Investigation of alternative water sources for fish farming using life cycle costing approach: A case study in North West Tasmania

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Abstract

In this case study, we investigated the options for freshwater sources for a medium-sized aquaculture business in North West (NW) Tasmania. We considered four different options for water sourcing including from local rivers, groundwater, drinking water from local water supply utility as well as from nearby irrigation schemes. Our investigation employed the life cycle costing (LCC) approach for assessing the different options. Based on the locations of the future aquaculture plant, water demand, water availability from various sources, local topography, net present worth of total capital cost, operational and annual maintenance cost of required infrastructures, we found that both the river and groundwater options performed equally well. However, given the uncertainties in the long term environmental and hydrogeological impacts on the aquifer water quantity and quality resulting from continuous extraction of groundwater, water supply from the rivers in NW Tasmania offered the most preferred option for aquaculture business in NW Tasmania. Our proposed methodology for the assessment of alternative water sourcing options demonstrated ranking of the options based on net present values (NPV) of capital, operational and maintenance costs as well as on the amount of greenhouse gas emissions (CO_2 equivalent) generated from options considered. This ranking approach can be employed to other industries where large amount of water is required for process operations.

Keywords: Freshwater sourcing, salmon bathing, alternative water sources, aquaculture, life cycle costing

Introduction

The demand for freshwater in primary industries such as aquaculture, dairy and livestock farms is increasing rapidly. Commensurate with the increasing demand from the consumers worldwide, primary industries are expanding their businesses and as a result freshwater from various sources are being procured to maintain smooth business operation. This poses an increased challenge to primary business operators, particularly since the supply of freshwater is limited and the quality of the freshwater often does not meet the required criteria of the industries. Therefore, efficient sourcing of water in term of cost effectiveness and long-term sustainability are vital for the industries that use large quantities of freshwater. Since the last two decades, the aquaculture of salmonids has been a major success of primary industry in Australia. In Tasmania, over the past two decades, the Atlantic salmon industry has seen an increase in the number and size of freshwater hatcheries and marine farms at various locations in the state. According to the Tasmanian Salmonid Growers' Association (TSGA 2015), the average annual turnover or gross output of salmon industry of Tasmania is $1.12 billion (i.e., the total value of industry production) and the industry supports approximately 2,786 FTE (full-time equivalent) jobs in the state. According to a confidential case study conducted for a medium sized Tasmanian aquaculture farm, its annual salmon production volume ranged between 6540 and 8210 tonnes in 2017. To date, the aquaculture industries of Australia, have invested a large sum of money to source freshwater for their business.

Water chemistry of freshwater is crucial in fish farming business. The salinity of water is the principal parameter that indicates the suitability of water for farming particular fish species. Salinity refers to the amount of salt in water (expressed as total dissolved solids, TDS). Categories of TDS given in Water Victoria (1989) expressed in electrical conductivity (EC) units are:

- Freshwater less than 800EC

- Marginal 800-2,400EC
- Brackish 2,400 - 8,000EC
- Saline more than 8,000EC

Adverse biological effects begin to occur in freshwater rivers when salinity exceeds 1,500EC. Almost all adult native freshwater fish species can tolerate quite high salinities (16,000EC) with some species able to withstand sea water (56,000EC). In Tasmania, the Australian and New Zealand Environment and Conservation Council (ANZECC) specified default values of conductivity (μS/cm) have been recommended to classify the water ecosystem types. For example, lowland rivers, upland rivers and lakes in Tasmania are classified with conductivity 125-2200, 30-350 and 20-30 μS/cm, respectively (DPIPWE 2018a).

The freshwater quality requirement for Atlantic Salmon farming were studied by Powell and Kristensen (2014) and is listed in Table 1.

Insert Table 1

One of the major fish health problems that affect the salmon farming industry is the Amoebic Gill Disease (AGD) caused by a parasite known as *Neoparamoeba perurans* in the gills of the salmonids (Young et al. 2007, 2008). Freshwater bathing of Atlantic salmons for 2-3 hr has been recommended as a treatment of AGD (Clark et al. 2003; Powell et al. 2015; Ruane & Jones 2013) and the salmon farming industries of Tasmania have adopted the freshwater bathing of farmed Atlantic salmons as part of their aquaculture practice. In a recent study, Mahbub and Sharma (2018) have reported that the lack of efficient sourcing and management of freshwater can potentially incur huge cost in aquaculture business. Hadjikakou et al. (2019) have presented a generalised framework for assessing water supply options that included life cycle assessment (LCA), life cycle costing (LCC), social impact analysis and multicriteria decision analysis (MCDA) of several indicators. The framework was evaluated against drinking and wastewater projects, helping utilities to incorporate different treatment technologies. Similarly, Sharma et al. (2009) applied LCA and LCC for water supply option assessment for large residential, commercial and industrial development as part of greenfield development of 3060 ha in Melbourne. As opposed to the study conducted by Hadjikakou et al. (2019) for water utilities, our study is focused on the local freshwater needs of aquaculture industry, where there is competition for freshwater resource among similar industries and agricultural producers. The availability of freshwater resources under environmental impacts and climatic/seasonal variability is stipulated by local regulatory authorities, which was considered in the assessment process and system design. Both LCA and water footprint analysis (WFA) have been reported in analysing the environmental aspects of freshwater usage in seafood production (Gephart et al. 2017). The LCA of freshwater use in large inland aquaculture industries includes detailed analysis of locations of water withdrawal as well as social dynamics of water extraction (Henriksson et al. 2012) compared to the simple and easy to conduct WFA (Pahlow et al. 2015). MCDA has been widely used in many studies on alternative option analyses for water consumptions (Zanghelini et al. 2018) as well as for water supply (Sikder and Salehin 2014) scenarios to date. To the best of authors' knowledge, MCDA in conjunction with stakeholders' consultation as well as economic and environmental impacts resulting from the use of huge amount of freshwater have not been applied to shore-based medium to large aquaculture industries producing seafood to date. Our investigation demonstrates an application of detailed framework for facilitating the freshwater sourcing to meet increased water demand of a shore-based aquaculture industry resulting from potential growth of their business. We then applied the developed framework as a case study to a local aquaculture company in North West (NW) Tasmania. Our methodology includes preferred site selection for freshwater sourcing and supply, analysis of the topography of the area, identification of possible water sourcing options, water quality analysis from various sources, seasonal water availability stipulated by local government water agencies, life cycle costing

(LCC) of different options and analysing and interpreting the results for a preferred water sourcing solution for aquaculture industry. Similar to Beh et al. (2014), we also incorporated variability in water demand and discount rates in LCC analyses in this case study as these were deemed the most significant for sequencing of water supply options at regional scale. The aim of this study is to develop a freshwater management framework that can be applied by the shore-based aquaculture farms during the initial planning phase for new as well as future expansion of their existing business for freshwater sourcing.

Methodology

A framework for freshwater sourcing is shown in Figure 1. The framework is described in the following steps:

1. Field and desktop investigations to understand local conditions and water requirements – this step requires collection of information on local topography, location of potential sites for fish farming, local climate, accessibility and water demand. For aquaculture business, the investigation of fish bathing process is required to ascertain the variation of the water demand over a period based on the planned business development. Local climate, topography, land use, and potential water sources need to be identified before analysing the freshwater sourcing scenarios.
2. Establishing specific objectives - In this step of the framework (Figure 1), establishment of specific objectives resulting from the field and desktop study covering the following aspects are required:
    - Water quantity and water quality required for aquaculture business
    - Economic and sustainable solution for water supply
3. Consultation and analyses of water sources - These specific tasks dictate the analyses of water sources through consultations with water professionals, civil contractors and

local stakeholders. These consultations reveal water available from various sources, existing infrastructures and required new infrastructures to supply water.

4. Develop water supply options - As shown in Figure 1, the consultations with water professional result developing the supply scenarios from different sources, namely river water, bore water, irrigation water and drinking water.
5. Analyses of Options - In this step, undertake analyses of various options considering the water balance assessment, river hydrographs, groundwater tables, safe yields of groundwater and quality of water into consideration.
6. Decision and Conceptual Design - After analysing the water supply options/scenario, a decision has to be taken whether the scenario is suitable for the fish bathing process operation irrespective of the cost and sustainability. A positive answer from the aquaculture industry results proceeding with the detailed conceptual design of water supply infrastructures in terms of intake and delivery pumping calculations, designing the pumping mains and balancing storage reservoirs. A negative answer from the aquaculture industry results revisiting the development phase of water supply scenarios to investigate alternative options as illustrated in Figure 1.
7. Life Cycle Costing (LCC) and Greenhouse Gas Emissions (GHG) assessment - For each suitable option, undertake LCC analysis based on the capital costs of infrastructures as well as operational and maintenance costs. Estimate the total CO_2 equivalent (CO_2-e) due to operational energy required for provisioning of water supply under each option.
8. Ranking of options - The LCC and CO_2-e analyses lead to the ranking of the suitable options and enabled to recommend the suitability of the options to the aquaculture industry.

Insert Figure 1

Study area

The terrain map (Figure 2) shows proposed delivery points of water at Stanley and Thousand Acre Plains and the relative locations of gauging stations at five rivers in NW Tasmania using Google Earth Pro software. The two delivery points and the five river gauging stations were selected through consultations with stakeholders and the aquaculture industry.

Insert Figure 2

The study area was located within the boundaries of surface water catchment number 27 and 28 as illustrated in the Tasmanian catchment map published by the Department of Primary Industries, Parks, Water and Environment (DPIPWE 2019). Additionally, the occurrences of porous intergranular aquifers in these regions are termed as high in the DPIPWE groundwater quality maps. As a result, there are several bores in these areas that yielded more than 10 L/sec flow rate at the time of drilling (DPIPWE 2018b).

The study area is approximately 1,575 km^2 and the distances between Stanley and the furthest river gauging station at Welcome River is ~61 km. The geological formation of NW Tasmania which includes the study region mainly contains tertiary basalt or fractured rocks. The groundwater quality in terms of total dissolved solids (TDS) in the deep and shallow aquifers in Forest and Smithton areas of NW Tasmania surrounding the study region are suitable for irrigation and all-purpose domestic use (DPIPWE 2018b). Additionally, the average annual precipitation in the study area ranged from 910 mm to 1074 mm (BOM 2019). The water flow data in the selected rivers in study area can be found in 'Assessment of Options' under the Methodology section.

Water demand

The predicted water demand of the aquaculture industry beyond June 2020 is given in the following Figure 3:

Insert Figure 3

We observe in Figure 3 that the monthly water demand over a 12-month cycle from July to June would increase from 0 to ~120 ML except during September. In general, the average monthly demand is around 62ML. Similar monthly water demand cycle is expected to repeat on yearly basis.

Water sourcing options

The following four options for alternative water resources for fish farming were considered for investigation in our study:

Option 1: Extraction of water from river sources in NW Tasmania

Option 2: Extraction of local groundwater from suitable location

Option 3: Sourcing water from local drinking water utility agencies (e.g., TasWater)

Option 4: Sourcing water from existing irrigation schemes in NW Tasmania (via Water Trading)

Other water sourcing options such as desalination and recycled water availability in NW Tasmania were also considered in our study. Amongst these, there is no desalination plant in the state of Tasmania to supply water for fish farming. Taswater maintains 14 water recycling plants in Northern Tasmania which recycle wastewater by removing mainly solids and pathogens (Dettrick and Gallagher 2002). Due to the sensitive requirement of freshwater chemistry for fish bathing, we did not include such recycled water as an option for fish bathing. We also considered the potential local water storages managed by Tasmania Irrigation which were in close proximity to the study area. The pricings of privately-owned water storages in Tasmania are not regulated by the Tasmanian Water and Sewerage Industry Act 2008

(Economic Report 2014), and as such we did not consider the privately-owned local water storages as an option.

We investigated the required pumping systems according to the Water Supply Code of Australia (WSAA 2011). The water reservoir design to contain and supply freshwater to aquaculture industries was performed according to methods described in Garg (2015). Detailed design of the water reservoirs was conducted using water balance analyses.

Assessment of Options

OPTION 1: EXTRACTION OF WATER FROM RIVER SOURCES IN NW TASMANIA

Based on the preferences of the aquaculture industry for future locations of fish farm at Thousand Acre Plains and at Stanley in NW Tasmania, four rivers, namely, Duck River, Black River, Montagu River, and Welcome River were considered for water supply. A comparative overview of the four rivers is illustrated in Table 2 and shown in Figure 2:

Insert Table 2

The water flow data of the four rivers were assessed from the Bureau of Meteorology website (BOM 2018). The monthly minimum flow of these four rivers were compared to the water demand of the aquaculture industry as shown in Figure 4. It is interesting to note that water demand for fish farming is high when flows in rivers are low during summer months and vice versa. It means that a high capacity balancing storage near the point of water extraction would be required to meet the annual water demand.

Insert Figure 4

It can be observed from Figure 4 that Black and Duck rivers have significantly higher flows compared to Montague and Welcome rivers from mid-June to mid-September. The most important point to observe from Figure 4 is the fact that the monthly demand of fish farm is significant from December to June when the flows in all four rivers are low. Moreover, the flows in Welcome River are particularly low compared to other three rivers. Based on the data of water flows in various rivers (Figure 4), considering limited information on water quality, required storage dam capacities, and distances between river intake locations and proposed fish farms (Table 2), it was concluded that Duck and Black rivers are the two most feasible options for sourcing freshwater. Therefore, only two rivers, namely, Duck and Black Rivers were considered for further assessments. The following options were investigated for water supply from Duck and Black rivers:

- Option 1a: Extraction of water from Duck River and delivery to Thousand Acre Plains
- Option 1b: Extraction of water from Duck River and delivery to Stanley
- Option 1c: Extraction of water from Black River and delivery to Thousand Acre Plains
- Option 1d: Extraction of water from Black River and delivery to Stanley

The infrastructures required for extracting water from Duck and Black rivers and supplying it to Thousand Acre Plains and /or Stanley areas for fish farming is listed in Table 3. It is observed that the balancing storage (dam) capacities required at points of water extractions from both the rivers are the same. However, it can change based on the monthly river water allocation / extraction permission by regulatory agency. It can be seen that the length of pipelines from both the river intakes will be almost same to the point of supply in Thousand Acre Plains. However, extra 8 km pipeline will be required to supply water from Duck River to Stanley in comparison to water supply from Black River to Stanley. As the pumping capacity required at intake structure at Black river is about 2.5 times more in comparison to Duck River due to high elevation of proposed storage location at Black river intake point (reduced level or RL 42 m as shown in Table 3), it will have financial impact on the annual recurring operating expenditure.

Insert Table 3

OPTION 2: EXTRACTION OF LOCAL GROUNDWATER FROM SUITABLE LOCATION

Based on the information on existing bore yields in the NW Tasmania from the groundwater information access portal of Tasmania (DPIPWE 2018b), the average expected safe yield of bores was estimated as 140 L/sec. We calculated that a battery of 6 new bores will be required to meet maximum monthly demand of 118 ML for salmon bathing. The following four options for groundwater supply to Thousand Acre Plains and Stanley areas were developed and assessed:

- Option 2a: Extract groundwater using 6 new bores in the proposed area and deliver to Thousand Acre Plains with a small storage reservoir (10ML) at delivery point to meet peak day demand
- Option 2b: Extract groundwater using 3 new bores in the proposed area and deliver to Thousand Acre Plains with a large storage reservoir (240ML) at delivery point
- Option 2c: Extract groundwater using 6 new bores in the proposed area and deliver Stanley with a small storage reservoir (10ML) at delivery point to meet peak day demand
- Option 2d: Extract groundwater using 3 new bores in the proposed area and deliver to Stanley with a large storage reservoir (240ML) at delivery point

Table 4 summarises the outcome of groundwater options with the list of infrastructures required for all four groundwater options.

Insert Table 4

OPTION 3: SOURCING WATER FROM LOCAL DRINKING WATER UTILITY AGENCIES

Based on the information gathered from the local drinking water supplier (TasWater), the following two options were investigated and assessed:

- Option 3a: Supply of drinking water from TasWater. This option was deemed not suitable for supplying water on yearly basis due to the limited capacity of supply and infrastructure capacity in TasWater's network.
- Option 3b: Combined Supply from TasWater and groundwater bores

Table 5 shows the results from the pumping calculations for combined option 3b. Detailed pumping calculations were conducted to supply water as a combination of borewater and TasWater in this option.

Insert Table 5

This option was only considered for water supply from combined sources to Thousand Acre Plains. Based on the distances from groundwater and TasWater sources to Stanley, such an option will be highly uneconomical for Stanley and hence, was not considered for design and LCC.

OPTION 4: SOURCING WATER FROM EXISTING IRRIGATION SCHEMES IN NW TASMANIA

In this option, we investigated if any of the existing irrigation schemes managed by Irrigation Tasmania has spare capacity to meet fish farming demand near Stanley and/or Thousand Acre Plains areas. The information on irrigation schemes in NW Tasmania were collected to initiate discussion with Tasmanian Irrigation management authority (Irrigation 2018), which are listed in Table 6.

Insert Table 6

According to Tasmanian Irrigation, the Duck Irrigation scheme (which is the only feasible scheme according to Table 6 from distance consideration), is fully allocated based on its planned capacity and as such no spare water is available from this scheme.

Methodologies Employed in Life Cycle Costing (LCC) Analyses

LCC using net present value (NPV) method combines the capital cost of infrastructure planned for providing services, replacement of components having service life less than the analysis period, annual maintenance and operation cost during the analysis period. The net present value of a future cost is calculated according to Eq. 1 (Gurung et al. 2016).

$$P = \frac{F\,(1+i)^n}{(1+r)^n} \qquad (1)$$

where *P* is the net present value of a future cost *F*, *i* is the current inflation rate and *r* is the current discount rate over an analysis period of *n* years.

Based on the information on producer price index (PPI) provided by the Australian Bureau of Statistics, current inflation rates of Heavy and Civil Engineering Construction as 2.6% as well as the current inflation rates of electricity, gas and water supply sector of Australia as 2.9% (ABS 2017) was considered in the analysis. Similarly, a discount rate of 6% as recommended for water infrastructure projects (DTF 2003) was applied for LCC. An analysis period of 30 years for the NPV calculation was used.

Results and Discussions

We have discussed each option in terms of the LCC as well as CO_2-equivalent greenhouse gas emissions. The social impact assessment was limited to stakeholder consultation, which was considered in water servicing option development and their assessment. These economic and environmental analyses including stakeholder consultation have resulted in subsequent ranking of the options based on multicriteria decision making analysis.

Life Cycle Costing (LCC) of Freshwater Souring Options

Life cycle costing (LCC) of river water, groundwater as well as combination of groundwater and TasWater options (i.e., options 1-3) was conducted to estimate the net present value (NPV) of the service provisions over an analysis period of 30 years. The LCCs of total expenditure based on the total capital cost, net present value of annual operational cost and net present value of annual maintenance cost over 30 years of analysis period are provided in Tables 7-9 for various alternative water servicing options.

Insert Tables 7, 8, 9

Figure 5 summarises the cost analyses of all the above-mentioned 9 options including the capital, operating and maintenance cost over analysis period of 30 years.

Insert Figure 5

It can be observed from the Figure 5 that Options 2a and 2b (groundwater to Thousand Acre Plains) resulted the lowest net present values (NPV). Under Option 2a, ground water is supplied from 6 bores at Forest and delivered to Thousand Acre Plains having 10ML balancing storage, while in Option 2b groundwater is delivered from 3 bores in the Forest region to Thousand Acre Plains having 240 ML balancing storage. Six pumps are proposed in Option 2a to meet peak water demand during May and June months (Figure 3) with small size storage, while in Option 2b three pumps are proposed to operate fixed hours every day and storing water in a large balancing storage to meet peak demand. The number of pumps operating under Option 2a on a particular day will depend on the water demand on that day and all six pumps will operate during peak water demand months. As the total length of pipe line from the proposed borefield in Forest region to the delivery point in these options were considerably shorter than the other 7 options (Tables 3 and 4) and a favourable downward slope was found from the source to delivery point (~0.4%), both options resulted comparatively smaller operational and capital cost than the other options. An important factor that needs to be considered particularly for the groundwater option is that the uncertainties in the long term environmental and hydrogeological impacts on the aquifer water quantity and quality resulting from continuous extraction of groundwater is currently unknown. Therefore, long term hydrogeological assessment of the region would be required, if either of the groundwater options are considered for water sourcing.

Amongst the river water options, both the options 1a (extraction from Duck river at Smithton to delivery at Thousand Acre Plains) and 1d (extraction from Black river at Forest to delivery at Stanley) performed well in terms of the NPV of the investment. The location of the 550 ML storage dam may become the most critical factor while choosing amongst the river water options.

An interesting option is the combination of groundwater with the TasWater supply (Option 3b). This option has resulted second highest NPVs amongst all other options (Fig. 5). This is mainly due to the fact that the aquaculture industry has to pay a high price per kilolitre of the treated water from the Smithton Water Treatment Plant (WTP) operated by TasWater over the analysis period of 30 years. However, negotiations with TasWater for the use of untreated water directly from TasWater's Deep Creek pumping station may result in reduced price for water usage from TasWater.

Environmental assessment based on greenhouse gas emissions (CO_2 equivalent)

According to Sharma et al. (2009), the greenhouse gas emissions from water supply infrastructure provisions embodied in material and construction is significantly small (about 10–15% of total emissions) in comparison to total emissions from energy required for operation of the systems and embodied in infrastructure during manufacturing process including energy required during construction phase. Inamdar et al. (2018) have demonstrated that the greenhouse gas (GHG) emissions in stormwater harvesting schemes are principally associated with the electrical energy consumption of the pumps. In our case study, we have calculated only the total energy required for pumping infrastructures over the analysis period for each option. From this, researchers can easily obtain the total CO_2 equivalent (CO_2-e) (Climate Change 2018) and about 10-15% of this value would then be considered as the greenhouse emissions from embodied energy in producing the infrastructures (pipes, reservoirs, pumping station and pumps) and their construction. In this way, very time-consuming estimations of embodied energy as well as the associated requirements of significant data and analysis tools can be avoided.

Stakeholder consultation for development of water servicing option and their assessment

Detailed stakeholder consultation on various aspects of the study was conducted during its various phases. We have engaged with key stakeholders such as Department of Primary Industries, Parks, Water and Environment (DPIPWE) of Tasmania, TasWater, local bore drillers, groundwater experts, civil contractors and Tasmanian Irrigation into discussions at the beginning of the conceptual phase of this case study to minimise any impact on the development and assessment of feasible and sustainable servicing options.

The consultation with stakeholders included availability of river water (quantity) during various seasons, location of good quality water in respective rivers, reliability of river sources, location of bore holes for required water supply and expected water quality, need for detailed hydrogeological investigations for long term groundwater availability, availability of water from irrigation water storages, availability of water from potable supply and cost of drilling bores including other civil infrastructure for various water servicing options. In this context, the extraction of groundwater (options 2a-d) would require detailed hydrogeological studies to determine long term safe yield. Amongst the remaining feasible options (Options 1a-d and 3b), significant civil construction work would be required for the river water supply options (i.e., options 1a-d). The combined Taswater and borewater supply option (i.e., option 3b) would use the existing TasWater supply network and some civil construction work for borewater supply.

Multi-criteria assessment

We calculated the relative standard weights of each option compared to minimum net present value (NPV) as well as the total CO_2-e emission for electrical energy consumption in Tasmania (Climate Change 2018) and tabulated the values in Table 10.

Insert Table 10

We have ranked the options based on the combined standardised weight of minimum NPVs and CO_2-e emissions, and hence the minimum values of weights represented the better ranked options as illustrated in Figure 6. Although the two groundwater options (2a and 2b) ranked higher than the river water supply options (1a, 1d and 1c) in Figure 6, the uncertainties in the long term hydrogeological impact of groundwater extraction have to be taken into account for water supply to aquaculture industry in this case study using the three top ranked options of Figure 6. Thus, water supply from Duck river to potential farming site at Thousand Acre Plains (Option1a) and water supply from Black river to Stanley (Option 1d) potential site are preferred options.

Insert Figure 6

Conclusions

In this study, a methodology for suitable water source selection for aquaculture industry based on economic considerations was developed and applied to case study site in NW Tasmania. We demonstrated the application of LCC and GHG assessment for optimal site selection to execute various water supply options required for process operations of an aquaculture industry in this case study. Our methodology included investigating different options of freshwater sourcing for an aquaculture industry with a view to facilitate executive decisions on investments required to extend their salmon production business beyond 2021. We considered sourcing water from local rivers, groundwater, drinking water from local water supply agencies as well as from irrigation networks. Based on the selected location of the future aquaculture site, water demand, water availability from various sources, local topography, net present worth of total capital, operational and annual maintenance cost; and GHG emissions; we concluded with the following suggestions from our investigations:

- Based on initial investigations of available limited groundwater bore data and discussions with local drillers, it can be concluded that groundwater in Forest area should be available in desired quantity for fish farming. However, detailed hydrogeological investigations would be required to understand sustainable yield from proposed bores and the impact of these new bores on existing bores in the region. The groundwater supply to Thousand Acre Plains will be economic in comparison to supply to Stanley. It is mainly due to the increased length of pipeline required to supply water to Stanley. There is also a need to investigate groundwater quality for assessing the suitability of water for fish farming.
- Out of five rivers (Duck, Black, Montagu, Welcome and Harcus) in NW Tasmania considered for alternative water supply, only Duck and Black rivers are recommended for water extraction considering availability of flows in these rivers and distances from potential extraction points at rivers and proposed locations for fish farming operations. Water extraction is permissible only over seven months during winter (April to November) and monthly water demand is always >20 ML except July and September, thus a balancing dam will be required to meet water supply across the year. Limited water quality data is available to check the suitability of water for fish farming and thus detailed water quality analysis would be required for further assessment. Considering

cost and GHG assessments only, water supply from Duck river will be economic to supply to Thousand Acre Plains and from Black river to Stanley.

- As mentioned by Gephart et al. (2017), aquaculture production now comprises half of the global seafood production, and hence we envisage the demand for freshwater in aquaculture businesses will continuously rise at global scale. Hence, the proposed framework/methodology presented in our study has wider application in global seafood-water nexus in terms of selecting the best possible water souring strategy. In this context, we recommend the future studies to incorporate other economic measures which were not covered in our case study such as internal rate of return (IRR) and payback period of investments along with net present values of investment in LCC analysis to compare different water sourcing options for aquaculture business operations. Some readily transferable policies for option assessment from our case study such as various stakeholder engagement at initial phase of the study to develop robust and sustainable options, estimation of environmental factors along with NPV analysis as well as source water quality assessment can be adopted locally as well as globally in areas where such studies for aquaculture business are conducted.

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Tables

Table 1: Fresh water quality requirement for Salmon bathing

Parameters	Prior to bathing	During bathing
Conductivity	< 500 µS/cm	< 1000 µS/cm
pH	6.0-6.7	6.0-6.8
ORP (Oxidation-	FW 40-100 mV	< 350 mV
TOC/DOC	< 3 mg/L	-
Ca^{2+} Concentration	< 10 mg/L	-
Na^{2+} Concentration	< 10 mg/L	-
O_2 saturation	90-110%	90-110%
CO_2 concentration	< 5 mg/L	< 25 mg/L
Water Characteristics	Freshwater < 5 ppt salinity	Freshwater < 5 ppt salinity

Table 2: Water availability comparison amongst the four rivers close to the Stanley wharf and the Thousand Acre Plains in Northwest Tasmania

River	Water available during the 7 months in winter (ML)*	Water Quality**	Gauging Station, Lat., Long.	Reliability of water extraction during winter	Land Use	Geology	Distance from the Point of Intake to Point of supply at Thousand Acre Plains, km	Distance from the Point of Intake to Point of supply at Stanley, km
Duck River	19000	EC↑, TDS↑	-40.87, 145.12	More reliable than Black	Dairy Farms	-	16.40	22.30
Black River	27000	EC↓, TDS↓ than Duck	-40.87, 145.30	Less reliable than Duck	Forested	-	15.70	14.20
Montagu River	15000	Better than Welcome	-40.78, 144.93	-	-	-	34.4	40.3
Welcome River	3000	EC↑	-40.78, 144.75	-	Forested	Sand stone	51	57

*Water extraction is only permissible over April to November months/ year
**EC for electrical conductivity (µS cm^{-1}), TDS for Total Dissolved Solids (mg L^{-1})

Table 3 Comparative Overview of Options to Source Water from Duck and Black Rivers

Option	Point of Intake	Point of Delivery	Pressure Main length (km)	Pressure Main Diameter*, (mm)	Pressure Main Flow (L/sec)	Intake main Length (m)	Intake Main Diameter* (mm)	Intake Main Flow, L/Sec	P1-Pump Power at Intake (KW)	P2-Pump Power at Storage Dam (KW)	Storage dam (ML)	Storage Tank at delivery (ML)
Option 1a	Duck River (RL=13m)	Thousand Acre Plains	16.4	DN355 301.6 mm	70	100	DN560 455.8mm	140	40	115	550	10
Option 1b	Duck River (RL=13m)	Stanley	22.3	DN355 301.6 mm	70	100	DN560 455.8mm	140	40	150	550	10
Option 1c	Black river (RL=42m)	Thousand Acre Plains	15.7	DN355 301.6 mm	70	100	DN560 455.8mm	140	100	130	550	10
Option 1d	Black River (RL=42m)	Stanley	14.2	DN355 301.6 mm	70	100	DN560 455.8mm	140	100	105	550	10

* AS/NZS4130 and TG 105 technical guideline SA Water (2011)

Table 4 Comparative overview all options for extracting groundwater at Forest region and supply to either Thousand Acre Plains or Stanley

	Point of Intake	Point of Delivery	Pressure Main length, km	Pressure Main Internal Diameter*, mm	Pressure Main Flow, L/sec	Pump Power, KW	Storage Dam at Delivery
Option 2a	starts at approximate location 40.858 S 145.206 E at the edge of the Back Line Road	Thousand Acre Plains	11.6	300 mm DN355 PN12.5 PE100	75	22 × 6	10 ML
Option 2b				250 mm DN315 PN16 PE100	45	22 × 3	240 ML
Option 2c	starts at approximate location 40.858 S 145.206 E at the edge of the Back Line Road	Stanley	17.5	300 mm DN355 PN112.5 PE100	75	40 × 6	10 ML
Option 2d				250 mm DN315 PN16 PE100	45	40 × 3	240 ML

* AS/NZS4130 and TG 105 technical guideline SA Water (2011)

Table 5: Comparative overview of option 3b for extracting groundwater at Forest region (Jan-Jun) and combining with TasWater supply (Jul-Dec) to Thousand Acre Plains

	Point of Intake	Point of Delivery	Pressure Main length, km	Pressure Main Internal Diameter*, mm	Pressure Main Flow, L/sec	Pump Power, KW	Storage dam at Thousand Acre Plains, ML
Option 3b Jul –Dec (TasWater)	Deep Creek Pump Station of TasWater	Thousand Acre Plains	up to a Junction (4.69 km)	203 mm (DN250, SDR 11, PN 16 PE 100)	31	22 KW at deep Creek Pump Station of TasWater	175
Option 3b Jan – Jun (Borewater)	Proposed Bore Area	Thousand Acre Plains	11.63	256 mm (DN315, SDR 11, PN 16 PE 100)	45	22 KW * 4 bores	

* AS/NZS4130 and TG 105 technical guideline SA Water (2011)

Table 6: Irrigation schemes in North West Tasmania

Irrigation Schemes	Capacity, ML/year	Distance, km		Remark
		From Stanley	From Thousand Acre Plains	
Duck Irrigation Scheme	5200	18	12	Distance feasible for water transport.
Dial Blythe Irrigation Scheme	2855	90	100	Distance not feasible for water transport.
Greater Meander Irrigation Scheme	36000	190	200	Distance not feasible for water transport.
Kindred North Motton Irrigation	2500	115	125	Distance not feasible for water transport.
Sassafras Wesley Vale Irrigation Scheme	5460	135	145	Distance not feasible for water transport.

Table 7 Analysis of total expenditure for river water option (Option 1)

Options	Total Capital Cost	Net Present value of Operational Cost	Net Present value of Annual Maintenance Cost	Net Present Value of Total Investment
Option 1a	12,103,807	1,654,086	142,314	13,900,208
Option 1b	15,560,205	2,076,339	161,937	17,798,480
Option 1c	11,725,246	2,235,080	146,675	14,107,001
Option 1d	10,854,189	1,933,472	141,062	12,928,722

Table 8 Analysis of total expenditure for groundwater option (Option 2)

Options	Total Capital Cost	Net Present value of Operational Cost	Net Present value of Annual Maintenance Cost	Net Present Value of Total Investment
Option 2a	9,420,877	1,257,233	185,496	10,863,605
Option 2b	9,465,664	1,460,422	146,602	11,072,687
Option 2c	13,413,637	2,285,878	322,653	16,022,167
Option 2d	13,447,976	2,336,675	201,584	15,986,235

Table 9 Analysis of total expenditure for combination of TasWater and groundwater option (Option 3)

Options	Total Capital Cost	Net Present value of Operational Cost	Net Present value of Annual Maintenance Cost	Net Present Value of Total Investment
Option 3	11,157,779	6,843,915	184,810	18,186,504

Table 10 Combined ranking of water supply options based NPVs and CO2-e emissions

Options	NPV of total investment, $	Standardised NPV relative to minimum, s1	% weight of NPV, w1	Total Electrical Energy Consumption by Pumps, KWhr	Total CO2-e emission, tonnes*	Standardised CO2-e emission relative to minimum, s2	% weight of CO2-e emission, w2	Combined ranks for NPV and CO2-e emission, s1*w1 + s2*w2
Option 1a	13900208	1.28	0.11	422010	80.18	1.32	0.1	0.26
Option 1b	17798480	1.64	0.14	529740	100.65	1.65	0.12	0.42
Option 1c	14107001	1.3	0.11	570240	108.35	1.78	0.13	0.37
Option 1d	12928722	1.19	0.1	493240	93.72	1.54	0.11	0.29
Option 2a	10863605	1	0.08	320760	60.94	1	0.07	0.16
Option 2b	11072687	1.02	0.08	372600	70.79	1.16	0.08	0.18
Option 2c	16022167	1.47	0.12	583200	110.81	1.82	0.13	0.42
Option 2d	15986235	1.47	0.12	596160	113.27	1.86	0.13	0.43
Option 3b	18186504	1.67	0.14	256608	103.76**	1.7	0.12	0.44

* emission factors for consumption of purchased electricity in Tasmania = 0.19 kg/KWhr

**292 ML drinking water to be purchased from TasWater (option 3b); Emission factor for consumption of purchased water from Taswater = 0.188 tonnes/ML (UTAS 2016);

The standardisation and % weight approach used for ranking of options has been adopted from Vavríková (2011).

Figures

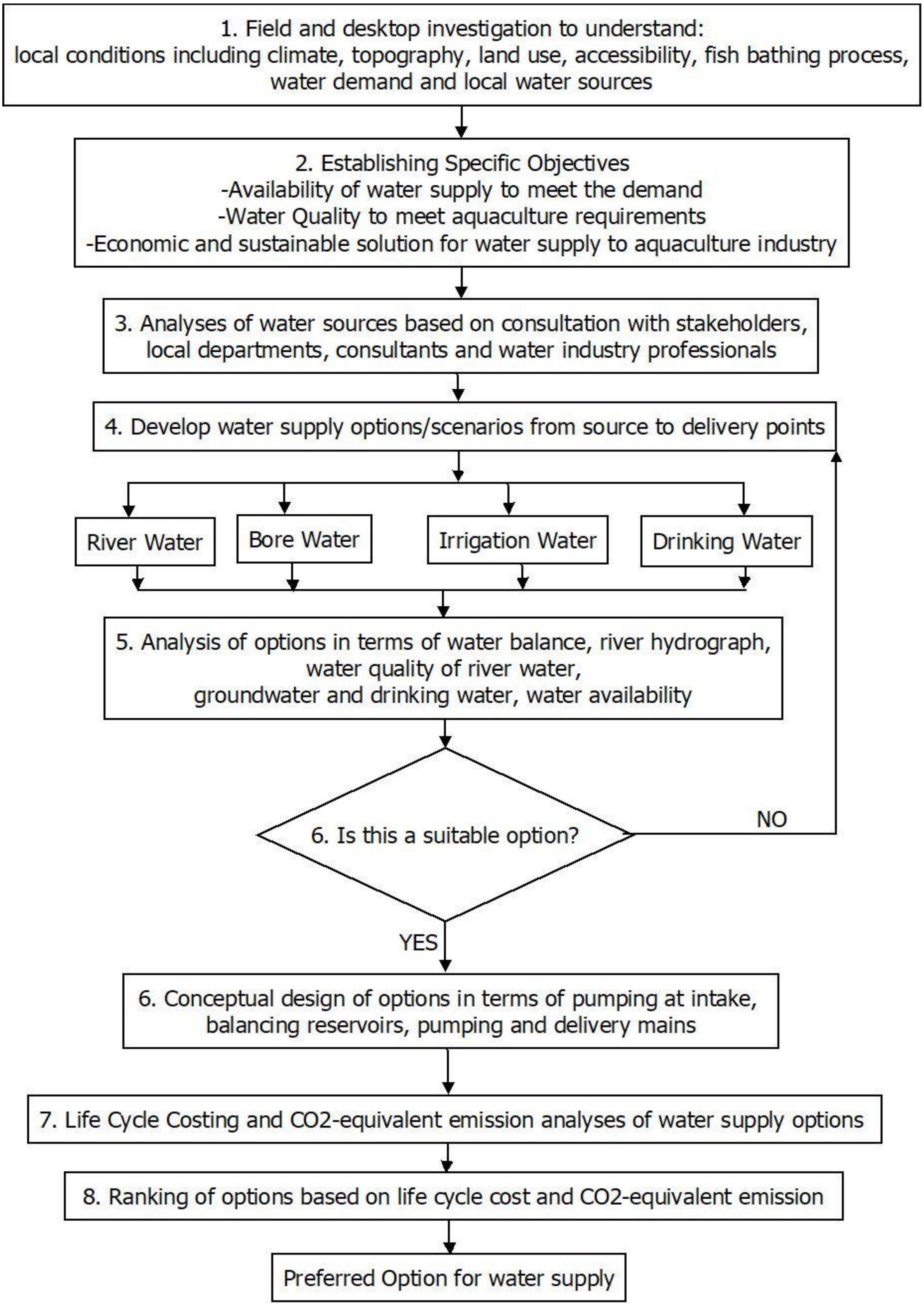

Figure 1 Methodology flow diagram for freshwater sourcing for aquaculture business

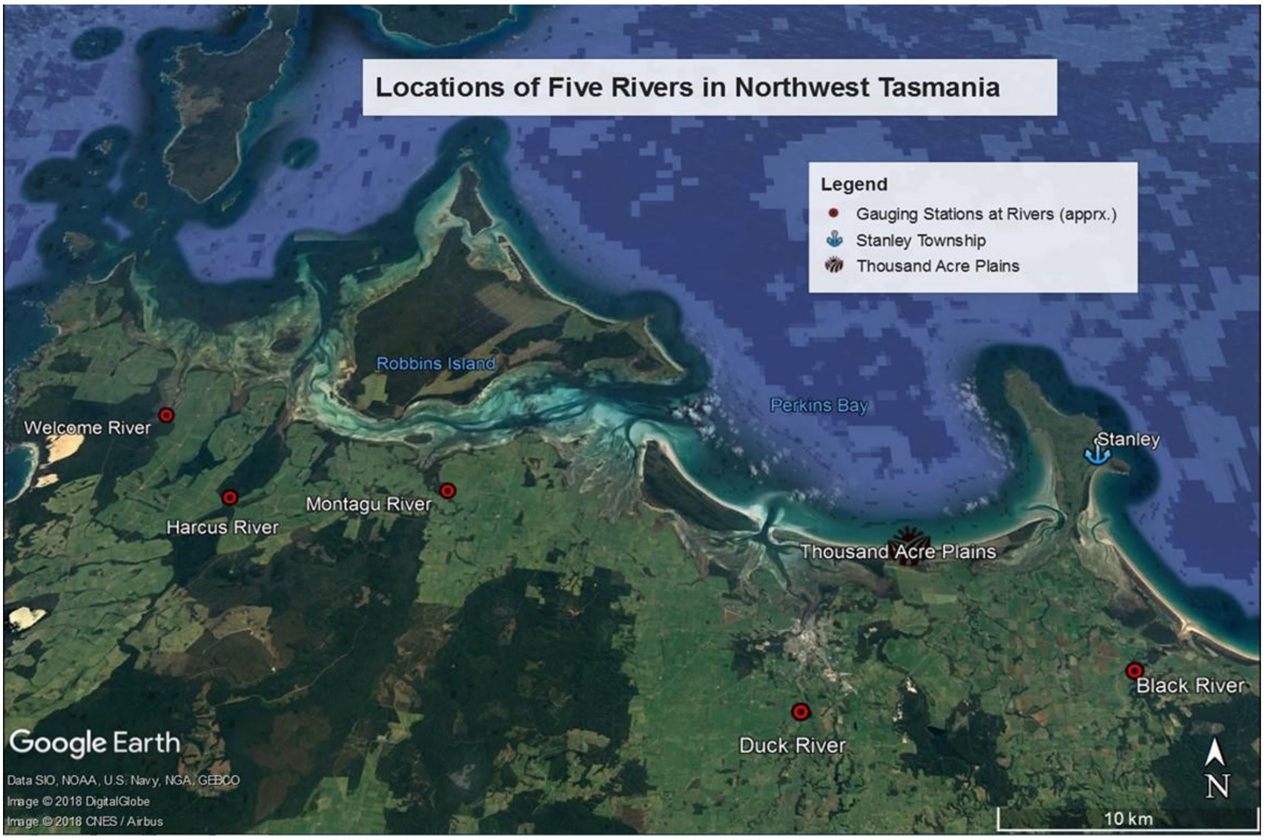

Figure 2: Map of North West Tasmania showing relative locations of gauging stations at five rivers, and the proposed delivery points of water at Thousand Acre Plains and Stanley Township

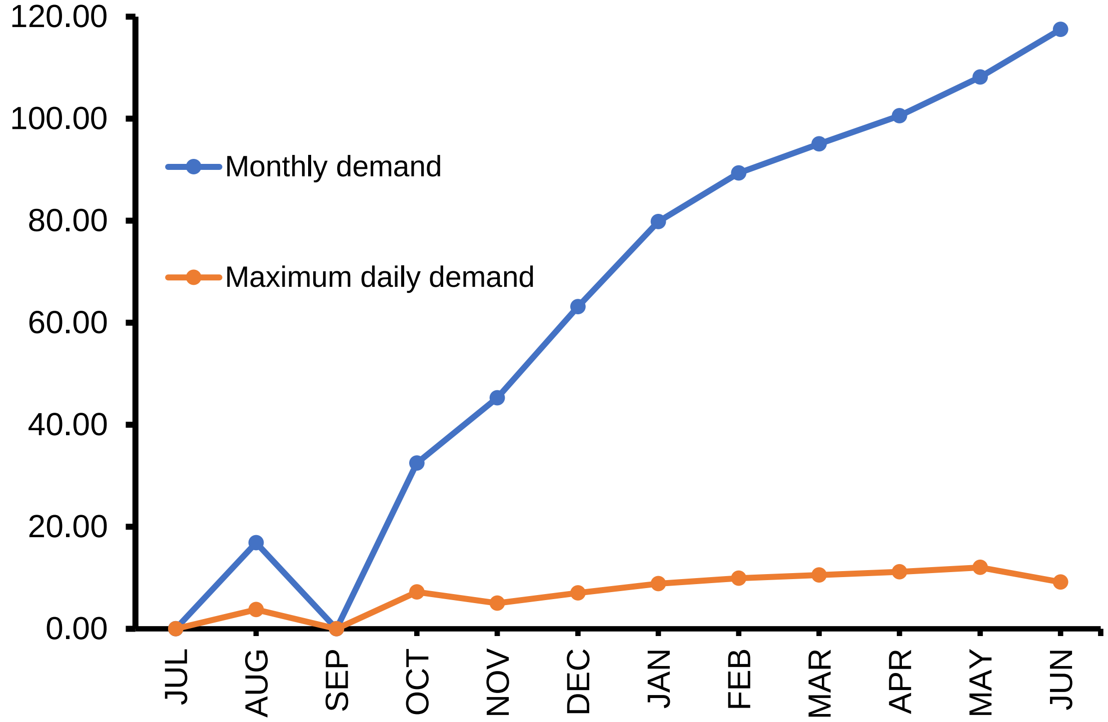

Figure 3 Monthly and daily freshwater demand in liner bathing with monthly and daily demand pattern predicted to repeat on yearly basis (Source: Medium sized aquaculture industry of Tasmania)

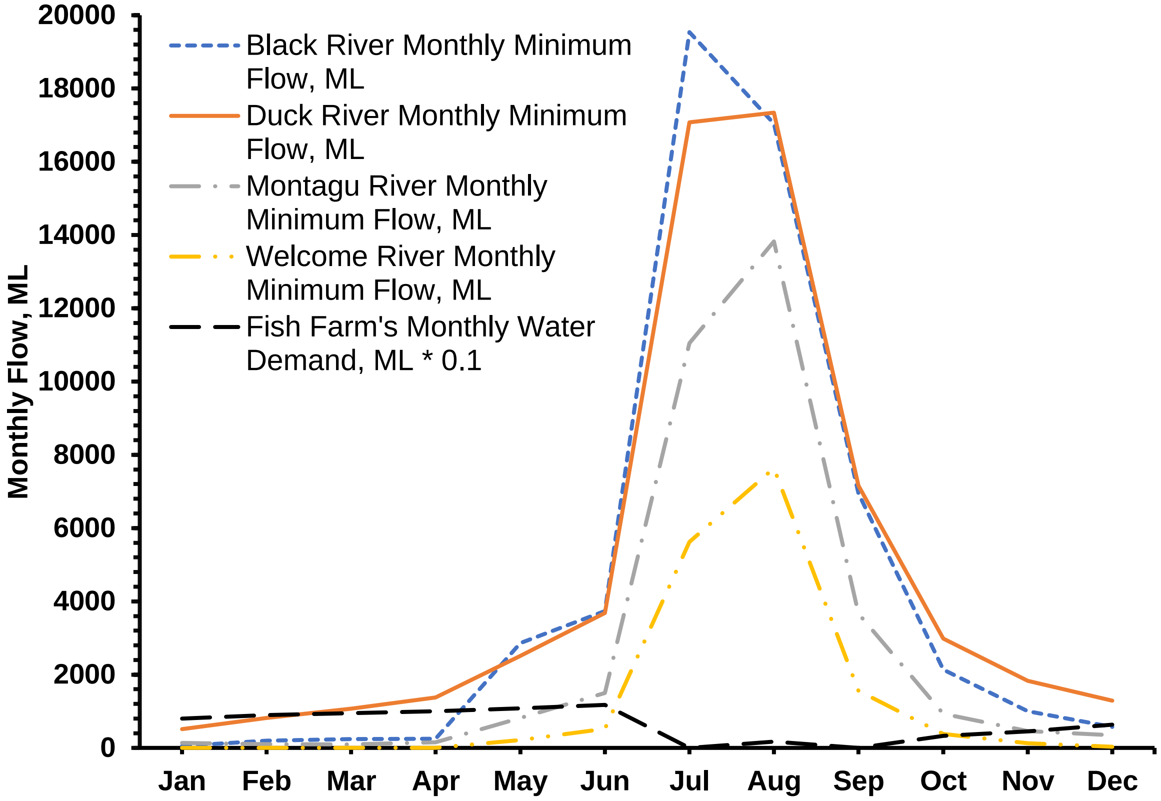

Figure 4: Comparison amongst the minimum monthly flow of the four selected rivers and water demand for fish farming (water demand of the aquaculture industry has been magnified by 10 in the graph); Source of river flow data: BOM (2018)

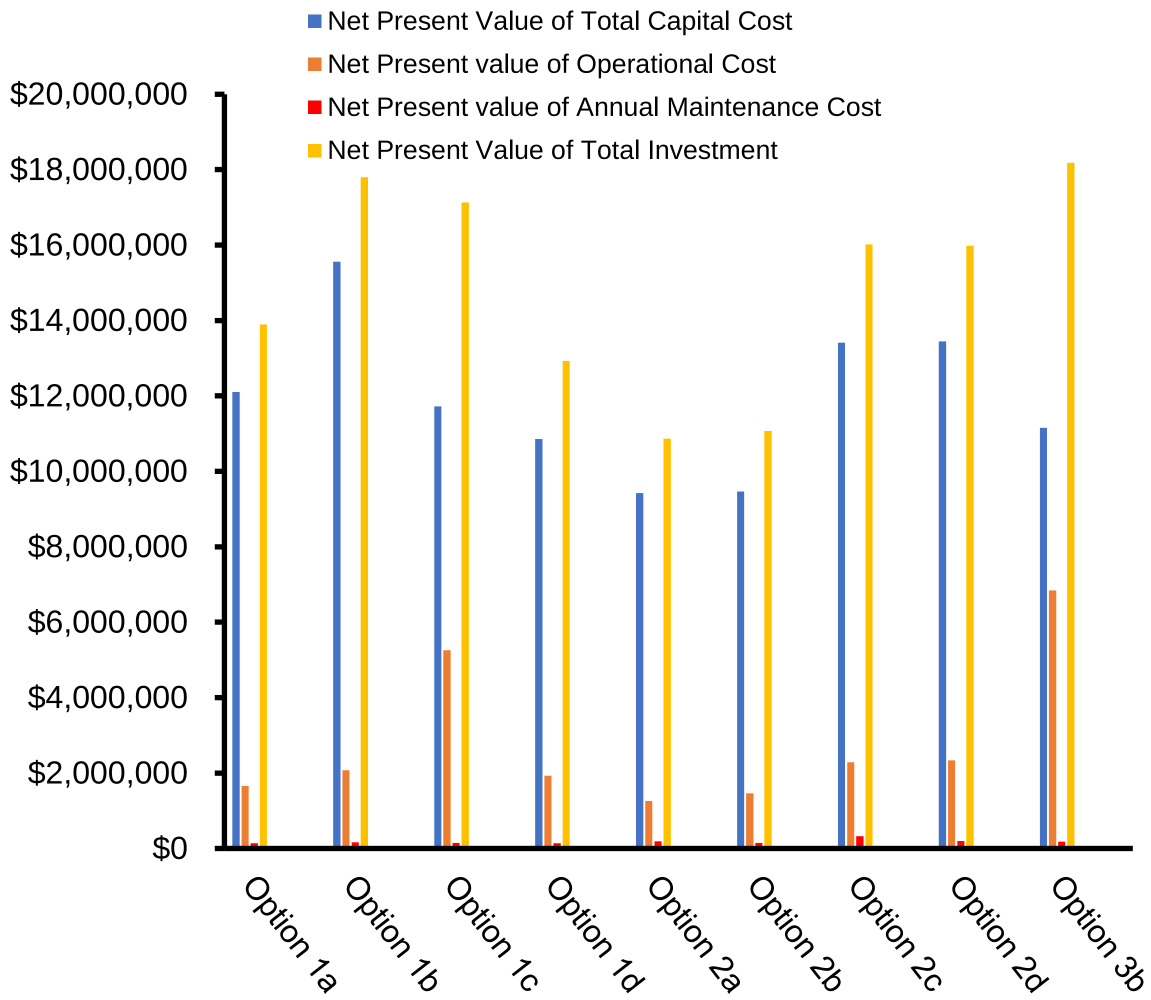

Figure 5 A comparative overview of net present value of investments resulting from extraction of freshwater from rivers (Options 1a-1d), bores (Options 2a-2d) as well as combination of TasWater and bores (Option3b)

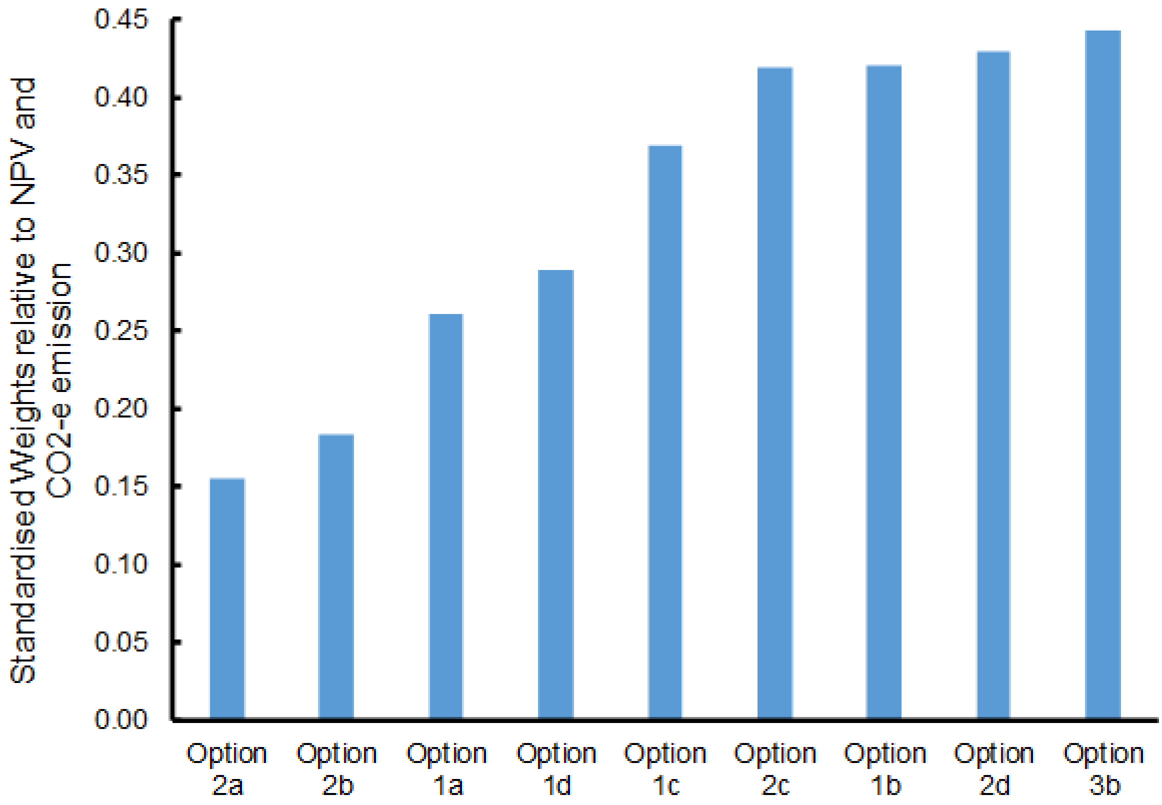

Figure 6 Ranking of options based on minimum NPVs and CO_2-e emission for electrical energy consumption in Tasmania