.3%	34	0.35%	1,543	15.7%	500	5.1%	170	1.70%	601	6.1%	9,821

Figure 3. Installed capacity by fuel type at year end (MW and % of total) [3]

The two largest hydropower schemes are located along the Waikato River in the North Island and Waitaki River in the South Island (see Figure 4 below). They both comprise a cascade of dams and are briefly described in the below sub-sections.

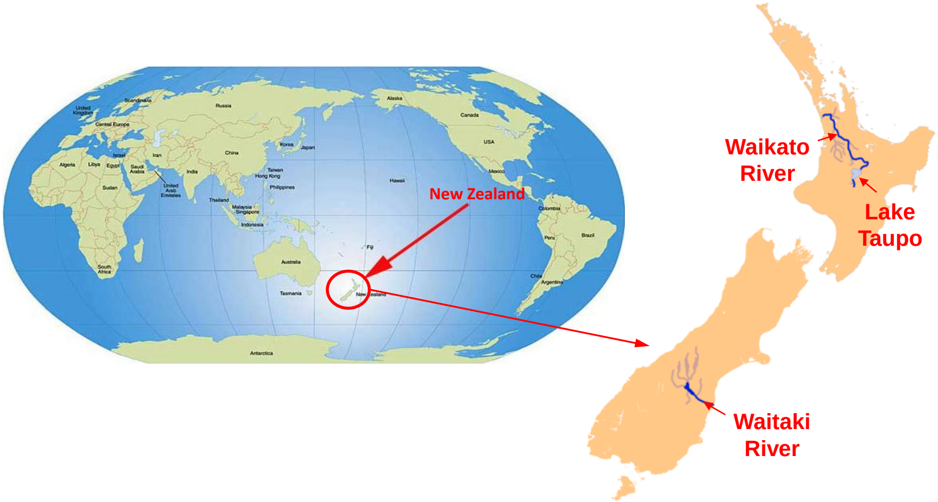

Figure 4.Location of Waikato and Waitaki Riversin New Zealand [5,6]

a. WAIKATO HYDRO SCHEME

There are nine hydro-stations on the Waikato River in the North Island, constructed between 1925 and 1964. These stations are now owned and operated by Mercury Ltd (one of the NZ's five large power generating companies)with a total generation capacity of about 1,060MW. The scheme is flexible and rain fed, allowing hydro output to be increased or decreased quickly and efficiently [7]. A major element in the system flexibility is Lake Taupo, a large natural lake in the headwaters covering an area of 6,970km^2(refer Figure 4). A summary of the nine hydro-stationsdownstream of Lake Taupoand their dam descriptions is presented in Table 1 below.

Table 1- Hydro-stations located along Waikato river[6, 7]

No	Station	Commissioning Year	Dam Height (m)	Dam Type	Generation Capacity (MW)
1	Aratiata	1964	18	Concrete gravity with an embankment wing dam	78
2	Ohakuri	1961	52	Earthfill embankment dam	106
3	Atiamuri	1958	46	Concrete gravity with an embankment wing dam	74
4	Whakamaru	1956	56	Concrete gravity with an embankment wing dam	106.5
5&6	Maraetai I& II	1952	87	Concrete arch dam	352
7	Waipapa	1961	37	Earthfill embankment dam	54
8	Arapuni	1927	64	Concrete gravity curved dam	192
9	Karapiro	1947	67	Concrete variable radius arch dam	96

b. WAITAKI HYDRO SCHEME

The Waitaki hydro scheme consists of eight power stations from Lake Tekapo to Lake Waitaki. Meridian Energy Ltd, a NZ large electricity generating company, owns and operates six of these stations (from Ohau A to Waitaki station), while Tekapo A & B stations are owned and operated by Genesis Energy Ltd (another large power company). The scheme hydro-stations detailsare briefly described in Table 2 below.

The Waitaki schemegenerates energy from water flowing from the Southern Alps mountain range eastwards and out to the sea, with a total generation capacity of 1,740MW.The scheme started in 1904 when the Government's Public Works Department recognised the electricity generation potential of the Waitaki

Valley.However, it was not until the late 1920s that it was possible to begin construction of such a large-scale project [8].

Table 2- Hydro-stations located along Waitakiriver[6,8]

No	Station	Commissioning Year	Maximum Dam Height (m)	Dam Type	Generation Capacity (MW)
1	Tekapo A	1951	12	Concrete gravity control structure	27
2	Tekapo B	1977	21	Earthfill embankment dam	160
3	Ohau A	1979	~15	Earthfill embankment dam	264
4	Ohau B	1984	56 (Ruataniwha dam)	Earthfill embankment dam	212
5	Ohau C	1985	~10	Earthfill embankment dam	212
6	Benmore	1965	118	Earthfill embankment dam with a concrete gravity intake	540
7	Aviemore	1968	49	Concrete gravity with an embankment wing dam	220
8	Waitaki	1935	33	Concrete gravity curved dam	105

3. Dam Industry Challenges

Some of the main challenges of the dam industry in New Zealand are summarised in the below sub-sections. Some of these challenges are common with many other countries while others are more specific to New Zealand.

a. Lack of Dam Safety Regulations

There is currently no comprehensive legally binding scheme to monitor and maintain the structural integrity of dams in New Zealand. Construction of new dams is governed by the Building Act (2004), requiring dams to meet standards outlined in the New Zealand Society of Large Dams (NZSOLD) Dam Safety Guidelines [8]. The same Building Act also includes a framework for dam safety management of operational dams,however regulations need to be issued by Government to bring the Dam SafetyScheme required by the Building Act into full effect.

In 2019,Dam Safety regulations were proposed by the NZ Government with the aim ofproviding a consistent and effective regulatory framework for dam safety [10]. The proposed framework is currently considered by the NZ Parliament. The dam safety framework will exempt dams below a certain threshold of height and reservoir volume. Remaining dams captured by the framework will be identified as "classifiable dams" and will meet the following classifiable threshold (refer Figure 5):

- at or above 4 metres in height and 20,000 cubic metres in volume, or
- less than 4 metres in height, but at or above 30,000 cubic metres in volume.

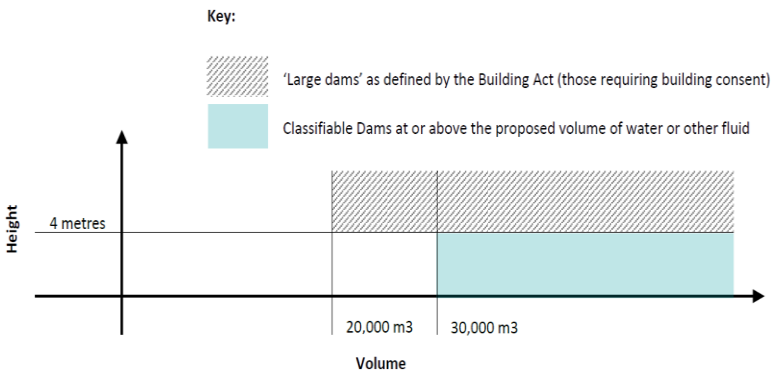

Figure 5. Proposed height and volume threshold for a classifiable dam [10]

TheNew Zealand Society on Large Dams (NZSOLD) Dam Safety Guidelines outline appropriate practices that should be considered during the investigation, design, construction, commissioning, assessment, rehabilitation and operation of dams. The Dam Safety Guidelines are based on technical bulletins published by the International Commission on Large Dams (ICOLD) and other internationally recognised references on dam engineering. The NZSOLD Guidelinesinclude a parent document, which covers overarching dam safety objectives and principles, and a series of separate supporting modules prepared to outline processes and criteria for the management of dam safety in accordance with the principles included in the parent document (see Figure 6).

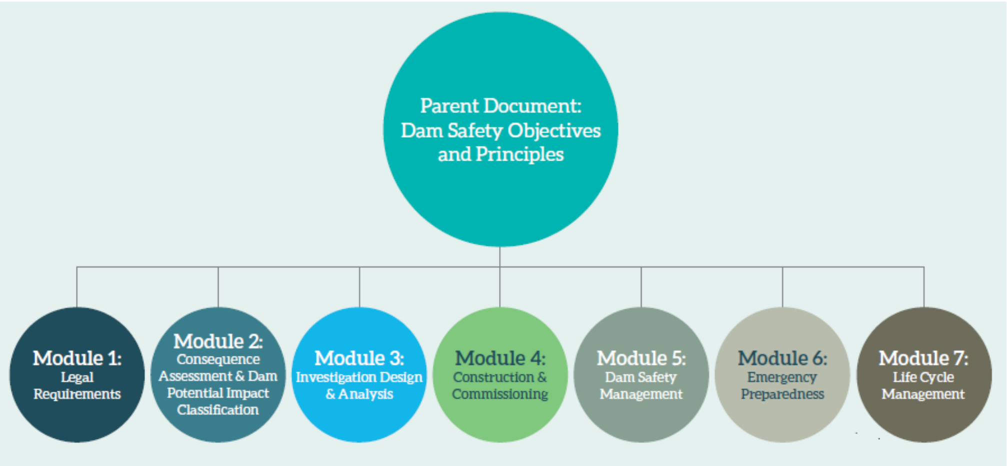

Figure 6. Structure of NZ Dam safety Guidelines [9]

In the absence of a dam safety scheme, some dam owners have voluntarily adopted dam safety policies and procedures primarily based on the provisions of the NZ Dam Safety Guidelines. Also, some regional authorities have placed maintenance requirements on the dams in their regions based on the Guidelines. It is anticipated that the Government's Dam Safety Scheme regulations will largely refer to the NZSOLD Dam Safety Guidelines.

b. AGING DAMS AND ASSOCIATED MAINTENANCE/ UPGRADE

Many of the dams of national significance in New Zealand have been builtin an era circa 30 to 90 years ago. As these dams age, there is a growing recognition of the scale of hazards that dams are exposed to, such as earthquakes, floods and storms. They also increasingly require a high level of maintenance and refurbishment activities to remain operational and resilient.Refurbishment works do not always receive the required amount of attention primarily due to funding issues or more immediate commercial priorities. Remediation of dam safety deficiencies may be technically difficult to achieve safely, especially if the reservoir cannot be taken out of service because there is a lack of a serviceable low level outlet. Recognising these challenges, the NZSOLD Dam Safety Guidelines allow a risk management approach to be adoptedto prioritise actions to reduce risk to levels that are as low as reasonably practicable.

In addition, there has been recently a proliferation of agricultural dams and new irrigation infrastructure. Many of these dams are constructed as off-river storage on flood plains.Some of these dams and structures are located downstream of the existinglarge dams and hence, can be affected by their operation.

Over time, increasing development is changing the risk profile of communities downstream of dams. Towns and communities are growing downstream of existing dams,increasing the number of people who could be impacted by a dam breach.

c. HIGH SEISMICITYAND FAULTS

New Zealand is located along the so-called "Pacific Ring of Fire", a tectonic plate boundary surrounding the Pacific Ocean, where many earthquakes and volcanic eruptions occur (refer Figure 7 below). It is associated with a nearly continuous series ofoceanic trenches,volcanic arcs andplate movements. For many decades, geologists noted the high number of earthquakes and active volcanoes occurring around the rim of the Pacific Ocean basin. About three-quarters of all active volcanoes in the world lie within the Pacific Rim [11].

Figure 7.New Zealand located on Pacific Ring of Fire [11]

As a result, New Zealand has historically experienced many large earthquakes (see Figure 8 below). The biggest recorded earthquake,Magnitude 8.2 Wairarapa earthquake in 1855,is of major significance in terms of the area affected and the amount of fault movement. The maximum horizontal movement along the fault was about 18m, which is the largest displacement along a vertical fault line ever recordedin the world [12].

Seismic hazard for large dam sites in the country is determined through a detailed national seismic hazard model that is based on internationally recognised probabilistic seismic hazard assessment methods. Advanced methods of earthquake geology are also used to determine the seismic hazard from discrete active faults near dam sites.

Considering extremely high seismic loading and associated fault displacements are now common for many dam sites in New Zealand. Design loads for dams can range from horizontal peak ground acceleration of 0.2g up to 1.2g. However,most of the existing dams (designed more than 30 years ago for 0.15g or less) have not been designed for the modern understanding of high ground accelerations, meaning that many of these require re-analysis of earthquake performance, and some require follow up mitigation works to reduce risk of dam breach.

At a few existing damsites, an active fault is running underneath the dam foundationalong the river whichcan potentially subject the dam to fault rupture displacements. Some of these dams have been designed to accommodate fault movement beneath the dam (e.g. Clyde concrete dam [13] and Aviemore embankment dam [14]), while others have received remedial measures such as filter buttresses to mitigate the effects of fault movement on the dam (e.g.Matahina Dam [15]). Clyde Dam (the largest concrete gravity dam in NZ completed in 1993) incorporates a slip joint which is designed to accommodate up to 2m of movement on the river channel fault [13].

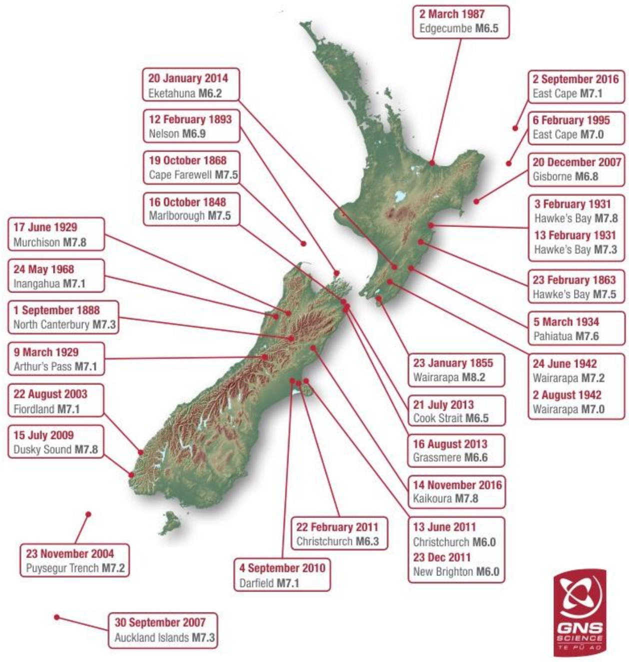

Figure 8.Large New Zealand Earthquakes[12]

d. NEW ZEALAND GEOLOGY& DAM FOUNDATIONS

A strong and competent dam foundation is essential for providing stability and limiting deformation and dam seepage. However, rock foundations in New Zealand have been largely affected by one or a combination of volcanic, tectonic, glacialor landslide activities.

A simplified geology of New Zealand is illustrated in Figure 9 below. Most of the South Island is made of indurated sandstone (known as greywacke)whichis often shattered or highly jointed by tectonism. In the west and south, the rocks have been transformedby heat and pressure to strong but foliated schist. Greywacke also forms most of the North Island, although much of it is covered by layers of more recent rock, such as volcanic deposits.The volcanic sources continue to be active, with the last destructive caldera eruption from Lake Taupo(see Figure 4) only 1,800 years ago. Engineering properties of the differentvolcanic deposits can vary significantly over short distances due to its formation nature.

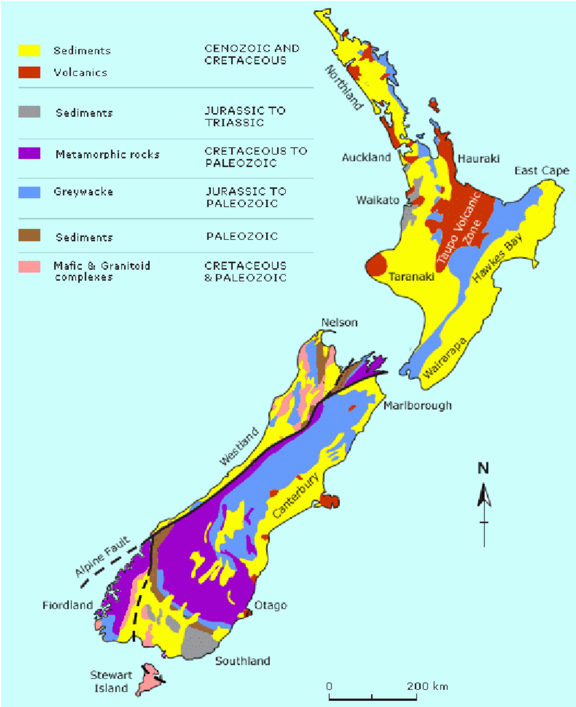

Figure 9.Simplified geological map of New Zealand [16]

e. CLIMATE CHANGE

Climate change is not likely to introduce any new types of hazards to the dams in NZ, but it will increasingly change the nature and extent of the impact from the climate hazards compounded by more frequent significant extremes and greater flooding [17]. Climate change effects over the next decades have been predicted with some level of certainty. Effects will vary from place to place throughout New Zealand, however, recent projection by the NZ Ministry for the Environment considers extreme rainfall to be likely to increase in most areas, with the largest increases being seen in areas where mean rainfall is also increasing (see Figure 10 below). These effects could subject the existing dams to the extreme flood events for which they have not been designed.

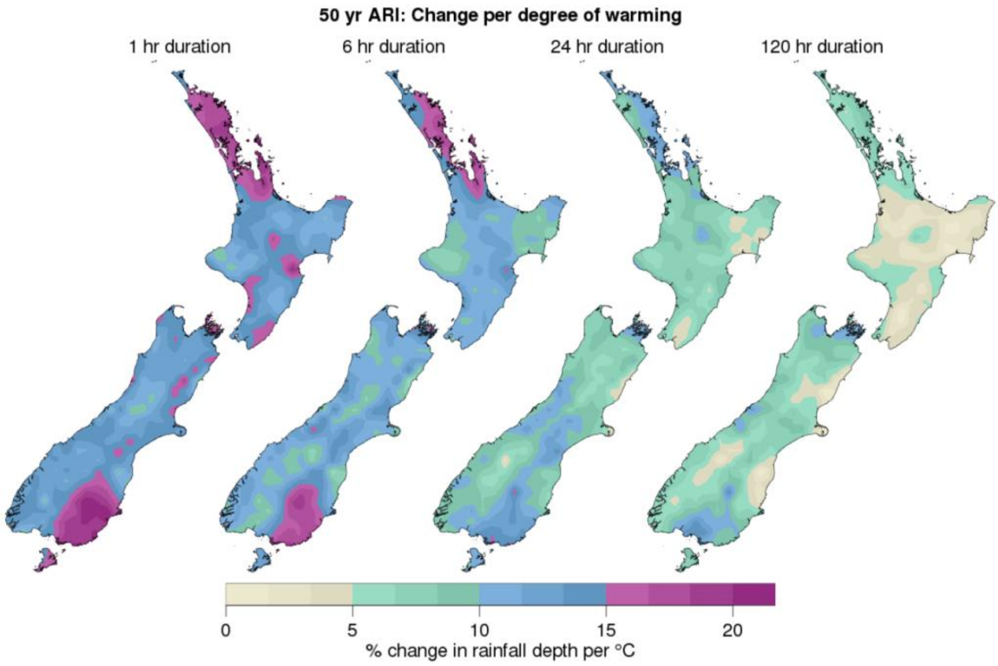

Figure 10. Change in the 50-year rainfall event magnitude for four different event duration [16]

f. ENVIRONMENTAL AND SOCIAL ACCEPTABILITY OF DAMS

Despite all the positive functions of dams, theyare still highly controversial in New Zealand as many other countries around the world [18]. While dams are providing recognised benefits to society and importantly are the basis for the strong renewable energy position of the country,there is strong well-organised opposition to new large dam developments. Part of this is based on environmental effects of dams on biodiversity, river sedimentation, and recreation impacts. Reactions to the environmental effects from intensification of agricultural activities (on the back of irrigation dams) are a growing source of opposition to dams as well. Safety concerns about the risk of dam breach are also causes for opposition. Nevertheless, environmental and safety risk mitigation actions have increased significantly in the last 20 years as the effects of dam construction on river environments is better recognised and successful mitigation measures are adopted.

4. CONCLUSIONS

This paper presented a brief summary of the dam engineering in New Zealand along with its current technical and socio-environmental challenges. New Zealand faces significant risks from natural hazards, being an island nation located on one of the most active tectonic plate boundaries in the world. While dams constructed from the 1980s onwards have been designed to be resilient in the face of these hazards, older dams are often not able to withstand the hazards now being identified. Dam owners and the dam engineering community have a process for identifying dam safety deficiencies and managing the increased risk while progressing through a programme to remediate dams and permanently reduce dam safety risks to the communities downstream of the dam.

While currently there is no explicit regulation for dam safety management of operating dams, many dam owners (and water regulators) use the NZSOLD Dam Safety Guidelines as a de-facto standard. The NZSOLD Guidelines refer to ICOLD bulletins and references of international best practice. Dam safety regulation is expected in the next few years and is anticipated to be based on the NZSOLD Guidelines.

5. ACKNOWLEDGMENT

The author is grateful to Peter Amos, managing director ofDamwatch Engineering Ltd and former chairman of NZSOLD,and Reza Darabi ofDamwatch Engineering Ltd for their review of this paper and valuable suggestions made during the review.

6. References

1. University of Canterbury (2018), "*New Zealand Inventory of Dams*," funding by Ministry for the Environment
2. Crawford-Flett, K. A. and Haskell, J. J. M. (2016). "*Lies, dam lies and statistics: the compilation and analysis of a New Zealand Inventory of Dams*," ANCOLD/ NZSOLD 2016 Conference, Adelaide, Australia.
3. Freeman Media Ltd (2018), "New Zealand Energy Infrastructure Map".
4. Leyland, B. (2019), "*Hydropower and renewable energy in New Zealand*," The International Journal of Hydropower & Dams, Vol. Twenty Six, Issue 4
5. https://www.reddit.com/r/MapsWithoutNZ/comments/5um193/we_all_know_what_the_world_map_should_look_like/
6. https://en.wikipedia.org/wiki/Main_Page
7. https://www.mercury.co.nz
8. https://www.meridianenergy.co.nz/who-we-are/our-power-stations/hydro/about-the-waitaki-hydro-scheme
9. NZSOLD.(2015), *"New Zealand Dam Safety Guidelines,"* New Zealand Society on Large Dams.
10. MBIE. (2019), *"Proposed Regulatory Framework for Dam Safety,"* Ministry of Business, Innovation & Employment.
11. https://digitallylearn.com/what-is-the-pacific-ring-of-fire-and-map-upsc-ias/
12. https://www.gns.cri.nz/Home/Learning/Science-Topics/Earthquakes/New-Zealand-Earthquakes/Where-were-NZs-largest-earthquakes
13. Foster, P. F. and Hatton, J. W. (1987), "*Seismic consideration for the design of the Clyde Dam*," Transactions of the Institution of Professional Engineers New Zealand: Civil Engineering Section, Volume 14 Issue 3, November 1987.
14. Mejia, L., Walker, J. and Gillon, M. (2005), "*Seismic Evaluation of Dam on Active Surface Fault*," Waterpower XIV Conference, Texas, USA, July 2005.
15. Mejia, L., Forrest, M., Bischoff, J. and Gillon, M. (1999), "*Upgrading of Matahina Dam for Foundation Fault Displacement*," Waterpower Conference, Nevada, USA, July 1999.
16. Hayward, B. W. (2009), "*Protecting fossil sites in New Zealand*," In: LIPPS J.H. & GRANIER B.R.C. (eds.), PaleoParks - The Protection and conservation of fossil sites worldwide.- Carnets de Géologie / Notebooks on Geology, Brest, Book 2009/03, Chapter 05.
17. MfE. (2018), "*Climate Change Projections for New Zealand*," Ministry for the Environment.
18. Boye, H. and de Vivo, M. (2016), "*The environmental and social acceptability of dams*," The journal of field actions, Special Issue 14 Environmental and social acceptability of major industrial projects: from risk management to shared prosperity