THE UTILISATION OF GEOTHERMAL SPRING WATER FOR TILAPIA AQUACULTURE TO PROMOTE FOOD SECURITY AND SKILLS DEVELOPMENT AT THE BRANDVLEI CORRECTIONAL SERVICES CENTRE

SA Joao, K Salie, TK Jackson, O Guwa & L Wilson

WATER RESEARCH COMMISSION

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Water Research Commission

by

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EXECUTIVE SUMMARY

One of the major constraints in South African warm-water aquaculture is low water temperatures associated with cold weather and winter months. The extreme cost of heating to raise the water temperature during these times is generally unfeasible; and for this reason, warm-water aquaculture is predominantly confined to one 6-month summer production cycle per year. Geothermal hot springs have thus been proposed as a viable alternative heat source for the support of warm-water aquaculture all year round.

A geothermal hot spring at the Brandvlei Correctional Facility in Worcester in the Western Cape, was identified as the start site for this 12-month project. The spring water at Brandvlei is approximately 60°C and emerges from the ground at 126 L/s and complies with all water drinking standards.

The overall aim of the project was to investigate a suitable method to use the heat from the Brandvlei geothermal spring to support the warm-water aquaculture of Nile tilapia, with focus on renewable energy, and creating food security and skills development opportunities. The specific aims were to firstly develop an appropriate method to harness the geothermal heat to support tilapia aquaculture; to then determine the cost-benefit of utilising geothermal heat for aquaculture; and to also provide a SWOT analysis evaluating the potential use of the test-system for fish production and skills development.

The project involved the design and installation of two separate single-tank recirculating aquaculture systems of 10 000 L each, that individually maintained a water temperature of 28°C for optimum Nile tilapia aquaculture. The 'control' system included a conventional heating method (a heat pump) and was referred to as the HP system; and the 'test' system included a heat exchanger which transferred heat from the Brandvlei geothermal spring to the fish-tank system's water and was referred to as the HX system. A kilowatt meter was included in each system to monitor and compare the electricity usage of the systems separately.

From the power consumption records it was seen that the HX system used significantly less power than the HP system at any given time. Records for monthly power usage for the period from November 2021 to April 2022, showed that the cost savings percentage was as high as 55.7% for the coldest month (April) when comparing the daily power usage for the HX system to that of the HP system.

It was seen that the average monthly power usage of the HP system had a strong negative correlation with the minimum average monthly temperature for Worcester, whereas the power usage for the HX system appeared to be relatively consistent over the months, having only a moderate negative correlation with minimum temperature. The power consumption records and historical temperature records for ambient temperature in Worcester were used in simple linear regression analyses to make predictions for what the systems may have cost to run for the full previous year of 2021. In terms of power usage, predictions indicated that the HX system would use 57.8% less power than the HP system for the full year of 2021. In terms of the average monthly cost for running and heating the 10 000 L systems, it was predicted that for 2021 it would cost between R3 838.50 and R3 423.00 monthly for the HP system and between R1 445.60 and R1 411.25 monthly for the HX system. Depending on the electricity user tariffs, this could be a cost-savings percentage of between 57.8 and 63.2% in favour of the HX system. It is expected that in colder weather or in winter months, the cost savings percentage would be higher to a point, and then the HP system would most likely need insulation to keep temperatures from dropping below 28°C.

Fish were stocked successfully in both systems, however, due to this being a 12-month project, a full growth cycle (±6 months) was not possible within this project's timeframe, but the co-management plan between Stellenbosch University and the Department of Correctional Services was established to ensure continued maintenance of the fish and the system until harvest at ±6 months.

Based on the results, it was concluded that geothermal energy may be a viable solution to producing warm-water fish species all year around feasibly, as long as there is a good management strategy in place. This project provides a system design that can be applied at other hot springs in South Africa, which in turn will promote the development of the aquaculture sector while also creating food security and skills development

opportunities. Besides the cost savings advantage, another major benefit of using a heat exchanger for geothermal aquaculture is that the geothermal water does not come into contact with the water of the aquaculture system. This means that even geothermal hot springs with poor water quality can be used, as it would just be the heat that would be harnessed from these springs.

A limitation that was identified during the project was with regard to the data collection, as the power consumption meters only recorded the total power used for each system each day and did not record at smaller intervals. It was therefore not possible to obtain accurate estimates of running and heating power consumption separately. A recommendation for improvement or for future studies would thus be to either set the meters to record power used for heating only, or to find a power recording programme that would record power usage at minute intervals. Installing a roof or cover over the systems is also recommended to protect the systems and managerial staff from the harsh elements of sun and rain during extreme weather. A remote alarm system would also be useful for notifying the manager and core project members about any system failure on their cell phone, as a delayed response to system issues can result in mass fish mortalities.

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LIST OF ABBREVIATIONS

BC	Before Christ
Bq	Becquerel
°C	Degrees Celsius
Ci	Curie
DB board	Distribution board
DL	Detection limit
DO	Dissolved oxygen
FCR	Feed conversion ratio
FLC	Fuzzy Logic Controller
HP system	Heat pump system
HX system	Heat exchanger system
ME	Mache unit
NTU	Number of transfer units
r	Correlation coefficient
R^2	Coefficient of determination
RAS	Recirculating aquaculture system
RQIS	Resource Quality Information Services
SANS	South African National Standard
SI	Standard international
SWOT	Strengths, weaknesses, opportunities, threats
TBW	Total body weight
TL	Total length
TMG	Table Mountain Group
UV	Ultraviolet

INSTITUTIONS

DAFF	Department of Agriculture, Forestry and Fisheries
DCS	Department of Correctional Services
DPW	Department of Public Works
DWS	Department of Water and Sanitation
SU	Stellenbosch University

CHAPTER 1: LITERATURE REVIEW AND SETTING THE SCENE

1.1. AN OVERVIEW OF GEOTHERMAL ENERGY

Brief description

Geothermal energy is a renewable energy source that is harnessed from the earth's core. This energy is derived from the heat produced during the formation of the planet and the decay of radioactive materials. Once produced this thermal energy is stored in magma or molten rock within the earth's crust, which allows for the surrounding groundwater to be heated. Heating either occurs when shallow bodies of water are formed above the magma or when the circulating water travels through the faults towards the hot rock (Van Nguyen et al., 2015). The heated water obtained from these geothermal sites hold great potential, however, this potential can be limited or increased depending on the chemistry and temperature of the water. The chemistry of the water obtained at these sites is determined by several factors, such as the type of rock, its mineral composition, the composition of rainwater and the temperature of the water (Olivier and Jonker, 2013). Furthermore, it is important to determine the level of dissolved minerals and microbial pathogen content that is present within the water as this test may render a geothermal source toxic for uses such as human consumption or aquaculture (Boyd and Lund, 2003). Geothermal water sources all over the world differ in regard to both chemical and physical characteristics, which is why water testing is imperative to each location prior to utilisation (Olivier et al., 2011). However, the differences between sites are not limited to water chemistry alone but also include the rate of heating, the flow rate, and the discharge of water. In general, a geothermal source with a low flow will have a lower temperature, which is the direct result of heat being lost as the water makes it way from the underground source towards the surface (Diamond and Harris, 2000).

Characteristics of geothermal springs

There are many ways in which geothermal springs are identified around the world, with a spring either being classified as thermal or non-thermal. The classification of a thermal spring varies as there are various national standards which exist. For example, Germany and Britain's standard states that a thermal spring must have a temperature that is higher than 20°C, while Japan and China's standard requires a thermal spring to be higher than 25°C, therefore these values do not conform strictly to a scientific standard (Liao, 2017). However, in South Africa, thermal and non-thermal springs are classified according to Kent (1949), which states that a spring is classified as warm when temperatures range between 25 and 37°C, hyperthermic or hot between 38 and 50°C and scalding when more than 50°C. Although all the springs in South Africa are of meteoric origin, the temperatures across the majority of these geothermal sources have remained constant for over 60 years (Olivier and Jonker, 2013) making this a largely underutilised resource. The geothermal springs located within South Africa are usually located in topographically low areas and are associated with deep geological structures (Olatunde et al., 2015). These geothermal springs are characterized by their temperature, but their potential for industrial and commercial uses largely depend on the chemistry of the water.

The water chemistry of a geothermal spring depends upon the type of rock in which the water is in direct contact with, as well as its mineral composition. The type of rock is purely dependent on the geology of the area in which the geothermal spring is located, thus, certain springs may be exposed to gaseous emissions as a result of the surrounding rock formations. These emissions commonly include carbon dioxide (CO_2), hydrogen sulphide (H_2S), methane (CH_4), sulphur oxide (SO_2) and ammonia (NH_3). This means that geothermal springs require constant monitoring, as these gases can become extremely toxic at high concentrations, having a lethal effect on aquatic life and the surrounding vegetation (Olivier and Jonker, 2013; Van Nguyen et al., 2015). Furthermore, it is not sufficient for these springs to be tested on a once off basis but instead, they should be subjected to constant routine monitoring as the water chemistry can change over time in response to geological changes. This is particularly important for thermal springs because minerals are more soluble within water at high temperatures; thus, increasing the risk of these springs being contaminated with arsenic, mercury, radioactive elements, and bacterial pathogens, which are found to naturally occur within geothermal sources (Olivier et al., 2011; Olivier and Jonker, 2013). These minerals or pathogens, although common, can be detrimental to living organisms, which is why thorough investigations must take place before the source can be determined as suitable for direct or indirect usage in any operation.

Global use of geothermal sources

Geothermal springs have been used for various reasons over the centuries, with the earliest documented use of a spring being recorded in 11000 BC in Japan. Spring water was commonly used over the years for activities such as bathing and the washing of clothes. However, other populations such as the ancient Greeks and Romans recognized the health benefits of the spring water and thus utilised the water in the performance of religious ceremonies and the heating of steam rooms. So, although there is significant archeological evidence supporting the use of these springs for multiple purposes over the centuries, these springs only began to be recognized and valued for their industrial applications in the eighteenth century. This industrial interest first began in Italy with the extraction of boric acid using the steam generated by the geothermal water. However, once this resource gained recognition in both the commercial and industrial industries, the research and investment into these springs significantly increased, with thermal energy being utilised for the generation of electricity in the nineteenth century (Van Nguyen et al., 2015).

Currently, it is estimated that over 73 countries across the globe are making use of a geothermal energy source for various applications (Olivier et al., 2011; Van Nguyen et al., 2015), with 24 utilising this source specifically in the generation of electricity (FAO, 2016). At present, the most widely utilised application of geothermal energy is its direct use in heat pumps to regulate the indoor temperature of buildings. This is closely followed by domestic applications which include the use of geothermal waters for swimming pools and spas; as well as for air space heating, an application which is more prominent in greenhouses (Van Nguyen et al., 2015; Towler, 2014). Due to the versatile application of spring water, interest has been steadily growing, particularly with regard to the use of geothermal water in agriculture. Although this resource has yet to be effectively utilised worldwide, there are a number of countries across the world who are already investing in this resource. China is currently using this water to irrigate rice fields, while other countries such as Iceland, North America, New Zealand, and Macedonia, have used these geothermal sources to heat greenhouses while simultaneously irrigating the soil for the production of both vegetables and flowers. More recently, however, the water from these springs is being used in aquaculture for rearing warm water aquatic species in countries with either unstable or cooler climates (Van Nguyen et al., 2015).

1.2. GEOTHERMAL ENERGY IN AGRICULTURE

Greenhouses, food drying, hydroponics, and aquaponics

Geothermal energy has been utilised in several agricultural sectors around the world, ranging from greenhouses, hydroponics, aquaponics, and the drying of agricultural products. Due to the current cost of electricity and fuel in South Africa, there has been a great shift towards the use of renewable energy sources. Thus, geothermal energy could be a lucrative option for the agricultural sector (Olivier and Jonker, 2013). This is because geothermal energy sources consist of temperatures ranging from 20 to 150°C making it a suitable option for heating, cooling, spas, greenhouses, aquaculture, and other industrial processes. These processes, when compared to the traditional utilisation of electricity or fuel, are both an energy saver and more cost effective (Van Nguyen et al., 2015). However, these are not the only benefits of geothermal energy. The excess steam and hot water can be utilised in the drying of agricultural products, which not only reduces waste but preserves the products for an extended period. This process of drying, using hot water or steam, is currently being used in countries like Greece, Thailand, Macedonia, Mexico, North America, Indonesia, and Kenya to dry agricultural products such as rice, wheat, tomatoes, fruit, beans, grains, onions, garlic, chilies, and cotton (Van Nguyen et al., 2015).

The utilisation of geothermal energy for the heating of greenhouses is an application which is being used across 34 different countries, making it one of the most common uses for this energy in the agricultural sector (Lund et al., 2010). Greenhouses are of great value to farmers as they allow farmers to control the conditions in which their crops are grown, thus not only increasing the performance and yields of crops but also protecting them from external threats such as pests and extreme weather conditions (Olivier and Jonker, 2013). Greenhouse agriculture enables fruits, flowers and vegetables which are native to warmer climates, to be grown in colder climates such as Norway; thus allowing for a variety of produce to be locally produced all year-round. Geothermal energy in combination with greenhouse agriculture will assist in decreasing both energy and operating costs, as well as improving the hygiene of these greenhouses. This is because the geothermal heating of greenhouses reduces the humidity levels thus helping to prevent condensation and lowering the occurrence of fungal infections in the plants, while simultaneously providing clean water and air (Van Nguyen et al., 2015). Yet, despite all these listed benefits, only two African countries, Kenya, and Tunisia, are currently making use of this energy source to heat their agricultural greenhouses. Kenya is focusing this energy on the production of flowers; while Tunisia is focusing on the production of fruit and vegetables such as cucumbers, tomatoes, melons, and peppers (Olivier and Jonker, 2013).

Even though countries tend to focus on the crop production sector when utilising geothermal energy, it is not the only sector making use of this energy source for heating. Presently the aquaculture sector claims approximately 3.37% of the worldwide geothermal heating capacity (Lund and Boyd, 2016). However, most of these aquaculture production systems, for which heat is being used, are not recirculating aquaculture systems (RAS) but are rather outdoor ponds and raceways. It is, however, important to note that when comparing all three systems, the indoor RAS design offers a much higher degree of control over fish production processes, as all steps can be monitored and adapted throughout the cycle. RAS set-ups are also found to effectively reduce water- and land usage, while minimizing the impact of an aquaculture system on the environment with regard to issues such as eutrophication (Timmons et al., 2018). Currently, geothermally heated RAS set-ups are virtually non-existent in Africa and therefore require further investigation, as there is great economic potential for this underutilised resource in South Africa.

Algae

Fish are not the only aquatic organisms that can be cultivated using geothermal energy. Other organisms, such as algae, have shown remarkable success in similar geothermal culture systems. Algae is of great economic importance as it is grown for a variety of commercial applications such as biofuels, cosmetics, pharmaceutical products, and food. These economically important species, which are cultivated for commercial use, include *Isochrysis*, *Chaetoceros*, *Dunaliella,* and *Arthrospira* (Spirulina) (Olivier and Jonker, 2013). Though, the most common algae type that is grown using geothermal energy is Spirulina, as it has an optimum temperature of between 35 and 37°C. Spirulina has shown to be a resilient algal species, as it thrives under high temperature and alkaline conditions, often being grown in shallow ponds that use paddle wheels for mixing the culture (Van Nguyen et al., 2015). These characteristics make it suitable for large scale cultivation.

Spirulina provides many medical benefits, which can be used in the treatment of high cholesterol, hyperlipidemia, and various cancers. These benefits are as a result of spirulina's unique composition, which consists of approximately 60% protein, numerous essential vitamins, high concentrations of ß-carotene, and fatty acids (Khan et al., 2005; Campanella et al., 2002), making this a lucrative organism for cultivation. However, the viability of this species for cultivation is hindered by the high costs of production, which can be largely attributed to the high temperatures, and thus high energy inputs, that are required for optimal growth. Energy costs can, however, be reduced or ultimately avoided through the use of geothermal energy sources, as the water from these sources will be able to maintain consistently high temperatures throughout the year (Olivier and Jonker, 2013). There are at present, three countries growing this species for commercial use; Limpopo in South Africa, California in the United Stated, and Bulgaria. The production and cultivation of this organism in both Limpopo and California is interrupted during the winter months, as the temperatures decline far below optimal levels. This is not the case for Bulgaria, however, as this country is able to maintain the necessary temperatures through their use of geothermal energy, which has not only allowed for year-round production but has also increased production whilst effectively decreasing production costs (Olivier and Jonker, 2013).

1.3. GEOTHERMAL ENERGY IN AQUACULTURE

The benefits

Over the years there has been a shift towards aquaculture as the primary producer of seafood. This shift has largely been in response to the declining wild stock populations. Aquaculture utilises a controlled environment to rear aquatic species in an effort to optimize productivity, to try and meet the ever-increasing demand for seafood (FAO, 2016). Currently, it is approximated that nearly half of all seafood that is being consumed worldwide is in fact cultured organisms which have been produced at aquaculture facilities. This makes aquaculture production a vital necessity in many developing countries where fish and other aquaculture products serve as the main source of protein for many underprivileged families. Fish as a food product therefore needs to be readily available at an affordable cost, as it not only forms part of many individuals' staple diet, but also serves as a great source of essential amino acids which greatly assists developing countries in their aim to combat malnutrition. Cultured fish products compete directly with poultry and livestock products, as the latter are often readily available and cost effective. However, aquaculture species are more efficient in converting food into body tissue, making it the most beneficial protein source (Liao, 1988). This is why it would be beneficial for countries to invest in aquaculture production, as this will not only assist a country financially but will also provide a healthy and high-protein food source to its population.

Although aquaculture production is of great value there are still many factors that need to be optimized in order to effectively utilise these systems, particularly factors affecting the growth and well-being of the fish during the production cycle. Two of the most important parameters in the production of aquatic species are temperature and dissolved oxygen levels. This is because these factors have the potential to significantly impact the feeding, growth, reproduction, and disease control of the aquatic species (Gharibi and Abbaspour-Gilandeh, 2019). Of these two parameters, water temperature is the most difficult to control as it is influenced by the prevailing environmental conditions. This limits the number of suitable candidate species that can be cultured in a particular environment, particularly species that are poikilothermic, as the performance of these species is directly linked to the surrounding temperatures. Therefore, in order for aquaculture to be a viable method for seafood production, it is important to have a means of maintaining temperatures within the optimum range for production (Ragnarsson, 2014). Although temperature appears to be a simple parameter to maintain and control, it is often hindered by financial implications in terms of the cost required to build the infrastructure that is necessary to implement and control the heating or cooling of the water (DAFF, 2018b). However, these costs could be reduced significantly if heat from a geothermal energy source was utilised, which in turn would make warm-water aquaculture a more viable option for South Africa. Currently, there are 22 countries across the world which are utilising geothermal energy for the heating of both aquaculture raceways and outdoor ponds; while its use in RAS set-ups is less frequent, usually because it is more complex and costly to set up (Lund and Boyd 2016; Lund and Toth, 2021).

In the aquaculture industry, the use of geothermal energy sources is appealing as it allows fish to be farmed throughout the year at optimal temperatures, creating the optimal environment for faster growth and allowing for shortened production cycles (Ragnarsson, 2014). Studies have shown that for warm-water species such as tilapia, and cold-water species such as salmon and trout, controlling the rearing temperatures can increase the growth rate of the fish by 50 to 100% which will successfully increase the number of harvests that can be carried out each year thus increasing farm profits (Lund, 2011; Ragnarsson, 2014). This is because unlike livestock animals, which can survive over a large temperature range, the growth rate of most aquatic species is severely affected when their environmental water temperature varies beyond a narrow species-specific range. One of the largest benefits of utilising geothermal water is that geothermal springs remain at a relatively constant temperature throughout the year, which is why aquaculture operations, such as that described by Gelengenis et al. (2006), have switched to using geothermal wells to prevent sudden drops in temperature occurring in their outdoor ponds. A decrease in temperature can have a negative effect on fish metabolism causing fish to lose interest in feeding (Johnson, 1981), with major deviations from the optimum range leading to fish mortalities which could ultimately bankrupt a small-scale farm. The use of geothermal energy in an aquaculture system can thus help to stabilize and support production in an aquatic environment, while offering a cheap alternative heat source to that which would otherwise be very costly i.e., by using electricity and fossil fuels.

Another study by Farghally et al. (2014), investigated the use of geothermal energy in aquaculture systems by simulating a design of a RAS set-up for catfish, using geothermal energy as a source for heating the water. This particular design was set up to completely automated, software was used to calculate heat losses, a heat exchanger was included to transfer heat from the geothermal water to the fish system, and different controllers were investigated to keep track of and maintain an optimal water temperature. It was found that the Fuzzy Logic controller had the best performance in comparison to the other two controllers as it the best at keeping the water at the desired temperature.

While other studies, such as the study by GharibiAsl and Abbaspour-Gilandeh (2019), used geothermal water directly in the farming of trout in aquaculture raceways. Although trout are a cold-water species, the environmental temperatures in the cold months at the study's site dropped the raceway temperatures to below optimal (<12°C). Geothermal waters were thus mixed directly with the water of selected raceways, to bring the temperature back up to optimal. The advantage of adding the geothermal water directly to the raceways means that time is not wasted with a heat exchange process.

All of these studies have shown the potential that geothermal energy has in aquaculture, however, in South Africa, aquaculture is still a small and underdeveloped sector with large potential for growth. One of the main limitations for South African aquaculture is the climate, as certain parts of the country have cooler climatic conditions with warm summer months (Gauteng and Free State); while others offer a more tropical climate with cooler winter months (Limpopo and Northern KwaZulu-Natal). This type of climate means that there are limitations to the type of species that can be farmed within South Africa; limitations that can be overcome if the water in these systems is heated or cooled to meet the required needs of the desired culture species during months that are not optimal in temperature.

Desired warm water species, such as tilapia and catfish, have been farmed with success during the summer months in South Africa in regions with a more tropical climate, and there is thus great potential to extend the production period for areas with access to a geothermal water resource. These two species have been identified as desirable for cultivation due to unique biological characteristics that they possess (Adeleke et al., 2020; Clark, 2019; Hecht et al., 1988). Furthermore, these are emerging species in South Africa and are both economically and commercially important, not only for South Africa but for Africa as a whole (DAFF, 2018a; DAFF, 2018b).

A study: Geothermal aquaculture with catfish

A study that was performed in 2014 by Farghally et al. focused on the rearing of catfish using geothermal water in Umm Huweitat, a small mining town located on the Red Sea in Egypt. Using RAS and geothermal water to heat and maintain the systems at optimal temperatures, catfish were reared at high densities, under controlled conditions. The water used for this study was obtained from a geothermal well which had a constant temperature of 70°C with a flow rate of 0.12 L/s. Although the water from the well was not used directly in the tanks, it was used for heating by means of a heat exchanger. For this to work, the geothermal water was pumped through one side of a heat exchanger and then back through into a re-injection well. There was then a secondary side of the heat exchanger which contained fresh water that was then circulated through the heat exchanger before being pumped into the tank system at a temperature of 50°C, mixing with the cooler water in the tank to obtain the desired temperature. This system chose to utilise a heat exchange method in an effort to prevent the water from the geothermal source mixing with the water in the rearing tank. The reason for this is that the geothermal water may not have been tested and therefore may not be suitable for the purpose of rearing fish. Alternatively, the water may have been tested but was deemed unsuitable for this particular purpose, thus a heat exchange method was employed.

The system was managed using the Geo-heat center software which was developed specifically for the use of geothermal water. One of the tools within this software package (HEATOOLS) was used to calculate the inevitable heat loss experienced by the indoor tanks. This calculation was performed using evaporative, convective, and radiant models. For this study, the system calculations assumed that it was dealing with an indoor pool or tank, meaning that evaporation and convective losses were driven by the natural convection of the air. However, for the system to operate effectively and correctly, and to calculate the necessary values, the following input data was required: the temperature of the geothermal fluid, the water temperature of the tank, the temperature of the air inside the building, the tank surface area, and the relative humidity inside the building containing the tank.

Heat exchangers are useful devices which are used to transfer heat between two or more fluid streams of different temperatures. These devices can be utilised using either direct or indirect contact, with indirect contact using plate walls to separate the hot and cold fluids to prevent any mixing. This form of heat exchange occurs between the plate wall interfaces. Direct contact heat exchangers are more accurate as they are able to harness more of the heat, usually through mass transfer, to reach the desired temperatures. Before a heat exchanger can be effectively used within a system, its performance needs to be predicted in order to determine the amount of heat loss that will occur to the surrounding environment. In this study, the epsilon-NTU (number of transfer units) method was used to make this prediction and they found that the FLC (Fuzzy Logic Controller) was the best controller to ensure that a temperature of 29°C was maintained in a RAS for the growth of catfish.

A study: Geothermal aquaculture with tilapia

A semi-intensive aquaculture study was conducted in 2015 in the semi-arid region of Mexico by Arredondo-Figueroa. This aquaculture operation took place in a pond that was 70 × 70 m, had a maximum depth of 4 m and covered an area of 4900 m^2. This pond had a maximum water volume of 14 700 m^3, with a minimum of approximately 6 480 m^3, with the water being supplied from three geothermal wells which were connected by 6'' hydraulic PVC tubes. The flow rate of each well was recorded at 769, 383 and 690 L/minute, respectively. The water obtained from these wells was directly injected into the ponds at temperatures of 35, 30 and 29°C throughout the year. The temperature and water quality of these wells made them optimal for aquaculture as the water could be used as-is, and no heat exchange system was necessary. Once these geothermal sources were declared suitable for the cultivation of fish, water quality parameters were measured once a week; except for the dissolved oxygen, salinity, conductivity, and specific conductivity, which was measured every five days during the study.

In total 10,000 Nile tilapia fingerlings, with an average weight of 3.0±0.5 g and an average length of 2.5±1.5 cm, were introduced into the pond. These fingerlings were not fed any artificial feed during the first four months of this study, they were instead left to feed on the naturally occurring microorganisms found within the pond. However, during the fifth and sixth month, the fingerlings were fed a 1.5 mm artificial feed containing 44% protein, with feed amounts calculated at 2% of the total body weight. Finally, in the seventh month, the fingerlings were fed a 3.5 mm artificial feed with 32% protein. The reason for the differing protein level content and the overall decrease in protein fed to these fingerlings over the course of this study is because the crude protein requirement for fish growth declines with the individual ontogenesis, which means that the dietary protein requirements decrease with the increase of the fishes' body size (Ye et al., 2016).

Biometric analysis was conducted over the production cycle of the fish. This was done by collecting 40 samples in which each individual's total length (TL) and total body weight (TBW) were measured. The growth performance indicators were also able to be calculated using the following information: initial body weight, final body weight, weight gain, daily weight gain, initial and final total length, gain of total length, daily gain of total length, specific growth rate, total consumption of feed, conditioning factor, feed conversion, and survival. Once obtaining this data, Excel was used to calculate and summarize the mean, standard deviation, and coefficient of variation. After 10 months in the pond the fingerlings were able to reach a commercial size, with a mean total body weight of 360 g. These fish were then harvested once a week, taking a total of 50 kg of fish per harvest, producing a total of three metric tons. Although this study was successful in achieving its aims, further research is still required to improve upon the system and growth rates so as to increase production.

1.4. GEOTHERMAL SPRINGS AND SOUTH AFRICA

According to Olivier et al. (2011) South Africa has over 90 thermal springs across the country with temperatures ranging from 25-67.5°C. However, Tshibalo et al. (2015) only managed to record 87 thermal springs falling within a similar temperature range (25-67.5°C). This discrepancy observed between these studies can be attributed to the fact that some of the springs have dried up due to drilling operations and the excessive pumping of water. Furthermore, it is likely that not all of the springs have been accounted for as some of the geothermal springs may be situated on privately owned land and are therefore not accessible, thus are yet to be accounted for (Olivier and Jonker, 2013). At this stage, South Africa is not using the available geothermal energy resources to their fullest potential as this source of energy has only recently started being investigated and considered as a viable option. This is largely due to the lack of research and financial investment available to South Africa for this alternative energy source (Olivier et al., 2011; Tshibalo et al., 2015). This is, however, starting to change, as South Africa is currently the country which has the highest level of carbon emission within Africa. Therefore, the use of an alternative energy source, such as geothermal energy, would significantly benefit the country by decreasing the carbon footprint (Dhansay et al., 2014; Tshibalo et al., 2015).

Currently in South Africa, geothermal water sources are only being utilised in resorts for leisure and tourism. Such examples include Amanzimtaba in Mpumalanga and Die Oog in the Western Cape. There is, however, a small number of areas that are bottling the water from the spring for therapeutic uses. Natural spring water has shown to contain multiple minerals while simultaneously having a balanced microbial content which provides multiple health benefits, such as assisting in the maintenance of overall gut health and skin care (Quattrini et al., 2016). So, although this energy source has been utilised in these niche, lucrative markets, geothermal energy is still not being utilised effectively in South Africa even though it has the potential to be one of the most important resources for the generation of a renewable electricity supply (Van Nguyen et al., 2014). The method of using geothermal energy for generating electricity is currently being implemented in 24 countries across the world, but studies have shown that the cost of this type of generation is still high in comparison to the traditional methods which use fossil fuels such as coal (Dhansay et al, 2014). Geothermal energy is, however, anticipated to become a more viable option in the coming years, while the government adjusts and makes provisions to lower the country's carbon footprint and find alternative energy sources (Olivier and Jonker, 2013).

Geothermal energy has shown to be a viable alternative energy source, with other African countries such as Kenya and Tunisia, demonstrating the potential that geothermal energy has to provide long-term reliable energy, particularly in the agricultural sector. So, despite the current obstacles South Africa is facing financially, this move towards a renewable energy supply can be made possible through government intervention with investment being made into the development of geothermal energy systems. Additionally, government policies and legislation along with the right institutional framework and co-ordination can contribute to the successful exploration and utilisation of geothermal energy resources (Van Nguyen et al., 2015).

Overview of geographic distribution and structural geology

In 2014, a study performed by Dhansay et al. reported that South Africa is underlain by the Kaapvaal Craton, a craton which comprises of some of the oldest rocks found on Earth. This craton and its surrounding crust form an insulation-like layer which deflects most of the heat given off by the underlying convective mantle and moves it towards the mantle lithosphere (<120 km). This unique geological profile is the reason why South Africa has low geothermal gradients, with some parts of South Africa having temperatures as low as 100-200°C at depths of approximately 2-3 km. Geothermal energy associated with volcanic activity can cause temperature ranges of anywhere between 200-300°C, however, because South Africa’s is considered to be tectonically stable with no evidence of volcanic activity, all the geothermal springs in this country are of meteoric origin (Tshibalo et al., 2015). Thus, the geothermal springs found in South Africa will only be located in regions which have a high annual rainfall, exceeding a minimum of 254 mm (Olivier and Jonker, 2013).

Geothermal springs that do not originate from volcanic activity are usually the result of faults within the Earth’s crust. These faults allow water to filter deep into the earth crust where it is heated by the surrounding rock formations (Olivier and Jonker, 2013). This means that the majority of South Africa’s geothermal springs only have the potential for low to medium energy. There are, however, certain parts of the country that have being identified as having potential for high energy production from geothermal heat (200-300°C). These high energy regions, which include Upington, Namaqualand, the northern sector of KwaZulu-Natal and more recently, Tshipise in Limpopo, and Brandvlei in the Western Cape, consist of hot dry rock systems that occur within granites or sedimentary basins (Tshibalo et al., 2015).

In total, South Africa has identified 75 geothermal springs, these springs are mainly found to occur within a 400 km band that spans from the Western Cape to KwaZulu-Natal, the Free State, Gauteng and Limpopo (Kent, 1952). Of the 75 geothermal springs located within South Africa, 28 are located in the Limpopo Province, 14 in the Western Cape, 13 in Mpumalanga, 10 in the Eastern Cape, 5 in KwaZulu-Natal, 4 in Free State, and 1 in the Northern Cape (Olivier and Jonker, 2013). The location and temperature of springs in South Africa can be seen in Figure 1.4.1.

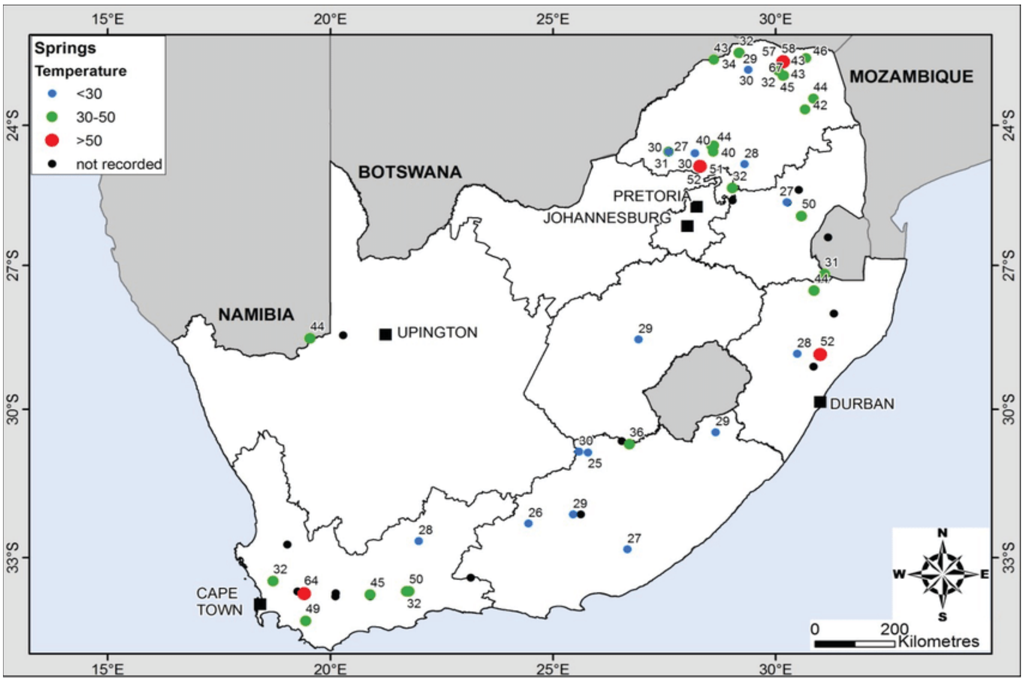


Figure 1.4.1 Location and temperature of Springs in South Africa (Tshibalo et al., 2015)

Springs that meet aquaculture requirements in South Africa

According to the water quality tests performed by Olivier and Jonker (2013), there are only a few geothermal springs that meet the minimum requirements for direct use within an aquaculture system, specifically for warm-water aquaculture. These water sources include, Brandvlei (Western Cape), Badsfontein, Florisbad, Baden Baden (Free State), and Riemvasmaak (Northern Cape). Despite the low number that are available for direct use, the remaining geothermal water sources can still be utilised indirectly for aquaculture applications, such as heating. Indirect methods do not allow spring water to directly come into contact with fish and will therefore minimize the risk of detrimental side effects that could be associated with impure or poor-quality water.

Although, only a few sites have been identified as suitable for the direct use in aquaculture, there have been a number of case studies that have been conducted at other locations in South Africa, to investigate other potential applications for these water sources. The first case study was conducted in Sagol, a site located in the north-eastern Limpopo Province by Olivier and Jonker (2013). This geothermal spring was found to have a temperature of 46°C, with a flow rate of 7 L/s, making it an ideal location for tourism due to the naturally warmer climate and the sites close proximity to the Kruger National Park, which brings in thousands of tourists each year. Sagole has already been used in an attempt to create a spa resort, with this resource being utilised for thermal pools; however, due to mismanagement, this facility has been left in disarray (Olivier and Jonker, 2013).

The Sagole spring has good quality water with mineral properties which can be of great benefit to the rural community and the traditional healers of the area. These benefits come from the high lithium levels found in this water source, a mineral which is known to alleviate depression; thus, this water source could potentially facilitate in the treatment of mental health. With this knowledge in mind, it was proposed that Sagole could be developed into an African Health and Wellness retreat (Olivier and Jonker, 2013). However, should the water not be directly used, the heat could still be harnessed and utilised in winter for space heating and the small-scale production of fruit and vegetables in greenhouses (1st tier). This water could then be reused once exiting the greenhouse systems to assist in the heating of aquaculture ponds for the cultivation of fish and algae (2nd tier). Once the heat of the water has been harnessed in both tier 1 and 2, it should be at a moderate temperature which can then be used for small-scale mineral extraction of B, Sr and Ti (3rd tier). The 4th tier would then be the final tier which will only be possible if the pH of the water remained neutral following mineral extraction. This tier would use the water for domestic uses such as bathing, sanitation, cleaning and washing. At present the community is not utilising the water from this geothermal spring and would thus not be affected by the commercial use of this water but would rather benefit from the opportunities created from this tier cascade in terms of employment and economic growth.

The second case study performed was also done in the Limpopo Province, at Siloam and Mphephu. These two water sources are only a kilometer apart but differ quite significantly. The first site, Siloam, was determined to have a temperature of 71°C with a flow rate of 1 L/s, when measured in 2012. At present, the community makes use of this spring water for domestic uses which include cleaning and food preparation. To effectively utilise this water source for commercial purposes, further drilling would be necessary to obtain higher volumes of water, as the current volume of the spring would be unsustainable long term. The second site, Mphephu, is a thermal spring which has two openings. The first opening has been recorded to have a temperature of 44°C and a flow rate of 6 L/s, however this site is currently located within a resort. The second opening has yet to be commercialized, as it is not well developed, with the locals currently using this site for bathing. Despite the lack of commercialization at this second opening, it does hold great economic potential, as the Mphephu thermal spring is surrounded by many tourist attractions.

Both sites were identified as having great economic potential. For Siloam, a geothermal cascade of heat- and water-use activities was proposed, where the 1st tier would only harness the heat from the spring; heat which could be used for commercial purposes such as electricity production, distillation, pasteurization, and crop drying. Other uses for this heat could include space cooling which can be implemented using either a heat exchange or geo-refrigeration method. Utilisation of geothermal heat for practices such as distillation could be of great value for the province of Limpopo, particularly because the liqueurs produced from the indigenous fruits such mangosteen, Kei apple, sandpaper raisin, and stem fruit have undergone consumer surveys, showing great market potential. Other processes such as pasteurization and crop drying could also provide a number of business opportunities for the Limpopo province, especially as they have a large number of goat farmers and goat cheese is a highly priced commodity. The 2nd tier would then focus on using the water directly for the production of spirulina, a commercially important alga, as the water will have cooled substantially following the heat exchange methods used in the previous tier. Despite all these opportunities and proposed developments for geothermal springs, Brandvlei geothermal spring has yet to be investigated and considered for such developments.

Challenges to geothermal use in South Africa

Geothermal energy in South Africa remains a severely underutilised resource, as many geothermal springs have yet to be investigated. However, this is not the case for all African countries, Kenya has in fact been identified as one of the most successful countries in terms of geothermal energy use with regard to generation of electricity and other commercial applications. This success can be directly attributed to the Kenyan government's approval of several acts in parliament to regulate geothermal water uses. This is because the Kenyan government intends to develop geothermal energy use by signing international treaties and conventions with the United Nations Framework Convention on Climate Change; the Convention on Biological Diversity; and the Ramsar Convention on Wetlands of International Importance (Van Nguyen et al., 2015).

Much like Kenya has done, South Africa could significantly benefit from legislation regarding the use of geothermal water, as this could greatly assist in the development of these renewable energy sources. In terms of policy and regulation, South Africa, like many other developing countries, does not have well-defined policies or budgetary allocations for this sector, thus hindering any sort of advancements or developments being made in this sector.

The lack of financial resources which are required to establish geothermal projects, remains a limiting factor in many countries which is why it is important for government to get involved during the initial phases of exploration and development of geothermal resources (Van Nguyen et al., 2015). Government or local investment in the initial phases of such ventures, can create opportunities for private or foreign investors, which will encourage increased interest in the use of geothermal resources for commercial production in South Africa, thereby assisting in the economic development of the country.

1.5. THE BRANDVLEI GEOTHERMAL SPRING

Currently, there have been over 90 thermal springs identified in South Africa, with a study by Olivier and Jonker (2013) indicating, after testing numerous parameters, that 52 springs were suitable for aquaculture development. Although this potential has been expressed, thermal springs in South Africa have yet to be utilised for aquaculture purposes.

The Brandvlei thermal spring has been identified as a suitable starting site for a thermal water aquaculture pilot study. When tested, Olivier and Jonker (2013) found that this spring complied with SANS drinking water standards and was thus fit for recreational use and consumption. This water is thus safe to use, with a constant high temperature and fast flow rate, which will be ideal for the culture of warm water fish, all year round.

Spring location and current use

The Brandvlei geothermal spring is located at 33°43'57.3"S and 19°24'48.2"E on the grounds of the Brandvlei Correctional Facility, approximately 14 km from Rawsonville and 19 km from Worcester, in the Western Cape, South Africa (Figure 1.5.1).

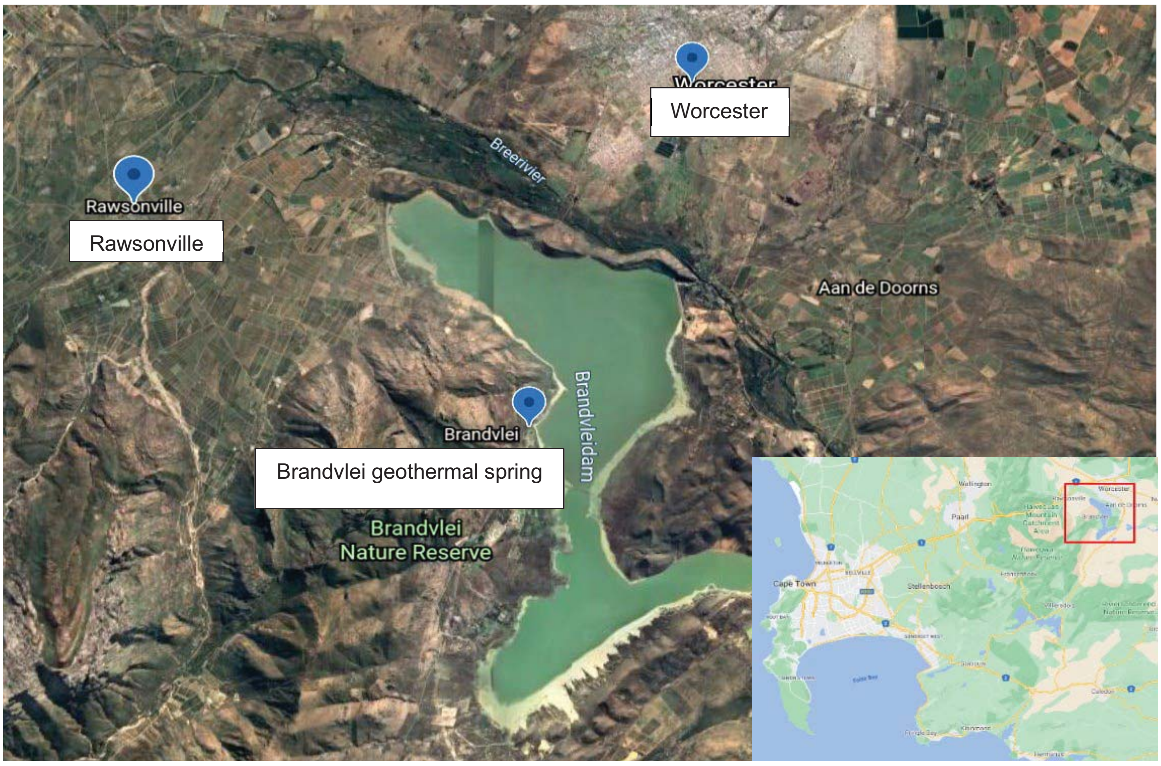


Figure 1.5.1 Location of the Brandvlei Geothermal Spring. The two closest towns are Rawsonville and Worcester.

An on-site view and an aerial view of the eye of the spring can be seen in Figure 1.5.2 and 1.5.3, respectively. According to an information plaque that was placed adjacent to the spring by the Geological Society of South Africa, the thermal water flows naturally out of the ground at a rate of around 126 L/s. This works out to approximately 11 million L/day. The plaque also states that the spring's water is approximately 64°C. According to the Department of Water and Sanitation (DWS, 2021b), temperature readings for the thermal spring have ranged between 54 and 62°C, and a recent study by Martin and Croukamp (2021) reported the measured spring temperature as 58°C.

Figure 1.5.2 The pond (right) is the eye of the Brandvlei thermal spring; the pond (left) is the storage pond into which excess water from the eye flows. The pumphouse can also be seen (left, top).

Figure 1.5.3 Aerial view indicating where the thermal water leaves the ground (Eye of Brandvlei thermal spring); the storage pond into which excess water from the eye flows; the pump house pumps water to the cooling towers which cool water for domestic use at the Brandvlei Correctional Facility.

The Brandvlei thermal spring is used as the sole source of water for all the buildings and facilities at the Brandvlei Correctional Facility. A portion of the thermal spring's water (approximately 2 million L/day) is pumped from the eye of the spring, up to mechanical cooling towers, where the temperature is reduced to around 20°C. The cooled water is then chlorinated and pumped into three storage reservoirs. A gravity reticulation system is then used to supply this water to the entire facility.

In 2004, plans were put in place to make use of another portion of the spring's water, and in 2010 an independent hot water reticulation system was completed, with piping spanning approximately 4 km, to provide a continuous supply of hot water directly to the Correctional Facility buildings. This system was designed to be capable of delivering an average of 40 m^3/hr of heated water to meet the existing demand (i.e., approximately 1 million L/day) (Jurgens, 2014).

The remainder of the spring water that is not used by the Facility, thus amounts to approximately 8 million L/day. This excess water flows from the eye of the spring, over into a second, lower, storage-pond, which is then managed and pumped by the Department of Water and Sanitation into the Brandvlei Dam, from which water is sourced for domestic and agricultural purposes by surrounding areas.

Hydrogeology

The Cape Supergroup comprises of sediments deposited from the early Ordovician to early Carboniferous period (500 and 340 million years ago). The Table Mountain Group (TMG), Bokkeveld and Witteberg Groups are subdivisions of the Cape Supergroup. The TMG is the lowest member of the Cape Supergroup and consists of a thickness of approximately 4 km of quartz arenite with minor shallow, yet extensive, shale layers (Duah & Xu, 2009).

The medium to coarse grain size and relative purity of some of the quartz arenites, together with their well indurated nature and fracturing from folding and faulting in the fold belt, enhances both the quality and exploitation potential of TMG groundwater (cold or hot) for agricultural, domestic and/or recreational water-use purposes (Duah & Xu, 2019).

The TMG contains two main aquifers separated by the thin but impermeable shales and siltstones of the Cedarberg Formation: the lower aquifer is the Peninsula Formation and the upper one is the Nardouw Subgroup (Diamond, 1997).

A spring is defined as "a natural flow of water from the ground, which can occur when geologic, hydrologic or human forces cut into underground layers of soil and rock where water is circulating, thus allowing water to rise to surface under pressure" (Erfurt-Cooper & Cooper, 2009). The water is heated either by direct volcanic activity, or by the geothermal temperature gradient as it passes through fractures and fissures in subterranean rock formations, resulting in pressure build-up that heats the water as it passes (Boekstein, 2012; Erfurt-Cooper & Cooper, 2009). All of South Africa's thermal springs are of meteoric origin, and are associated with crustal faulting, which occur mainly in areas with high rainfall (Tshibalo et al., 2010). South Africa is relatively well-supplied with thermal springs for a non-volcanic country (Boekstein, 2012).

The origin of the heated Brandvlei spring water was first described by Diamond in 1997. Diamond (1997) stated that it is likely that the structure of the Brandvlei hot spring is similar to the "Pipe Model" type described by Donaldson (1982), where cool water infiltrates to certain depths through cracks and fractures, it is heated in an extensive fracture system and then rises to the surface through a single fracture due to head differences between the deep hot water and the cold surface water.

Diamond indicated that the recharge area for the Brandvlei Spring must be located at higher altitudes than the spring itself and that the recharge of the spring could easily occur on the north-eastern flanks of the Stettyns mountain range, in the vicinity of the 1300 m high Victoria Peak. From there, the groundwater travels north-eastwards, ending up at a depth of 3 to 4 km at the base of the TMG, where it is then vertically below the Brandvlei Spring. Diamond (1997) stated that a fault that runs to the surface near the spring pools, which was traced for about 20 km, could, at depth, provide the break in the otherwise impermeable siltstones and shales of the Cedarberg Formation, through which the heated water would have to flow.

The original proposed cross-sectional diagram describing water flow to the Brandvlei spring by Diamond (1997) has since been modernised and can be seen in Figure 1.5.4 (Tshibalo et al., 2015). Figure 1.5.5 presents a second illustration which is a simplified conceptual model of the fractured rock TMG aquifer system that can also be used to describe the water flow to the Brandvlei spring (Wu, 2005).

Figure 1.5.6 shows the surface geology surrounding the Brandvlei spring, which is comprised of Quaternary sediments made up of light-grey to red sandy soil, according to the 1:250 000 map of Council for Geoscience. Figure 1.5.6 also depicts a fault zone near which the Brandvlei thermal spring lies (DWS, 2021a). In 2008, a groundwater model report by the Department of Water Affairs and Forestry, predicted that water can take up to 400 years to travel through the aquifer to the Brandvlei hot spring and that the catchment area for the spring is over 280 km^2.

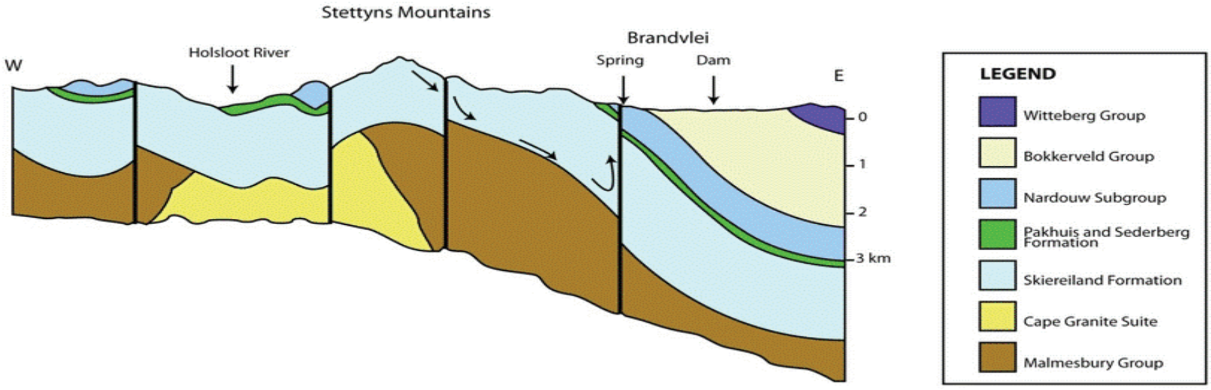


Figure 1.5.4 Cross-sectional diagram of water flow to the Brandvlei spring. The Nardouw Subgroup, Skiereiland (Peninsula) formation, and Pakhuis and Sederberg (Cedarberg) Formation collectively represent the TMG in this illustration. (Tshibalo et al., 2015)

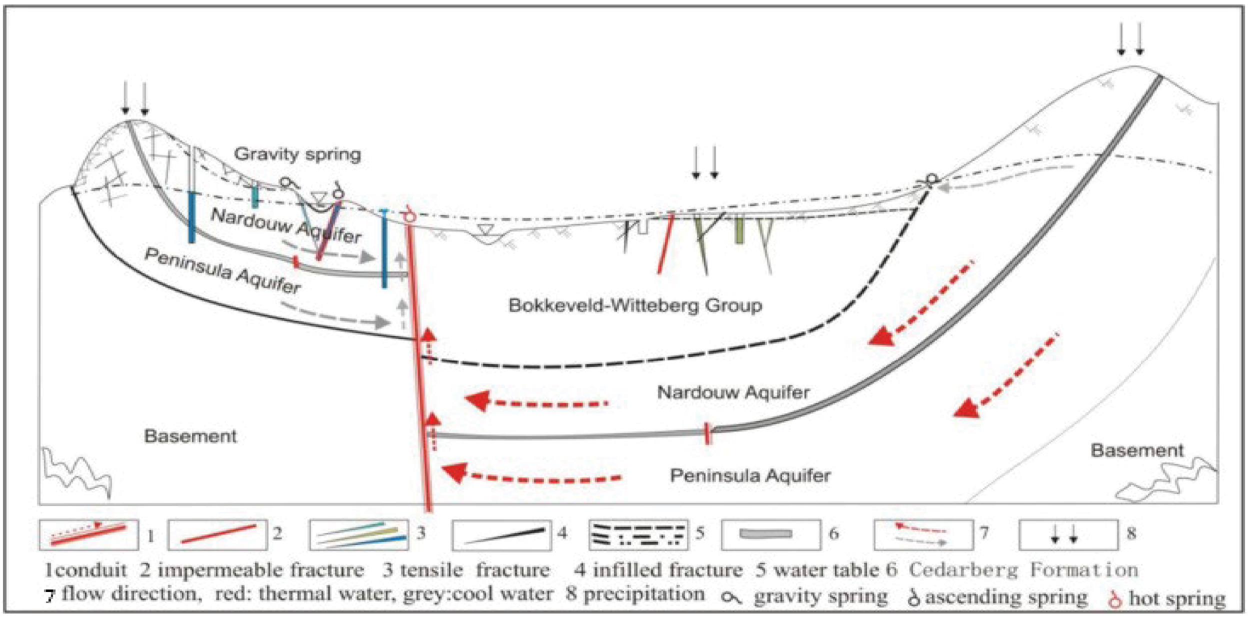


Figure 1.5.5 Simplified conceptual model of the fractured rock TMG aquifer system, applicable to the Brandvlei geothermal spring (Wu, 2005)

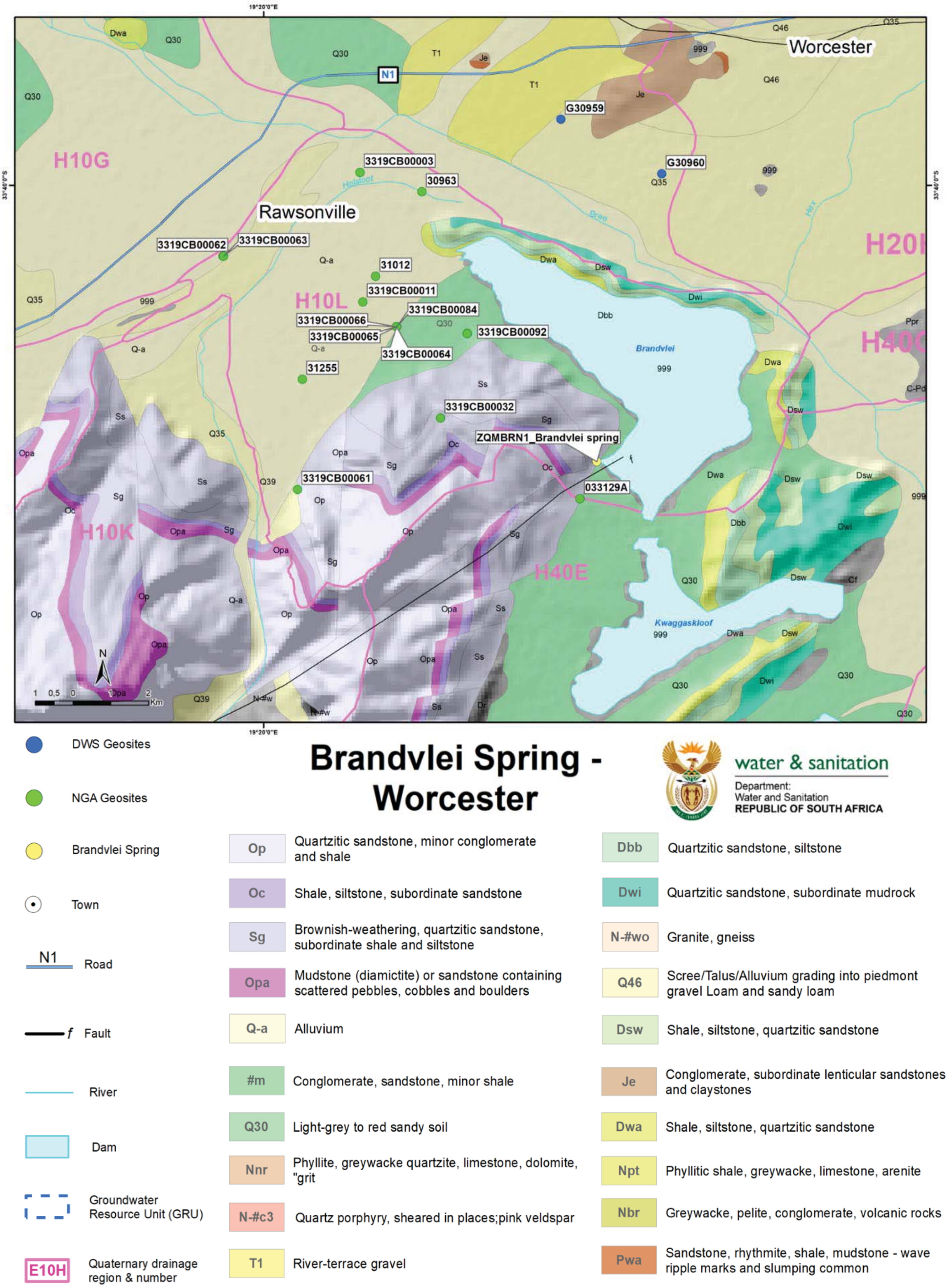


Figure 1.5.6 A 1:250 000 map depicting the surface geology of the area surrounding the Brandvlei spring. The thermal spring is located near a fault zone and is said to be derived from fissures that form part of the Nardouw Subgroup (DWS, 2021a).

Water quality

The Brandvlei spring falls under the Breede Water Management Area for the National Department of Water and Sanitation (DWS, 2021a). The spring is included in the Department's National Groundwater Quality Monitoring Programme (ZQM stations) and is station number ZQMBRN1 (Figure 1.5.7). The groundwater quality for the ZQMBRN1 geosite has been monitored from 1994 until April 2017, when the ZQM programme was put on hold due to Resource Quality Information Services (RQIS) experiencing financial constraints. It is planned, however, for sampling to recommence in September 2021, once approval has been received from RQIS head office.

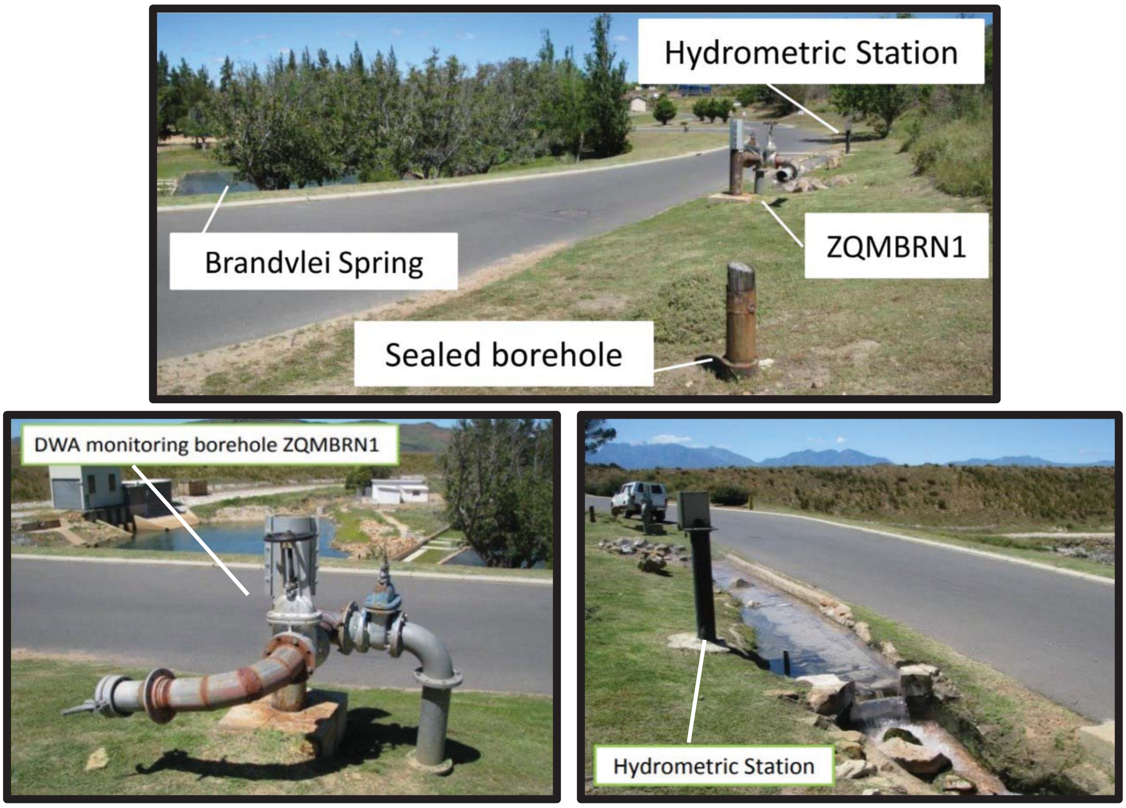


Figure 1.5.7 Geothermal spring water samples are taken by the DWS at borehole ZQMBRN1 to assess water quality. This water is from the same source as the eye of the thermal spring, originating from the same fractured zone. (Photo credit: Brian Dyason, DWS)

The land on which the spring is situated is governed by the Department of Public Works (DPW) and a water management technician from this department has been monitoring the water quality of the spring and other drinking water sites at the Brandvlei facility since January 2020. The average for each water quality parameter over time, was calculated for the water quality reports from both the DPW and the DWS. These average values, along with measurements obtained from other literature papers (Olivier & Jonker, 2013; Boekstein, 2012; Duah, 2010) can be seen in Table 1.5.1.

Table 1.5.1 Average water quality measurements for the Brandvlei spring, at and over different dates

	Standard limit**	Duah (2010)	Boekstein (2012)	Olivier & Jonker (2013)	DWS (2021b)	DPW (2021)
Date of analysis		**May 2008**	**Mar. 2012**	**2013**	**Nov. 1994 to Apr. 2017**	**Jan. 2020 to May 2021**
Temperature (°C)			57		58.02	
pH	**≥5.0-≤9.7**	5.5	5.9	6.6	7.2	6.62
Electrical Conductivity (mS/m)	**170**	9		8.9	9.84	8
Total alkalinity (as $CaCO_3$) (mg/l)					13.32	15.51
Total dissolved solids (mg/l)	**1200**		47	47.7		
Ammonia as N (mg/l)	**1.5**	0.18			0.06	<0.02
Nitrate + Nitrite as N (mg/l)	**12**	0.9	0.7	1	0.2	0.67
Main cations (mg/l)						
Sodium (Na)	**200**	7.55	9	10	8.07	
Magnesium (Mg)	**70**	1.85	2.6	2	2	1.96
Potassium (K)	**50**	2.25	2.3	2	2.18	
Calcium (Ca)	**150**	3.35	2.4	4	3.95	3.36
Silicon (Si)			19.4		18.14	
Anions (mg/l)						
Flouride (F)	**1.5**		0.2	0.2	0.18	0.22
Chloride (Cl)	**300**	14.1	14.5	14	14.27	13.45
Sulphate (SO4)	**250**	3.5	1.6	1.7	3.18	1.57
Trace elements (mg/l)						
Aluminium (Al)	**0.3**		0	0.001	< DL	
Arsenic (As)	**0.01**		0	0.001	< DL	
Boron (B)		0.03	0	0.013	< DL	
Barium (Ba)			Trace	0.009	Trace	
Chromium (Cr)	**0.05**		0	0.001	Trace	
Cobalt (Co)	**0.5**		0	0		
Copper (Cu)	**2**	0		0.001	< DL	
Iron (Fe)	**0.3**	0.02	0		< DL	
Lead (Pb)	**0.01**		0	0	< DL	
Lithium (Li)			Trace	0.01		
Manganese (Mn)	**0.1**	0	0	0.001	< DL	
Mercury (Hg)	**0.006**		0	0.0006		
Molybdenum (Mo)			0	0.0003	< DL	
Nickel (Ni)	**0.07**		Trace	0.002	< DL	
Phosphorus (P or *PO4)		0.23	Trace		*0.12	
Selenium (Se)	**0.04**		0	0.002		
Strontium (Sr)			Trace		0.009	
Vanadium (V)	**0.2**		0	0.001	< DL	
Zinc (Zn)	**5**	0.01	0	0.034	0.01	

Trace = Measurable quantities of trace elements lower than 0.1 mg/l
<DL = Less than the Detection limit
**Standard limit according to the South African national standards for drinking water (SANS 241: 2015)

The Brandvlei spring was originally recorded as the hottest spring in South Africa (64°C); however, in 2004, a spring near Siloam in Limpopo was found to be 67.5°C, although it decreased back down to 62°C again in 2010 (Olivier et al., 2011). More recent records have also indicated that the Brandvlei spring temperature is closer to 60°C or just under (DWS, 2021b; Zablocki, 2017; Boekstein, 2012). Still, this spring is considered to be thermophilic and scalding, with the potential to induce third degree scalding injuries in less than 3 seconds.

The Brandvlei spring is also considered to be mildly acidic, with most records reporting a pH of under 7. For this reason, the Department of Correctional Services add a carbonate-based additive to the water at the pump house to neutralise the water prior to it being pumped up to the cooling towers. The spring otherwise conforms to all the standards for drinking water (SANS 241: 2015) and is thus fit for recreation and consumption, as previously reported (Olivier & Jonker, 2013).

Many thermal waters, including some in South Africa, are said to be 'radioactive', due to the presence of trace elements of radon. Radon is a radioactive, inert gas with an atomic number of 86, and a mass number of 222 for the most stable isotope (^{222}Rn). It naturally occurs as a result of α decay of radium-226, which in turn is derived from a natural decay series, originating from uranium (^{238}U) in rocks, soil and groundwater. Radon is a colourless, odourless, and chemically inactive gas that is 7.6 times heavier than air. It readily dissolves in water, particularly if water is slightly acidic and not rich in minerals, as well as in alcohol and fatty acids (Zdrojewicz & Strzelczyk, 2006).

There are conflicting ideologies surrounding the exposure to radon. On one side, radioactive gas is widely considered a carcinogenic health hazard by environmental and health agencies, with numerous articles relating prolonged and/or high doses of radon exposure in mines and homes to increased risks for lung cancer (Park et al., 2020; Lorenzo-Gonzale, 2020; Becker, 2004). On the other side, it is said that radon exposure can be used as an effective treatment in medical applications relating to painful inflammatory and degenerative joint and spine diseases, high blood pressure and various cancers (Kojima et al., 2019; Becker, 2004). This practice is termed 'radon therapy' and according to a literature review by Becker (2004) the benefits in the adequate use of low-dose radon exposures far exceed the hypothetical lung cancer risk attributed to the inhalation of low radon concentrations.

As stated on the information plaque, the Brandvlei spring is very weakly radioactive, but lacks specific medicinal properties. Literature to support this statement is, however, somewhat lacking. The radon content at Brandvlei was first investigated by Mr J. Muller, a consulting Chemist, in 1946. The water was reported to contain 50 to 53 Mache units per litre, while collected gas from the spring contained 450 Mache units per litre (Kent, 1949). Mache units (ME) have since become obsolete, and the conversion equation to the current SI unit for radioactivity (Becquerel) is as follows:

$$1 \text{ ME/L} = 3.64 \text{ Eman} = 3.64\times10^{-10} \text{ Ci/L} = 13.4545 \text{ Bq/L}$$

- *ME: Mache unit = defined in 1930 as the quantity of radon per litre, commonly used to evaluate the radioactivity of mineral springs.*
- *Eman = A term used since 1921 for the Rn content of the atmosphere as a concentration unit.*
- *Ci: Curie = Quantity of any radioactive substance in which 3.7×10^{10} disintegrations occur each second.*
- *Bq: Becquerel = Defined as one nuclear disintegration per second. Replaced the Curie as the official SI radiation unit in 1975. Usually presented in Bq/L for water, and Bq/m^3 for air.*

The radon content at Brandvlei thus works out to approximately 673 to 713 Bq/L in the water, and 6054,5 Bq/L (≈6,05 MBq/m^3) in the gas. Kent (1949) stated that the radon content was rather high for a water of this type, referring to a hot spring in the Cape system.

A second study by Boekstein (2012) investigated radon concentrations in the water of hot springs in the Western Cape (Table 1.5.2). The concentration that was recorded for the Brandvlei spring water was 75 Bq/L, which is much less than the values that were obtained in 1943. The Brandvlei radon concentration was also lower than that recorded for six of the nine hot springs in the Western Cape. A table of radon concentrations in water samples from groundwater and spa waters from various regions across the world is provided for context in Table 1.5.3 (Vogiannis & Nikolopoulos, 2015).

Table 1.5.2 Radon concentrations in water from hot springs in the Western Cape (Boekstein, 2012)

	Brandvlei hot spring	Goudini Spa	Avalon Springs	Baden Klub	The Baths	Caledon Spa	Warmwater-berg Spa	Calitzdorp Spa	Toor-water
Radon (Bq/L)	75	80	98	49	258	49	274	12	86
Date of analysis	Jun. 2012	Mar. 2012	Mar. 2012	Mar. 2012	Apr. 2012	Mar. 2012	Mar. 2012	Jul. 2012	Jul. 2012

Table 1.5.3 Radon concentration in water samples from groundwater and spa waters collected from various regions across the world. In some cases, values of radon concentration in the indoor spa premises are given. Dosage ranges per year are also given for patients and workers (Vogiannis & Nikolopoulos, 2015).

Region		**Rn in water (Bq/L)**			**Rn in air (Bq/m^3)**	**Dose**
		Min	**Max**	**Mean**		
Herculane spa					$<7.4 \times 10^6$	
Ikaria Island Greece					$0.18–30.48.10^3$	
	Apollon spa			(22.0 ± 1.4) 0.102		0.001–0.589 (mSv/year) for patients
	Spilaion spa			(10.7 ± 1.4) 0.102		0.001–18.9 (mSv/year) for workers
Sudety Mountains, Poland	Klodzka valley	0.18	1332.8 ± 28.0			
Badgastein, Austria		2	775		10–5,200	14–48 mSv/year occupational, based on the PAEC measured values 1–44 mSv/year conversion factor of 1.43 Sv/J h m^{-3}
Bavarian crystalline region						>20 mSv 10% of the processing plant workers
Extended region in Slovenia				5–62.9		
Spanish spas		20	824		3560–6650	200 mSv/year to the bronchial epithelium and 24 mSv/year to the total body
Sudety Mountains in Poland	Radon content in groundwater		3000			
Groundwaters in Brazil		0.1	122	Log-normally distributed, with a modal value of 49 Bq/L		
China groundwater		0.71	3735	Geometric mean 147.8 kBq/m^3		
Medicinal groundwater of Ladek Zdrój (Poland)		134	1284			

Table 1.5.4 Effects of Radon-222 on human health according to the South African Water Quality Guidelines (DWAF, 1996)

Radon-222 Range (Bq/L)	Effects
Target Water Quality Range 0-11	***No significant effects either with drinking water or on showering***
11-33	No risk on drinking water, slight risk in showering in a non-ventilated area
33-100	No risk on drinking water. Moderate risk in showering in a non-ventilated area
>100	Increasing risk on showering of inhalation of radon gas, leading to an increased risk of lung cancer

According to the latest version of the South African Water Quality Guidelines (1996), the risk of lung cancer from inhaling radon gas, while showering, increases from a slight risk at 11 to 33 Bq/L to a moderate risk at 33 to 100 Bq/L, with the risk increasing further at concentrations that are more than 100 Bq/Lin water (Table 1.5.4). According to the World Health Organisation (2021), the risk of lung cancer increases by about 16% per 100 Bq/m^3 increase in long time average inhalation exposure to radon gas. With regards to drinking-water, a higher radon dose is usually received from inhaling radon (when dissolved radon in drinking-water is released into indoor air) compared with ingestion (World Health Organisation, 2021).

With the radon concentrations from the two studies at Brandvlei being quite different and many years apart, it is recommended that further investigation be done with regards to the radon content of the Brandvlei spring prior to making any final conclusions about health and safety.

1.6. PROJECT MOTIVATION AND AIMS

As mentioned, a major constraint to most freshwater fish culture in South Africa is the large variation in water temperatures that occur between summer and winter months. As the more popular aquaculture species thrive in either warm or cold waters, this variation often limits fish farmers to a half yearly growth period which limits production. For warm-water aquaculture, the use of electricity or fossil fuels to heat water through the colder months is extremely costly and usually unfeasible. Geothermal hot springs have thus been proposed as a viable alternative heat source for the support of warm-water aquaculture all year round.

To date, geothermal resources have yet to be used to support warm-water aquaculture in South Africa. The Brandvlei geothermal spring was identified and selected to be the site for this project, due to its consistently high temperature (±60°C) and flow rates (126 L/s). Additionally, the set-up of an aquaculture system at this location within the Brandvlei Correctional Facility, would provide food security and skills development opportunities that would contribute positively towards the Facility's self-sustainability initiative and re-integration after incarceration programme.

The 12-month project thus aimed to investigate a suitable method to use the heat from the Brandvlei geothermal spring to support the warm-water aquaculture of Nile tilapia, with focus on renewable energy, food security and skills development. The specific aims for this project that needed to be addressed are as follows:

1) To develop an appropriate method to harness geothermal heat to support tilapia aquaculture.
2) To determine the cost-benefit of utilising geothermal heat for aquaculture.

3) To provide a SWOT analysis on the application of the test-system for fish production and skills development.

Within the 12-month timeframe, the necessary permissions and permits had to be obtained, the systems had to be designed and installed, the fish introduced, the power consumption of each system recorded, and the findings then compiled into this final report.

In the chapters that follow, the methodology and system design are provided, describing system components and their function; the steps taken during site preparation, system installation and fish introduction; and optimal water quality parameters for tilapia aquaculture. The results and discussion chapter provide information on the cost savings potential of using the geothermal heating method in comparison to a conventional method that is often used for heating in aquaculture. The conventional method, a heat pump, was used in a separate recirculating aquaculture system as a control. Two SWOT analyses are also provided in this chapter, one evaluating the potential for continued use of the system past the project end-date, and one evaluating the system for its potential as a training facility in the future. The final chapter provides a summary of the project, highlighting milestones that were achieved, while also providing recommendations for improvements. A co-management plan between Stellenbosch University (SU) and the Department of Correctional Services (DCS) was used to ensure the continued management of the system until the first harvest, where after re-stocking will be considered for future skills development training and fish production.

2.1. DECIDING ON A SUITABLE SYSTEM

A suitable aquaculture production system

There are three main types of on-land aquaculture production systems, namely: an earthen pond system, a flow-through system, and a re-circulating aquaculture system (RAS). An earthen pond system will not be suitable at Brandvlei, as the temperature and water quality parameters cannot be controlled in such a system. A natural eco-system is usually responsible for nutrient and oxygen control in a pond, and water exchange is typically minimal.

A flow-through system or raceway system is designed to allow for a continual flow of freshwater through the system, often being set-up alongside rivers to ensure an adequate supply of water. With the high flowrates of the Brandvlei spring, there would be sufficient water to set up a small flow-through system, however, these flow rates would not be able to support a larger scale system if the plan was to upgrade and culture fish at a commercial scale. The control and removal of nutrients from fish- and feed-waste would also be more difficult with the large quantities of water leaving the system.

A RAS system is thus the system of choice for Brandvlei. This type of system re-circulates the same water continuously from the fish tanks, through mechanical and biological filters, and back to the fish tanks. Being a closed system, this design requires far less water (only for top-up, due to water loss from evaporation and when filters are backwashed), while allowing the ability to control temperature, water quality and effluent disposal; given that the correct technical components are included in the design.

A suitable heat introduction method

Conventional water heating methods can vary, but usually involve the use of electricity or fossil fuels. The use of submersible heating coils or heating rods is one way of adding heat to a system. This can be done using polypropylene heating coils connected to a boiler (typically powered by natural gas) or to an inline heating system (Malone, 2013). The heating coils themselves can be placed in the sump or directly in the tank. A thermostat is then used to turn the boiler or heating system on, when the tank temperature drops below a set value; and off again, once the tank has been heated to the required temperature. A basic depiction of heating rods in a system can be seen in Figure 2.1.1.

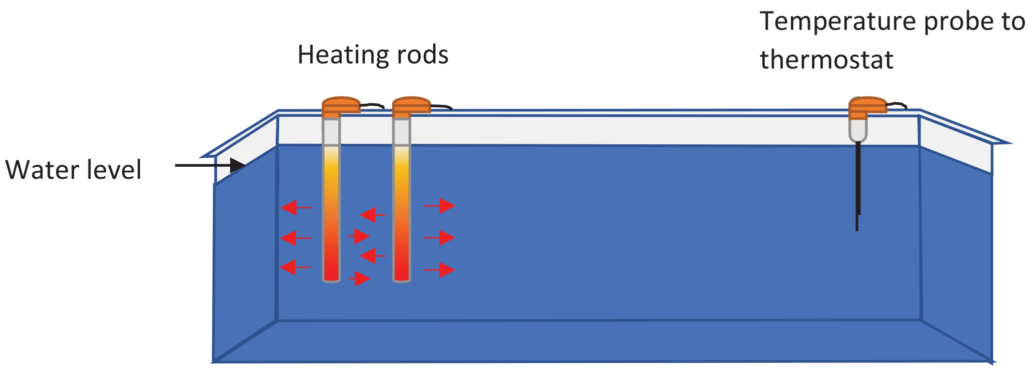


Figure 2.1.1 A diagram of heating rods that can be used to heat a water body. A temperature probe that is connected to a thermostat will measure the temperature of the water and the thermostat will turn the heating rods on and off when the water temperature is not within the required range.

The heating power input for heating rods/coils usually equals the heating power capacity, which means that the costs for heating water with this method are very high. Heating rods or submersible heaters are popularly used by hobbyists in warm water ornamental fish tanks where the water volume that requires heating is relatively small. As a water body becomes larger, the costs of heating by means of heating rods or coils quickly becomes unfeasible, and a new heating approach, such as the use of a heat pump, can be implemented to reduce heating costs.

The graph in Figure 2.1.2 gives an indication of how much it would cost to raise the temperature of a large porta-pool containing 10 m^3 of water, by between 1 and 15°C, according to three different electricity user tariffs as specified by the City of Cape Town (2021). It is estimated that 11.6 kWh of energy is required to raise 10 m^3 of water by 1°C.

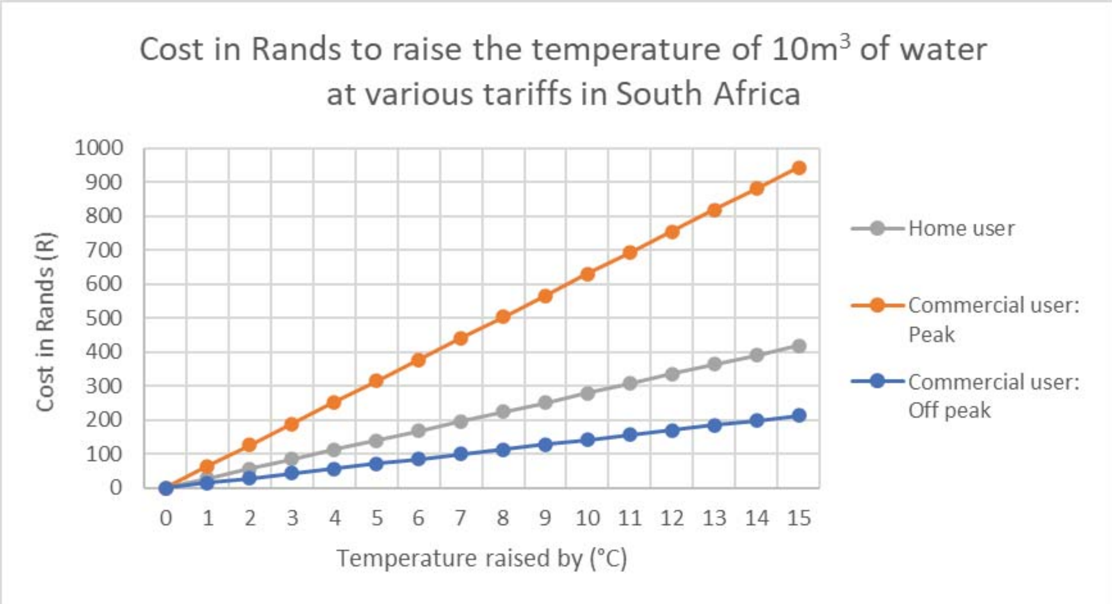


Figure 2.1.2 The cost to raise 10 m^3 of water by between 1 and 15°C according to tariffs specified by the City of Cape Town for 2021/22. Home user: tariff for <600 kWh usage is 240.04 c/kWh. Commercial user: large power user, low voltage, peak/high demand months (June-Aug) is 541.29 c/kWh; Off peak/low demand months (Sept-May) is 121.62 c/kWh. (City of Cape Town, 2021)

Let's consider a theoretical example. A small tilapia farm consists of 5 porta pools of 10 m^3 each, all at a temperature of 28°C. During a cold night, the temperature of each pool drops by 5°C. To bring the temperature of all five porta-pools back to 28°C would cost between R353.54 and R1 573.50 (tariff dependent). In a winter month, it could be possible to have a 5°C drop every night. Heating the water each morning back to 28°C would amount to a month-end cost (30 days) of between R10 606.30 and R47 205.00 (tariff dependent). With these costs in mind, it is easy to see why maintaining optimal warm-water fish production during winter months quickly becomes unfeasible. Being able to harness the heat from an alternative heat source, like a geothermal hot spring, will allow for heating of an aquaculture system at a reduced cost, in comparison to conventional heating methods that use electrical energy or energy from fossil fuels.

Heat pumps are often used for the heating of swimming pools, so it would make sense for this type of heating equipment to be applied in a RAS set-up. Heat pumps rely on a heat exchange system and operate like an air conditioner working in reverse. An air conditioner uses an evaporator (cold coil) to remove heat from the air inside a house, and then discharges it outside using a condenser (hot coil), during warm weather. During cold weather, the heat pump makes use of reversible valves to interchange the evaporator and the condenser. Thus, the hot coil inside and the cold coil outside allow for heat to be removed from outside and discharged inside by the system (Baird et al., 1993).

A diagram that explains the heat exchange process can be seen in Figure 2.1.3. Heat pumps transfer heat by circulating refrigerant through a cycle of evaporation and condensation. Refrigerant is a substance that can be found in either a fluid or gaseous state and is able to readily absorb heat from the environment. A compressor pump is responsible for pumping the refrigerant between two heat exchanger coils. Refrigerant is evaporated at low pressure in one of the coils and while in its gaseous state it absorbs heat from its surroundings. The refrigerant is subsequently compressed on its way to the second coil, where it condenses at high pressure. At this point, it releases the heat that it absorbed earlier in the cycle. As heat pumps rely on the extraction of heat from the surrounding air, they can become less efficient in cold weather.

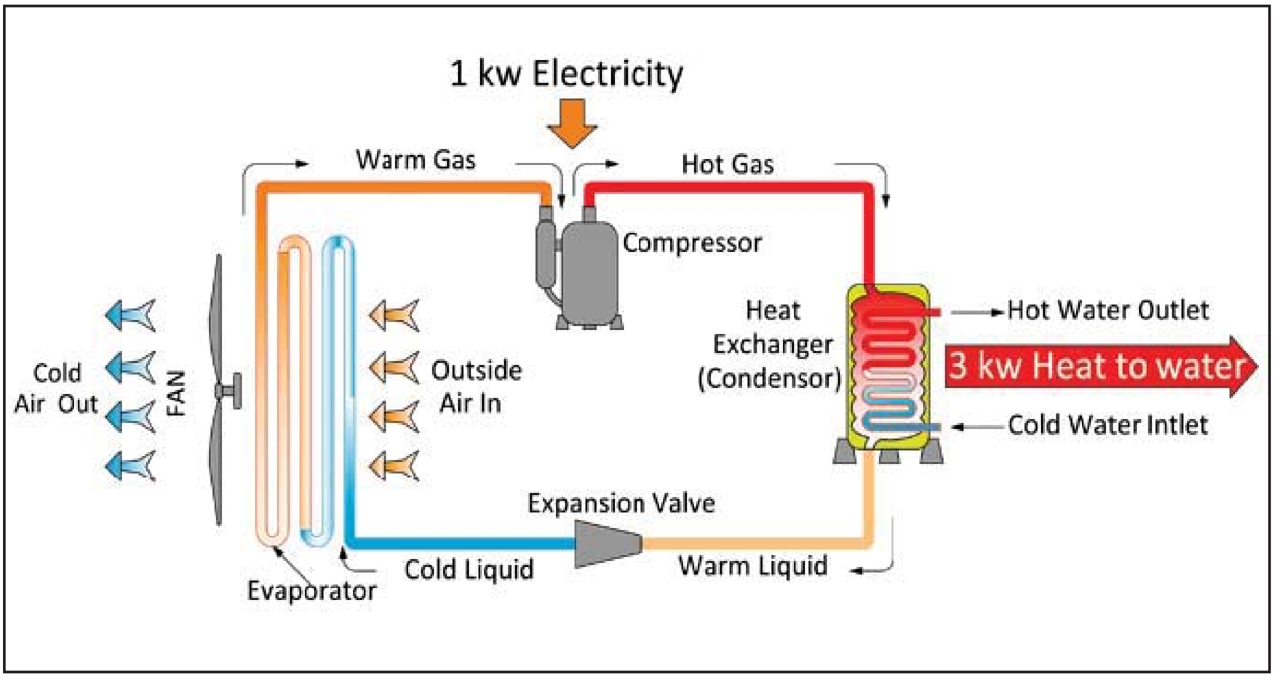


Figure 2.1.3 How a hot water heat pump works (Energen Hybrid Systems, 2021)

One of the earliest systems to use geothermal water for heating was developed by the Oregon Institute of Technology for rearing freshwater prawns (Smith, 1981). This system used five sets of black iron pipes laid across the bottom of the pond. Each line had holes drilled into the pipes to allow geothermal water to be discharged through the holes to provide heated water to the pond when the pond temperature dropped. Solenoid valves operated by Honeywell Temperature Controllers were used to regulate temperature in this system. The valves opened only when they were triggered, when the water temperature dropped below the set point (27°C). The valves opened to discharge warm geothermal water into the system and automatically closed when the temperature reached 27°C again.

The research team at Stellenbosch University worked closely with aquaculture design specialists from Deep Blue Aquatic Systems (Gordon's Bay, Cape Town) to design two separate single-tank RAS systems; one which consisted of a conventional heating method (as a 'control') and one which used heat from the Brandvlei geothermal spring, to maintain an optimal temperature for tilapia aquaculture (28°C) in both systems. For simplicity and to minimize water use from the spring, it was decided to avoid using a heating method that involved the mixing of geothermal water directly into the system. The conventional heating method or 'control' thus involved the use of an air-to-water heat pump (AQUAHEAT SF0010P STD Heat Pump); while the geothermal heating method consisted of a water-to-water flat-plate heat exchanger. The heat pump and an example of a heat exchanger can be seen as A and B in Figure 2.1.4, respectively. A diagram depicting how this heat exchanger works can be seen in Figure 2.1.5.

Figure 2.1.4 A: Air-to-water heat pump that will be used for the 'control' RAS setup. B: Water-to-water flat-plate heat exchanger that will be used to heat the RAS water using the geothermal water as a heat source.

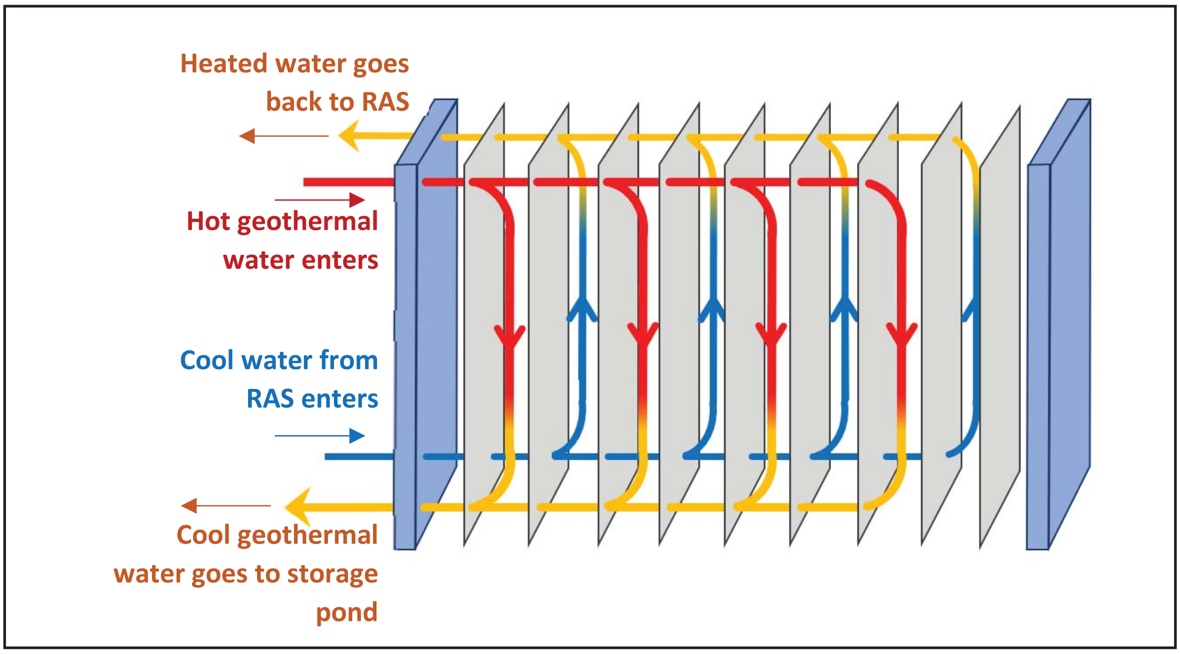


Figure 2.1.5 How a flat-plate heat exchanger will work at the Brandvlei system

The heat pump that was used had a heating capacity of 5.36 kW and an electrical power input requirement of 1.13 kW. In comparison to a heating rod or element that would cost between R14.14 and R62.94 to raise the water temperature of 10 m^3 by 1°C (Figure 2.1.2); the use of this heat pump would only cost between R2.45 and R13.27 (tariff and efficiency dependent) to supply the same amount of heat. This is a cost reduction of almost 80%.

It was expected that the heat exchanger would be even less costly and more successful at heat transfer than the heat pump, as the geothermal water had more heat to offer, in comparison to the air from which the heat would be extracted by the heat pump. Faster heat transfer would therefore occur with the heat exchanger, thus reducing the amount of pumping time and thereby also reducing electricity usage and cost. Cold weather would also have minimal, if any, effect on the efficiency of the heat exchanger in comparison to the effect it would have on the heat pump, as the temperature of the geothermal water had been reported to remain unchanged over winter months, whereas cooler air temperatures surrounding the heat pump would reduce its efficiency.

A suitable fish species – Nile tilapia

There are nearly 100 different types of tilapia species, of which several species are cultured commercially, with the Nile tilapia (*Oreochromis niloticus*) being identified as the most desirable for commercial production (Towers, 2010). Nile tilapia and Mozambique tilapia (*Oreochromis Mossambicus*) are both important freshwater species to the South African aquaculture industry. Both species are relatively hardy and can readily adapt to a wide range of environments and culture systems; however, the indigenous Mozambique tilapia grows at a much slower rate than that of the Nile tilapia, and this tends to make them less feasible for production (DAFF 2018b). The Nile tilapia, on the other hand, has been recognized for its fast growth and reproductive capability, making it a reliable spawner with a higher-than-average survival of eggs and fry. These characteristics make Nile tilapia the most farmed species of tilapia in the world (DAFF, 2018b) and the second largest farmed fish group, after carp, in terms of production volume (FAO, 2018).

Tilapia can be cultured using various systems such as ponds, raceways, cages, RAS and aquaponic systems, however, these fish tend to perform particularly well in RAS, because of their ability to tolerate crowding and deteriorating water quality conditions. The farming of tilapia using RAS is more predominant in colder and more temperate regions, where the surrounding environment can greatly affect the production. These systems are, however, costly as they require energy for heating, pumping, and filtering of the water; all which are necessary for optimal production (Mjoun et al., 2010). The Nile tilapia is an omnivorous, filter feeder that is able to feed on a variety of organisms, including invertebrates, larval fish, macrophytes and detritus. They do, however, still require a high protein diet (50%) when fed commercial fish feeds, which, although is lower than the African catfish requirement (60%), is still one of the largest contributing factors to high feed costs. This is why a large amount of research is being conducted into raising tilapia on feed with ingredients from lower trophic levels, so as to assist in minimizing production costs (DAFF, 2018b; Turker et al., 2003; Kabir et al., 2019; Arthur et al., 2010).

Nile tilapia are observed to grow optimally at temperature ranging from 22°C to 29°C with spawning occurring at temperatures of 22°C or higher. While this species can survive at lower temperatures, studies have shown that at 20°C the growth rate of this species significantly declines with temperatures becoming lethal at approximately 11-12°C (Mjoun et al., 2010). This observed decline in growth can be attributed to the fact that this species becomes less active at lower temperatures and at 17°C they stop feeding altogether, which will ultimately result in their death (DAFF, 2018b). When temperatures are too high, the fish metabolism speeds up to a point where the organs and body become stressed and fish can experience organ damage or even suffocate. High temperatures can also kill off the beneficial bacteria in the system, upsetting the microbial balance and contributing further to immunological stress.

A study by Azaza et al. (2008) focused on identifying the optimal temperature for growth of the Nile tilapia. This study found that tilapia grew optimally at temperatures ranging between 26 and 30°C, while temperatures falling below or above this range caused a decrease in the growth rate and body length. This was confirmed by El-Sayed & Kawanna (2008), who also showed that the FCR for fry was best at a temperature between 26 and 30°C. The optimal pH and oxygen levels for culturing Nile tilapia is also known to range between 6 and 9 and between 4 and 6 mg/L, respectively.

Tilapia is a species that is consumed worldwide, with a global appeal, therefore making it the second most consumed fish following carp. This is because tilapia is considered to be the best alternative white fish to hake. This consumer appeal in combination with the steady advances being made in aquaculture technology, have caused the global production of tilapia to be on an upward trend for the last 20 years. Currently, the Chinese market is the largest market for farmed tilapia (DAFF, 2018b), with Asia leading the production of tilapia in 2015, producing 4 million tons, followed by Africa (700,000 t) and South America (450,000 t).

In South Africa, tilapia production contributed approximately 18% to the overall freshwater species production, with a significant increase being observed between 2011 to 2015. In 2015, 325 tons of farmed tilapia were recorded, all of which were produce by small-scale farmers utilising either recirculating aquaculture systems or pond culture systems. Although South Africa is showing a steady increase in the production of tilapia, it is still relatively small in comparison to other African countries and the rest of the world (DAFF, 2018b).

Although both the tilapia and catfish species were suitable for use in this project at this site, Nile tilapia was chosen due to its close resemblance to hake, which was the type of fish predominantly fed to inmates at the Correctional Facility.

2.2. SYSTEM COMPONENTS AND WATER FLOW

The designed research unit for Brandvlei consisted of two recirculating aquaculture systems each with a circular Porta Pool of 10 m^3, a filtration system (Speck pump, sand filter, UV filter and a bio-filter with air-blower which circulated 10 m^3 per hour), a DB power board, and a heat source (The HP system used a heat pump, extracting heat from the surrounding air; the HX system used a heat exchanger to extract heat from the spring water). A kilowatt meter was included in each system to monitor the electricity usage of the systems separately. The Porta Pools were placed on Correx sheeting (an extruded polypropylene board that is environmentally friendly and recyclable) to ensure that they were constructed on a smooth even surface, and each filtration system (excluding the bio-filter) was constructed on a chipboard skid tray for structural support and neatness. The plan view of the research unit is given in Figure 2.2.1, while Figures 2.2.2 and 2.2.3 are diagrams depicting the direction of water flow from one component to the next in both the HP system and the HX system.

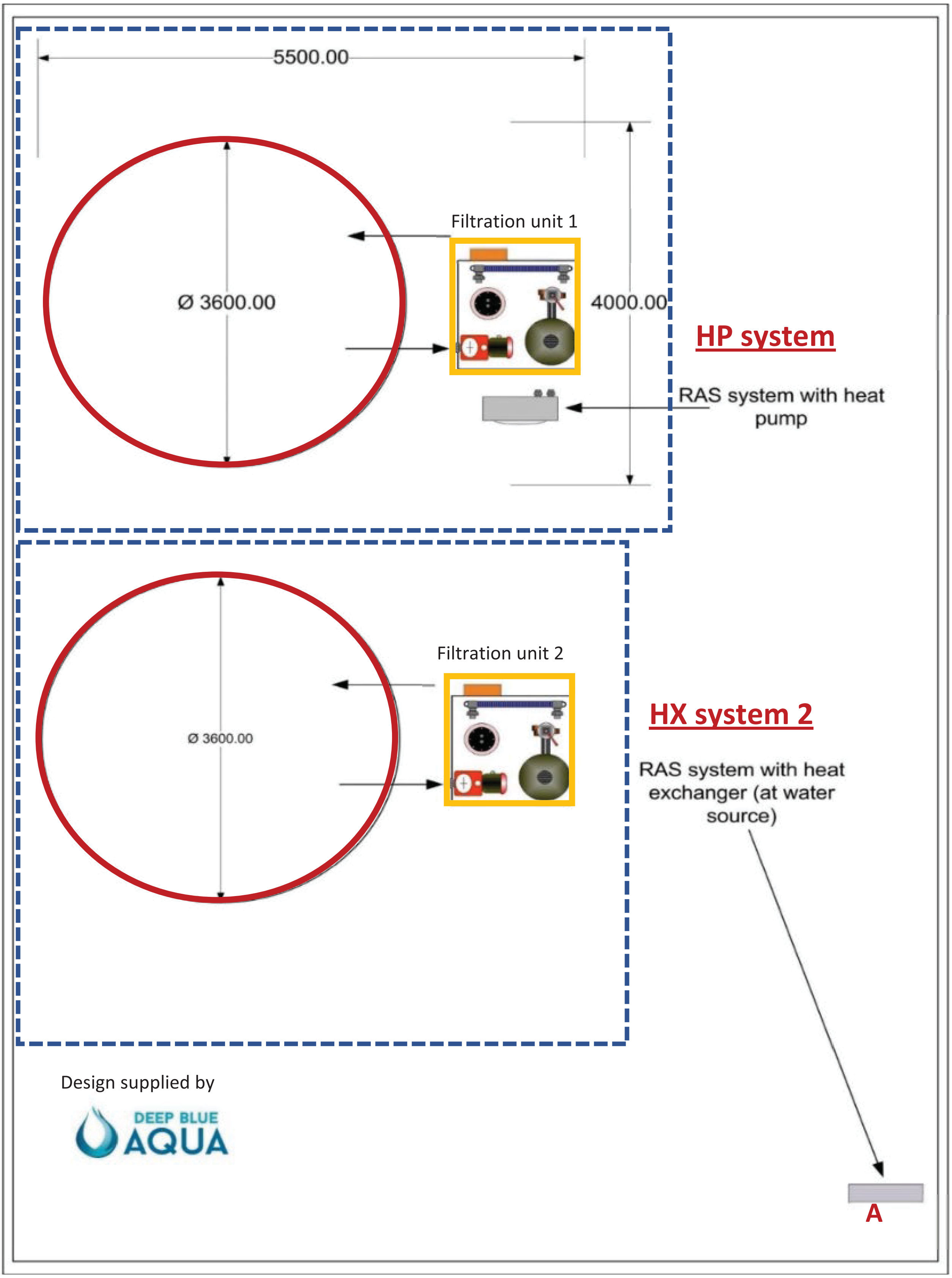


Figure 2.2.1 Plan view of the Brandvlei aquaculture research unit. A – Heat exchanger. (Design supplied by Deep Blue Aquatics)

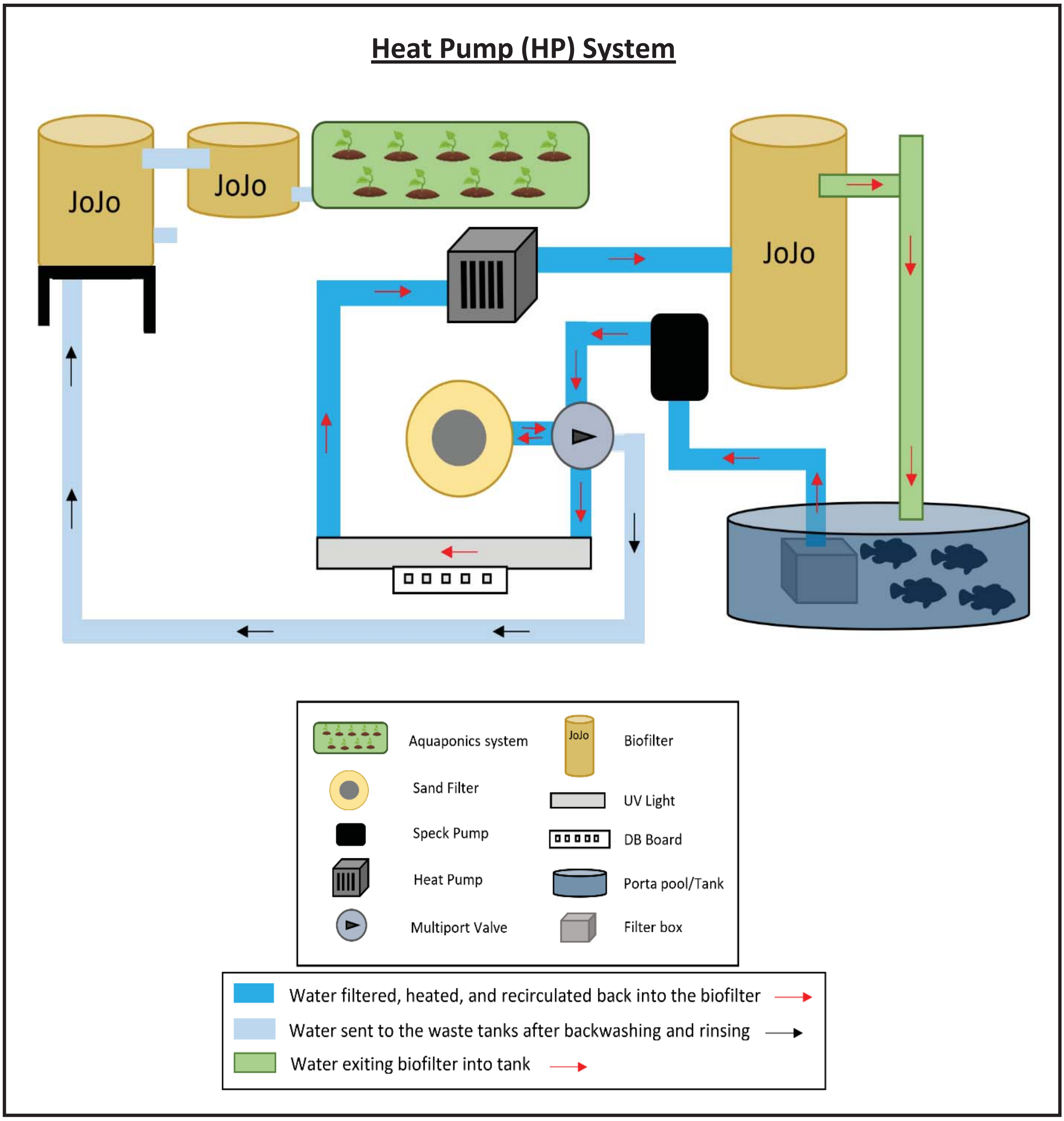


Figure 2.2.2 Diagram depicting water flow and the different components of the heat pump system

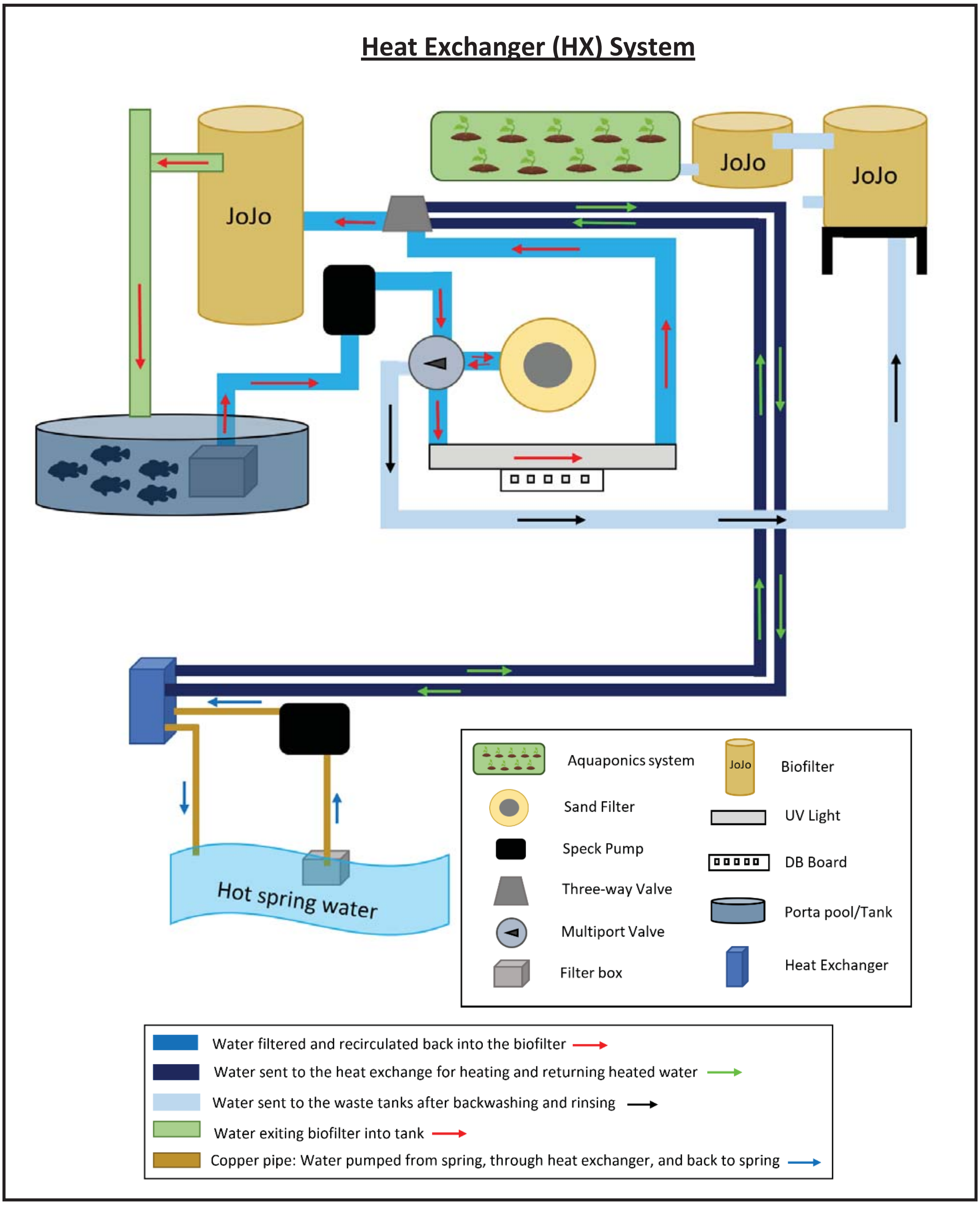


Figure 2.2.3 Diagram depicting water flow and the different components of the heat exchanger system

Summary of components and their function

The following section gives a summary of the system components. A basic description and function of the components is provided, as well as an explanatory diagram, a photo, and the corresponding symbol that was used in Figures 2.2.2 and 2.2.3 to represent that specific component. Figure 2.2.4 describes the layout of the summary for each component.

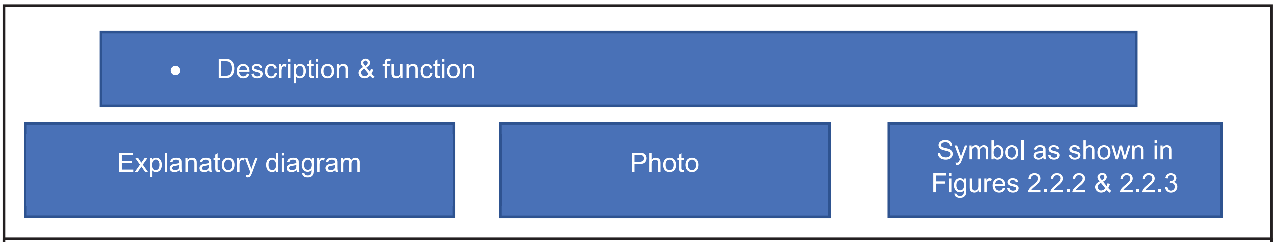
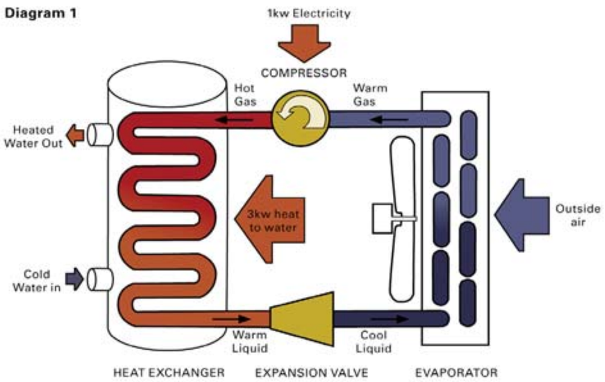
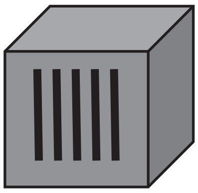


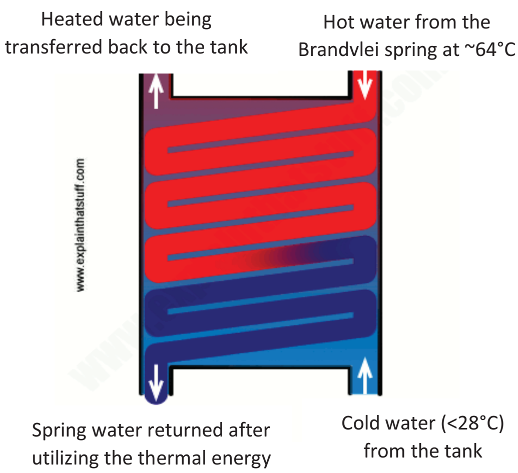
Figure 2.2.4 Layout of the summary for each component in the system

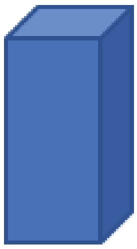
- **Heat Pump –** A heat pump is a water heater that uses electricity to move heat from the surrounding air into the water passing through the heat pump, instead of generating heat directly. Water flows continuously through the heat pump, however the heat transfer process is only switched on when a built-in thermometer detects that the water temperature has dropped below a certain temperature.



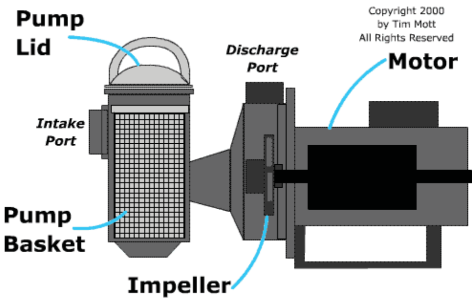


- **Heat Exchanger –** A device that allows the transfer of thermal energy from one fluid to another. Under normal conditions, heat will move from a warmer fluid to a colder fluid.

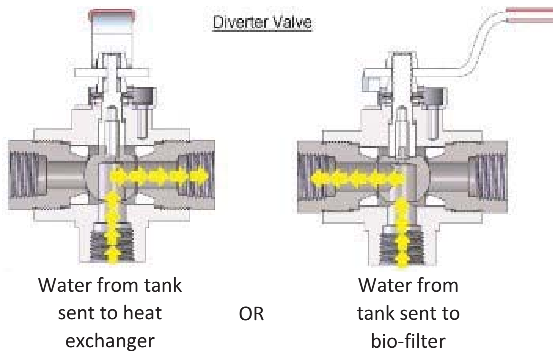


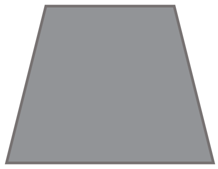


- **Speck Pump –** The pump's main task is to circulate water. It does this by pulling water in through an inlet (intake port), funneling the water through a filter and then pumping the water back out via the outlet (discharge port).

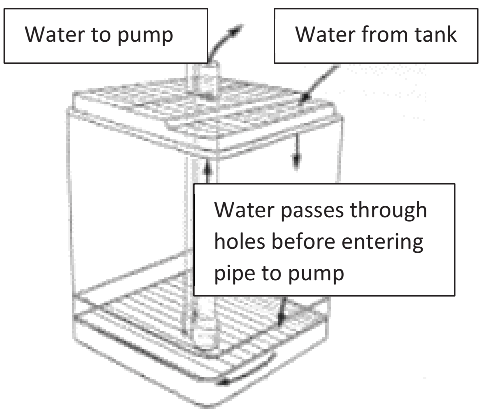


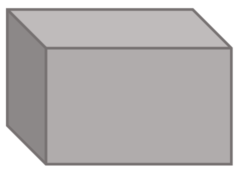
- **Three-way valve –** A 3-way control valve shuts off water flow in one pipe while opening water flow in another pipe. In a modulating or 3-point floating application the valve can also mix water from two different pipes into one pipe or divert water from one pipe into two different pipes. In the HX system, a temperature probe has been placed in the porta pool tank that is connected to the 3-way valve. When the temperature drops below 28°C, then the 3-way valve diverts water towards the heat exchanger to be heated. Warm water is then returned to the bio-filter. When the temperature probe detects that the temperature of the porta pool has returned to 28°C, the 3-way valve switches to send water directly to the bio filter, bypassing the heat exchanger water-heating circuit.



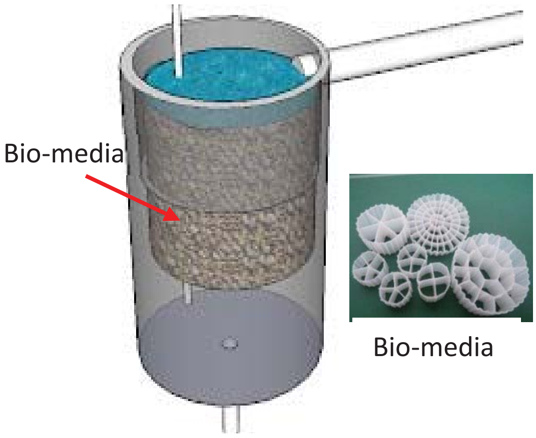


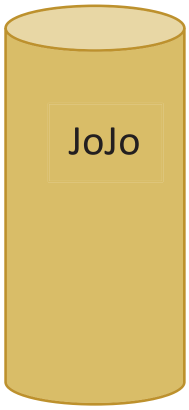
- **Filter Box –** Prevents solid waste moving into the pipes ensuring that the pipes remain unclogged. A filter box was used at the inlet in both the 10 000 L tanks and also at the inlet to the hot water pump that feeds the heat exchanger.



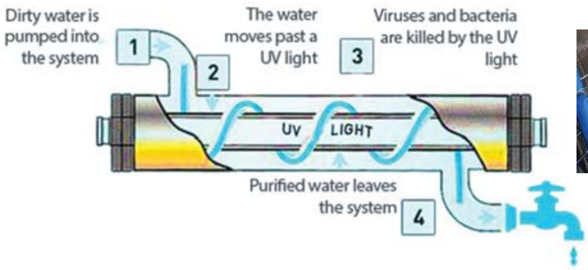


- **Biofilter –** Biofiltration is a pollution control technique that uses a bioreactor containing living material to capture and biologically degrade pollutants. Naturally occurring bacteria occupy the Bio-media and convert toxic ammonia (NH_3) from fish waste, into Nitrite (NO_2^-) and then into Nitrate (NO_3) which is less toxic than its precursors at higher concentrations. Nitrates can be removed through water changes. In aquaponic systems, nitrates are removed by the plants. An air blower is included in the biofilter in both systems to supply oxygen to the aerobic bacteria.

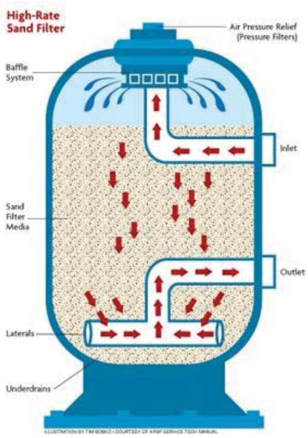


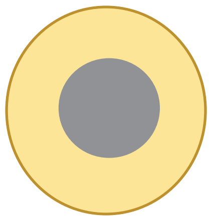


- **UV Light –** Ultraviolet light kills or inactivates microorganisms by destroying nucleic acids and disrupting their DNA, leaving them unable to perform vital cellular functions. The water passes through a cylinder surrounding the UV bulb, sterilizing the water in the process.

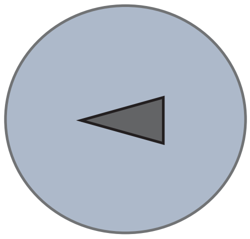


- **Sand Filter –** Sand filtration is used for the removal of suspended matter, as well as floating and sinkable particles. The wastewater flows vertically through a fine bed of sand and the particles are removed by way of absorption or physical encapsulation.





- **Multi-Port Valve for sand filter –** By changing the position of the lever, you can direct the water coming from the pump around or through your filter in different ways. One should turn off the pump system before changing between lever positions.



Functions

- ❖ **Filter**

The lever should be on this setting most of the time. This is the setting that provides normal filtration of the tank by pushing the water through the filter media that then traps any dirt and debris before the water is returned to the tank.

- ❖ **Waste**

This setting draws water from the tank and sends it straight to the waste outlet without passing through the filter. This setting is used to drain or partially drain the tank or if there is a lot of dirt and debris on the bottom of the tank.

- ❖ **Closed**

This setting is only used when servicing the pump and the tank system should never be run on this function.

- ❖ **Backwash**

When using this function, the flow of water through the filter is reversed so that all the dirt and debris that the filter has cleared from the tank water which has accumulated in the filter medium is then flushed out and sent to waste. You should backwash your filter for about 2-3 minutes or until the wastewater runs clean. This can usually be seen in the clear plastic sight glass on the Multiport valve.

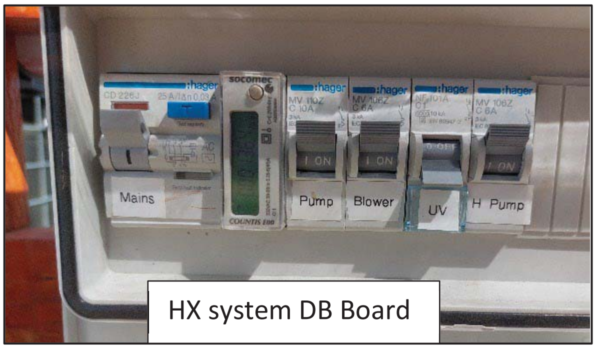
- ❖ **Recirculation/Bypass**

In this position, the filter is bypassed. Water is drawn in from the pump and then returned straight to the tank. In some instances, if you are adding chemicals, then it can be used to make sure that the chemicals are thoroughly dissolved through the tank water without going through the filter.

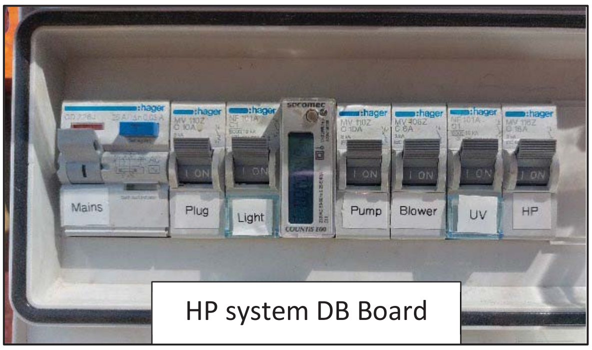
- ❖ **Rinse**

Rinse is to clear any dirt out of the clean side of the sand before you start sending it back to the tank and should be performed after backwashing until water is clear again. This can usually be seen in the clear plastic sight glass on the Multiport valve.

- **DB Board –** A distribution board (DB) is where the electrical supply is distributed from the point of supply. The main supply cable comes into the board and is then distributed to the breakers and from there to all the circuits.

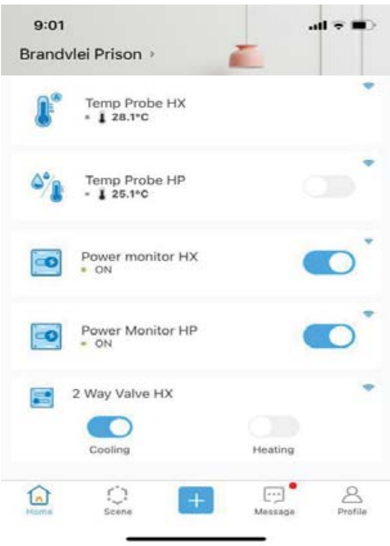


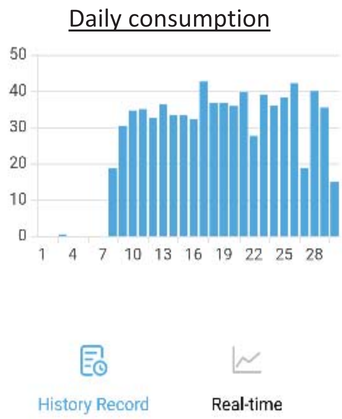
HX system DB Board



HP system DB Board

- **Kilowatt monitoring system –** Sonoff kilowatt meters were used to monitor the power consumption in each system. The mobile application, eWeLink, was then used to monitor the daily power consumption, remotely. This app could then also be used to check that the systems were running optimally. If on the app, the systems were offline, it meant that the power to the systems had tripped, or the Wi-Fi device had run out of data. A Wi-Fi device was necessary to allow for remote, anytime monitoring. If the system's power consumption was lower than normal for an extended period, it could be an indication that a heating system was not working.





Figures 2.2.5 and 2.2.6 show how the components were set up on the chipboard skid tray for the HP system and the HX system, respectively. Solid fish waste would be removed from the RAS systems by the sand filter, and organic waste converted into nitrates by the bio-filter. When the RAS filtration systems were backwashed, the wastewater was pumped into a 2000 L JoJo tank and allowed to settle. Excess water in the backwash tank would be slowly siphoned out of the tank to feed the grass in the field at a minimum distance of 15 m from the closest waterway leading to the overflow pond. The small quantities of excess water, slow siphoning speed and large distance from the waterway made it very unlikely that nutrients would enter the overflow pond, and the grass would also play a role in nutrient uptake. Alternatively, the wastewater from this tank could be used to feed an Aquaponics set-up or a vegetable garden in the adjacent field. An aquaponics system would ensure that wastewater and excess nutrients are re-cycled, rather than discarded, while also eliminating any risks of nutrients entering the spring-water overflow pond.

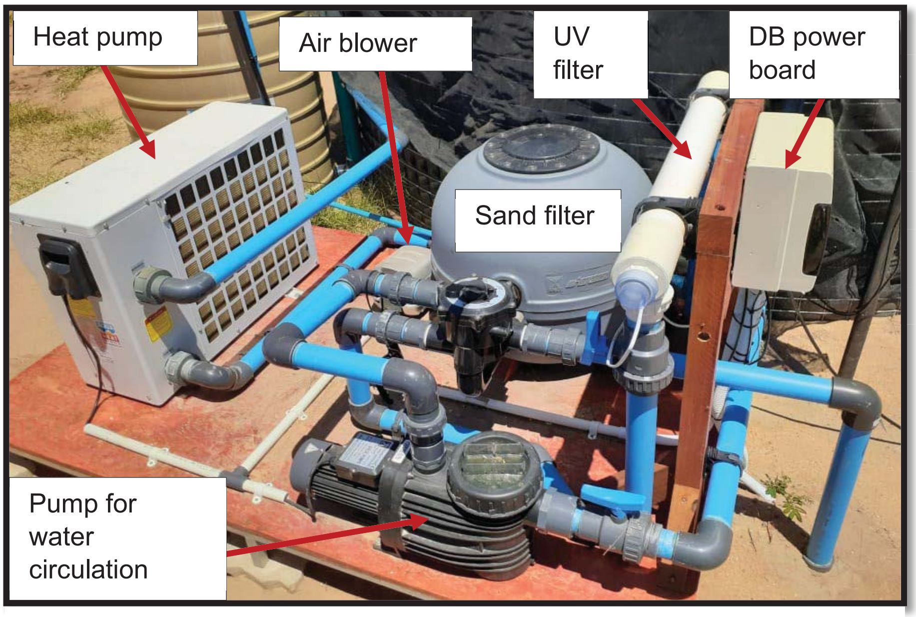


Figure 2.2.5 RAS components on the skid tray for the HP system

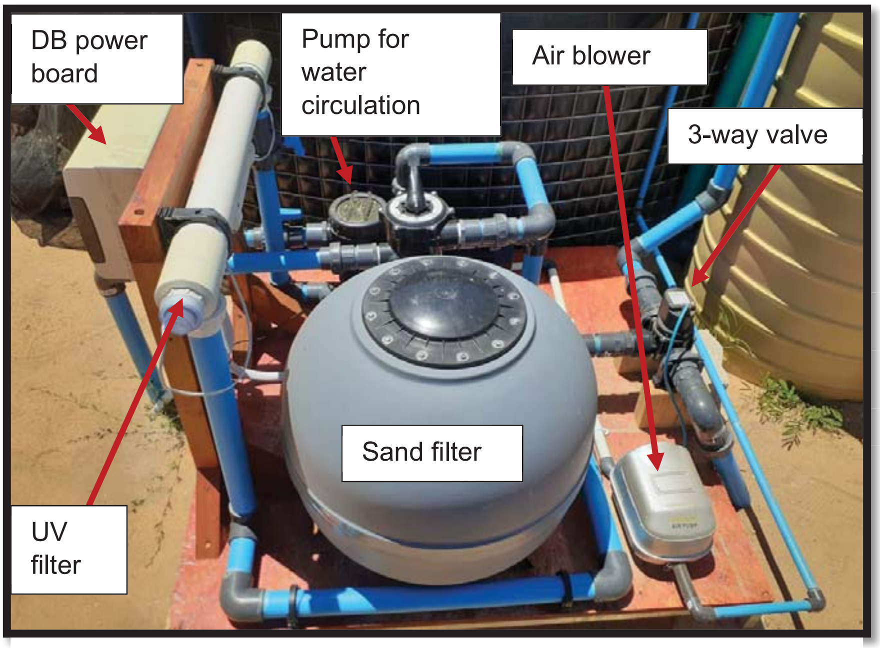


Figure 2.2.6 RAS components on the skid tray for the HX system

2.3. SITE PREPARATION AND SYSTEM INSTALLATION

At the beginning of the project, the site, as indicated by the red square in Figure 2.3.1, was selected for planned placement of the two recirculating aquaculture systems.

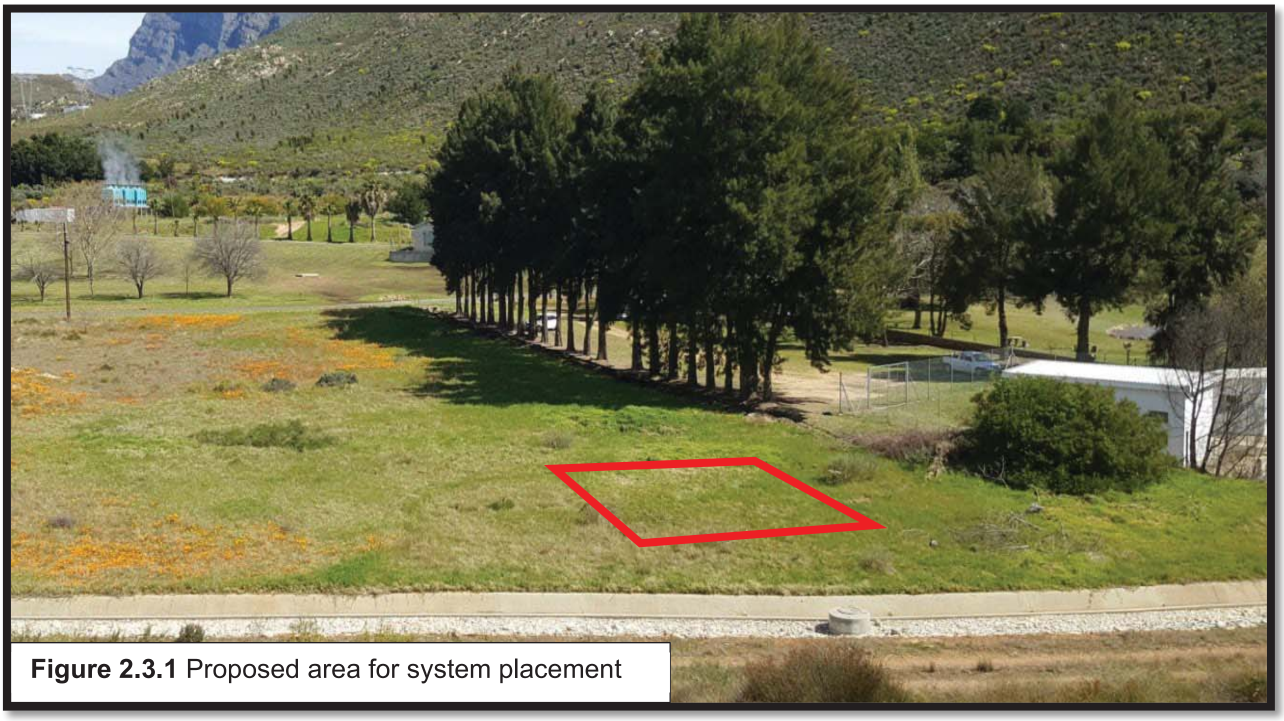


Figure 2.3.1 Proposed area for system placement

Figure 2.3.2 gives an aerial view of the planned placement for the systems, again indicated by the red square, while also showing the site in relation to the hot spring source and the pump house. The water that was required for the filling and top-up of the systems was sourced from a cold-water tap found about 100 m from the systems. Electricity for the systems was sourced from the main DB board at the pump house and was fed into two separate DB boards, one for each system. The Correctional Facility diverts hot spring water via a channel to the pump house for use in their hot water reticulation system. As the heat exchanger had to be placed in close proximity to the hot spring water, it was installed alongside this hot water channel against the corner of the pump house building. When water in the HX system dropped below 28°C, an automatic three-way valve was used to divert the system water via the heat exchanger where it would pick up heat from the hot spring water in a non-contact heat transfer process. The heated water was then returned to the system. A temperature probe was used to detect when the system had returned to 28°C and the three-way valve would then switch back to the usual re-circulating filtration cycle.

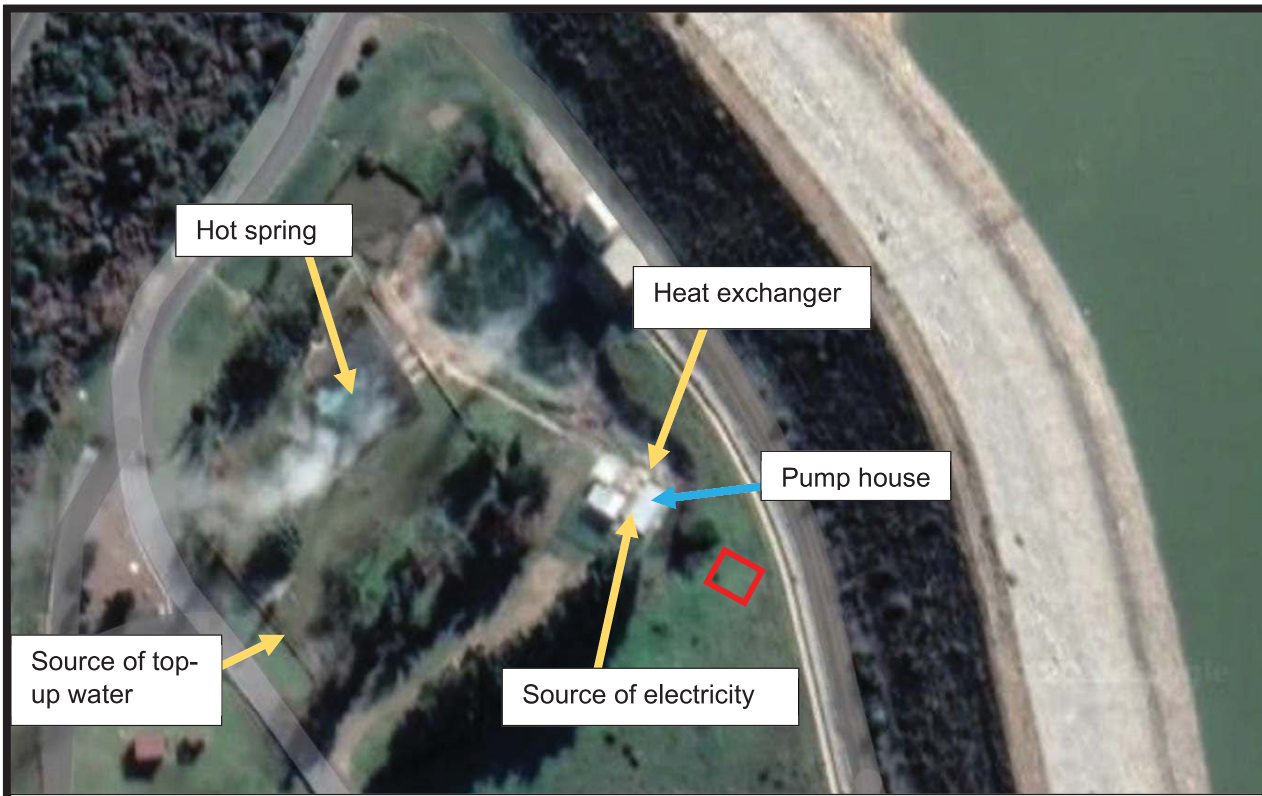


Figure 2.3.2 Aerial view of proposed site (red square) in relation to other elements i.e., the pump house, heat exchanger placement and source of water and electricity

Figure 2.3.3 indicates the proposed site before levelling. Figure 2.3.4 shows the site after DCS had assisted with ground clearing and levelling. And Figure 2.3.5 was taken during the installation process of the two systems by Deep Blue Aquatic Systems and when DCS was in the process of cementing in poles for a perimeter fence.

Figure 2.3.3 Proposed area for levelling and system placement

Figure 2.3.4 Site after ground was cleared and leveled by DCS

Figure 2.3.5 Site during system installation and cementing of fencing poles

The installation of the two systems was completed on the 10 November 2021 and the installation of the fence and gates was completed on the 22 November 2021. Figure 2.3.6 shows the HP system running, with water flowing from the bio-filter into the 10 000 L tank. Figure 2.3.7 shows the heat exchanger that was mounted on a concrete slab above the hot spring water channel which feeds the pump house. Figure 2.3.8 shows the system on the day that installation was completed, and Figure 2.3.9 gives a view of the completed system with the perimeter fence and gates as seen from the Brandvlei dam wall.

Figure 2.3.6 Water flowing in HP system

Figure 2.3.7 Heat exchanger at the corner of the pump house

Figure 2.3.8 System after installation

Figure 2.3.9 Completed system with perimeter fence and gates

2.4. FISH INTRODUCTION

Nile tilapia were successfully introduced into the systems at the beginning of 2022. Fish were first acclimated to the water quality of the system by performing water changes, whereby half of the water in the travel tank was drained and then replaced with water from the systems (Figure 2.4.1). This was then repeated until the temperature and pH of the travel tank was the same as that of the systems. Fish were then batch weighed (Figure 2.4.2) and then counted and released into the systems (Figure 2.4.3), alternating batch by batch between the HP and HX tanks. A mixture of red- and dark-coloured Nile tilapia were stocked (Figure 2.4.4).

A total of 412 fish were placed in the HP system, with the average individual fish weight being 48.495 g. A total of 402 fish were placed in the HX system, with the average individual fish weight being 48.010 g. The stocking densities of the HP and HX tanks at stocking were thus 1.998 and 1.93 kg/m^3, respectively. As a full production cycle wouldn't be possible in the 12-month project timeframe, a co-management plan between SU and DCS was put in place to ensure the continued management of the systems until the average individual fish weight reaches approximately 500 g, or until the stocking density reaches 20 kg/m^3, which is the stocking density recommended for Nile tilapia in RAS setups by DAFF (2018b).

Figure 2.4.1 Fish acclimation to system's water

Figure 2.4.2 Fish weighing

Figure 2.4.3 Fish counting and release

Figure 2.4.4 A mixture of red and dark Nile tilapia

2.5. WATER QUALITY

Water quality parameters were monitored daily after fish introduction. Dissolved oxygen (DO) levels were measured using an IP67 Waterproof Dissolved oxygen meter (Figure 2.5.1 Left) and pH with a handheld pH meter (Figure 2.5.1 Right). Both meters also measured temperature. The optimal water quality levels that are recommended for Nile tilapia can be seen in Table 2.5.1 (DAFF, 2018b).

Figure 2.5.1 Left: IP67 Waterproof Dissolved oxygen meter; Right: pH meter

Table 2.5.1 Optimal levels for water quality parameters for Nile tilapia according to DAFF (2018b)

Water quality parameter	Optimal level
Optimal temperature range	27-32°C (Mengistu et al., 2020)
pH	6-9
DO	4-6 mg/L
Ammonia	Less than 2 mg/L NH_3-N
Nitrites	Less than 5 mg/L NO_2-N

It was already noticed at the beginning when both systems were first filled and were at about 22°C, that the HX system took significantly less time to reach 28°C in comparison to the HP system. When the temperature of the heated water coming from the heat exchanger was measured, it was approximately 35°C. Incoming water at this temperature would quickly heat the system, especially at flow rates of 10 m^3/hour. In comparison, the HP system seemed to lose more heat than it could gain at colder air temperatures in November, dropping to around 23°C on some mornings, even when the heat pump was working at full capacity. This indicated that the systems, or at least the HP system, shall likely require insulation to be able to maintain the optimum temperature during colder weather.

Ammonia and nitrite levels were also monitored daily when fish were first introduced. The nitrogen cycle involves the conversion of ammonia to nitrite, and then from nitrite to nitrate, by beneficial bacteria in the bio-filter (Figure 2.5.2). Ammonia is built up from fish excretion and uneaten food. Nitrosomonas, a bacterium, converts the ammonia into nitrite, which is converted into nitrate by nitrobacter, another bacterium. During both chemical conversions by the bacteria, H+ is released causing a reduction in pH. Ammonia and nitrite are toxic to fish at lower concentrations, whereas; nitrate is also toxic to fish but only at a much higher concentration level. It is thus important to have a well-functioning bio-filter to prevent the build-up of toxic ammonia and nitrite in a system. Regular monitoring of these levels in the beginning will provide an indication of how well the bio-filter is working. Once the bio-filter is established and stable, measurements can be done weekly instead of daily, if all other parameters are acceptable and fish behaviour is normal. To reduce nitrate levels, routine water changes are required (Linbo, 2009).

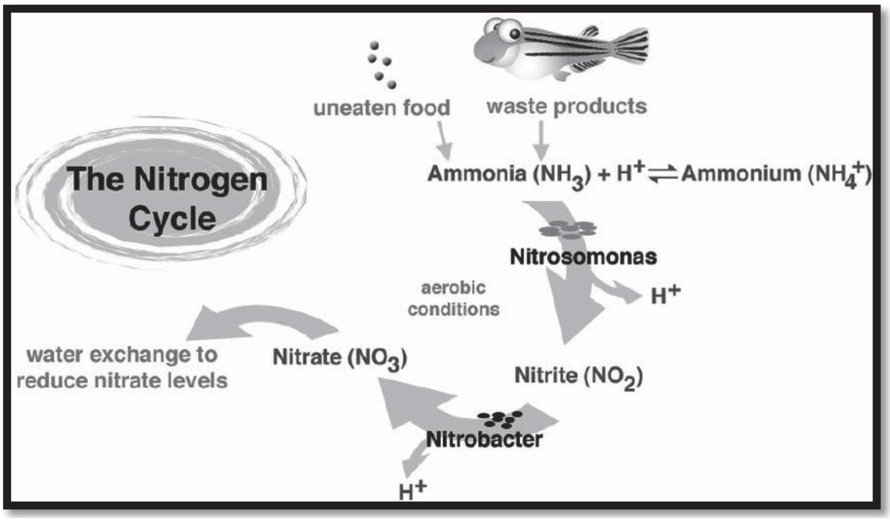


Figure 2.5.2 The nitrogen cycle in aquaculture systems and aquarium tanks. (Linbo, 2009)

3.1. THEORETICAL COMPARATIVE POWER CONSUMPTION

Two power consumption meters were used to monitor the daily power consumption in kilowatts of each system. The Speck pump, air blower and UV light were included in the monitoring of both systems, as well as the heat pump for the HP system; and the heat exchanger pump and automatic three-way valve for the HX system. The theoretical power usage of each component as provided by the supplier specification sheets, can be seen in Table 3.1.1. The average power required to run each system without any heating components was thus expected to be approximately 0.84 kW, which was the same for both systems (Table 3.1.2). At any given time, when both systems were heating, the HX system was expected to use approximately 41.8% less power than the HP system, based on the theoretical values. It should be noted however that the total amount of power required for the heating of each system each day would vary, depending on how long each heating system took to bring the respective 10 000 L body of water back to 28°C.

Table 3.1.1 Theoretical power usage of components in the HP and HX system

Component	Power usage	
	HP system	HX system
UV filter	55 W	55 W
Air blower	35 W	35 W
Speck pump	750 W	750 W
Heat exchanger pump	-	250 W
Automatic 3-way valve	-	4 W
Heat pump unit	1.04 kW	-

Table 3.1.2 Theoretical power usage of each system when they are running and not heating versus when they are running and heating

	HP	HX
Running & no heating	0.84 kW	0.84 kW
Running & heating	1.88 kW	1.094 kW

3.2. RECORDED POWER CONSUMPTION AND DAILY TEMPERATURE

A power consumption graph is given in Figure 3.2.1 which provides the recorded daily power usage of the HP system in comparison to the HX system from 9 November 2021 to 11 April 2022. The minimum daily temperature is also provided on the secondary axis and can be seen as the green line. The minimum daily temperature was used rather than the average or maximum daily temperature, as heating in the system would be initiated when ambient temperatures were low, and it was thus expected that the correlation would be more prominent between power usage and minimum daily temperature.

It is clear from Figure 3.2.1 that the HX system used less power than the HP system at any given time. There also seemed to be some correlation between power usage of each system and the temperature; as when the temperature decreases, power usage can be seen to increase, and vice versa. This correlation is more obvious with the HP system, which is understandably due to the HP system having to use more power to heat the water on colder days. It can also be seen that the power usage of the HX system remains relatively constant over the period of recordings, while that of the HP system appears to be significantly higher in the cooler months of November and April.

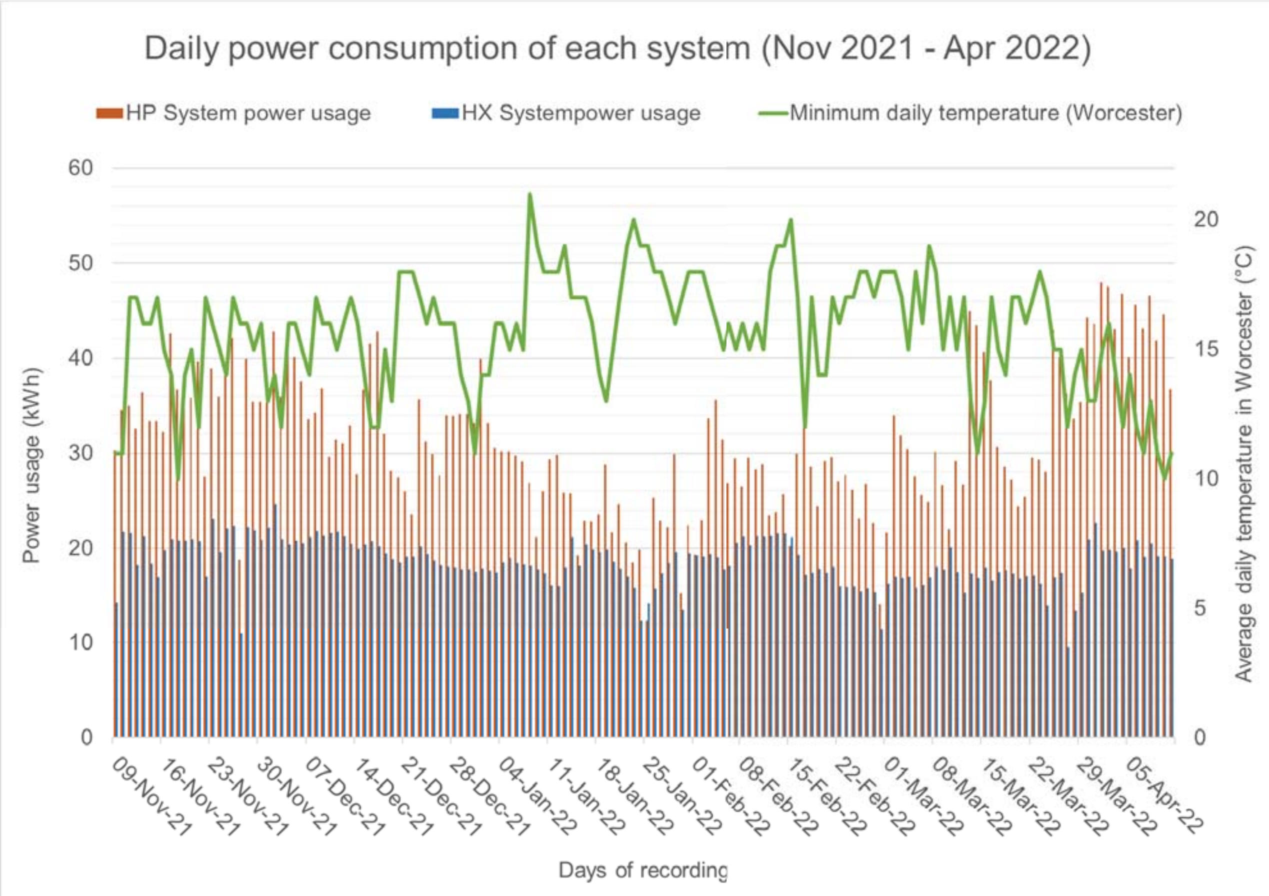


Figure 3.2.1 The daily power consumption for the HP and HX systems, and minimum daily temperatures for Worcester (sourced from AccuWeather, Inc.).

When comparing the average temperature for each month from 9 November to 11 April, it was noted that January, February, and March were the hotter months; while April, November and December were the colder months. This can be seen in the graph of Figure 3.2.2. Different symbols on the graph represent significant differences in average monthly temperature and standard error bars for each month are also provided (Statistical analysis: ANOVA and Bonferroni (Dunn) t Tests, $P<0.05$).

A graph of the average daily power usage per month was also constructed and can be seen in Figure 3.2.3. Power usage was significantly more for the HP system in comparison to the HX system for each of the months that were recorded. There was less of a difference in power usage between the HP and HX system for the months of January and February. This is because these summer months are known for being two of the hottest months of the year, which means that the tanks could be maintained at 28°C with minimal additional heating. Nevertheless, the HP system was still seen to use significantly more power than the HX system in these months, which means that even in the warmest weather, the HX system was still more efficient.

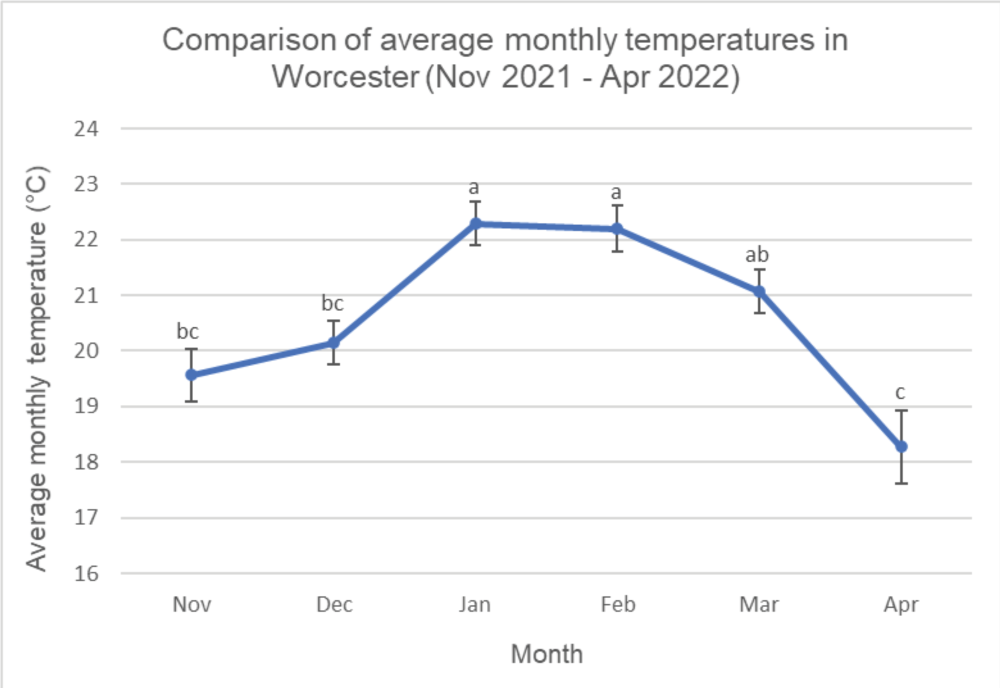


Figure 3.2.2 The average monthly temperature (°C) with standard error bars for Worcester, based on measurements sourced from AccuWeather, Inc. from 9 November 2021 to 11 April 2022. [a,b,c] Means with different superscripts differ significantly ($P < 0.05$).

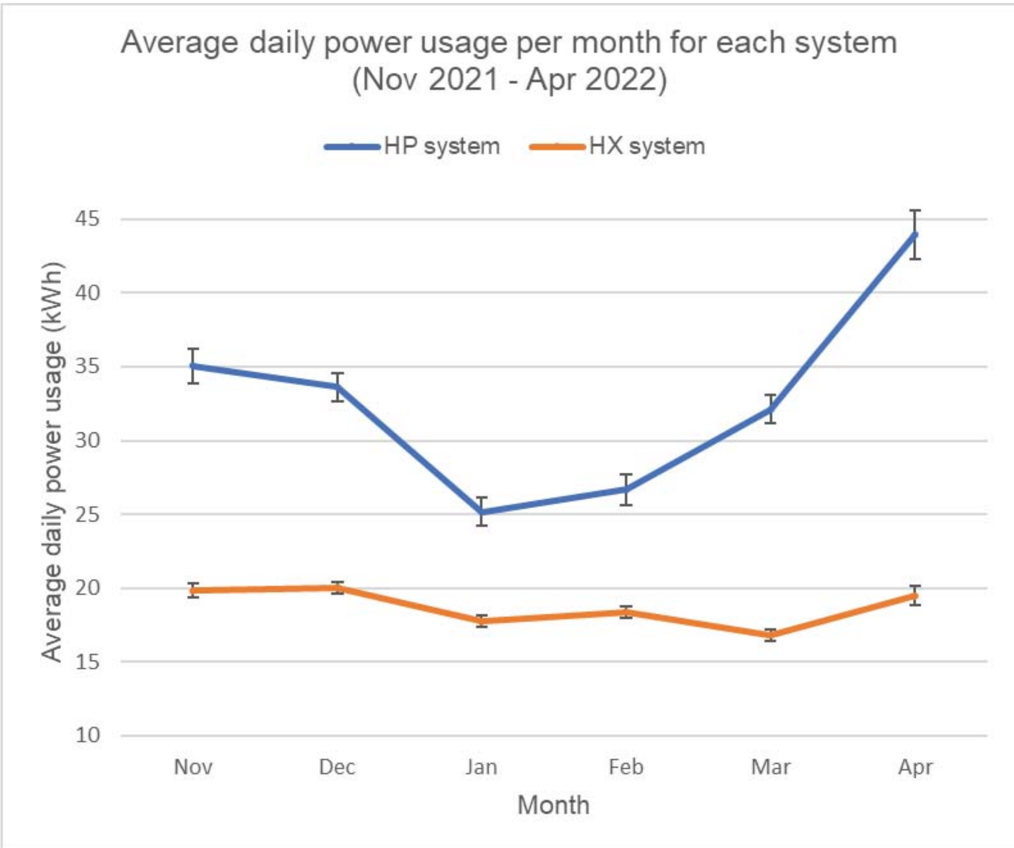


Figure 3.2.3 The average daily power usage given per month (with standard error bars) for the HP and HX system

When looking at Figures 3.2.2 and 3.2.3 together, the power usage line for the HP system appears to have a strong indirect relationship with average monthly temperature. When considering Pearson's correlation coefficients (r) to assess potential correlations between power usage and daily temperature, it was found that correlations were negative and strongest between power usage and the minimum recorded daily temperature (Table 3.2.1). This is because when temperatures were low, more power was required to heat the systems, and the power usage trend would thus better correlate with the minimum temperature, as was hypothesized earlier in this section.

Correlation coefficients for the HP system were based on monthly averages for power usage and minimum temperature because the average values better described the trend; while for the HX system, correlation coefficients were based on daily records because the relatively constant average monthly values did not provide evidence of a significant straight-line relationship between the monthly averages for power usage and minimum temperature.

The HP system indicated a strong negative correlation with minimum temperature, while the HX system indicated a moderate negative correlation with minimum temperature. This again supported the fact that the HP system required more power for heating than the HX system.

Table 3.2.1 Pearson's correlation coefficients (r) describing the relationship between average monthly temperatures and average monthly power consumption for the HP system; and between daily temperatures and daily power consumption for the HX system.

	Temperature		
Power consumption	**Minimum**	Average	Maximum
HP system	**– 0.997**	– 0.979	– 0.915
HX system	**– 0.297**	– 0.286	– 0.215

3.3. COMPARATIVE COSTS

When relating the power consumption of each system back to cost, we referred to two different electricity user tariffs as specified by the City of Cape Town (2021). It can be seen in Table 3.3.1 that the total power (running and heating) used for 15 days in November when the systems were fully operational would cost between R675.00 and R1 331.00 for the HP system, in comparison to between R387.00 and R764.00 for the HX system (tariff dependent). This shows that over the 15-day monitoring period, the HX system cost 42.6% less to run, compared to the HP system.

In December, the total power cost would have been between R1 267.00 and R2 501.00 for the HP system, and between R755.00 and R1 490.00 for the HX system. The HX system therefore cost 40.4% less to run in December, compared to the HP system. The total cost for December is just more than double that of November, as power usage data was recorded for only 15 days in November but was recorded for 31 days in December.

For January and February, the cost savings percentage for the HX system in comparison to the HP system was 29.6 and 31.1%, respectively. The drop in cost savings percentage from November to February could be attributed to less power that was used for heating during these summer months. Theoretically, if the minimum temperature remained at 28°C across a full month, no heating of the systems would be required, and the power consumption should be equal for both systems (Table 3.1.2). The cost savings percent would thus become more profound as temperatures decreased on cold days and in winter months. As seen for the months of March and April, the cost savings percentage increased to 48.5 and 55.7%, respectively, and this percentage is expected to be even greater for the actual months of winter (June to August).

Table 3.3.1 Cost in Rands of total recorded power usage of each system for the months of November 2021 to April 2022, based on two electricity user tariffs, and cost savings percentage of using the HX system in comparison to the HP system.

Month	Tariff	HP system cost (Rands)	HX system cost (Rands)	Cost saved (%)
*November 2021	Off peak	675	387	42.6
	Home	1 331	764	
December 2021	Off peak	1 267	755	40.4
	Home	2 501	1 490	
January 2022	Off peak	949	668	29.6
	Home	1 873	1 319	
February 2022	Off peak	909	626	31.1
	Home	1 793	1 236	
March 2022	Off peak	1 211	623	48.5
	Home	2 389	1 230	
**April 2022	Off peak	588	261	55.7
	Home	1 160	514	

Off peak = Commercial user: large power user, low voltage, off peak/low demand months (Sept-May) is 121.62 c/kWh; Home user = tariff for <600 kWh usage is 240.04 c/kWh (City of Cape Town, 2021). *For 15 days in November 2021. **For 11 days in April 2022.

An unfortunate limitation that was realised, was that the power consumption meters only recorded the total power used for each system each day and did not record at smaller intervals. It was therefore not possible to obtain accurate estimates of running and heating power consumption separately. Manual monitoring was possible however for an accurate estimation, manual recording of power consumption for each system would be required at minute intervals, which was not reasonable. On days when manual recordings were done it was observed that the power usage for running the systems without heating varied above and below the theoretical value of 0.84 kW. This can also be seen on the graph in Figure 3.1 where on certain days the total power usage for the HX system is seen to be below the value of 20.16 kWh which is the theoretical power usage for running the system for 24 hours without heating. Nevertheless, it is still possible to get a good idea of costs saved based on total daily power consumption. Improvements to this study would thus involve either changing the power meters to record power used for heating only (comparing power used by heat pump versus the power used by 3-way valve and heat exchange pump), or to find a power recording programme that would record power usage at minute intervals.

3.4. POWER CONSUMPTION AND COST SAVINGS PROJECTIONS FOR 2021

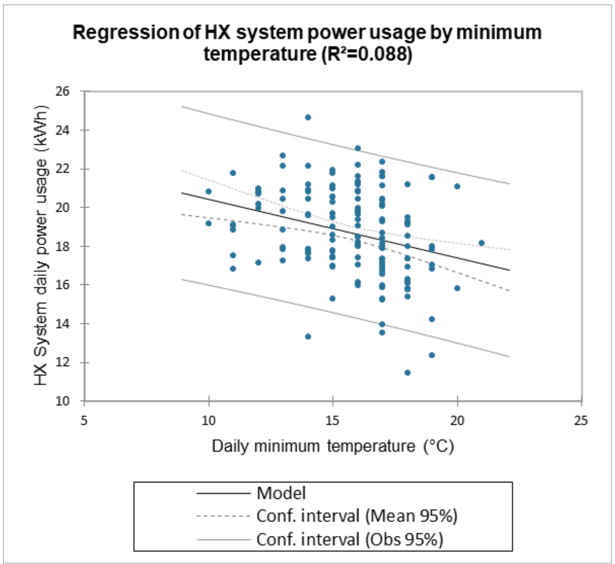
A simple linear regression analysis was performed for the HP and HX system separately, to make predictions of the cost of running each system for all twelve months in 2021 based on historical temperature records for that year (AccuWeather, Inc.). The mathematical formula that was used is as follows:

$$Y = \beta_0 + \beta_1 X + \epsilon$$

Where Y represents daily power usage for the HX system, and average monthly power usage for the HP system; β_0 is the intercept of the best-fitting line; β_1 is the gradient of the best-fitting line; X represents the minimum daily temperature for the HX system analysis, and average monthly minimum temperature for the HP system analysis; and ϵ represents the residual error.

As mentioned earlier, the use of average monthly values was suitable for the regression analysis of power usage on minimum temperature for the HP system, due to the high coefficient of determination value (R^2=0.994) and a significant regression coefficient which indicated a significant linear relationship between the two variables. For the HX system, daily values were used because even though there was a great deal of variation around the regression line (R^2=0.088), the regression coefficient was still significant indicating a significant linear relationship between the two variables.

The fit of the linear model is better for the HP data than for the HX data as seen by the R^2 values in Figure 3.4.1. This is again because the HP system requires more power for heating when ambient temperatures drop, over and above the power required for running the system; in comparison to only minimal power being required for heating the HX system above the running power requirements.



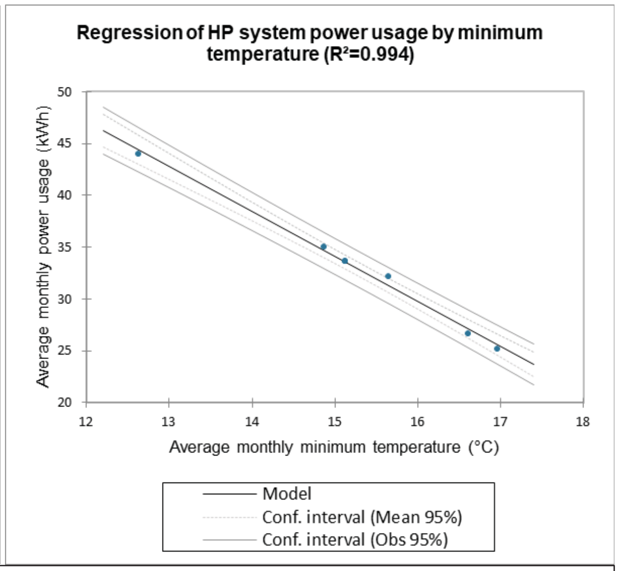


Figure 3.4.1 Regression for the HX system of daily power usage on daily minimum recorded temperatures for Worcester, and for the HP system of average monthly power usage on average monthly minimum temperatures for Worcester. Values are based on measurements from November 2021 to April 2022.

Although the fit of the linear regression model was not very high for the HX system, the model was still used to make approximate predictions. Predicted monthly power usage and the cost savings percentage predicted for using the HX versus the HP system for the full year of 2021 can be seen in Table 3.4.1. The total predicted power savings for the HX system in comparison to the HP system for the year of 2021 was 57.8%, based on regression model equations that were formulated using the current recorded data (November 2021 to April 2022).

It should be noted that for the months of June, July, August and September, predictions were based on extrapolation as the obtained regression model equations were based on temperatures that were more than 10°C.

Table 3.4.1 Predictions of monthly power consumption and power savings for HP and HX system for 2021 based on average monthly minimum temperatures recorded for Worcester in 2021

Month in 2021	Average monthly minimum temperature (°C) in 2021	predicted power consumption (kWh)		Predicted cost savings (%)
		HP system	HX system	
January	16.9	797	568	28.7
February	17.1	699	512	26.8
March	15.0	1053	586	44.3
April	13.1	1266	584	53.9
May	10.0	1734	633	63.5
June	9.4	1757	619	64.8
July	6.7	2177	664	69.5
August	7.4	2082	658	68.4
September	8.9	1813	622	65.7
October	11.4	1548	620	59.9
November	14.0	1149	576	49.9
December	15.1	1040	585	43.7
Predicted totals for 2021	**-**	**17115**	**7228**	**57.8**

The total predicted cost of running and heating the systems for 2021 can be seen in Table 3.4.2. These values work out to an average monthly running and heating cost of between R3 838.50 and R3 423.00 for the HP system and between R1 445.60 and R1 411.25 for the HX system. The reason that the amounts are similar between the commercial user and the home user is because during peak months (June-Aug) the commercial user pays a higher tariff per unit of electricity. The percentage cost saved by using the HX system instead of the HP system for a year is thus more for a commercial user (63.2%) than for a home user (57.8%), as the HX system would use less power than the HP system for heating in the peak months when electricity is more expensive.

Table 3.4.2 Predicted total cost of heating and running the HP and HX system for 2021 based on two electricity user tariffs, using regression equations and average monthly minimum temperatures recorded for Worcester in 2021

	Total predicted cost for 2021	
	Commercial user	Home user
HP system	R 46 062.00	R 41 076.00
HX system	R 16 935.00	R17 347.00
Cost saved (%)	63.2	57.8
Commercial user: large power user, low voltage, peak/high demand months (June-Aug) is 541.29 c/kWh; Off peak/low demand months (Sept-May) is 121.62 c/kWh. Home user: tariff for <600 kWh usage is 240.04 c/kWh. (City of Cape Town, 2021)		

In terms of power usage and cost savings, the HX system is clearly more efficient. Prediction models will become more accurate as more data is collected, especially over the winter months. Once fish have been harvested at the end of the growth cycle, production data will aid in making further cost projections which can be used to estimate costs and requirements for expansion.

3.5. FISH GROWTH

Due to this being a 12-month project, a full growth cycle (±6 months) was not possible within this project's timeframe, but the co-management plan between SU and the DCS was established to ensure continued maintenance of the fish and the system until harvest at ±6 months. Harvest production parameters (survival rate, growth, feed conversion ratio, etc.) thus did not fall within the scope of this project but would be measured and recorded past the project end-date, nevertheless.

A fish weighing day was held prior to compiling this final report, when fish had been in the system for two months. There was a large variation in size of the fish (10-250 g for HP; 15-200 g for HX), due the unfortunate large variation in size at stocking. However, the average fish weights had increased by more than 1.8 times since stocking. For the HP system, the average fish weight increased from 48.5 to 88.6 g; while for the HX system, the average fish weight increased from 48 to 88.9 g. It should also be noted that two technical issues relating to the system design hampered growth for a few weeks after fish introduction, so feeding and growth were not optimal during those times.

Figure 3.5.1 shows how the fish were confined to a smaller area in the tank for easier netting and weighing. In Figure 3.5.2 the photo on the left shows fish being released again after weighing; and the photo on the right shows fish that have already been released after weighing as they swim around in the larger area of the tank. Figure 3.5.3 shows a Nile tilapia from the HP tank after being weighed.

Figure 3.5.1 Confining fish to a smaller area for easier netting prior to weighing

Figure 3.5.2 *Left*: Fish being released after weighing; *Right*: Fish swimming in larger area after weighing.

Figure 3.5.3 A Nile tilapia from the HP tank after 2 months in the system

3.6. SWOT ANALYSES

In order to assess the application of the project test-systems for fish production and skills development, two SWOT analysis tables were compiled looking at the strengths, weaknesses, opportunities and threats associated with firstly, the continued use of the system past the project end-date for fish product-use and distribution; and secondly, to assess the potential of the system as a training facility for aquaculture skills development. These two analyses are provided in Table 3.6.1 and 3.6.2 respectively.

Table 3.6.1 SWOT analysis looking at the potential for continued use of the system past the project end-date for fish product-use and distribution

Strengths	**Weaknesses**
• The only geothermal aquaculture system in the country which will allow for cost effective farming throughout the winter period • The available resources on site allow for large scale farming and rotational production of fish all-year round. • The geothermal hot spring provides a constant temperature for the fish to grow optimally thus the fish remain in the production cycle for a shorter period, increasing profits and limiting overhead costs • Would provide a sustainable and more cost-effective supply of protein to the inmates • Assists in the development of new skills and there is the availability of labour on site • There is the availability of market should the aquaculture setup be expanded into a commercial supplier of tilapia • The site has a large amount of open land and resources, therefore there is the capacity to grow and expand	• High cost of fingerlings and feed does increase the cost of production • Lack of investment and/or funding • Requires constant observation and committed staff to manage the facility • No alert alarms currently on site (budget restrictions); alarms are necessary for any aquaculture system to alert of system power issues, to prevent the possibility of large-scale mortalities • Power supply issues to the facility causing excessive stress and wear on the systems
Opportunities	**Threats**
• Provide a constant supply of tilapia to the South African market as other farms are at limited capacity or non-operational in winter • Development of skills while supplying a constant and sustainable resource to Brandvlei and other correctional centres • Strategic use of the fish waste in farming of vegetables and fruit can be highly beneficial • Investigating alternative feeds which could lower production costs • On-site processing develops skills and increases the value of the fish should the facility wish to sell to a commercial market	• Delayed response to power cuts on weekends where generators may run out of fuel and there is a delay before it is refilled • Lack of 24hr on-site labour (especially weekends) • Lack of alarms and cameras for constant monitoring of the fish and the systems • Lack of funding

Table 3.6.2 SWOT analysis looking at the potential of the system as a training facility for aquaculture skills development

Strengths	Weaknesses
1. This site allows for hands on practical experience and training 2. Low-cost duplicate environments 3. Knowledge gained in a specialised field that will assist in making a candidate more hireable once leaving the facility 4. While gaining essential skills, the individuals are growing fish and producing a necessary and sustainable protein for the facility 5. Individuals will gain strong technical skills as well as theoretical knowledge which they will apply on site 6. There are varied training scenarios at different levels of the life cycle/production cycle of the fish 7. Cost effective training 8. Not limited to certain individuals who have prior knowledge, all skills and knowledge can be gained by on-site experience	• The current setup can only handle a small number of individuals at a time • Requires knowledgeable individuals to constantly supervise the trainees • It is not a multi-user friendly site as each individual needs to be aware of what the other has done or has not done at any given time • Long periods of repeating the same skills; new skills can only be developed when the fish reach the next stage of the production cycle • Limited testing kits and meters which are costly to replace if damaged
Opportunities	**Threats**
• The site can be expanded to allow for larger training groups • A rotational production cycle will allow for groups to be exposed to various scenarios allowing for greater skills development • Flexibility in training schedules will allow for multiple groups participating at any given time • Regional interest and collaboration with other facilities or institutions	• Commitment to the expansion of the facility and skills development • Limited or no funding for continued production and expansion • Lack of regulation and communication • On-site mistakes if not controlled or accounted for could result in long term issues which could be detrimental to the functioning of the aquaculture facility

CHAPTER 4: CONCLUSION AND RECOMMENDATIONS

This 12-month project was able to successfully use wasted heat energy from a natural hot spring located at the Brandvlei Correctional Facility in Worcester to support sustainable warm water tilapia aquaculture by using a heat exchange process to extract heat from the hot spring water and transfer it to the water of a 10 000 L fish system.

In order to test whether this alternative method of heating was viable in a warm-water aquaculture setting, two separate single-tank RAS systems were designed and installed in close proximity to the hot spring. The one system consisted of a conventional heating method (as a ‘control’), and the other used the heat from the Brandvlei geothermal spring to heat the system’s water. Both systems were designed to maintain an optimal temperature for tilapia aquaculture (28°C). For the ‘control’ heating method, a heat pump was used, and the system was referred to as the HP system; and for the ‘geothermal’ heating method, a flat-plate heat exchanger was used, and the system referred to as the HX system. Kilowatt meters were then used to monitor and record daily power consumption for each of the systems separately.

Fish were stocked successfully in both systems, however, due to this being a 12-month project, a full growth cycle (±6 months) was not possible within this project’s timeframe, but the co-management plan between Stellenbosch University and the Department of Correctional Services was established to ensure continued maintenance of the fish and the system until harvest at ±6 months.

From the power consumption records it was seen that the HX system used less power than the HP system at any given time. Records for monthly power usage for the period from November 2021 to April 2022, showed that the cost savings percentage was as high as 55.7% for the coldest month (April) when comparing the daily power usage for the HX system to that of the HP system.

It was seen that the average monthly power usage of the HP system had a strong negative correlation with the minimum average monthly temperature for Worcester; whereas the power usage for the HX system appeared to be relatively consistent over the months, having only a moderate negative correlation with minimum temperature. The power consumption records and historical temperature records for ambient temperature in Worcester were used in simple linear regression analyses to make predictions for what the systems may have cost to run for the full previous year of 2021. In terms of power usage, predictions indicated that the HX system would use 57.8% less power than the HP system for the full year of 2021. In terms of the average monthly cost for running and heating the systems, it was predicted that for 2021 it would cost between R3 838.50 and R3 423.00 monthly for the HP system and between R1 445.60 and R1 411.25 monthly for the HX system. Depending on the electricity user tariffs, this could be a cost-savings percentage of between 57.8 and 63.2%. It is expected that in colder weather or in winter months, the cost savings percentage will be higher to a point, and then the HP system would most likely need insulation to keep temperatures from dropping below 28°C.

Besides the cost savings advantage, another major benefit of using a heat exchanger for geothermal aquaculture is that the geothermal water does not come into contact with the water of the aquaculture system. This means that even geothermal hot springs with poor water quality can be used, as it would just be the heat that would be used from these springs.

As mentioned in Chapter 3, a limitation for data collection was that the power consumption meters only recorded the total power used for each system each day and did not record at smaller intervals. It was therefore not possible to obtain accurate estimates of running and heating power consumption separately. A recommendation for improvement would thus be to either change the power meters to record power used for heating only (comparing power used by heat pump versus the power used by 3-way valve and heat exchange pump) or to find a power recording programme that will record power usage at minute intervals.

Another recommendation would be to put a roof over the system. This would protect the system components from sun damage and would also prevent excessive heating of the systems during very hot summer days, as we observed the water temperatures of the two tanks reach 33°C on some days in January. The fish still survive at these temperatures, but their feeding rates decrease which reduces growth and production. We are currently using thick black shade netting to cover each tank, to act as a sunscreen and to prevent birds or predators from accessing the fish, while also preventing fish from jumping out of the tanks. If a roof was constructed, thinner netting with 1 x 1 cm holes could be used to cover the tanks, which would allow for easier feeding and appetite monitoring. A roof would also prevent excess rain from entering the system and would provide cover for feeding and system management during winter months. There would also be less chance of electrical faults with a roof covering.

The cell phone signal at the system is very limited, which can make communication with a manager at the system difficult. Especially if there is an issue or emergency, it can become tedious to hike up the dam wall each time to find signal and then back down again each time to troubleshoot. A solution would be to set up a router and Wi-Fi Omni Antenna at the site which the manager and essential project members can then connect to.

A final recommendation would be to consider purchasing and setting up a remote alarm system which would notify the manager and core project members about any system failure on their cell phone. This will encourage an immediate response and quick remedial action; whereas currently, a fault in the system would only be picked up by being at the system itself, or otherwise by accessing the power consumption application on a cell phone and seeing that the systems are offline.

APPENDIX

Tilapia training workshop attended

Two of our team members, Samantha Joao and Tassin Jackson, attended a very informative Tilapia Aquaculture Training Workshop from the 28 June to 1 July 2021 in Muldersdrift, Johannesburg. The course was given by a company called David Fincham Aquaculture and included course material and activities on water quality, details on the Tilapia species, marketing, the business side (feed, labour, costs), and we were given the opportunity to get hands-on experience in a RAS tilapia system. Some pictures from the workshop can be seen below.

From Left: David Fincham, Samantha Joao, Tassin Jackson, Gugulethu Muleya, Nontobeko Ntsinde.

Pictures from the Tilapia Aquaculture Workshop hosted by David Fincham Aquaculture in Muldersdrift, Johannesburg.

Demonstration workshop provided at the HP and HX systems

A demonstration/training workshop was held in January 2022, a week after fish were stocked into the systems for interested members from the Department of Correctional Services. Two sessions were held, one in the morning at 10:00 and another in the afternoon at 14:00, with the aim of accommodating those who may have had different work schedules. In both sessions, a brief overview of each system's components was provided, and the purpose of the project was explained. Water quality parameters and the importance of taking these measurements was discussed. Attendees witnessed the addition of biofilter bacteria to the systems; a feeding demonstration was also provided; fish behaviour and best practices for feeding was discussed; and it was shown how to measure each of the important water quality parameters with the appropriate test kits and meters.

There were 12 members from DCS who attended the first session and 24 members who attended the second session. The DCS members who attended were from numerous correctional service centers including medium security, maximum security, the youth center, and agriculture center. The area commissioner officer and the regional head of DCS facilities in the Western Cape were also present. Responses and feedback were all positive and there was genuine excitement for the possibilities surrounding aquaculture at this site in the future. Some pictures from the workshop can be seen below.

View of the system from outside the fence

Water quality parameters being explained and demonstrated.

Members who attended the workshop at 10:00.

Members who attended the workshop at 14:00.

Feedback: An intern's experience

Mr. Lyle Wilson was enrolled as an intern at Stellenbosch University towards the end of 2021. He spent two days gaining aquaculture skills and knowledge on a tilapia fish farm in Paarl at the beginning of 2022. He has been co-managing the system at Brandvlei since fish introduction, alongside a member from DCS, and will continue to do so until the time that fish are ready to be harvested. The following feedback was given by Mr. Wilson regarding his experiences in the aquaculture systems this year.

<u>**My experiences on a fish farm**</u>
by Lyle Wilson

"Working on a fish farm was a new experience for me. Reading journals and articles about the practice does not prepare you for the challenge of being there.

Your day starts at seven, where you visit your site, check that the water levels are correct, checking that the water flow is correct and most importantly that none of the fish have died overnight. Once that has been done, you start with your first feeding.

Feeding is not a difficult task, but a constant and important task. You cannot forget to feed at any point during the day. Lack of feeding hinders the growth of the fish, something that costs money on a farm. Feeding is carried out using a growth formula that is based on a percentage of the weight of the fish. It is important to be there in person when feeding, as often the fish will respond differently if certain optimal conditions are not met. If they are not feeding it could also be another sign that something in your system is incorrect. For optimum growth, feeding is recommended to occur five times a day. This means that when taking care of other matters around the fish farm you must be consistently aware of the next feed.

There is also continual site maintenance that needs to happen. Feed needs to be topped up, water levels checked, waste disposed of and implements cleaned. While seeming mundane, if this is forgotten it slows down the schedule for the day. Fish have to be moved and weighed to monitor growth. This task needs to be handled with haste, as the shorter the time taken to complete, the better for the individual fish. When it comes to preparations for harvest, specimens need to be prepared for humane death. This involves preparing them in a tank of clean water before killing and freezing for shipping to their destination.

One of the overarching tasks at a fish farm is water quality management. Measuring dissolved oxygen, pH and temperature are at the core. Once you learn how to use all the probes, the testing still requires attentiveness as mistakes lead to incorrect interpretations. The equipment also needs to be well maintained and carefully used as they are expensive and sensitive. You can adjust the pH and acidity using calcium carbonate and calcium hydroxide. This process is time consuming as the chemicals need to first be individually put into suspension, before being slowly added to the system to prevent the fish going into shock. Secondly to these are other chemical tests. These tests look at the iron, nitrogenous waste, calcium, copper and other elements for presence in the water. These require precision to ensure that the test is being accurately administered.

Overall while running a fish farm appears to be a series of easy tasks, it is anything but that. You need to be familiar with your system, where the water flows, the direction of flow, where the water channels to after the tanks and what process occurs in the filters, sumps and other equipment. This familiarity allows you to problem solve, isolate a problem and correct it. Problems in a system need to be solved quickly to prevent mortalities. These problems don't keep office hours either.

Continues on next page…

You also need to have time. Once you complete a task you realise it is time for a feeding and depending on the size of your farm it could take a while. In the interim another issue arises that may need solving. So, while individually it may not be challenging, all these tasks together are quite daunting. This is compounded by the fact that these issues often have knock on effects with the end result affecting the fish. It is therefore important to solve the issues as soon as they arise.

Working on a fish farm was an experience. But overall, it taught me the importance of understanding your system thoroughly, from the mechanics to the biology and chemistry. This allows you to problem solve effectively and efficiently. It prevents issues from becoming calamities and most importantly, the loss of fish."

Co-management plan

A meeting was held on the 22 November 2021 with relevant members from the DCS to discuss collaborative management of the aquaculture test system at Brandvlei for 2022.

It was decided that a member from Stellenbosch University (Mr. Lyle Wilson) and a member from Brandvlei Correctional Services (Mr. Johan Coetzee) would be assigned to co-manage the systems until September 2022, where after the DCS must decide whether they would like to continue with the systems or otherwise the systems will need to be deconstructed and removed. For the initial three months after fish stocking, Mr. Wilson will be on site more frequently (20 days and nights per month) to develop a suitable daily routine with Mr. Coetzee for optimal system and fish management.

The routine will involve the following:

1. Three checks
    - Check how the fish are behaving
    - Check for water leaks
    - Ensure that the water is being recirculated – water is flowing
2. Then remove mortality's and begin first feed. The feed will be calculated at the percentage of body weight per fish.
3. Perform water quality tests which include checking the pH, temperature, and dissolved oxygen.
4. Perform a back wash of the sand filter and then rinse the system (every second day).
5. Top up the system with new water to replace the water lost through backwashing and rinsing.
6. Another 4 feeds should take place throughout the day before dark. It is better to hand feed the fish, to ensure that feed is not wasted as an excess waste can contribute to poor water quality and subsequent issues in the system.
7. After the final feed, the feed bucket for each tank must be weighed to determine the total amount of feed eaten per tank.
8. The final task for the day would be to siphon the water from the waste tank onto the grass in the field at least 15 m from the closest waterway. This will be temporary until the aquaponics system can use this water after it is constructed in February 2022.

At the end of the initial three months, a new schedule will be drawn up between Mr. Wilson and Mr. Coetzee for co-management for the next three months, with the idea that Mr. Coetzee will take more management responsibility. This will be the best route to follow to encourage successful hand-over of the systems to DCS at the end of the data collection process in September 2022.

Once a month, the project team will visit the site to weigh and count fish so as to obtain updated growth data. The DCS has also mentioned that they would like to put a team of inmates together who can work and learn skills in the system and who will be managed by Mr. Coetzee.

A co-management guide is given as *Appendix A* at the end of this document, which provides information and tips for successful management of the systems at Brandvlei. Information on re-stocking was not provided in this guide, as production data will first need to be collected up until harvest before stocking suggestions can be given. In terms of future optimization, it is also too early to provide recommendations other than what was suggested in Chapter 8.

REFERENCES

Adeleke, B., Robertson-Andersson, D., Moodley, G. and Taylor, S. (2020). Aquaculture in Africa: A Comparative Review of Egypt, Nigeria, and Uganda Vis-Ã-Vis South Africa. *Reviews in Fisheries Science & Aquacultur*e, 1–31.

Akinwole, A.O. and Faturoti, E.O. (2007). Biological performance of African Catfish (*Clarias gariepinus*) cultured in recirculating system in Ibadan. *Aquacultural Engineering*, 36: 18-23.

Arthur, R.I., Lorenzen, R., Homekingkeo, P., Sidavong, K., Sengvilaikham, B. and Garaway, C.J. (2010). Assessing impacts of introduced aquaculture species on native fish communities: Nile tilapia and major carps in SE Asian freshwaters. *Aquaculture*, 299(1-4), 0–88. https://doi.org/10.1016/j.aquaculture.2009.11.022

Azaza, M. S., Dhaïef, M. M., Kraïem, M. M. (2008). Effects of water temperature on growth and sex ratio of juvenile Nile tilapia *Oreochromis niloticus* (Linnaeus) reared in geothermal waters in southern Tunisia. *Journal of Thermal Biology,* 33: 98-105.

Badiola, M., Basurko, O.C., Piedrahita, R., Hundley, P. and Mendiola, D. (2018). Energy use in recirculating aquaculture systems (RAS): a review. *Aquacultural engineering*, 81, 57-70. https://doi.org/10.1016/j.aquaeng.2018.03.003

Baird, C. D., Bucklin, R. A., Watson, C. A. and Chapman, F. A. (1993). Heat pump for heating and cooling water for aquacultural production. Circular 1096, Florida Energy Extension Service, Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences, University of Florida, USA.

Becker, K. (2004). One century of radon therapy. *International Journal of Low Radiation*, 1, 333. https://doi.org/10.1504/IJLR.2004.005434

Boekstein, M.S. (2012). Revitalising the healing tradition – Health tourism potential of thermal springs in the Western Cape. Thesis submitted in fulfilment for the degree of Doctor of Technology: Tourism Management, Faculty of Business at the Cape Peninsula University of Technology.

Boyd, T.L. and Lund, J.W. (2003). Geothermal Heating of Greenhouses and Aquaculture Facilities. Proceedings of the International Geothermal Conference, 14-19.

City of Cape Town (2021). Tariffs, fees and charge book, Annexure 8, 2021/22 Budget. Available at: https://resource.capetown.gov.za/documentcentre/Documents/Financial%20documents/Electricity%20Consumptive%20Tariffs.pdf

Craig, S. (2017). Understanding Fish Nutrition, Feeds, and Feeding. College of Agriculture and Life Sciences. 420-256

Dhansay, T., de Wit, M. and Patt, A., (2014). An evaluation for harnessing low-enthalpy geothermal energy in the Limpopo Province, South Africa. *South African Journal of Science*, 110(3/4), 1–10. https://doi.org/10.1590/sajs.2014/20130282

DAFF. (2018a). Catfish sharptooth feasibility study final report. Pretoria. South Africa.

DAFF. (2018b). Nile and Mozambique tilapia feasibility study final report. Pretoria. South Africa.

Department of Water Affairs and Forestry, South Africa (2008). The Assessment of Water Availability in the Berg Catchment (WMA 19) by Means of Water Resource Related Models: Groundwater Model Report Volume 9 – Breede River Alluvium Aquifer Model. Prepared by Umvoto Africa (Pty) Ltd in association with Ninham Shand (Pty) Ltd on behalf of the Directorate: National Water Resource Planning. DWAF Report No. P WMA 19/000/00/0408.

Diamond, R. (1997). Stable isotopes of the thermal springs of the Cape Fold Belt. Submitted as fulfilment for the degree of Master of Science, Department of Geological Sciences, University of Cape Town.

Diamond, R.E. and Harris, C. (2000). Oxygen and hydrogen isotope geochemistry of thermal springs of the Western Cape, South Africa: Recharge at high altitude? *Journal of African Earth Sciences,* 31 (3/4) 467-481. https://doi.org/10.1016/S0899-5362(00)80002-0

Donaldson, I.G. (1982). Heat and mass circulation in geothermal systems. *Annual Review of Earth and Planetary Sciences*, 10: 377-395.

DWAF – Department of Water Affairs and Forestry (1996). South African water quality guidelines, *Volume 1: Domestic Water Use, Second Edition*, 1996.

D.W.S. (2021a). Brandvlei spring status quo report. Sub-directorate geohydrology, Department of Water and Sanitation, South Africa.

D.W.S. (2021b). Water quality records for Borehole ZQMBRN1, November 1994 to April 2017, Department of Water and Sanitation, South Africa.

D.P.W. (2021). Water quality records for Brandvlei thermal spring, January 2020 to May 2021, Department of Public Works, South Africa.

Duah, A. and Xu, Y. (2009). Climate variability and its impact on groundwater recharge to the Table Mountain Group aquifers in South Africa. Groundwater and Climate in Africa. Proceedings of the Kampala Conference, Uganda, June 2008, 181-189.

El-Sayed, A.M. and Kawanna, M. (2008). Optimum water temperature boosts the growth performance of Nile tilapia (*Oreochromis niloticus*) fry reared in a recycling system. *Aquaculture research*, 39(6), 670–672. https://doi.org/10.1111/j.1365-2109.2008.01915.x

Energen Hybrid Systems (2021). Energen Hot Water Heat Pumps – How hot water heat pumps work. Energen Hybrid Systems Limited. Available at: https://energenhybrid.com/products/energen-heat-pumps.aspx

Erfurt-Cooper, P. and Cooper, M. (2009). Health and Wellness Tourism: Spas and Hot Springs, Bristol, Blue Ridge Summit: Channel View Publications, 2009. https://doi.org/10.21832/9781845411138

FAO. (2016). State of world fisheries and aquaculture. Food and Agriculture Organization of the United Nations. Rome, Italy.

Farghally, H. M., Atia, D. M., El-Madany, H. T. and Fahmy, F.H. (2014). Control methodologies based on geothermal recirculating aquaculture system. *Energy*, 78: 826-833.

Gelengenis, J., Dalabakis, P. and Ilias, A. (2006). Heating of a fish wintering pond using low-temperature geothermal fluids, Porto Lagos, Greece. *Geothermics,* 35: 87-103. https://doi.org/10.1016/j.geothermics.2005.10.004.

GharibiAls, S. and Abbaspour-Gilandeh, Y. (2019). Evaluation of the direct use of geothermal energy on heat factors required for cold-water fish pisciculture. *Aquaculture,* 512: 734291. https://doi.org/10.1016/j.aquaculture.2019.734291

Hecht, T., Uys, W. and Britz, P.J. (1988). Culture of sharptooth catfish, *Clarias gariepinus*, in southern Africa. National Scientific Programmes Unit: CSIR, SANSP Report 153, 146.

Johnson, W. C. (1981). The Use of Geothermal Energy for Aquaculture. Proc. 1st Sino/U.S. Geothermal Resources Conf., Tianjin, PRC. https://doi.org/10.1016/0375-6505(86)90009-X

Jurgens, C.J. (2014). Brandvlei Correctional Farm: Hot Water Reticulation System. IABSE Symposium Report, September. https://doi.org/10.2749/222137814814070055.

Kabir, K.A., Verdegem, M.C.J., Verreth, J.A.J., Phillips, M.J. and Schrama, J.W. (2019). Effect of dietary protein to energy ratio, stocking density and feeding level on performance of Nile tilapia in pond aquaculture. *Aquaculture,* 511, 634200. https://doi.org/10.1016/j.aquaculture.2019.06.014

Kent, L.E. (1949). The thermal waters of the union of South Africa and South West Africa. *South African Journal of Geology,* 52(1), 231-264.

Khan, M., Shobha, J., Mohan, I., Naidu, M., Sundaram, C., Singh, S., Kuppusamy, P. and Kutala, V., (2005). Protective effect of Spirulina against doxorubicin-induced cardiotoxicity. *Phytotherapy Research,* 19(12), 1030-1037. https://doi.org/10.1002/ptr.1783

Kojima, S., Cuttler, J. M., Inoguchi, K., Yorozu, K., Horii, T., Shimura, N., Koga, H. and Murata, A. (2019). Radon therapy is very promising as a primary or an adjuvant treatment for different types of cancers: 4 case reports. *Dose-Response,* 17(2), https://doi.org/10.1177/1559325819853163

Lekang, O. I. (2007). Aquaculture engineering. Blackwell Publishing, Oxford, UK (2007). 76

Liao, Z. (2018). Thermal Springs and Geothermal Energy in the Qinghai-Tibetan Plateau and the Surroundings. *Springer Hydrogeology*. https://doi:10.1007/978-981-10-3485-5

Linbo, T. L. (2009). Zebrafish (Danio rerio) husbandry and colony maintenance at the Northwest Fisheries Science Center.

Lorenzo-Gonzalez, M., Ruano-Ravina, A., Torres-Duran, M., Kelsey, K., Provencio, M., Parente-Lamelas, I., Piñeiro-Lamas, M., Varela-Lema, L., Perez-Rios, M., Fernandez-Villar, A. and Barros-Dios, J., (2020). Lung cancer risk and residential radon exposure: A pooling of case-control studies in northwestern Spain. *Environmental Research,* 189, 109968. https://doi.org/10.3390%2Fijerph18031228

Lund, J.W., Freeston, D.H. and Boyd, T.L. (2011). Direct utilisation of geothermal energy 2010 worldwide review. *Geothermics,* 40(3), 159–180. https://doi.org/10.1016/j.geothermics.2011.07.004

Lund, J.W. and Boyd, T.L. (2016). Direct utilisation of geothermal energy 2015 worldwide review. *Geothermics*, 60, 66–93. https://doi.org/10.1016/j.geothermics.2015.11.004

Lund J.W. and Toth, A.N. (2021). Direct utilisation of geothermal energy 2020 worldwide review. *Geothermics*, 90: 101915. https://doi.org/10.1016/j.geothermics.2020.101915

Malone, R. (2013). Recirculating Aquaculture Tank Production Systems: A Review of Current Design Practice. Southern Regional Aquaculture Center, Publication No. 453, October 2013.

Martins, C.I.M., Aanyu, M., Schrama, J.W. and Verreth, J.A.J. (2005). Size distribution in African catfish (*Clarias gariepinus*) affects feeding behaviour but not growth. *Aquaculture,* 250: 300-307. http://doi.org/10.1016/j.aquaculture.2005.05.034

Martin, J.W. and Croukamp, L. (2021). Exploration into the potential for a low-enthalpy geothermal power plant in Cape fold belt. *Geothermics*, 89, 101934. https://doi.org/10.1016/j.geothermics.2020.101934

Mengistu, S. B., Mulder, H. A., Benzie, J. A., & Komen, H. (2020). A systematic literature review of the major factors causing yield gap by affecting growth, feed conversion ratio and survival in Nile tilapia (Oreochromis niloticus). Reviews in Aquaculture, 12(2), 524-541.

Mjoun, K., Rosentrater, K. A. and Brown, M. L. (2010). Tilapia: Profile and economic importance. North Central Agricultural Research Laboratory, USDA Agricultural Research and Department of Wildlife and Fisheries Science. South Dakota State University, South Dakota.

Olatunde, D., John, O. and Georges-Ivo, E. (2015). Hydrogeochemical setting of geothermal springs in Limpopo Province, South Africa. *Research Journal of Chemistry and Environment,* 19(1): 82-93.

Olivier, J., Venter, J.S. and Jonker, C.Z. (2011). Thermal and chemical characteristics of thermal springs in the northern part of the Limpopo Province, South Africa. *Water SA*, 37(4):427–436. http://doi.org/10.4314/wsa.v37i4.1.

Olivier, J. and Jonker C.Z. (2013). Halogen content of thermal spring waters in Limpopo Province, South Africa: possible origin and impact on game.

Olivier, J. and Jonker, N. (2013). Optimal utilisation of thermal springs in South Africa. Water Research Commission Report No. TT 577/13, Pretoria, South Africa.

Omosowone, O., Dada, A. and Adeparusi, E. (2015). Effects of dietary supplementation of fumaric acid on growth performance of African catfish *Clarias gariepinus* and *Aeromonas sobria* challenge. *Croatian Journal of Fisheries,* 73: 13-19.

Park, E., Lee, H., Kim, H., Sheen, S., Koh, S., Park, K., Cho, N., Lee, C. and Kang, D., (2020). Residential Radon Exposure and Cigarette Smoking in Association with Lung Cancer: A Matched Case-Control Study in Korea. International Journal of Environmental Research and Public Health, 17(8), 2946. https://doi.org/https://doi.org/10.3390/ijerph17082946

Quattrini, S., Pampaloni, B. and Brandi, M.L. (2016). Natural mineral waters: chemical characteristics and health effects. *Clinical Cases in Mineral and Bone Metabolism*, 13(3):173-180.

Ragnarsson, Á. (2014). Utilisation of geothermal energy in Iceland 2010-2014. International Geothermal Conference. Proceedings World Geothermal Congress 2015 Melbourne, Australia, 19-25 April 2015

Tshibalo, A.E., Olivier, J. and Venter, J. (2010). South Africa Geothermal Country Update (2005-2009), Proceedings: World Geothermal Congress 2010, Bali.

Tshibalo, E., Dhansay, T., Nyabeze, P. Chevallier, L., Musekiwa, C. and Olivier, J. (2015). Evaluation of the Geothermal Energy Potential for South Africa. Conference Proceedings: World Geothermal Congress 2015, Melbourne, Australia.

Towler, B.F. (2014). The Future of Energy. Academic Press, May 2014. https://doi.org/10.1016/C2013-0-19049-6

Turker, H., Eversole, A.G. and Brune, D.E. (2003). Filtration of green algae and cyanobacteria by Nile tilapia, *Oreochromis niloticus*, in the Partitioned Aquaculture System. *Aquaculture*, 215(1-4), 0–101. https://doi.org/10.1016/s0044-8486(02)00133-3

Timmons, M.B., Guerdat, T., Vinci, B.J. (2018). Recirculating Aquaculture (4th edition). Ithaca: Ithaca Publishing Company. 775

Van Nguyen, M., Arason, S., Gissurarson, M. and Pálsson, P.G. (2015). Uses of geothermal energy in food and agriculture – Opportunities for developing countries. Rome, FAO, 1-6

Vogiannis, E.G., and Nikolopoulos, D. (2015). Radon sources and associated risk in terms of exposure and dose. *Frontiers in public health*, 2, 207. https://doi.org/10.3389/fpubh.2014.00207

World Health Organisation (2021). Radon and health, Fact sheet. Available at: https://www.who.int/news-room/fact-sheets/detail/radon-and-health

Wu, Y. (2005). Groundwater recharge estimation in Table Mountain group aquifer systems with a case study of kammanassie area. Submitted in the fulfilment for the degree of Doctor of Philosophy, Department of Earth Sciences, University of the western Cape.

Zablocki, O., Van Zyl, L.J., Kirby B. and Trindade, M. (2017). Diversity of dsDNA viruses in a South African hot spring assessed by metagenomics and microscopy. *Viruses*, 9(11): 348. https://doi.org/10.3390/v9110348

Zdrojewicz, Z. and Strzelczyk, J. (2006). Radon treatment controversy. *Dose-Response*, 4(2). https://doi.org/10.2203/dose-response.05-025.Zdrojewicz