Identifying potential sites for large-scale Pumped Hydroelectric Energy Storage (PHES) in New Zealand

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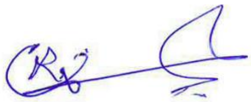	Reviewed by:	Channa Rajanayaka
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Executive summary

The Ministry for Business, Innovation and Employment's (MBIE) NZ Battery project is currently investigating options to address New Zealand's 'dry year problem'. One solution is to use Pumped Hydroelectric Energy Storage (PHES). Various types of pumped hydro schemes have been proposed, with a generation capacity ranging from 5,000 to 12,000 GWh (5 to 12TWh). The aim of this study was to develop a Geographic Information System (GIS) based method to identify surface water catchments in New Zealand that could be used to develop pumped hydro schemes.

A set of screening criteria was first set by MBIE to determine a 'first pass' list of potential sites. The 'first pass' parameters were initially based on physical parameters related to Lake Onslow which has been identified as a possible site in previous studies. A set of GIS-based algorithms were developed to identify potential water sources and storage areas according to the defined criteria.

The results of two iterations of the GIS search (straight dams and curved dams) have been presented to MBIE and the results of the curved dam iteration are illustrated within this report. A total of 1331 potential sites were identified for the given criteria. However, many of these sites were multiple options at single locations such that only 95 separate locations were identified.

It is possible for the developed algorithms to be adjusted to account for additional criteria (for example environmental or financial feasibility) in the future.

1 Introduction

The Ministry for Business, Innovation and Employment's (MBIE) NZ Battery project is investigating options to address New Zealand's 'dry year problem'. The 'dry year problem' refers to periods when New Zealand's hydro storage reservoirs receive insufficient inflows to meet consumer demand for electricity. The shortfall is characterised by the 5,000 GWh (5 TWh) difference between the power produced by average annual inflows to hydro-power facilities, and the power produced by minimum annual inflows (such as those occur during 'dry years'). With the move to 100% renewable energy generation in New Zealand, fossil-fuels (thermal generation) will no longer be able to meet the shortfall in hydropower generation during such dry years. An alternative source of renewable energy is therefore being sought.

One solution to the 'dry year problem' is to use Pumped Hydroelectric Energy Storage (PHES) or 'pumped hydro'. PHES involves pumping water to storage facilities at higher elevations during low electricity demand, and then releasing it during high demand. Various types of pumped hydro schemes have been proposed, ranging from 5,000 to 12,000 GWh (5 to 12 TWh) in their capacity. Whilst it is envisaged that a large naturally-contained elevated basin will be required to meet the 5 TWh shortfall, it is also recognised that smaller schemes (of 0.5 to 5 TWh) could also be used to mitigate the dry year risk.

The aim of this study then, was to develop a Geographic Information System (GIS) that could be used to identify surface water catchments suitable for storing a large body of water. Candidate sites needed also to be close to an adequate supply of water that can be pumped.

1.1 Initial screening criteria

An initial set of screening criteria were set by MBIE to determine a 'first pass' list of potential PHES sites. The criteria relate to identification of water sources of sufficient size; natural catchments that could support development of a reservoir of sufficient volume; and a minimum elevation difference between source and storage. Table 1-1 illustrates the initial criteria used.

Table 1-1: Initial screening criteria for identification of potential PHES sites in NZ.

Parameter	Description
Size of basin	Identified locations must be big enough to allow for impoundment of volume of water that would allow an equivalent power generation capacity of a least **1 TWh.**
Head	Head should be greater than **300 m** difference between upper reservoir and lower water source (reservoir or run of river).
Distance	Upper reservoir will need to be **within 30 km** of the lower water body (this relates to tunnel length).
Dam length	Maximum dam length (or cumulative length if more than one required), should be less than **3 km.**
Dam height	Dam height will be constrained to **120 m**.
Restrictions	The whole of New Zealand's North and South Islands should be explored in the 'first pass' screening (i.e., **no restrictions** on national park areas etc).

2 Previous research

Previous research on potential PHES schemes in New Zealand, is dominated by reference to the potential of a scheme based at Lake Onslow. First proposed by Associate Professor Earl Bardsley in 2005 (Bardsley 2005), a number of variations have since been proposed for this scheme. The largest, Onslow-Manorburn scheme (12,000 GWh) would have almost three times the storage of all existing hydro schemes in NZ (~4,500 GWh), and would involve damming the Teviot River to increase the capacity of the existing Lake Onslow by flooding the Manorburn depression (Bardsley 2020). Natural inflows to the scheme would be augmented by pumping water from the Clutha River (at Lake Roxburgh) via a 24 km tunnel and up a 600 m rise in elevation. The generation capacity of such a scheme would be up to 1,300 MW. A more conservative version of this scheme omits the storage area of the Manorburn depression.

Other potential options for PHES schemes in New Zealand have included somewhat smaller options in the upper Ngaruroro River catchment (Karaminik and Bardsley 2020); Lake Moawhango and Lake Whakamaru (McQueen 2019a); and between Lakes Hawea and Wanaka (in Majeed 1990).

Whilst the Onlslow scheme has been met with a range of responses (e.g., Kear and Chapman 2013; Harvey et al. 2021), Majeed (2019) showed that for an operating range of 720 – 780 m amsl which would support a capacity of 4,000 – 11,000 GWh, an Onslow-Manorburn scheme would have the potential to create a more efficient operation of all South Island hydro power stations (with less spill); potentially reduce flood peaks in the lower Waitaki River (due to reduced spill from lakes Tekapō and Pūkaki); reduce need to send power from the North Island during times of low hydro inflows in the South Island; and provide additional capacity to buffer short-time variability of wind and solar power.

McQueen (2019b) developed a GIS based evolutionary algorithm to find a quasi-optimal upper reservoir location for a PHES scheme that would use Lake Roxburgh as the lower reservoir and to identify upper reservoir locations for a closed loop scheme. McQueen (2019a) then developed a Pumped Hydro-energy Storage Assessment tool (PHAT) which used polygon outlines to optimise reservoir outlines for PHES schemes. The tool was applied to Lake Onslow and Roxburgh, and lakes Moawhango and Whakamaru. McQueen noted that apart from Lake Onslow area, few other potential PHES sites had been identified and reported within New Zealand other than Lake Wanaka/Lake Hawea, Lake Pūkaki/Lake Tekapō and a very small scheme in Stewart Island.

A number of different methods for identification of potential PHES sites have been used internationally (see more comprehensive review in Lu et al. 2018). Notable examples include Rogeau et al. (2017) who developed a GIS-based system for identification of small PHES (14 to 33 GWh) from both existing lakes and natural depressions, and found their model to be most sensitive to maximum, distance between supply and storage lakes (and their maximum altitude), and the maximum distance to the electrical grid. Soha et al. (2017) and Zheng and Sahraei-Ardakani (2020) developed a similar approach to identify multiple opportunities from smaller PHES systems (worth up to a total of 1.7 GWh) from existing infrastructure (old mine works in mid-mountain areas in Europe, and existing water and wastewater infrastructure in California). Nzotcha (2021) adopted a multicriteria approach to rank the applicability of sites identified from existing reservoir data and topographic data at a national scale and used the depression identification scheme of Planchon and Darboux (2002) to identify potential sites from the topographic data.

The 100% Renewable Energy group from the Research School of Electrical, Energy and Materials Engineering at the Australia National University (ANU) used a global GIS-algorithm approach at a national scale to identify off-river PHES sites (Blakers et al. 2017). The ANU algorithms were used to identify off-river locations for supply and storage reservoirs from digital elevation maps (after Petheram et al. 2017). In addition to location and size criteria, they used cost implications to optimise reservoir to storage size ratios at each location (Lu et al. 2018). Implications of evaporative losses from the scheme were also considered. Sensitivity analysis of the method showed that the number of sites (and their storage capacity) were most sensitive to the maximum dam-wall height. It was noted that the developed method could also be used to identify sites adjacent to existing water bodies, old mining pits and seawater.

Andrade et al. (2020) developed a similar integer programming approach to select grid cells from a Digital Elevation Model (DEM) that would conform to create reservoirs to meet minimum storage requirements. The search algorithm included consideration of costs of embankments, water conveyance systems and electromechanical equipment requirements.

3 Methodology

Similar to many previous studies to identify potential PHES sites (as described above) this study uses highest resolution DEM data available to perform a national-scale search for potential PHES sites in New Zealand. In addition, this study utilised existing river network data and a surface water body (lakes and reservoirs) inventory. Using these data with ArcPro GIS and python programming language, reaches that could be dammed to produce lake that could be filled from a downstream source were identified. Table 3-1 summarises the data sources used for this study.

Table 3-1: Data sources used in identification of potential PHES sites.

Data Source	Description
Digital Elevation Model	High resolution (up to 8-30 m) DEM of New Zealand.
Digital River Network (DN2)	River network established to allow upstream and downstream tracing within the national drainage network. This is used for determining the river geometries, cumulative catchment area, elevation, and stream order.
NZ River Maps	Estimates of environmental conditions across the New Zealand river network (https://shiny.niwa.co.nz/nzrivermaps/) as calculated by Booker and Woods (2004). This is used to find the mean flow of potential river water sources.
Lake data	NIWA's lake volumes database for New Zealand determined using method of Nilsson et al. (2010).

3.1 Search parameters

The following subsections describe the criteria applied to identify locations for potential PHES.

3.1.1 Volume of dam

The identified locations for potential PHES should be able to hold at least 1 TWh of energy. To allow a geometric search to be made in GIS, this value converted to an equivalent volume of water, and an associated lake surface area.

We know that an object with mass m (kg), held at height h (m) has potential energy E (J), given by:

$$\mathrm{E} = \mathrm{mgh} \qquad \text{Eq.1}$$

where g, $\text{gravitational force} = 9.8\ \mathrm{m/s^2}$. However, due to the inefficiencies of turbines and water races, not all that energy will be realised; thus we need to multiply E by an efficiency factor η (assumed to be 0.9). One cubic meter of water weighs 1000 kg, and as $1\ \mathrm{J} = 0.000278\ \mathrm{Wh}$, the energy (in Wh) of a volume of water V ($\mathrm{m^3}$) stored by a PHES with an operating efficiency η at height h is given by:

$$\mathrm{E} = 2.7\eta\mathrm{Vh} \qquad \text{Eq.2}$$

To create a PHES with the potential to create 1 TWh, assuming a minimum head of 300 m and 0.9 efficiency factor, the required approximate volume ($\mathrm{m^3}$) will be:

$$V = \frac{1\times10^{12}}{2.7\times0.9\times300} \approx 1\times10^{9}$$ Eq.3

In practice, the dam would not be completely emptied, thus a larger volume of stored water would be required (as determined by the minimum dam operating level).

3.1.2 Flow of potential river water sources

If it is assumed that a dam of the required volume (as described above) is allowed two years to fill, it will need to be filled at a minimum rate, r (m^3/s), of:

$$r = \frac{1\times10^{9}}{3600\times24\times365\times2} \approx 20$$ Eq.4

For all rivers within the New Zealand , the percentile of 20 m^3/s of the median flow is 97.7%, this means that only 2.3% of rivers in New Zealand will have a large enough flow rate to fill a dam of the required volume. In practice, it is assumed that only half of the flow in a river would be taken; thus a median flow rate of 40 m^3/s is required, for which only 2% of rivers in New Zealand have a flow in excess of.

3.1.3 Volume of potential lake water sources

The lake dataset used in this study consists of lakes that range in size from $5x10^4$ to $5x10^{10}$ m^3, (50th percentile = 6 x 10^5 m^3). Only 0.8% of the lakes have a volume greater than 10^9 m^3 (the volume equivalent to produce 1 TWh of energy). However, the source lakes will not be completely drained; a lake will only be considered a source if, after taking all the inflows into account over a two-year period, the lake volume drops to at least half of its original volume. To estimate lake inflow, a rainfall input of 1,100 mm is assumed (mean annual rainfall in New Zealand), and a runoff coefficient of 35%. This means if a source lake has a cumulative upstream catchment area of A (m^2), then the volume of water added (m^3) over two years is:

$$A \times 2 \times 1.1 \times 0.35$$ Eq.5

A lake with cumulative upstream area (A) and of volume (V) will be considered a source if:

$$\frac{V}{2} + 2 \times 1.1 \times 0.35 \times A > 1 \times 10^{9}$$ Eq.6

3.2 Data processing

The first stage of finding potential PHES sites was to identify river reaches or lakes that met the above criteria for potential water source. The second stage was to identify catchments that could potentially hold the required volume criteria. The third stage involved estimating where dams could be built at each identified potential PHES location. The final stage was to produce summary tables and statistics of the search results. The steps within each of these stages is described below:

3.2.1 Stage 1 - map existing water features

- Process input data including geometry of the river lines (*lines.shp*) from the Digital River Network (DN2) and create coverage for centroids for each river reach (at the Strahler 1 scale).
- Create shapefiles for lake polygons and lake centroids.

3.2.2 Stage 2 - identify water sources

- Create a file that maps each river reach ID to a list of source reach IDs that meet the river source criteria defined in Table 1-1.
- Create a file that maps each river reach ID to a list of potential sources of water that meet the lake source criteria defined in Table 1-1.

3.2.3 Stage 3 - building dams

- Many reaches identified in the above stage will be duplicated so a unique list of reaches with potential water sources is created.
- Regional DEMs used in analysis built parallel on the New Zealand eScience Infrastructure (NESI).
- Build dams in parallel on NESI at identified candidate locations.
- Gather dam results and group overlapping dams (those that have been built very close to one another on the same stretch of river).

3.2.4 Stage 4 - summary

- Create summary file of search results, to include the parameters given in Table 3-2.

Table 3-2: Descriptive parameters of potential PHES sites identified in NZ.

Column name	Description
Rid	River reach ID number
Wall height (m)	Maximum height of dam wall
Wall length (m)	Total length of dam wall
Number of dams	Number of dams built to enclose water-body
Dam lake area (m^2)	Area of lake surface
Dam lake vol above DEM (m^3)	Volume of proposed lake based on digital elevation model
Energy (Whr)	Total energy potential of the proposed dam
Best source	Source of water which produces the highest potential power
Source elevation (m)	Elevation of the source water body (at draining lowest point)
Source flow (m^3/s)	Median flow of river if source is a river, otherwise 0

Column name	Description
Distance (m)	Distance from centroid source (lowest drainage point) to base of dam wall on dam river reach
Head (m)	Elevation change between the water source and the storage dam. Elevation of the storage dam is taken as the average of the elevation of the base of the dam and the top of the dam. Elevation of the water source is taken as the elevation at the most downstream location
Fill time (yrs)	Amount of time needed to fill the dam to operating level given the expected flow rate
Pre-existing lake name	Name of any pre-existing lake at location of proposed dam (if there is one)
Dam lake vol (m^3)	The volume of the lake formed by the dam including the volume of any pre-existing lake. This was not used in energy calculations since it was assumed pre-existing lake water would not be used
Dam lake vol above DEM (m^3)	The volume of the lake formed by the dam not including any pre-existing lake. This is the available water that can used for energy production

During the development of the search algorithm, there was three main iterations of the site search, or 'scans', of the country (referenced as Scan 1, 2 and 5). These are described below:

- Scan 1: finds the optimal dam storage volume (thus energy potential) with respect to the height and width of the dam wall criteria. Angle of dam relative to river reach is allowed to vary to increase lake volume (so dam doesn't need to be perpendicular to stream outflow from dam).
- Scan 2: criteria for minimum dam size changed to 0.5 TWhr in the North Island (still 1 TWhr in South Island) and fixed the bug in Scan 1 where the height of the dam was too large.
- Scan 5: switch to method similar to Blakers et al (2017) which draws dam structure along catchment boundary (so no straight dams). This allows identification of locations which might have been previously missed by the straight dam structure criteria.

A summary of the differences between all of the iteration during the development process is shown in Table A-1. This information may be useful for any future changes to the search criteria that may be requested. Results for Scan 1 are illustrated in Figure B-1 and Figure B-2 for the South Island and North Island respectively.

4 Results

The results of the final search ('Scan 5') are illustrated in Figure 4-1 and Figure 4-2 for the South Island and North Island respectively. The figures illustrate the identified potential storage site (*main.dams*), the location of the dam wall (*main.walls*), and the distance to the nearest water source (*main.lines*). Existing lake water bodies are also shown for reference.

The results have been provided in Geopackage format [*dams_grouped.gpkg*] (an open, non-proprietary, platform-independent and standards-based data format) which can be read by any geographic information system. Because there was usually more than one dam option identified at each location, a second Geopackage file (*dams.gpkg*) was provided to illustrate the second options for each location (these were sub-optimal options for which the combination of dam dimensions and distance source would result in a lower potential power supply than the optimal choice for the location). Figure 4-3 for example illustrates multiple lake outline options identified at the Lake Onslow location for the given search criteria (with filled red area illustrating the optimal option for potential power generation). Figure 4-4 illustrates the corresponding multiple dam walls and supply lines at the Onslow site.

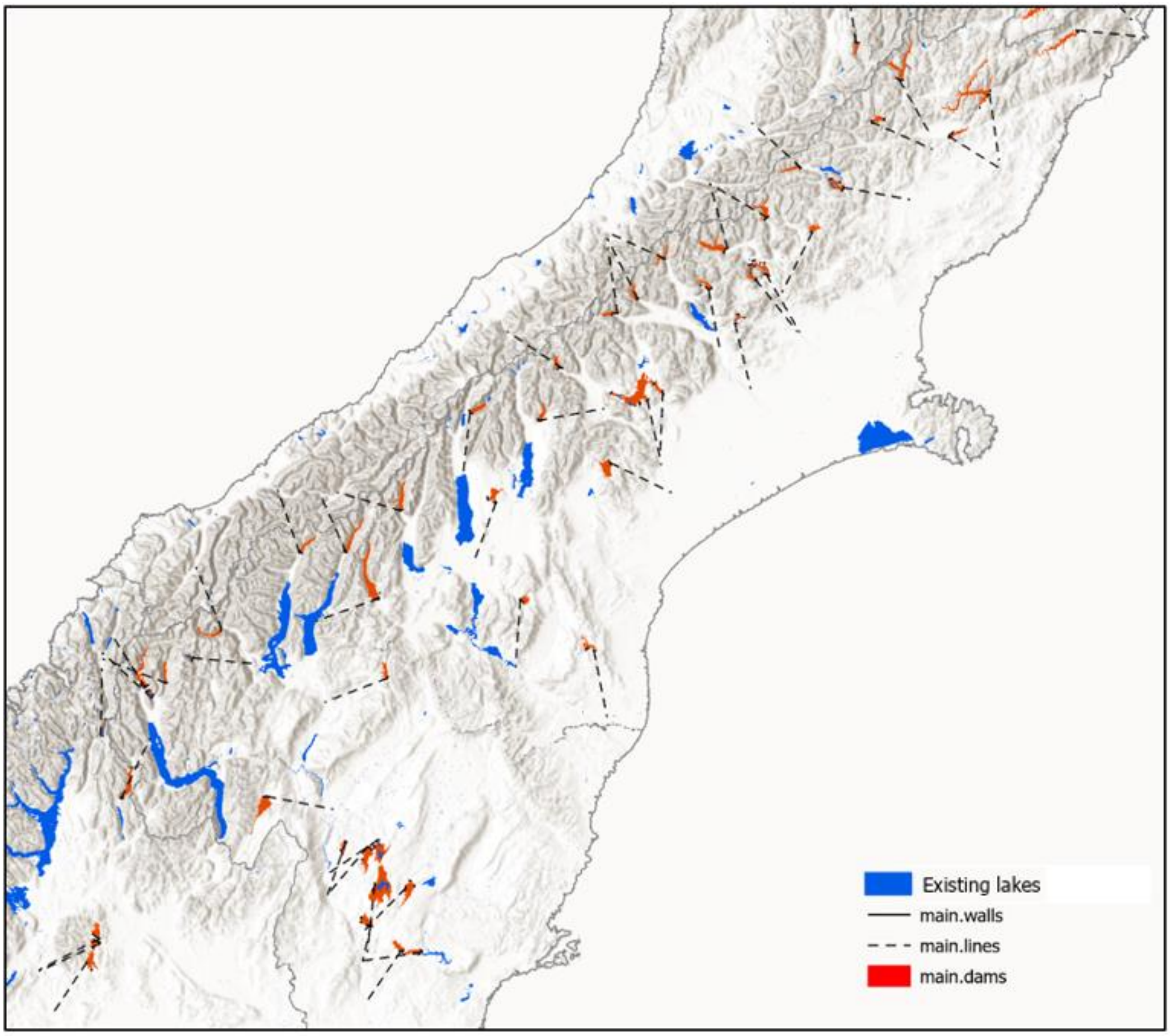

Figure 4-1: South Island sites identified for potential PHES site indicating location of identified dams, dam walls, and shortest distance to identified source water.

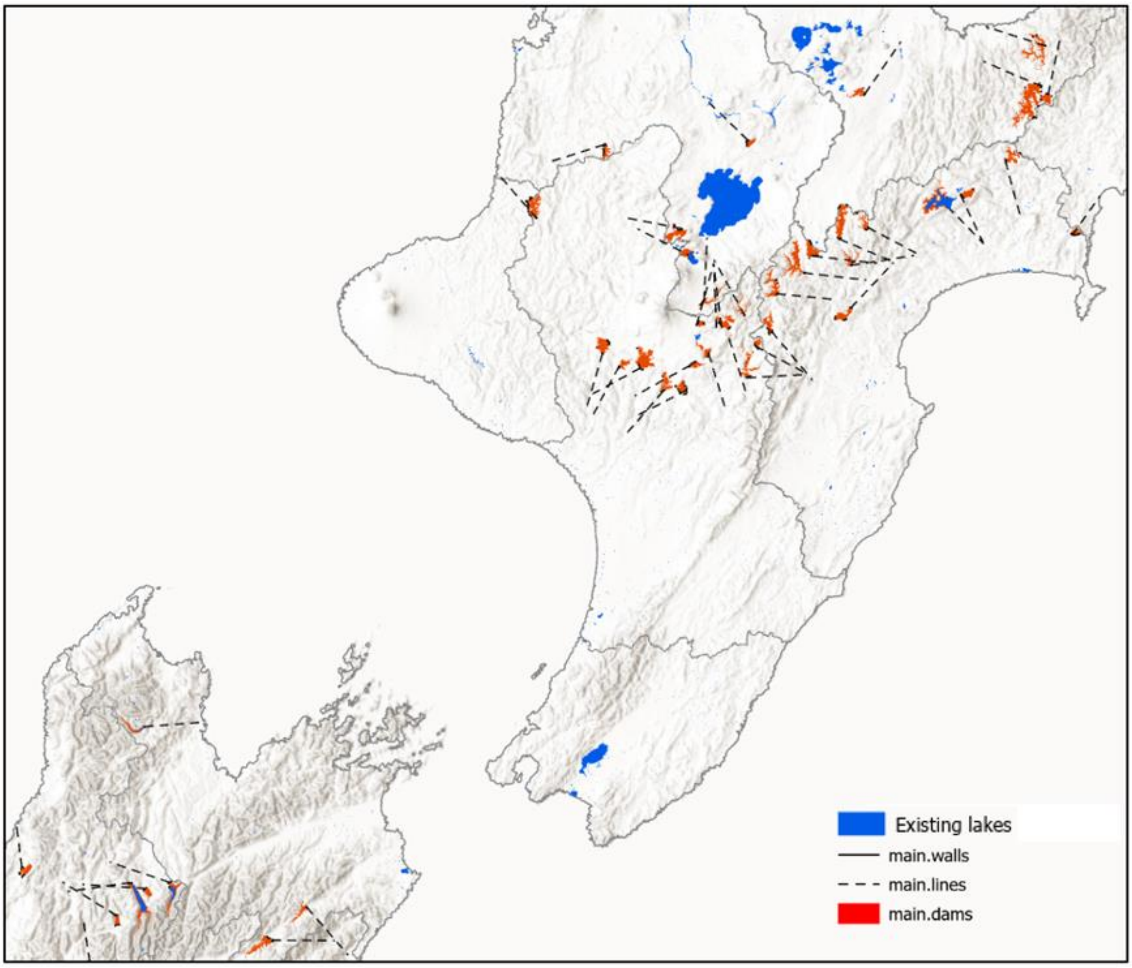

Figure 4-2: North Island sites identified for potential PHES site indicating location of identified dams, dam walls, and shortest distance to identified source water.

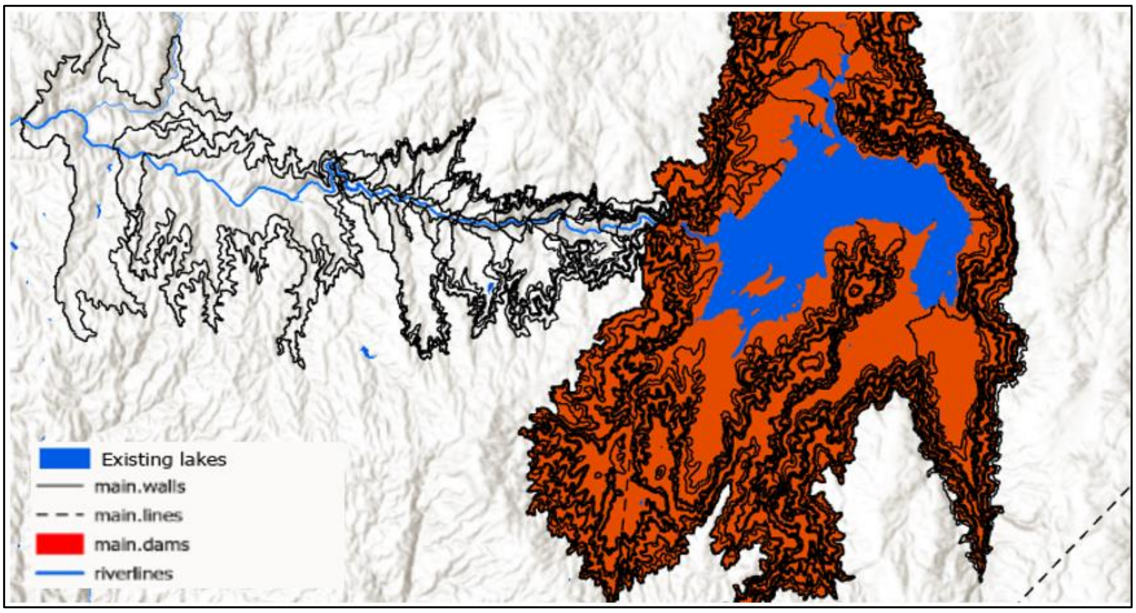

Figure 4-3: Multiple PHES dam outlines options identified at the Lake Onslow location.

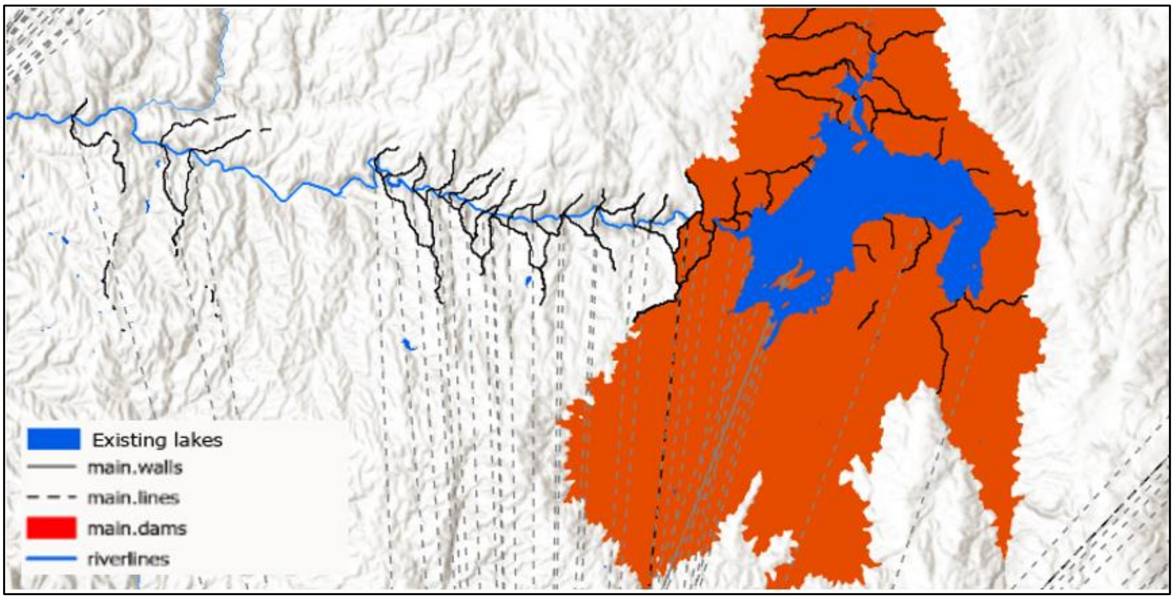

Figure 4-4: Multiple dam walls and water source line options identified at the Lake Onslow location.

Figure 4-5 and Figure 4-6 illustrate in more detail the optimal dam site locations identified within the vicinity of Lake Taupō and Lake Onslow respectively. Figure 4-7 illustrates summary data for the top 15 sites identified in New Zealand (with respect to potential power capacity). It can be seen that PHES sites with a potential power capacity up to 11.5 GWh have been identified. Equivalent fill time, head, and source and storage specifications are shown indicating the variability in site conditions and source and storage accessibility relative to each other.

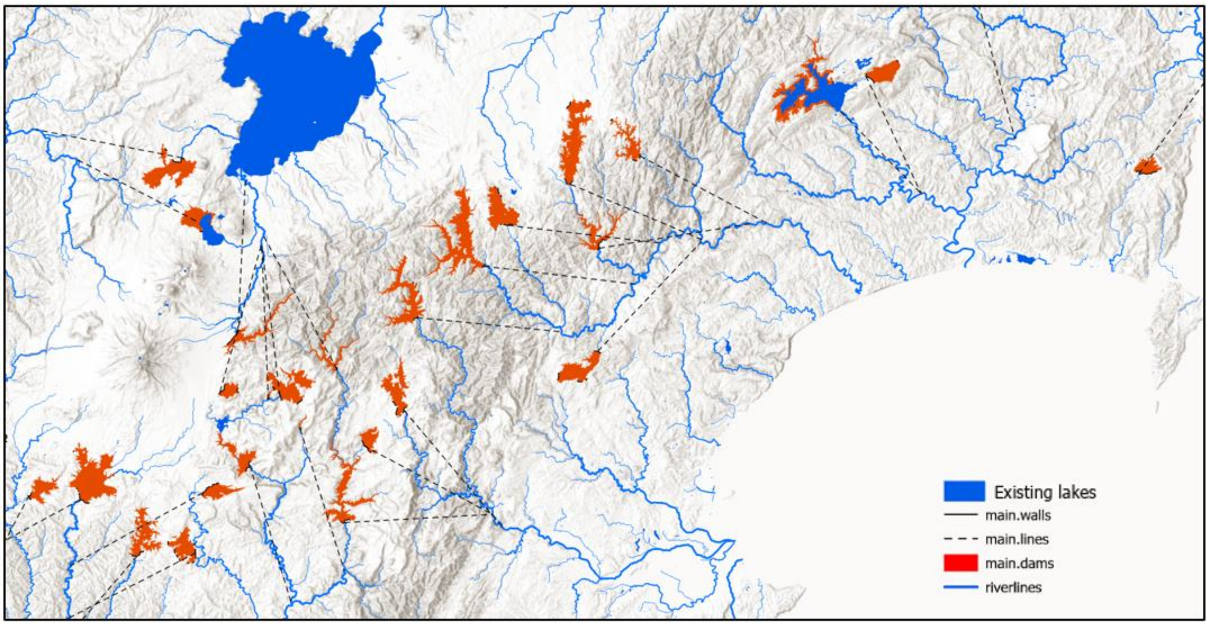

Figure 4-5: Details of potential PHES sites identified around Lake Taupō.

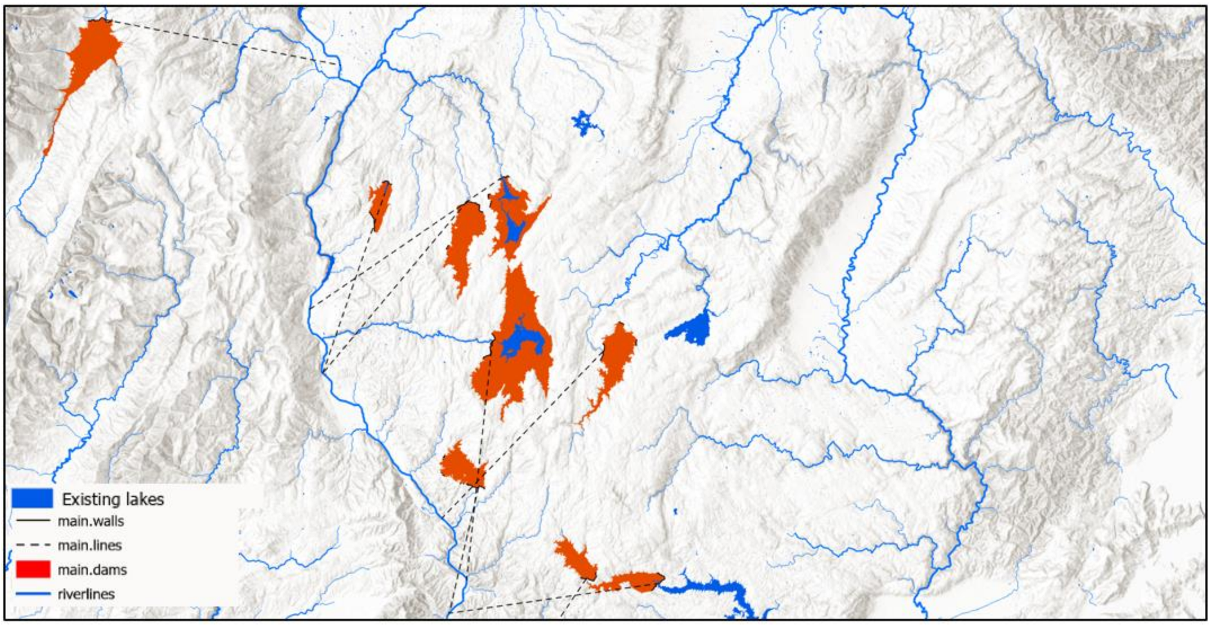

Figure 4-6: Detail of potential PHES sites identified around Lake Onslow.

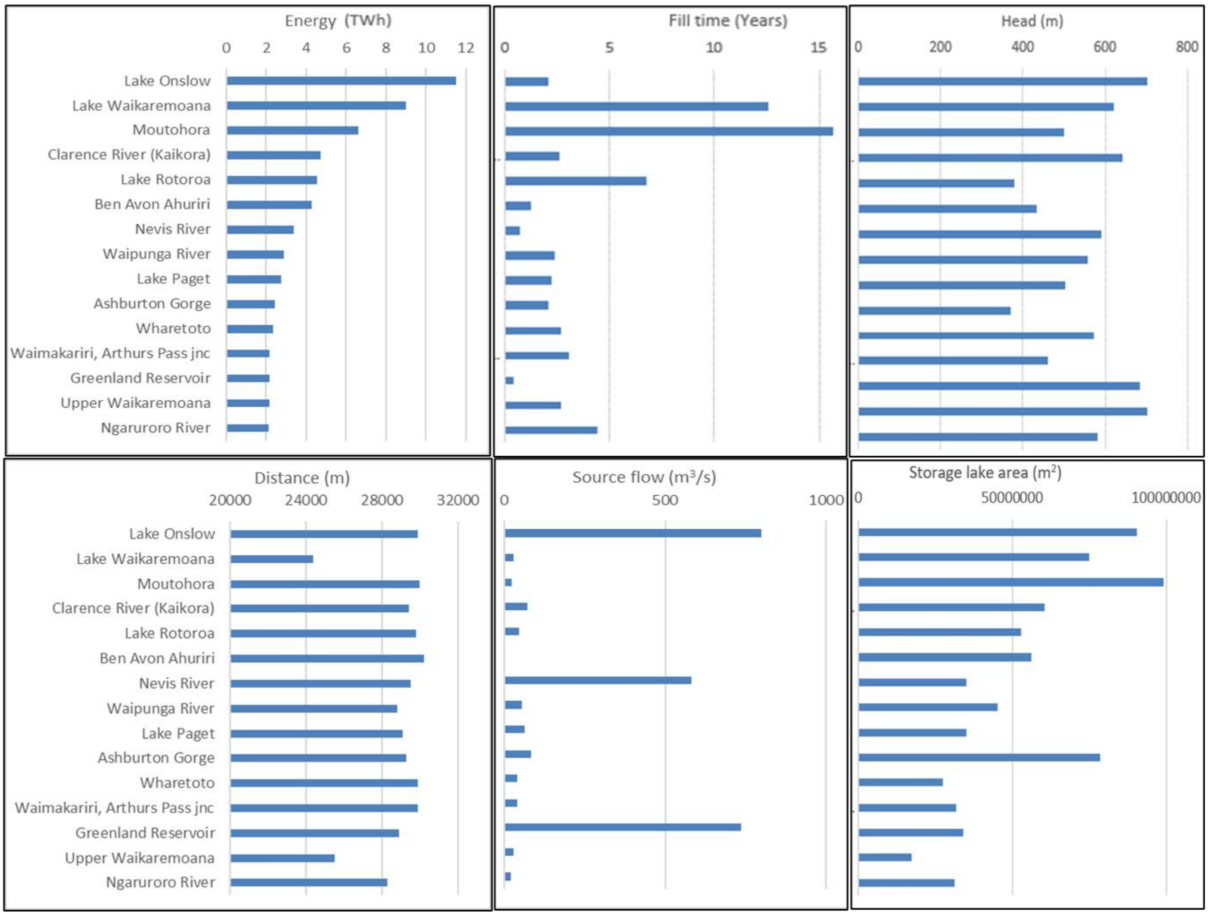

Figure 4-7: Energy (TWh), fill time (years), head (m), distance from source (m), source flow (m³/s), and storage lake area (m²) of the top 15 sites (ranked by Energy).

5 Discussion

The ‘first pass’ search parameters used in the study were based on physical parameters associated to the Lake Onslow proposal as identified in previous studies (see section 2) in that they represent a relatively large storage facility with a relatively large available supply. Results from initial searches however, yielded multiple South Island options but only a small number of North Island results. The search criteria for north Island sites was therefore changed to allow consideration of smaller storage options (down to 0.5 TWh scale). This was done to allow consideration of potential of multi-dam PHES schemes in the North Island that would operate in conjunction with existing hydro-power schemes and infrastructure.

One potential North Island scheme would utilise the head water catchments of the Ngaruroro River which would be used to store water from Lake Taupō. The total potential of such a scheme for example could then be calculated from the upper Ngaruroro basin right through to the Karapiro dam on the Waikato River (over 120 km downstream of Lake Taupō).

The Azim Gorge option for example, (above Lake Moawhango) consists of three dam locations. The middle one should by itself enclose a smallish reservoir, which with the two other lakes consists of a lake of about 27 km^2. The head (to Lake Moawhango) for three dams would be approximately 280 m. If include the head of all potential stations on the Tongariro (c. 400 m) and Waikato (c. 280 m) these can add to local potential to get around 1.5 TWh in total.

The developed system in this study is different from the PHES pumped hydro atlas (Blakers et al. 2017) which looked for closed system pumped hydro options which identified matched upper and lower reservoirs of similar size. Their scan included New Zealand but identified dams of smaller than is currently of interest to the NZ Battery Project (up to 150 GWh for 18 hours operation). The Blakers et al. (2017) approach could also not deal with multi-dam systems in multiple catchments, focussing instead on the associated costs of single penstocks and tunnel systems.

It was noted that at any particular site, a number of combinations of the search criteria (as shown in Table 1-1) could be satisfied and hence multiple dam options can be found for any site. For example, there may be variations in dam wall height and length which will in turn impact the total dam volume and distance to water source (but both options still meet the original criteria). To provide a relative ranking at each site, multiple options were ranked and referenced relative to the option which provided optimal energy potential.

The Petheram (2017) method was used to build dam structure and locations such that dams are built along catchment or watershed boundaries, the maximum dam length constraint was increased to 6 km to allow for greater dam aspect variability that is captured within the GIS system when following a catchment boundary (rather than being a realistic constructed dam length). The results dataset however, will allow results to be filtered back using the original 3 km dam length if this is required.

A number of very small dams near Moawhango have been included in the dataset. However, it is noted that if the maximum height was increased above 120 m, there would be the potential to enclose these small dams in a single dam. There would be similar flexibility in the developed GIS-based search system if this flexibility is required.

The developed algorithm uses the river network digital elevation model only, as a result, candidates for PHES scheme development may cross existing water bodies, national parks and non-viable infrastructure corridors. Future development of the developed system could preclude the identification of such non-viable sites if the criteria is required.

Future development of the GIS-based search algorithms could also include a function to optimise specific objective functions such as ratios of total scheme energy, dam height, dam length, distance and elevation difference between source and storage. Such an objective function could be designed to maximise the potential energy generation of a scheme option whilst minimising the cost. Scheme costs could be represented as a function of dam height and length, and similar specifications related to capital and operational expenditure of tunnel and other infrastructure construction.

6 Summary

The approach developed in this study was to first determine sites where there was sufficient water to supply 1 TWh schemes in the South Island and 0.5 TWh schemes in the North Island (to be used as part of a conjunctive system). The criteria for any potential supply are 1) that there is enough water to fill a dam to its operating level within 2 years, and 2) that the supply could not be completely drained of water at any time.

The second stage of the search was to identify catchments within 30 km of the potential supply locations, that have an elevation difference of greater than 300 m.

Finally, the topography around each potential storage area was investigated to determine what kind of, and how large, a dam would be required to store the required volume of water needed to produce the required power. Criteria of a maximum dam height of 120 m, and maximum length of 3 km were specified to limit the size of potential cost of dam construction.

It should be noted that no other screening criteria were used, but that subsequent refinement of the identified dams, with respect to environmental, cultural, engineering, logistical, legislative or financial feasibility, could be made in future.

Deliverables from this project (as described in section 4) included geo-packaged data of two types of search algorithm: one for straight dams, and a second for contour-following dams.

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Appendix A Search iteration details

Table A-1: Summary of search tool iterations.

Scan	Description
1	• Dam angle optimised for highest energy potential • Straight dams • Height over-estimation since dams include neighbouring, potentially lower elevation valleys. Height defined from the reach on which dam is built from. • More dams than Scan-0 since we are allowing 1 TWhr.
2	• Corrected dam height calculation • Search criteria changed to find 0.5 TWhr dam in North Island (and 1 TWhr in South Island) • Dam angle optimised for highest energy potential • Straight dams, no saddles • Recording fill-time for each site; distance to source • Drawing line from dam to source.
3	• Using the ANU/Petheram (2017) catchment boundary method to form dams, to include saddle dams. • Each dam is identified by reach id, but dam not necessarily built at bottom of that reach, rather it will be built on watershed catchment boundary for that reach • Maximum length has been increased to 6 km, since the dam along the boundary method overestimates actual distance (due to topo variation (jagged boundary)).
4	• As Scan 3 but with addition of two dams near Moawhango that would not have met original criteria (no indication of how catchments could be joined however).
5	• As Scan 4, but with source elevation and flow recorded.

Appendix B Scan 1 results

Figure B-1: Scan 1 results for the South Island (blue lines illustrate river network and black lines indicate identified storage basins according to initial criteria).

Figure B-2: Scan 1 results for the North Island (blue lines illustrate river network and black lines indicate identified storage basins according to initial criteria).