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ASSESSING THE FEASIBILITY OF REHABILITATING SAND AND AGGREGATE QUARRIES INTO WATERBODIES AND VERTICAL FARMS

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Executive Summary

- This study addresses the issue of end-of-life quarries, where once sand and aggregate extraction activity ceases, a large pit is left in the ground. Current rehabilitation options of light pasture and industrial zones fail to utilise the unique opportunities these sites possess.

- Sustainability and innovation are key drivers in rehabilitation. Economic viability is also a major driver, providing incentives for quarry owners, and further ensuring rehabilitation is successful and feasible.

- Social context incites effective implementation of rehabilitated quarry uses. Operators should align with the needs of stakeholders, the community, and local iwi to implement successful rehabilitation.

- This study investigates the viability of sustainable, innovative, and long-term economic rehabilitation for three western Christchurch quarries: McLeans Island, Miners Road, and Pound Road Quarries.

- Following the directive of ChristchurchNZ, this study investigates two rehabilitation options for end-of-life quarries: vertical farming and waterbodies.

- Each rehabilitation option was investigated through literature reviews, case studies, and secondary analysis, supported by site visits, interviews, and schematic drawings.

- Vertical farms grow high-value crops in controlled environments in multi-storey buildings. The case study quarries have a depth of up to 15 m, which provide a construction platform for vertical farm developments without encroaching into the skyline.

- Vertical farming utilises resources, land, energy, and water to maximise agricultural efficiencies. It is a closed system which ensures food security against climate change and extreme weather events. The location of these sites is within proximity to New Zealand's second-largest city, and a major air transport hub, Christchurch International Airport.

- Solar can be implemented on buildings or separately, offsetting production costs. Vertical farms and associated solar have the potential to be developed in progressive stages as a quarry nears the end of life.

- Waterbody rehabilitation is a multi-faceted proposal, allowing for ecological, recreation, or economic activity to occur. Procedures, in addition to public notification, are proposed to minimise and avoid aquifer interaction, as well as birdstrike mitigation. The aquifer

bore is the recommended water source to fill the water body with minimal contamination risk to the aquifers.

- Recreation, aquaculture and floating solar are proposed as economically viable options for waterbody uses.

- McLeans Island Quarries is within the bird strike zone of the Christchurch International Airport. Therefore, it is not recommended for rehabilitation as a waterbody. It has a relatively shallow depth (1-6 m) which would increase the visual impact of vertical farm development. This location requires further rehabilitation investigations due to its location limitations and shallow depth.

- The analysis found that Miners and Pound Road Quarries are suitable sites for vertical farming and waterbody operations to commence post-quarry due to their locations and quarry depths.

Acknowledgements

We would like to thank ChristchurchNZ and our community partner, Adele Radburnd, for the opportunity to work on this project. Her guidance and willingness to provide industry contacts and useful resources have played a key role in the success of this research project. We are grateful to our supervisor Sam Hampton for proofreading our work and providing critiques throughout the research process. Many thanks to Don Chittock from Fulton Hogan for providing insight into the nuances of the quarry industry standards. We would like to thank the representatives from Environment Canterbury for guidance, insight, and their expert opinion.

1. Introduction

Rehabilitation is widely recognised as essential in moving to more sustainable practices. Quarry rehabilitation is well-researched, but each quarry site requires an individual analysis of rehabilitation options (Copland et al., 2017; Koca & Kincal, 2004; Olusegun et al., 2009; Pearson, 2021; Tsolaki-Fiaka et al., 2018). Currently, the Canterbury Plains and Christchurch have aggregate quarries that are coming to the end of their extraction lives (Copland et al., 2017; Pearson, 2021).

In collaboration with ChristchurchNZ, this study looks to investigate sustainable, innovative, and long-term economic quarry rehabilitation options that take advantage of the unique landscape. The aim is to assess the viability of rehabilitating western Christchurch sand and aggregate quarries. McLeans Island, Miners Road, and Pound Road Quarries are the focus of this study (Fig. 1). Operations at these sites began prior to the 2017 legislation, in which quarries are required to have a rehabilitation plan (Christchurch District Plan, 2021.).

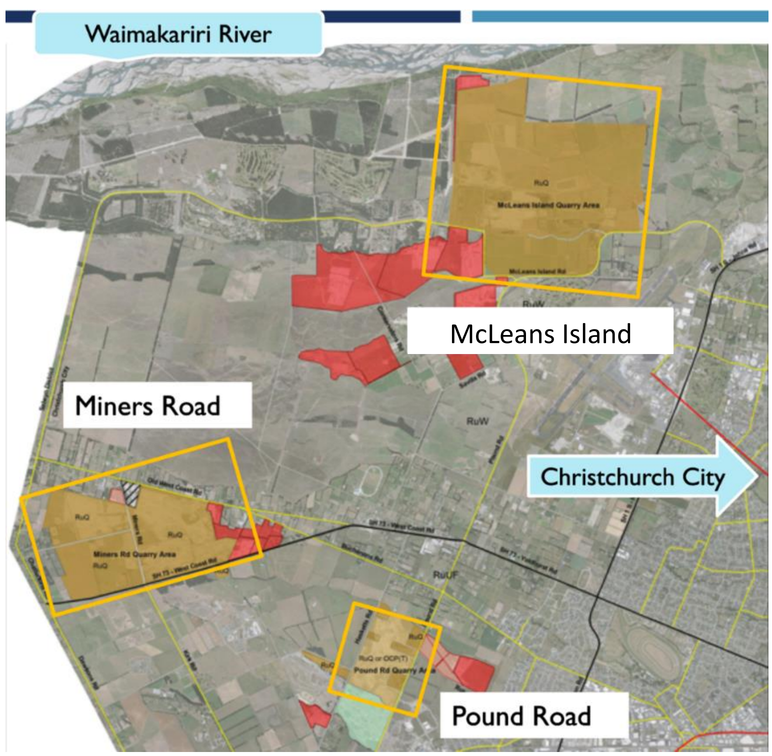

Figure 1. Map showing the locations of the western Christchurch quarry sites used in this research. Adapted from ChristchurchNZ.

1.1. Key elements of case study quarries

- Aggregate extraction pits range from 1 to 15 m deep and up to 6.5 km^2 (Table 1).
- Pit depth and aggregate extraction can occur down to 1 m above the aquifer system (Resource consent decision, 2021).
- Proximity to flight paths of Christchurch International Airport.
- Not required to have rehabilitation plans.

Table 1. Depth and areas of quarry sites

Site	Potential maximum quarry pit depth (m)	Approximate maximum quarry pit area (m)
Miners Road	14	3.4 km^2
Pound Road	15	1.0 km^2
McLeans Island	1-6	6.5 km^2

1.2. Research Question Rationale

For sustainable development, degraded land from quarrying must be rehabilitated, for land is a finite resource (Ministry for the Environment & Stats NZ, 2021). The current industry standards for quarry rehabilitation are light pastures and industrial use. While these are cost-effective and simple, they do not offer innovative or sustainable land use. The negative effects of taking these approaches to quarry rehabilitation have been well-researched and advised against (Koca & Kincal, 2004; Olusegun et al., 2009; Tsolaki-Fiaka et al., 2018).

1.3. Rehabilitation

There are numerous quarry rehabilitation options (City Planning, Strategy and Transformation Group, 2018). Rehabilitation options are tailored to the quarry environment, rehabilitation costs, community, and drivers.

"Viability" in our research question 'Assessing the feasibility of rehabilitating sand and aggregate quarries into waterbodies and vertical farms', refers to the economic and environmental sustainability of a rehabilitation plan.

The key drivers for the rehabilitation of West Christchurch quarries are:

1) **Innovation**: Establishing Christchurch's economic contributions by challenging established industries.
2) **Sustainability**: Ensuring land is utilised to its full potential without further degradation.
3) **Economic viability**: Provides an incentive for quarry owners to rehabilitate and ensures rehabilitation is feasible and successful. This is required as our quarry sites have existing use rights and do not need to adhere to sections 17.2.2.13 & 17.8.3.14 of the Christchurch District Plan (2021), which requires new quarries to rehabilitate.
4) **Community**: Rehabilitation options must benefit the community. The Miners Road Quarries produce loud constriction noise, are viewed as eyesores, and have negative health implications for the local community, including suspended particulate matter in the air which results in respiratory illnesses (Olusegun et al., 2009; Stuff, 2020). In 2020, the community opposed quarry expansions; and while consent was given, scepticism of any quarry rehabilitation plans may be expected because of the community's experience during quarry operations (Stuff, 2020).

1.4. Social and Cultural Context of Rehabilitation

The interdisciplinary nature of quarrying and its rehabilitation requires integrating multiple perspectives and consulting various vital experts. This strategy ensures that socio-cultural factors are drivers of rehabilitation. Additionally, community stakeholders can voice concerns at varying stages of the project.

This project proposes to rehabilitate quarries in western Christchurch that will cease operation in approximately 15 years. ChristchurchNZ's interest is ensuring the resource-depleted pit is utilised for sustainable economic development of Christchurch City and stimulates innovation.

Rehabilitation proposals must consider the cultural effects that land degradation generates. Te Tiriti o Waitangi's primary principles are participation, protection, and partnership (Harmsworth, Awatere, 2013). Engaging with Ngāi Tahu and Ngāi Tūāhuriri should be prioritised to nurture relationships with iwi and ensure rehabilitation includes both pakeha and Māori perspectives (Roberts, 1995). Mātauranga Māori recognises the land as living, which provides for people and has intergenerational impacts. Westernised perceptions of sustainability are similar, with the Brundtland commission defining sustainability as "meeting the needs of the present without compromising the ability of future generations to meet their own needs". To prioritise the re-vitalisation of taonga land and soil, an agenda would be required, which could be derived from the Matapopore design guide (Wixon, 2015) and consultation from mana whenua. Cultural and social sustainability is highly feasible, with core principles treating the land like a living entity.

1.5. Selected rehabilitation options - Waterbodies and vertical farms

ChristchurchNZ has previously developed a document outlining quarrying rehabilitation options (City Planning, Strategy and Transformation Group, 2018). Dal Sasso et al. (2012), highlight how each quarry site has specific restrictions, aims, and voices involved.

Considering previous investigations and discussions with ChristchurchNZ, two rehabilitation options were identified and investigated within this study (1) vertical farming, and (2) waterbodies (Copland et al., 2017; City Planning, Strategy and Transformation Group, 2018; Pearson, 2021). Vertical farming was chosen for its innovation, economic incentive, climate resilience, and use of the quarry pits depths. Waterbodies were chosen as they also utilize quarry pit depth and shape, are a common rehabilitation practice worldwide.

Both waterbodies and vertical farms are economic options and can facilitate progressive development, which is when quarry operations can continue while the rehabilitation process begins in resource-depleted areas. This is a requirement for rehabilitation as ChristchurchNZ and Fulton Hogan have emphasized the importance of a progressive rehabilitation plan to allow for a gradual decline in quarry operations.

2. Methodology

The nature of the project entailed using mostly qualitative, secondary research to explore the existing concepts of vertical farms and waterbodies and applying the results to the three quarry sites.

2.1. Literature Review

The literature review sub-themes were selected due to perceived project relevance. The study aims to establish a broad understanding of quarry rehabilitation processes, in addition to investigating potential uses for the quarry post-operation. A summary of the key findings from each subtheme is below.

2.1.1. Economic, legislative, and community drivers of quarry rehabilitation

Economic incentives prove to be the most influential factor in quarry rehabilitation, with the legislative framework and social structures interacting to inform each of the structures.

2.1.2. Social and cultural context of quarry rehabilitation

Effective rehabilitation requires implementing rehabilitation strategies with consistent partnership, participation, and protection of cultural perspectives. Sustainability transgresses cultural perspectives, with the underlying discourse emphasising the need to maintain biodiversity and the natural environment for future generations.

2.1.3. Key limitations of the aquifer system in quarry development and rehabilitation

Christchurch has a shallow water table, allowing for unique opportunities for interaction with aquifer systems. It was found that waterbodies have direct interaction with aquifers through aquifer intersection, whilst vertical farming does not require interaction. It identified the potential contamination risks to both waterbodies and groundwater.

2.1.4. What are vertical farms and the requirement for their development

This literature review outlines how feasible vertical farming is as a rehabilitative quarry option. Vertical farming has the potential to revolutionise the horticulture industry in the face of climate resilience adaptions. It employs resource-efficient strategies; however initial start-up costs hamper the attractiveness of this option.

2.1.5. The role of waterbodies in quarry rehabilitation

Quarry lakes can accumulate water through either rainfall or aquifer interaction. Four main proposals for waterbody use are recognised: aquiculture, solar power arrays, recreation, or conservation. Each has varying degrees of economic, social, and sustainable return.

2.2. Secondary Analysis

The core of our research methodology is the synthesis of secondary information to form a cohesive understanding of the proposed rehabilitation options. To assess the feasibility of rehabilitating sand and aggregate quarries into water bodies and vertical farms, analyses of existing case studies, theoretical, and experimental data, formed the bulk of our findings. Secondary data has the benefits of being cheaper and faster to obtain than primary data but comes with limitations. While the research conducted is broadly relevant to the target locations, secondary data is only relevant to a certain degree.

2.3. Gap Analysis

Once acquiring foundational knowledge, a gap analysis was undertaken to determine whether any constraints would affect the viability of vertical farms or waterbodies at case study sites. The process identified research gaps, including solar panels, birdstrike risk to aeroplanes, lake water sources, and progressive development.

2.4. Primary Analysis

2.4.1. Interviews

Two separate interviews were conducted with Fulton Hogan and Environment Canterbury representatives. These were carried out following the literature review findings, providing us as interviewers with a solid base understanding of our research project. It ensured relevant questions that provided further information than was sourced or identified within the literature.

2.4.2. Fulton Hogan

ChristchurchNZ recommended engaging directly with Fulton Hogan. Contact was via email correspondence and an in person interview was carried out on the 23rd of September 2022 at Miners Road Quarry for 1 hour 15 minutes. The purpose of the interview was to find out what Fulton Hogan currently does for rehabilitation and why, whether they are open to other rehabilitation options, and what their plan is once quarry operations finish. A semi-structured interview approach was used, following several predetermined questions, allowing for flexible and open-ended conversation (Galletta & Cross, 2013). The interview began with introducing ourselves and ensuring a voice recording and notes could be taken. Once we communicated our intentions, Fulton Hogan were more comfortable in engaging with our interview questions (Galletta & Cross, 2013).

Only interviewing one quarry operator was a limiting factor of our methodology and the research we have produced as a result may not reflect the greater perspectives of quarry operators.

2.4.3. Site visit

On September 23rd, 2022, a site visit was conducted at Fulton Hogan quarry on Miners Road following the interview. The purpose of the site visit was to get a realistic understanding of the scale and size of the project and how waterbody and vertical farms may fit into the area. The interviewees gave us a tour around the outskirts of the quarry.

2.4.4. Environment Canterbury

Email correspondence with Environment Canterbury (ECan) enabled questioning regarding the viability of the proposed rehabilitation options. Through email we received useful links to documents that helped answer questions surrounding consent and feasibility of building a waterbody, involving birdstrike risk to aeroplanes and aquifer contamination. An interview of an ECan staff member via a phone call on the 3rd of October 2022 for 20 minutes was also undertaken. This interview was focused on how to locate more documents associated with how quarry rehabilitation activity affects Christchurch groundwater. A structured interview format was used, with predetermined questions aligned in both topic and order.

2.4.5. Conceptual Models

To support the development of the proposed rehabilitation options conceptual models and visual aids were produced using Sketchup, Google Earth, and PowerPoint. Schematics provide a visual representation of the rehabilitation options in the context of our quarry sites. They provide scope, design, and reasonings behind the proposed rehabilitation options, through perspective views.

3. Vertical Farm Rehabilitation

3.1. What are vertical farms?

Vertical farms are fully enclosed buildings with vertically stacked rows of commercially grown crops. Vertical farming is suitable as it is innovative, provides economic incentive, is climate resilient, utilises the quarry depths, and sites are easily linked to distribution centres. Vertical farms are resilient, they provide growing environments isolated from the exterior environment, allowing specific conditions to be met to influence the flavour, texture, and growth rate of the crop (Birkby, 2016; Januszkiewicz & Jarmusz, 2017). These conditions are controlled via adjustable illumination, water, nutrients, temperature, and humidity. As these are controlled environments these operations can produce all year-round, independent from seasonal fluctuations, weather, and adverse climate events. Quarry pits are ideal for vertical farming because they envelop the industrial structures. The following sections provide details on methods of vertical farming, benefits, managing limitations, and solar integration.

3.2. Vertical farming methods

There are three prominent vertical farming methods: hydroponics, aeroponics, and aquaponics. The most common vertical farming method, hydroponics, is the cultivation of plants through the submersion of roots in a continuously monitored circulating nutrient solution (Al-Kodmany, 2018; Birkby, 2016). Aeroponics, by contrast, cultivates plants through delivering moisture and nutrients via mists from air-atomizing spray nozzles (Benke & Tomkins, 2017, Birkby, 2016). Aquaponics creates a symbiotic relationship between aquatic animals and plants, with waste produced by fish being the main source of nutrients for the plants (K. et al., 2016; Kalantari et al., 2017). Aquaponics is not considered in this study, as literature highlights major issues with the method's complexity at large scales, leading to ecosystem instabilities resulting in costly crop and fish deaths (Birkby, 2016; Cammies et al., 2021).

3.3. Vertical farming benefits

3.3.1. Enclosed, controlled environment

Being isolated from the exterior environment is a benefit in and of itself. Environmental isolation makes the crop immune to seasonal variation, extreme weather events, crop disease, weeds, and pests (Al-Kodmany, 2018; Banerjee & Adenaeuer, 2014; Van Gerrewey et al., 2021). This leads to reliable high crop productivity all year round whilst potentially eliminating the need for pesticides and herbicides (Al-Kodmany, 2018).

The enclosed system allows for reuse of vertical farm greywater through recycling technologies. As a result, hydroponic and aeroponic systems consume 70% and 98% less water respectively, and up to 60% less fertilizer than traditional farming (Birkby, 2016; Banerjee & Adenaeuer, 2014; Farah, 2014). Additionally, the enclosed system minimizes leaching of agrochemicals and nutrients into the exterior environment and groundwater (Al-Kodmany, 2018; Benke & Tomkins, 2017). This is pertinent for our quarry sites, as they are situated within the Christchurch Drinking Water Protection Zone (refer to section 4.4.1). The low agrochemical usage in vertical farms has led multiple countries to allow vertically farmed produce to be labelled as certified organic. This allows vertical farms to have greater leverage and cost competitiveness at local supermarkets, increasing economic viability (Van Gerrewey et al., 2021; Wan, 2018).

3.3.2. Land use efficiency

Another key advantage of vertical farming is land use efficiency by building up and not out. For example, to produce 1 kg of Romaine lettuce, traditional farming uses 93 m^2 of land, whereas a vertical farm with 10 levels uses only 0.3 m^2. (Avgoustaki & Xydis, 2020). Vertical farms are not dependent on pre-existing land conditions. Therefore, unproductive land, such as old quarries, can become productive land (Al-Kodmany 2018; Benke & Tomkins, 2017; Van Gerrewey et al., 2021). Due to Miners and Pound Road Quarries' depths (14 m and 15 m respectively) they have higher land use efficiency than the McLeans Island site (1-6 m).

3.3.3. Progressive Site Development

Vertical farms can be developed in stages. Using Rehman's (2021) 300 m^2 scalable vertical farm model, multiple moderately sized vertical farms can be constructed one after another rather than a long construction stage of a monolithic vertical farm (Figure 2).

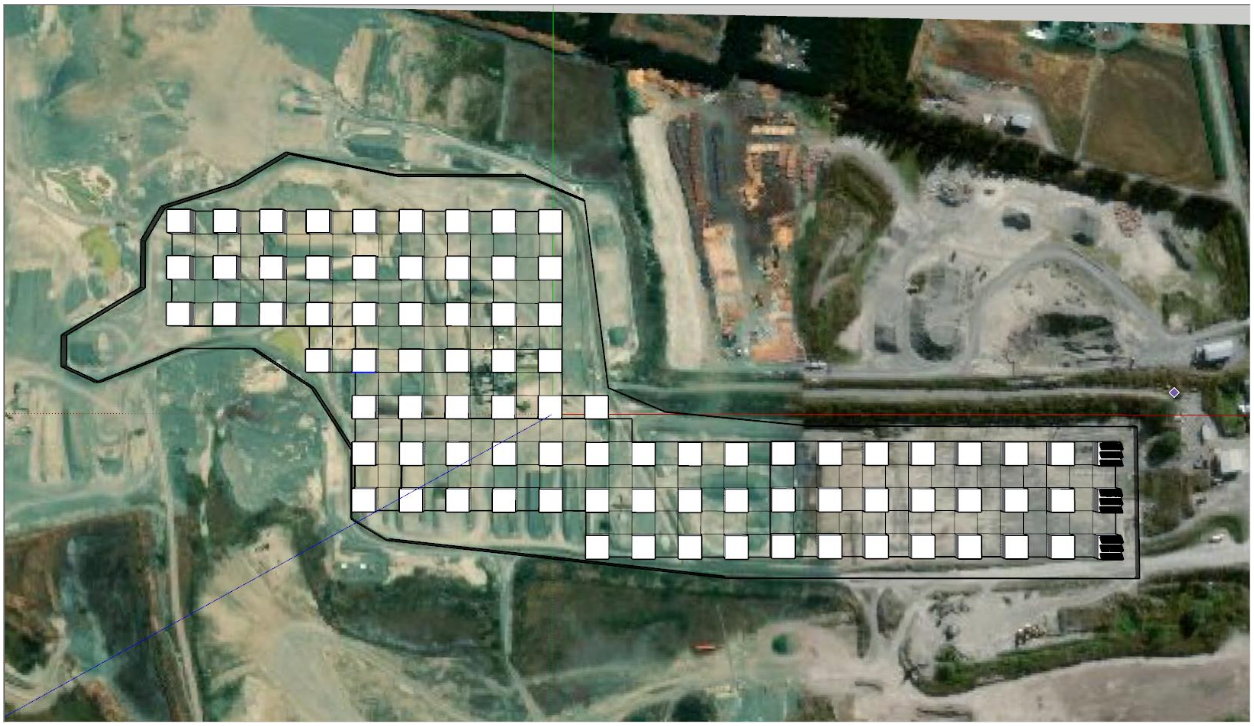

Figure 21. Visual representation of 300 m^2 vertical farm arrangement on the northern portion of the Fulton Hogan Quarry on Miners Road. The rightmost farms show an example of the solar array on the rooftops.

3.3.4. Food Security

Vertical farms help to improve food security by increasing resilience to climate change and providing a reliable, continuous supply of produce. New Zealand relies upon its agriculture industry to feed the population, with 80 % of vegetables consumed originating from New Zealand (Aitken & Warrington, 2019). It is a highly profitable industry, accounting for $6.2 billion in export profits in 2019. Despite New Zealand's need to produce food for the population and to generate income, available agricultural land area has decreased by 1.9 million hectares (Stats NZ-Tataurange Aotearoa, 2021). This, accompanied by a projected 17.5% increase in New Zealand's population by 2050 creates a necessity for vertical farms (Stats NZ–Tatauranga Aotearoa, 2020).

Vertical farms can be built anywhere with adequate infrastructure, are more productive than traditional farming, are climate change resilient, and increase food security.

3.4. Limitations

3.4.1. Upfront cost

The upfront cost is the main obstacle to vertical farming (Al-Kodmany, 2018; Butturini & Marcelis, 2019). The combined cost per square meter of a vertical farm for land acquisition, construction, and deployment of technology is 10 times greater than a high-tech greenhouse (Butturini & Marcelis, 2019). Compared to conventional and greenhouse farming, operational costs for vertical farms are much higher. These costs arise from high electricity usage, salaries of a highly educated workforce, and maintenance costs (Al-Kodmany, 2018; Van Gerrewey et al., 2021). Despite much lower water, fertilizer, and nonexistent pesticide and herbicide usage, the cost of Romaine lettuce from vertical farms is approximately 2 and 5 times that of high-tech greenhouse and conventional farming respectively (Butturini & Marcelis, 2019; Tasgal, 2021).

3.4.2. Crop species

The economic viability of a vertical farm is limited by the diversity of appropriate crop species. Appropriate crops are characterized by a large ratio of salable plant parts, ease of harvesting, rapid growth, and reliability (Gerreway et al., 2021). The most common crops used in vertical farming are leafy greens, herbs, strawberries, tomatoes, soy, and cannabis (Al-Kodmany, 2018; Garber, 2022; Gerreway et al., 2021).

3.4.3. Electricity usage

A reliable supply of electricity is an essential component of vertical farms (Graamans et al., 2017). In the event of a power outage, illumination required for photosynthesis, temperature control, climate control, water pumps, and air pumps will cease. A grace period of up to 8 hours in hydroponics and aeroponics systems will occur before oxygen deprivation leads to plant root death due to the air pumps deactivating (K. et al., 2016; Shah et al., 2019). Extended power outages lasting longer than 8 hours may lead to costly mass crop failures throughout the entire facility. This issue necessitated the need for backup generators which would further increase the initial cost of the vertical farm.

3.4.4. Solar

Vertical farming is a highly efficient farming method in all aspects besides electricity use. Vertical farms commonly utilise solar panels on the roofs and sun-facing sides of buildings (Rehman, 2021). Solar energy can offset electricity costs for vertical farms by approximately 38% per annum (Rehman, 2021). The rapid developments in solar panel technology in the past decades have led to increased efficiency, durability, and lowered purchasing costs (Duran et al., 2021).

3.4.4.1. Solar Case Study

In this case study, we present the solar production for a 300 m^2 vertical farm. Using Rehman's (2021) model with 1 x 2m SunPower solar panels, a 9*12 or 108-panel roof can be installed. This panel arrangement with optimum tilt angles of 43.3° (-15° in summer, +15° in winter) can supply electricity for an average of 3.77 floors of a vertical farm within the quarry pit throughout the year (University of Oregon, 2022).

Using state-of-the-art SunPower Maxon 5 AC solar panels as the basis of the economic findings; an RRP of $519.80, plus additional costs from inverters, tilting mounts, and labour costs requires approximately 8 years and 138 days of continuous operation to break even, assuming an average electricity cost of 29.6¢/kWh (Ministry of Business, Innovation and Employment, 2022; Hoare, 2021; NIWA, 2019). This means a return on investment should occur before quarry operation ends.

break-even point falls within the projected, remaining 15 years of quarry operations, making solar an economically viable strategy. Progressive Development: Solar

As discussed earlier vertical farms can be progressively developed in stages according to the operations occurring within the pit. Solar can be implemented in this staged vertical farm approach, or look to be developed onsite, independent of vertical farming infrastructure. Generated power can be used to offset quarrying operations or support electrification of the operation.

3.5. Resource consent

The Christchurch City Council requires a resource consent to change the land use from a rural quarry zone to an agricultural/industrial zone. Resource consents identify all activities involved, such as land use change and discharges, in relation to the Christchurch District Plan (2021) and the Land and Water Regional Plan (Environment Canterbury Regional Council, 2018). The Resource Management Act (1991) is a key piece of legislation that vertical farms must comply with.

Resource consent application recommendations according to requirements within the Christchurch West Melton zone include (Environment Canterbury, 2020):

- **Full surrender of resource consent – CON550**
- **Install or alter a bore – CON001**
- **Take and use of groundwater – CON200**
- **Discharge of contaminants into the land from an onsite wastewater system – CON070**

3.6. Site Suitability for Vertical Farms

There is not necessarily a minimum depth required for a vertical farm. Instead, the scalability of a vertical farm is limited to the maximum pit depth of 1 m above groundwater. Using Miners Road as an example, the maximum height of a vertical farm could be up to 14 meters tall without intrusion on the skyline (Fig. 3). A vertical farm at the McLeans Island site is a less viable option as it could only be 1-6 m tall, and therefore has lower land-use efficiency (Table 2).

Figure 32. Schematic of a vertical farm in the Miners Road Quarry pit.

Table 2. Site Review suitability for vertical farms

Site	Potential maximum quarry pit depth (m)	Approximate maximum quarry pit area (m)	Vertical Farm Suitability
Miners Road	14	3.4 km^2	✓
Pound Road	15	1.0 km^2	✓
McLeans Island	1-6	6.5 km^2	✗

3.7. Summary

Vertical farms are an economic, innovative, and sustainable rehabilitation option for deep quarry pits that can envelop tall structures. The key benefits are water and land use efficiencies, a closed controlled system, food security, and economic return. While a vertical farm could be built at the

McLeans Island site, this option is better suited for the Miners and Pound Road Quarries due to their depths. Their depth allows for multi-storey farms without encroachment into the visual amenities of the Canterbury Plains, allowing for higher land use efficiency than at the McLeans Island site.

Solar offers a progressive development solution that compliments the remaining 15-year lifespan of the quarry and the consistent need for electricity. A solar farm offsets electricity cost and can make a return on investment before the quarry operation ends. Finally, these solar panels can be integrated into vertical farms at minimal added cost.

4. Waterbody Rehabilitation

4.1. Introduction

Waterbodies are a commonly used practice in the rehabilitation of quarries (Mt Cook Alpine Salmon Ltd, n.d.; Otchere et al., 2004; Reuters, 2022). They align with ChristchurchNZ and Ngāi Tuāhuriri's interests and values, by supporting Christchurch's economy and protecting biodiversity (Wixon, 2015; Matapopore Urban Design Guide, 2015). Quarry operators, such as Fulton Hogan, support and have undertaken this rehabilitation type in other areas of New Zealand, as it helps re-naturalise the landscape (Fulton Hogan, personal communication, September 23, 2022).

The following outlines and identifies whether waterbodies are viable and suitable for the western Christchurch quarries. It discusses benefits, water sources, constraints, and the different uses of waterbodies.

4.2. Benefits

Waterbodies provide many benefits for people and the environment. It is consistent in research that blue spaces, such as lakes, promote well-being (Britton et al., 2020; Olive & Wheaton, 2021; Pasanen et al., 2019). Waterbodies support biodiversity and ecosystem services by providing habitats for native freshwater biota (Schallenberg et al., 2013). They help mitigate climate change through carbon sequestration and hydrological buffering. However, our quarries are exposed to land intensification which may counteract the above benefits (Schallenberg et al., 2013).

4.3. Sources of water

A requirement to form an artificial waterbody is the need for a suitable water source to fill the pit and maintain the water level. All techniques stated below require an impermeable layer on the lakebed, such as bentonite clay, to stop the water, nutrients, and contaminants from infiltrating groundwater resources.

4.3.1. Rainfall

Rainfall is one water source used for artificial waterbodies. The Singapore Hindhede Quarry flooded from a combination of rainfall and groundwater seepage (Zhao, 1997). However, this method is not feasible in Christchurch due to the dry climate, only receiving approximately 618 mm/yr on average. In comparison, Singapore receives approximately 2165.9 mm/yr (Macara, 2016; Service Singapore, n.d.).

4.3.2. Aquifer

Aquifers of the Canterbury Plains can provide water for waterbody rehabilitation options. There are two methods for utilising the aquifer as the water source, both offering progressive development, aquifer bore and aquifer intersection. An aquifer is a feasible water source because 375 million cubic metres flow underneath Christchurch annually at a rate of 25 m per day (Environment Canterbury, 2019). Of that, 152 million cubic metres are allocated for Christchurch, but not all are used, leaving room for other activities such as a waterbody (Environment Canterbury, 2019). To take water from the aquifer, a resource consent process will need to be undertaken (Horizons Regional Council, 2017).

4.3.2.1. Aquifer Bore

A bore is drilled into the deep aquifer creating a pressure gradient, allowing water to flow to the ground surface without a pump (Fig 4; Marinho, 2021). Bores utilise an artesian aquifer which is naturally pressurised due to the confining, impermeable layers surrounding it. Equipment may be used to regulate and control the flow of water (British Columbia, n.d.). Further analysis is required to determine the artesian aquifer system, as there is conflicting literature on whether the quarries are within an unconfined or semi-confined aquifer zone (Golder Associates, 2013; Environment Canterbury Regional Council, n.d.).

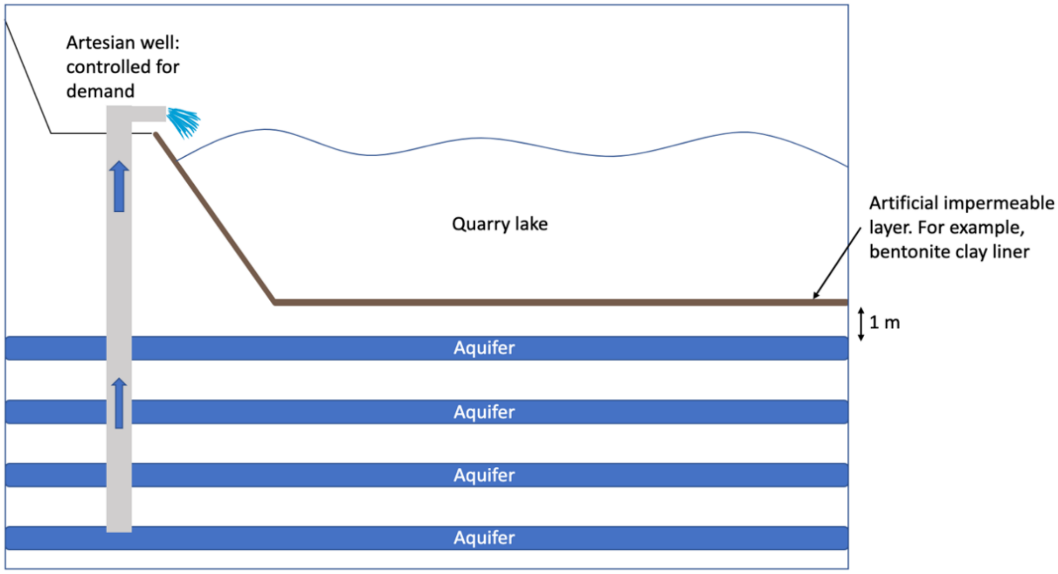

Figure 43. The diagram shows the layered aquifer system and how a bore interacts with the deeper aquifer and acts as a one-way system to reduce contamination. (Christchurch City Council, 2016).

4.3.2.2. Aquifer Intersection

Aquifer intersection involves digging into or below a section of the water table, so groundwater rises and floods the pit through seepage (Seelen et al., 2021). Seepage is the percolation of groundwater and varies depending on the subsurface permeability and water levels in the springs (Ellis et al., 2007). Aquifer intersection is the simplest method, but it requires resource consent. Current resource consent requirements limit the extraction of gravels to 1 m above the aquifer, as the sites are located in the Christchurch Drinking Water Protection Zone (Fig. 6).

McLeans Island site is within a semi-confined aquifer zone, and aquifer sourcing of water into pits has occurred in this area following quarrying, i.e. present-day site of Isaac Salmon Farm, and Lake Roto Kohatu during the 1980s (Fig. 5). This site has the potential for creating a water body via aquifer intersection. Further analysis is required to determine the suitability of the quarry pits of Miners and Pound Road Quarries for sourcing water via aquifer intersection.

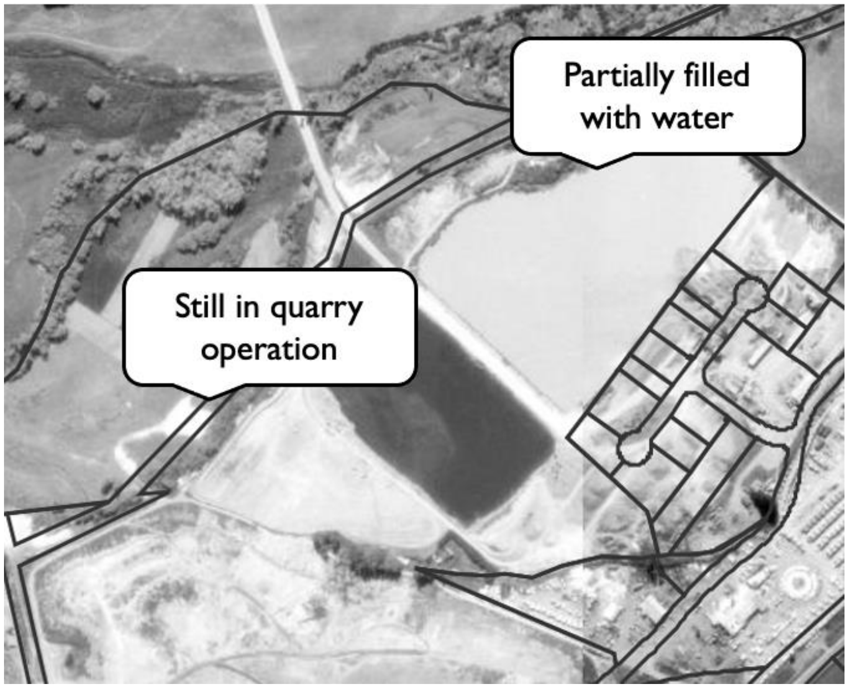

Figure 5. Roto Kohatu Reserve 1980-1984 when it was partially rehabilitated into a waterbody while in quarry operation (Environment Canterbury Regional Council, n.d.).

4.4. Constraints

4.4.1. Christchurch Drinking Water Protection Zone

All three quarries lie within the Christchurch Drinking Water Protection Zone (CDWPZ) (Fig. 6). The CDWPZ's purpose is to regulate activities interacting with the aquifer, because of the high groundwater table, and the permeable sand and gravel subsurface (Golder Associates, 2013). Activities above the CDWPZ must comply with the Canterbury Land & Water Regional Plan to reduce contamination risk, including quarry operation and rehabilitation (Environment Canterbury, n.d; Environment Canterbury Regional Council, 2018). Quarry operators are not allowed to dig within 1 m of the aquifer (Mitchell, 2016). This is a key constraint for the viability of rehabilitating quarries into waterbodies and requires changes in resource consent (see section 3.5.)

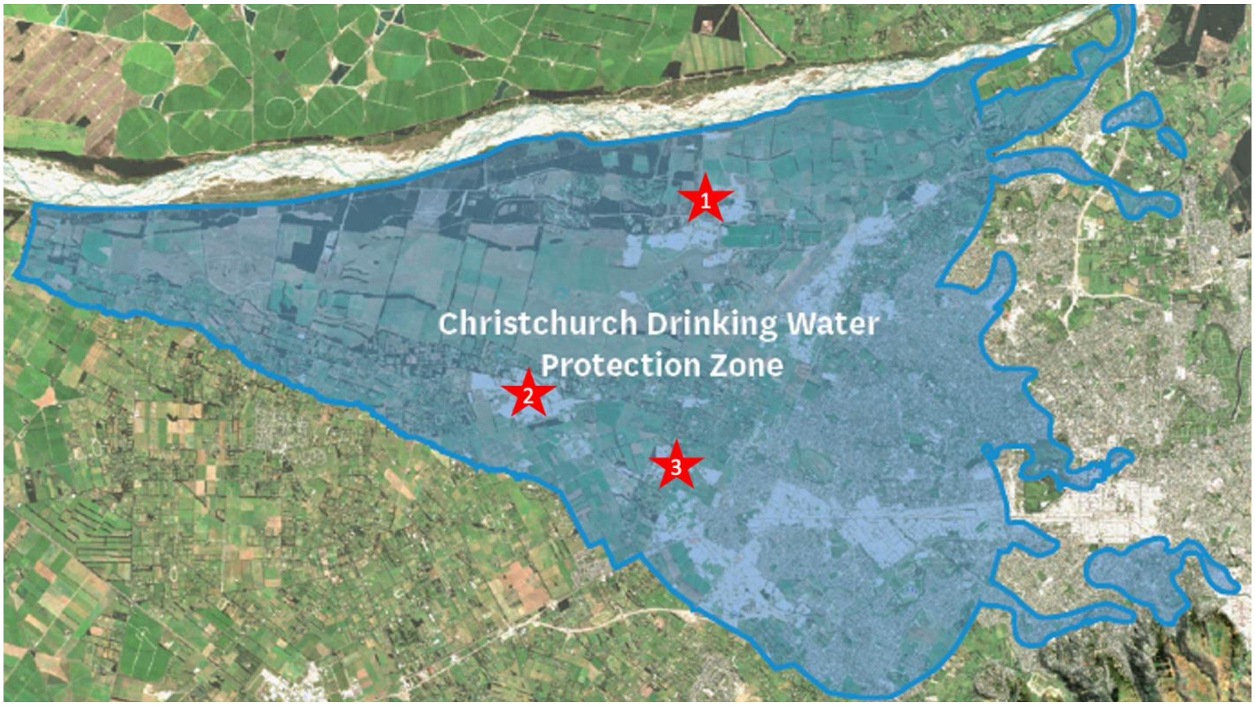

Figure 6. Map of the Christchurch Drinking Water Protection Zone adjusted to show the case study locations within the zone. (1) McLeans Island Quarries, (2) Miners Road Quarries, (3) Pound Road Quarries. (Environment Canterbury, n.d.).

4.4.2. Potential contamination of Christchurch's drinking water

Prior to development, it is critical to know how an artificial waterbody may affect Christchurch's drinking water supply. 25% of Christchurch's drinking water is extracted from the shallowest aquifer and 75% from deep aquifers (Christchurch City Council, 2016). Under an aquifer bore system, the waterbody does not pose a risk of contaminating the deep aquifers due to the one-way system (Fig. 4). However, a system which excavates into the groundwater increases the risk of contaminating the shallowest aquifer. Contaminants from surface runoff into the lake will enter the aquifer as there is less material to filter contaminants out (Castagna et al., 2014). Given these risks and relationships, it is recommended that aquifer bores are the most suitable due to minimal aquifer-waterbody interaction.

4.4.3. External Contaminant Sources

During rehabilitation, externally sourced materials will be required (i.e., hard fill, soils). These can pose a contamination risk to the quarry's surrounding environment, waterbody, and connected groundwater systems. Controls on the quality of externally sourced materials are key to reducing the risk of introduced contaminants. It may affect the aesthetic properties of the groundwater, causing possible concerns for the public about the quality of their drinking water (McGarry et al., 2016; Scott, 2019). However, it was found that this level of effects on water aesthetics do not make it unsuitable to drink (Scott, 2019). These results conclude it is viable to rehabilitate a quarry from a contamination perspective, but public perception poses a limitation.

4.4.4. Waterbody contamination

To ensure the waterbody is viable and useable, the main water sources, groundwater and surface runoff, need to have minimal contamination (Land Air Water Aotearoa, 2022). Most natural lakes have an inflow and outflow of surface waters leading to the cycling of water. However, quarry lakes often have little interaction with surface waters compared to groundwater, which strongly influences the lake water quality (Seelen et al., 2021). If the groundwater is taken from the deeper aquifer, contamination will be minimal because there are no surface contaminants and the aquifers can filter out the small number of contaminants present (A & H Drilling, 2018; Li et al., 2021). If the groundwater is dug into, it will likely be contaminated by surface runoff and can more easily infiltrate into the shallowest aquifer used for drinking water. This is because there is less material for the contaminants to be filtered through.

4.4.4.1. Waterbody contamination mitigation

To ensure lake water quality is maintained, management practices need to be undertaken. Wetlands create a natural buffer zone on the lake edges. The plants take up nutrients from groundwater and surface runoff through their roots, improving the lake water quality (Gibbs & Hickey, 2012; Fig. 7).

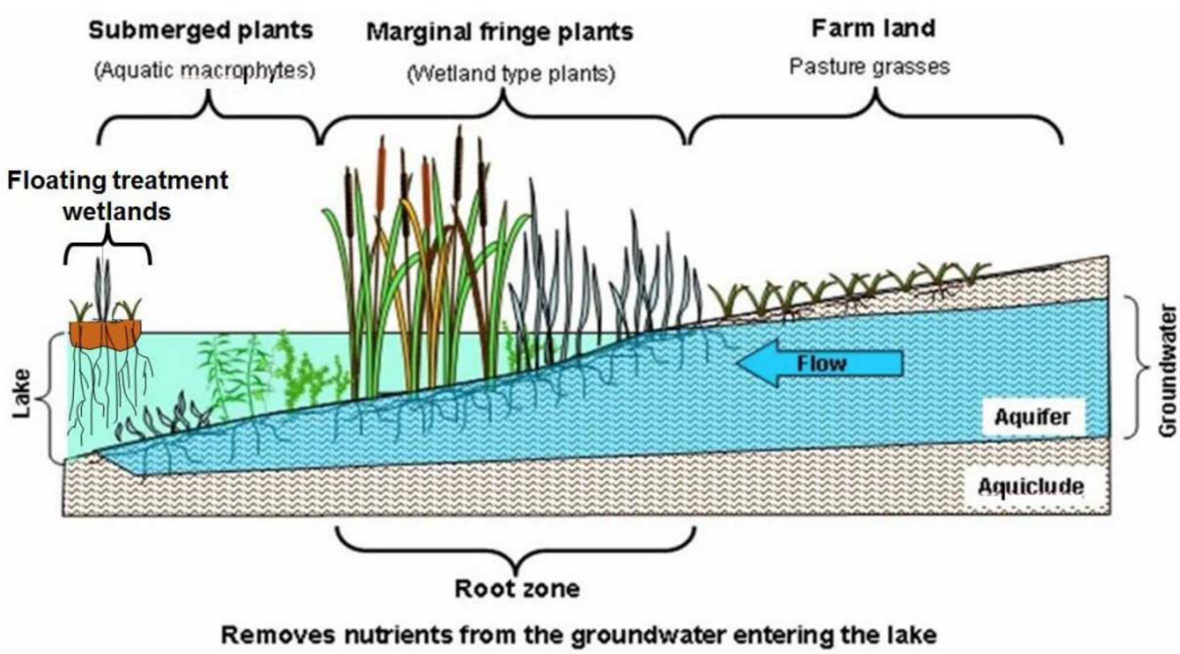

Figure 7. Cross section of a marginal wetland buffer zone and how nutrient contaminants are stopped from entering the lake. (Gibbs & Hickey, 2012).

It is fundamental to model the lake water quality and is suggested to use a combination of the modified MODFLOW-NWT model and DYRESM-CAEDYM (El-Zehairy et al., 2018; Gibbs & Hickey, 2020). These models show the interaction between the lake and groundwater, predicting the future water quality of an unbuilt waterbody. These preliminary assessments help ensure the waterbody rehabilitation will be successful.

Public consultation and long-term community trust are crucial (Han et al., 2021). Effective inclusion of community members throughout the whole rehabilitation process, including planning and results, is key to having a successful project. It is useful to clearly communicate any information about controversial actions, such as interacting with the aquifer, so the public can have informed opinions (Han et al., 2021).

4.4.5. Christchurch International Airport Birdstrike Management Area

Birdstrike risk is another major constraint for building a waterbody in Christchurch. Birdstrike is when an aircraft collides with flying birds, interfering with aircraft navigation and control during taking off and landing (Christchurch District Plan, 2021). It is recognised as a significant threat to the aviation sector globally and there has been a rise in birdstrike due to the increasing number of flights (Coccon et al., 2015; Hu et al., 2020).

The Christchurch Birdstrike Management Area is within 3 km of the airport runway and has been created to address activities that have the potential to attract birds, such as the proposed waterbody rehabilitation option (Christchurch District Plan, 2021). Fulton Hogan on Miners Road recognised this as a constraint and was concerned about the potential risk (Fulton Hogan, personal communication, September 23, 2022). However, waterbody development is permitted at the Miners and Pound Road Quarries, as they are outside the zone and do not pose a high birdstrike risk (Christchurch District Plan, 2021; Fig. 8). Only McLeans Island Quarries are within the zone, making them less viable to build a waterbody (Fig. 8). However, this does not exclude McLeans Island Quarries from being developed as waterbodies. Waterbodies can still be permitted in the Christchurch Birdstrike Management Area if birdstrike risk can be mitigated and the requirements of the Christchurch District Plan (2021) are met.

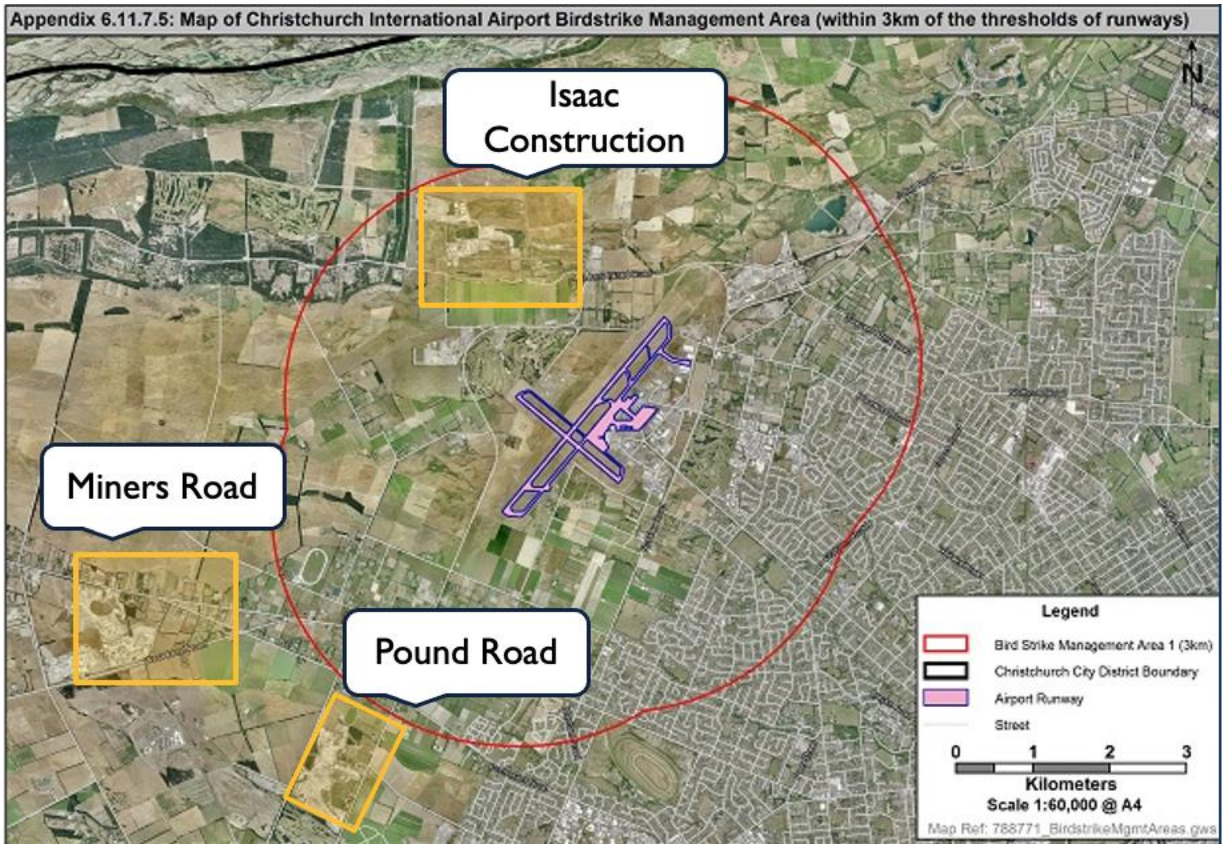

Figure 8. Modified map of the birdstrike area around the Christchurch International Airport, with locations of the quarries identified (Christchurch District Plan, 2021).

5. Waterbody Rehabilitation Uses

The structure of the waterbody is determined by quarry extraction and pit dimensions. Case study quarry sites have large areas and are up to 15 m deep. Pit depth allows the water to stratify into stable layers (Seelen et al., 2021). Deep quarry lakes also have higher water quality as shown by their lower nutrient and chlorophyll-a concentration in comparison with shallow waterbodies (Seelen et al., 2021).

The following provides overviews and options for the proposed uses for rehabilitated waterbodies (Figure 9).

Figure 9. Schematic drawing showing potential uses for a quarry waterbody. (A) Ecological waterbody, (B) Recreational waterbody, (C) Floating Solar Arrays, (D) Aquaculture.

5.1. Ecological Waterbody in Quarry Pits

An ecological waterbody focuses on conserving native terrestrial and aquatic biota. An example is the Shorncote Quarry in the United Kingdom, where the quarry flooded and provided a habitat for native birds and fish (Hills, n.d.). A study of 51 quarry lakes in the Meuse and Rhine catchment areas found that quarry lakes have a significant contribution to macrophyte diversity by supporting distinctly different macrophyte communities (Seelen et al., 2021). Quarry lakes often have much steeper banks than natural lakes, creating a shorter littoral zone and no marsh zone, developing a unique lake ecosystem (Seelen et al., 2021).

While this meets sustainability goals, there is no direct economic incentive. Further, as these quarry pits lie below the ground surface level of the Canterbury Plains, development as an ecological site does not conform to the landscape and ecological history of the area. As a braided river environment, standing water bodies are found towards the coast. With the quarry pits being at a lower level than the surrounding plain, connection to existing waterways is limited, without effectively flooding the entirety of the pit.

5.2. Recreational Waterbody in Quarry Pits

A recreational waterbody is very similar to an ecological waterbody with increased human interaction. Lakes provide many recreational opportunities such as boating, fishing, swimming, kayaking, and are a source of Mahinga kai (Schallenberg et al., 2013). An example is Roto Kohatu Reserve, formerly a gravel quarry which has been developed into two freshwater lakes: Tahi and Rua.

The economic benefit of a recreational waterbody makes this option more desirable for quarry owners. Outdoor recreation contributes $845 million to New Zealand's GDP (Skills Active, 2020). An example of a recreational opportunity is Kaikanui Aqualand NZ, which has a series of inflatable bouncy pontoons operating for 6 months of the year (Law, 2021). Other examples of economic opportunities include a rowing lake, sailboat hire, and water polo.

While lake services provide important economic opportunities, biodiversity and ecosystem functions require additional protection through positive engagement with people who may use the lake. Disturbance, if not mitigated, can impact species and habitat quality. For example, shore access and boating could potentially reduce vegetation cover and compact soil, impacting the soil matrix (Seelen et al., 2021). Recreational activity can also affect disturbance-sensitive taxa and add contaminants to the water. The overall impact of recreation is dependent on the magnitude, duration and frequency of activities (Seelen et al., 2021).

5.3. Aquaculture in Quarry Pits

Aquaculture is another use of quarry waterbodies and is commonly used in quarry lakes worldwide. The aquaculture industry accounts for 45% of the world's fish supply for human consumption as of 2009 (Subasinghe et al., 2009). Aquaculture is the production of aquatic organisms by controlling their rates of growth, mortality, and reproduction for commercial harvest (Otchere et al. (2004). With increasing demand and decreasing fish stocks, capture fisheries will not be able to meet demand. Aquaculture is an opportunity to bridge this and can contribute more effectively to global food security (Subasinghe et al., 2009). Aquaculture increases household food supply, improves nutrition, preserves aquatic biodiversity through re-stocking, recovers protected species, and reduces pressure on fishery resources if done sustainably. However, aquaculture can have negative effects on the environment if not managed correctly (Frankic & Hershner, 2003).

There are two types of aquaculture systems; an open system and a closed system (Fig 10; Fig 11). In an open aquaculture system, fish are kept in a mesh cage where water can flow through to replenish oxygen and remove waste (Otchere et al., 2004). This only uses a section of the lake, allowing for the waterbody to have multiple uses, such as recreation and solar. However, as the system interacts with the rest of the lake, pathogens may spread and fish could escape. The open system is also more expensive because fish food needs to be brought, unlike in capture fisheries, and the cage may become damaged by extreme weather events (Otchere et al., 2004).

The closed aquaculture system uses the entire lake (Fig. 11). Water is filtered and circulated with expensive pumping equipment. This system can deliver more fish and produces high-quality, consistent products. However, a closed system has a higher risk of rapid spread of diseases and the use of antibiotics may lead to the development of antibiotic-resistant bacteria in sediment under fish farms (Otchere et al., 2004).

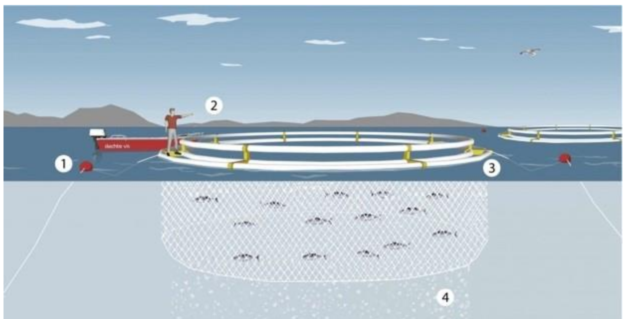

Figure 10. Open aquaculture system. (1) The cage is moored to the lake floor. (2) Fishmeal feeds are added to the cages. (3) Buoyant tubes keep the cages afloat. (4) Fish feces and waste fall through the cages (Otchere et al., 2004).

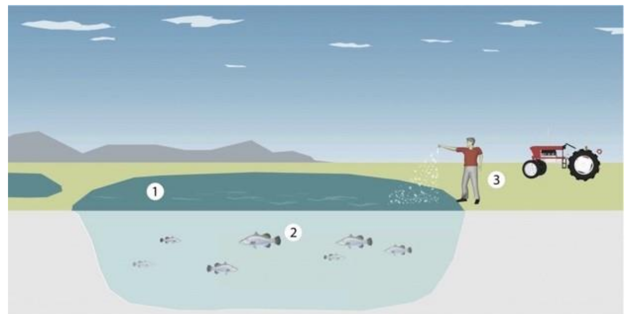

Figure 11. Closed aquaculture system. (1) The pond exists in a closed system. (2) Species including barramundi are grown using this system. (3) Feed is added to the system (Otchere et al., 2004).

There are many examples both worldwide and within New Zealand including the Cobble Hill limestone quarry pit in Canada which is used to breed trout (Otchere et al., 2004). The Issacs Conservation Area is a more local example. This is an old quarry site in Christchurch which is also used as a salmon hatchery before they are moved to the Makenzie Country to be grown and then sold (Mt Cook Alpine Salmon Ltd, n.d.).

5.4. Floating solar arrays

Another economic option for waterbodies is floating solar arrays. These are photovoltaic systems that float on the water surface (Fig 12.). Solar modules sit on a pontoon structure which is moored in place, and outdoor cabling is used to transfer the electricity generated (Ingole et al., 2020; Patil Desai Sujay et al., 2017).

Floating solar generates more electricity and has a longer lifespan than ground or rooftop-mounted solar due to the water's cooling effect. The pontoons shade the water reducing evaporation by up to 70%, improving water quality, and limiting algae growth. It is cost-competitive with other solar systems and is land-use efficient (Ingole et al., 2020; Patil Desai Sujay et al., 2017). Floating solar is a relatively new technology. New systems are still in development, and knowledge is limited on the long-term impact on water quality and local ecosystems (Lima et al., 2021).

Floating solar arrays require a waterbody. The depth and ecological characteristics of the waterbody are of less importance. The limiting factor is the surface area of the waterbody, as this will limit the number of panels. However, floating solar is commonly added to quarry waterbodies such as the plant in Western Germany owned by Quartzwerke. This PV plant has 5,800 modules on 360 floating elements and will produce 3 megawatts (MW) of power (Reuters, 2022).

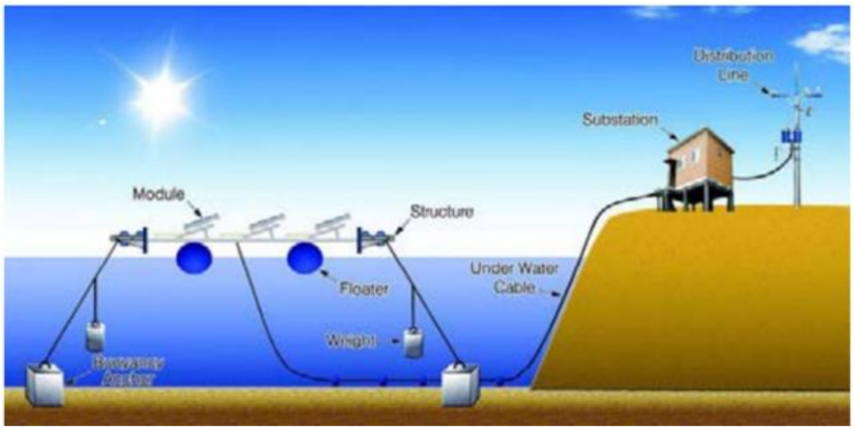

Figure 12. Floating photovoltaic plant layout (Ingole et al., 2020; Patil Desai Sujay et al., 2017).

5.5. Waterbody Summary

For Miners and Pound Road Quarries we would recommend using an aquifer bore to supply water for the quarry lake. Both sites are suitable for all waterbody types, due to their combination of depth and location outside of the birdstrike management area (Table 2). On the other hand, for the McLeans Island site, we recommend using either the aquifer bore or aquifer intersection methods. The birdstrike management area limits the waterbody options, size, and scope. We do not recommend McLeans Island using the waterbody for recreation, ecology, or aquaculture because these pose a risk to the birdstrike management area. However, floating solar covers the water's surface, making it more viable (Table 1).

Table 3. Suitability of each quarry site for all waterbody options.

	Miners Road	Pound Road	McLeans Island
Ecological	✓	✓	✗
Recreation	✓	✓	✗
Aquaculture	✓	✓	✗
Floating Solar	✓	✓	✓

6. Research Limitations

The time constraints placed on this project led to limited decision-making, which influenced the methodological approach and determined the quantity of primary data we could acquire. In conjunction with short time constraints and the need to do background research on quarrying, we found there was limited time to consult various specialists and visit other quarries. In addition to this, our project is a part of a university course so we do not have a budget to conduct our own research in depth. This would have also been beneficial to help us apply our learnings to the given quarry sites. If further research was conducted, we would have liked to carry out additional primary data with a wider scope.

As university students, we are qualified in our disciplines, but we are limited by our lack of industry experience. For example, further research into aquifer interactions and the likelihood of resource consent approval is required but are beyond the scope of our studies.

The primary data gathered was limited from only interviewing one quarry company, Fulton Hogan at Miners Road. Valuable information was obtained, but only represents Fulton Hogan operations and values. Given more time, interviews with other quarry companies from McLeans Island and Pound Road Quarries would have been useful to conduct to apply rehabilitation options more comprehensively to specific quarry sites.

7. Conclusion

This report has outlined the viability of vertical farming and waterbody rehabilitation strategies for Miners Road, Pound Road, and McLeans Island Quarries. Regarding the innovative, sustainable, and economic drivers, these proposed options will utilise the post-quarrying landscape. We have concluded that Miners and Pound Road Quarries are suitable sites to rehabilitate into vertical farms and waterbodies (Table 3). McLeans Island site has more limitations affecting the suitability of waterbodies, regarding birdstrike management, and vertical farms, regarding depth (Table 3). They do not complement the existing site attributes such as location in the birdstrike management area and shallow depth. We suggest there needs to be further investigation into other rehabilitation options for McLeans Island Quarries.

Table 4. Suitability of each quarry site for the rehabilitation options.

	Miners Road	Pound Road	McLeans Island
Vertical Farms	✓	✓	✘
Waterbodies	✓	✓	?

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