



# Potential of Atmospheric Water Harvesting in South Africa

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## DECLARATION

I, Palesa Tolerance Moji, hereby declare that the contents of this thesis represent my own work and that the dissertation has not previously been submitted for academic examination towards any qualification. The dissertation represents my own opinions and not necessarily those of North-West University.

All intellectual concepts, theories, methodologies, mathematical derivations and model developments used in this thesis and published in various scientific journals (except those used for review articles) were derived solely by the candidate and first author of the published manuscripts. Where appropriate, the intellectual property of others was acknowledged by using appropriate references. It should be noted that the referencing style, equations, figures and tables of the journal articles and conference papers were altered from their original published format to adopt consistency for the complete thesis submission. Furthermore, the manuscript content in this thesis was modified from submitted and/or published versions to accommodate the examiners' comments.

The co-authors contributed to conferences and published manuscripts to assist in building my dissertation and gain publishing experience for my work to be counted amongst the best in the world in an international platform of researchers. The following individuals have co-authored my work on publications: Prof Frans Waanders, Prof Elvis Fosso-Kankeu, Prof Karabo Ntwampe, Prof Ali Al Allili and Dr Hermant Mittal.

Signed: PT Moji

Date: 31 August 2025

## **DEDICATION**

I dedicate this research work to my daughters, Thozama and Hlubandisa Mkabane. I want you to know that any dream is possible and that hard work pays off, even if it takes time. All great efforts do get noticed and rewarded by the universe! Remember the power verse I gave you: "I can do all things through Christ who strengthens me".

To every African child, your background does not determine your future. You can become anything you wish to be.

## **PREFACE**

The Research compiled within this dissertation was conducted as part of EFFORTS FROM AFRICA, particularly South Africa, towards answering a call by the United Nations's sustainable development goals (SDGs) to create a sustainable world for future generations. The study shares a possible solution to answering SDG Number 6 of clean water and sanitation. As the world is changing due to climate change, which negatively impacts freshwater availability for drinking, harvesting water from the atmosphere can be considered one of the options for drinking water solutions.

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## **ABSTRACT**

The objective of this research project is to assess the viability and accessibility of employing atmospheric water harvesting (AWH) as an alternative drinking water source at a time of drought or upon downtime of conventional drinking water supply systems due to maintenance and natural disasters in South Africa, particularly in a semi-arid high-altitude region. The researcher was further motivated by the droughts that occurred and intensified in 2014 and 2015. The drought was recorded in 2014 in Cape Town in the Western Province, then expanded inland for over two years. Additionally, the lowest amount of rainfall in South Africa was recorded during this time since records began in 1904. This highlighted the need to explore alternative methods of obtaining water for crops, water supplies, and power generation due to the possibility of worsening climate forecasts. The inability to do so would lead to intensified food, energy and water shortages. Furthermore, population growth has been forecasted to reach nine billion by 2050. As such, food production will have to increase by 50%, along with an estimated increase of 15% in freshwater withdrawals. This underscores the urgency of proactive measures to sustainably meet growing demands amid changing climatic conditions.

The study is based on research conducted from a site in a semi-arid region of South Africa (Ga-Rankuwa, global positioning system location 25.5864° S, 27.9876° E, Gauteng Province), which elucidates the use and performance of atmospheric water generators (AWGs) to harvest water from the atmosphere. The success of this direct AWG technology is based on the science of ambient temperature (T) and relative humidity (RH), in which water formation is favoured from temperatures above 15 °C and RH above 30%. The relative humidity decreases as temperature increases, and a balance should be obtained to achieve maximum water harvesting possibilities. Daily and hourly data of dry bulb temperature (T) and RH records have been taken at the case study site from January 2020 until the end of January 2021 to assess variations of these parameters and their impact on water harvesting throughout all seasons in a year. Even though the research happened during the COVID-19 pandemic, this facility continued normal operations as it was categorised as an essential service in terms of the government's COVID-19 operations. The operations had been functional for three months before the commencement of this research. As such, the outcome of this study was aimed at adding value that would result in more growth in the business.

Concurrently, water collected during this time was sampled for drinking water quality assessments at different stages of the AWG's treatment equipment as per the South African National Standard for Drinking water 241(SANS 241). A meteorological study was conducted throughout a Typical Meteorological Year (TMY) for the site study area. The literature review explains TMY as a tool incorporating 8760 hourly climatic conditions, representing long-term ambient observations. A site study TMY consists of collecting climate data from hourly climate simulations each year from 2015 to 2020. The TMY served as a climatic tool that assisted productivity pattern predictions of these AWGs at the time of study. The collected data demonstrated high water productivity, particularly during the spring and summer seasons, due to rain pattern formation during this time. This favours high humidity in the atmosphere. Low productivity occurred between autumn and winter when there was almost no humidity and ambient temperatures were low. At times, there was no production at all for five consecutive days during the winter season. Other observations were made while exploring this technology, such as the electrical control instrumentation of the AWGs with set points indicating when the generator should be switched on and off and how energy consumption played a role in this case. There were two AWGs with a capacity of 5000 L water production per day, and each consumed 105 kW/hr at full capacity, illustrating that the technology is energy-intensive.

A community engagement initiative was implemented during the study using questionnaires and consent forms. This undertaking set out to evaluate the acceptability of Atmospheric Water Harvesting (AWH) technology within the community as the study narrates the "potential" of this technology while simultaneously raising awareness of its existence and benefits. Impressively, approximately 80% of the population engaged expressed support for the technology. This favourable outcome underscores the acceptability of AWH technology. It suggests that communities are receptive to embracing technological changes, even in the context of their drinking water sources.

AWGs produced up to 6,997 L/day in summer (20°C, 70% RH) but only 500 L/day in winter (9°C, 17% RH), confirming seasonal limitations in semi-arid regions. Approximately 98% of water samples met SANS 241 standards, with 2% exceeding HPC limits due to winter inactivity. Community acceptance reached 66.6% across age groups, favoring quality over cost; R19/kL for AWH vs. R12/kL for municipal water. Energy costs were high (R25/kL), suggesting solar integration for cost reduction. Future research should test AWH in diverse climates using the developed simulation model and explore adsorbent-based systems to enhance productivity and scalability.

## PUBLICATIONS

The following papers were published during the course of the study:

<b>Paper Title</b>	<b>Water Yield of Atmospheric Water Generators During Summer Season in South Africa</b>
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<b>Paper Title</b>	<b>Awareness of Atmospheric Water Harvesting Technology in a Community: Case Study of Pretoria North in South Africa</b>
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## NOMENCLATURE

The following lists English and Greek symbols and abbreviations used in this thesis, arranged in alphabetical order.

### English Symbols

- CGS:** Cost of Goods Sold, used in Net Profit Margin calculation (Equation 7)
- COP:** Coefficient of Performance, measure of cooling system efficiency (Equation 6)
- C<sub>p</sub>:** Specific heat capacity of wet air (J/kg °C), used in Specific Energy Consumption calculation (Equation 3)
- d:** Humidity ratio (kg H<sub>2</sub>O/kg dry air), used in water mass calculations (Equations 4, 5)
- d<sub>condenser</sub>:** Humidity ratio at condenser outlet (kg H<sub>2</sub>O/kg dry air), used in water mass calculations (Equations 3, 4)
- d<sub>2,i</sub>:** Humidity ratio at inlet of desorption process (kg H<sub>2</sub>O/kg dry air), used in water mass calculation (Equation 5)
- d<sub>2,o</sub>:** Humidity ratio at outlet of desorption process (kg H<sub>2</sub>O/kg dry air), used in water mass calculations (Equations 4, 5)
- DBT:** Dry Bulb Temperature (°C), ambient air temperature unaffected by moisture
- EC:** Electrical Conductivity (mS/m), measure of ions in water
- h<sub>fg</sub>:** Enthalpy of condensation (J/kg), used in Specific Energy Consumption calculation (Equation 3)
- HPC:** Heterotrophic Plate Count (cfu/ml), microbial water quality parameter
- I:** Interest on capital or operational costs, used in Net Profit Margin calculation (Equation 7)
- Ma:** Mass of dry air (kg), used in humidity calculation
- MHI:** Moisture Harvesting Index, tool to assess AWH feasibility
- M<sub>w</sub>:** Mass of water vapor (kg), used in humidity calculation
- M<sub>water</sub>:** Mass of water produced (kg), used in water mass calculations (Equations 4, 5)
- NPM:** Net Profit Margin, financial performance indicator (Equation 7)
- OPE:** Operating Expenses, e.g., maintenance, technology, human resources (Equation 7)
- OTE:** Other Expenses, e.g., office supplies, administrative costs (Equation 7)

**P<sub>th</sub>**: Dryness threshold precipitation (mm), used in Köppen-Geiger Climate Classification

**P<sub>w</sub>**: Partial pressure of water vapor in the air (Pa), used in Relative Humidity calculation (Equation 1)

**P<sub>s</sub>**: Summer precipitation (mm), used in Köppen-Geiger Climate Classification

**P<sub>sw</sub>**: Saturation pressure of water vapor (Pa), used in Relative Humidity calculation (Equation 1)

**P<sub>wmin</sub>**: Lowest precipitation in winter (mm), used in Köppen-Geiger Climate Classification

**Q<sub>condenser</sub>**: Total cooling load (J), used in Specific Energy Consumption calculation (Equation 3)

**R**: Revenue generated, monthly or annually (Equation 7)

**RH**: Relative Humidity (%), measure of water vapor in the air (Equation 1)

**RR**: Recovery Ratio, fraction of water vapor harvested as liquid water (Equation 2)

**SEC**: Specific Energy Consumption (kWh/m<sup>3</sup>), measure of energy efficiency (Equations 2, 3)

**T**: Temperature (°C), ambient air temperature

**T<sub>2,i</sub>**: Temperature at inlet of desorption process (°C), used in Specific Energy Consumption calculation (Equation 3)

**T<sub>ambient</sub>**: Ambient temperature (°C), used in Specific Energy Consumption calculation (Equation 2)

**T<sub>ann</sub>**: Annual mean temperature (°C), used in Köppen-Geiger Climate Classification

**T<sub>condenser</sub>**: Temperature at condenser (°C), used in Specific Energy Consumption calculation (Equation 3)

**T<sub>min</sub>**: Monthly mean lowest temperature (°C), used in Köppen-Geiger Climate Classification

**T<sub>1</sub>**: Time for sorption process (h), used in water mass calculation (Equation 4)

**T<sub>2</sub>**: Time for desorption process (h), used in water mass calculation (Equation 5)

**TCB**: Total Coliform Bacteria (cfu/ml), microbial water quality parameter

**TDS**: Total Dissolved Solids (mg/L), measure of dissolved substances in water

**TR**: Tax-related deductions or liabilities, used in Net Profit Margin calculation (Equation 7)

**V<sub>1</sub>**: Vapor flow for sorption process (m<sup>3</sup>/h), used in water mass calculation (Equation 4)

**V<sub>2</sub>**: Vapor flow for desorption process (m<sup>3</sup>/h), used in water mass calculation (Equation 5)

**WBT**: Wet Bulb Temperature (°C), temperature affected by moisture in the air

### **Greek Symbols**

**ρ<sub>1</sub>**: Vapor density for sorption process (kg/m<sup>3</sup>), used in water mass calculation (Equation 4)

**ρ<sub>2</sub>**: Vapor density for desorption process (kg/m<sup>3</sup>), used in water mass calculation (Equation 5)

### **Abbreviations**

**AMD**: Acid Mine Drainage, pollution from mining activities

**ATP**: Adenosine Triphosphate, indicator of microbiological activity

**AWH**: Atmospheric Water Harvesting, technology for extracting water from air

**AWG**: Atmospheric Water Generator, device used for AWH

**CIP**: Cleaning in Place, maintenance process for AWG equipment

**COP**: Congress Of the People, South African political party referenced in SDG-6 context

**Cwb**: Köppen-Geiger classification for warm temperate, winter dry, warm summer climate

**Bsh**: Köppen-Geiger classification for hot steppe or desert climate

**ENSO**: El Niño Southern Oscillation, climate phenomenon affecting weather patterns

**EPA**: United States Environmental Protection Agency, regulatory body for environmental standards

**GDWQ**: Guidelines for Drinking Water Quality, WHO standards

**HFC**: Hydrofluorocarbon, type of refrigerant (e.g., R407C)

**HMI**: Human-Machine Interface, control interface for AWGs

**HVAC**: Heating, Ventilation, and Air Conditioning, system relevant to AWG operation

**IDWS**: Israeli Drinking Water Standards, regulatory standards for water quality

**MOF**: Metal-Organic Framework, material used in adsorption-desorption cycles

**NTU**: Nephelometric Turbidity Unit, measure of water turbidity

**OEM:** Original Equipment Manufacturer, provider of AWG design specifications

**POPIA:** Protection of Personal Information Act, South African data protection law

**RO:** Reverse Osmosis, filtration method used in AWGs

**SANS:** South African National Standard, standard for drinking water quality (SANS 241)

**SAWS:** South African Weather Service, provider of weather data

**SDG-6:** Sustainable Development Goal No. 6, UN goal for clean water and sanitation

**SPHs:** Super Porous Hydrogels, material used in adsorption-desorption cycles

**TMY:** Typical Meteorological Year, tool for climatic condition analysis

**UV:** Ultraviolet, disinfection method used in AWGs

**WHO:** World Health Organization, international health regulatory body

### 1.1 Problem Statement

South Africa is a semi-arid and drought-stricken country with an incapacitated water supply and management system. According to ESI Africa, “South Africa is forecasted to approach a physical water scarcity by 2025 whilst climate change is expected to worsen the situation to create a water deficit of 17% by 2030 (ESI Africa, 2020). The degradation of water sources due to pollution has become a critical concern. The simultaneous deterioration of the water infrastructure has exacerbated it. Both issues pose significant challenges to water supply and have wide-ranging impacts on communities and ecosystems (du Plessis, 2023a and b). The following is a summary of the significant challenges facing the drinking water network in South Africa:

a) Open to atmosphere water containmentment

- The bulk of South Africa’s water comes from dams and rivers; it then gets pumped into smaller dams and holding tanks that are not enclosed, resulting in more evaporation back into the atmosphere.

b) Non-revenue water

- Water is lost due to ageing infrastructure from leaks and unaccounted water stolen and unnoticed. It exacerbates water scarcity and can compromise the reliability of water supply.

c) Climate Change

- Heat waves result in less rain in the normal rainy seasons and rain falling at unexpected times with floods and more infrastructure damage.

d) Water pollution

- Water is polluted due to irresponsible activities by communities and industries, primarily due to a lack of knowledge about water scarcity and climate change issues.
- Various agricultural runoffs and improper waste disposal cause water pollution.

## 1.2 Background

Contaminated water poses risks to human health, disrupts ecosystems and affects aquatic life. From 2014 to 2016, South Africa experienced the worst drought, which created a national dialogue that brought water security to the front page of most forums. The drought helped highlight existing vulnerabilities and challenges facing the water system in South Africa and the extent of these challenges (Crookes *et al.* 2018). While the root cause of water scarcity is based on the geographical location of a place and changing climate conditions, Chitonge (2020) explained that there was a broader approach to water scarcity studies, which has to be characterised by different orders. The article describes scarcity at four levels, namely:

- natural water scarcity by geographic location,
- natural water scarcity by climate change,
- water scarcity by humans,
- scarcity induced by social impact.

Chitonge (2020) further describes the importance of classifying water scarcity in this manner. It allows thorough thinking about each scarcity cause and, as such, pinpoints exactly a root cause solution instead of grouping all the possible causes in one space. The approach produces effective management strategies and can be tracked more easily. The progress of task groups addressing these challenges can be tracked.

In a book chapter, du Plessis (2023b) shares critical information concerning South Africa's impending freshwater crisis and the cause and possible solutions to the crisis. The author highlights a trend in events that occurred over 30 years. The author describes these events as unfavourable water governance decisions and political failures towards committed deliverables as the major reasons for the collapse of freshwater resources. Aging and non-maintained water infrastructure and inadequate water access services are also identified. Consequently, these events lead to reactive water management practices, which have led to no improvement and increased degradation of freshwater resources.

An overall lack of service delivery exists nationwide, leading to further water and social decline. Primary water problems are prioritised according to urgency. Suitable recommendations have been

given to assist in transforming the country's current complex water predicament into "simpler" water problems, but real success has not been achieved due to the reasons mentioned. South Africa's already scarce freshwater resources and decaying infrastructure will persist and possibly collapse if no significant actions or interventions are implemented (du Plessis, 2023b). It is forecasted that by 2025, 3 billion people scattered over 52 countries will experience water shortages (Hoy, 2009). As future climate predictions continue to worsen, alternative crops, water sources and methods of electricity production will need to be considered; failing to do so will result in increased food, energy, and water insecurity (Piesse, 2016).

Water resources continue to be depleted due to the rapid increase in population growth, while industrialised water demands continue to grow. Acid mine water drainage (AMD) pollution has been mentioned as the leading pollution contributor in the country, with a considerable storage footprint as artificial dams' containment declines (Ochieng *et al*, 2010). Over time AMD penetrates through the earth's upper crustal layers, causing seepage and releasing harmful chemicals, which become effluent to the environment and cause a significant threat to the environment, animals and human beings. In addition, several other processes, such as excessive rainwater during violent storms, household pollutants and commercial sewage, also lead to these environmental challenges. The key driving factors for inadequate treatments have been excessive urbanisation and demographic growth. Therefore, there is a need to explore better, cost-effective and environmentally sustainable approaches.

Addressing these challenges requires a comprehensive approach, including water quality management, infrastructure investment, and sustainable water resource management practices. Efforts to upgrade and maintain infrastructure, implement pollution control measures, and promote water conservation contribute to ensuring a reliable and clean water supply for communities. The success of atmospheric water harvesting (AWH) is described in this project. It is showcased as a viable alternative to drinking water during both temporary and permanent downtimes of existing water infrastructure caused by maintenance or natural disasters. Moreover, the initiative of this AWH research project aligns and contributes towards the United Nations Sustainable Development Goal number 6 (SDG-6), which aims to ensure access to clean and safe drinking water as well as sanitation for impoverished communities worldwide (Arora & Mishra, 2019). By addressing water scarcity challenges and providing a sustainable water source, the project contributes to a South African effort by the Congress Of the People (COP) and the entire global community solution to improve water accessibility and sanitation, especially in disadvantaged communities.

### 1.3 Novelty of the Study

This research introduces a pioneering, context-specific investigation into the feasibility, quality, economic viability, and community acceptance of Atmospheric Water Harvesting (AWH) in South Africa's semi-arid, high-altitude regions, a location where traditional water infrastructure is increasingly unreliable due to climate change, pollution, and aging infrastructure.

The novel aspects of the study are:

1. Largest AWH Pilot Site in Africa

- The study is conducted at the largest atmospheric water harvesting site in South Africa and the continent, representing a unique scale for evaluating the real-world performance of AWGs.

2. First Comprehensive Seasonal Analysis of AWG Performance in South Africa

- It is the first known longitudinal study in the region to monitor AWG performance over all four seasons, accounting for the impacts of temperature and relative humidity fluctuations on water production in a semi-arid, high-altitude environment.

3. Microbial and Physio-Chemical Quality Assessment Over a Full Year

- The study undertakes a rigorous water quality analysis of three treatment stages across raw, filtered, and final water, benchmarked against SANS 241:2015, providing evidence of safety and suitability for potable use.

4. Customised Operational Optimisation Strategy for AWGs

- Unlike previous "always-on" approaches, this research proposes a novel sensor-triggered operation model to optimise energy use and water yield based on atmospheric conditions — making it more sustainable in power-constrained areas.

5. Socio-Economic Integration and Community Acceptance Study

- It includes a community-based evaluation of AWH acceptance, ethically guided by POPIA, which provides new insights into public perception, social feasibility, and trust in AW as a drinking water source.

6. Cost-Benefit Analysis Tailored to the South African Context

- The study provides localised economic data comparing AWH with conventional water sourcing methods, identifying practical investment pathways, especially under intermittent power and water supply constraints.

7. Alignment with UN SDG-6 for Water and Sanitation Access

- The project directly contributes to Sustainable Development Goal 6, and serves as a model for water resilience and adaptation strategies in developing countries experiencing climate-induced water stress.

## 1.4 Study Aim

The primary objective of this research is to evaluate the affordability and viability of atmospheric water harvesting (AWH) in South Africa, particularly as an alternative source of drinking water. This assessment encompasses both the potential use of AWH as a supplementary water provider in areas facing challenges in receiving fresh water and its role as a primary potable water source. Additionally, the study showcases the use of AWH during periods of water scarcity, such as droughts, which are becoming more prevalent due to changing climatic conditions.

The case study highlights the use of atmospheric water generators (AWGs) as the leading equipment piloted for harvesting vapour from the air to produce drinking water. The study site chosen is situated in a high-altitude inland province of South Africa. The versatility of AWGs has been highlighted because they can serve as a crucial water source during intermittent standard water supply outages or in the aftermath of unfortunate catastrophes. The research explores the potential of AWH to reduce the dependency on municipal water supplies, offering relief to overstretched water resources. Additionally, the system's adaptability allows for integration into existing supply networks, ensuring it can be utilised as needed (Zohra *et al.*, 2020). The research study seeks to provide insights into the practicality and economic feasibility of implementing AWH, particularly in a South African context, to offer a sustainable solution for water provision.

This technology has not gained widespread exposure within the country despite its potential. The selected site for the study represents the largest of its kind in the country and on the continent at the time of this publication. The research aims to contribute to disseminating knowledge and information, fostering a better understanding of AWH and its implications for water sustainability. By showcasing this technology's practical application and benefits, the research endeavours to bridge the awareness gap and promote the adoption of innovative water solutions in South Africa.

## 1.5 Study Objectives

### 1.5.1 Assess the production impact of seasonal variation on the performance of AWG in a high altitude, semi-arid region in South Africa.

Daily, hourly, weekly, and monthly AWG temperature and relative humidity (RH) readings were recorded from January 2020 until January 2021. There were challenges experienced during this period, such as inconsistencies in data recording, particularly at the commencement of the

project, and a missed production window of AWGs, which led to a need for their calibration of control and instrumentation.

### **1.5.2 Optimise the performance of the AWGs based on the seasonal variation (South African context).**

The objective forms part of objective 1.3.1 due to the vapour compression cycle, and different patterns and behaviours of the AWGs in different seasons were observed in relation to their performance on water production. An “ALWAYS ON! NARRATIVE” is not supported on AWGs due to mechanical energy waste. AWGs should be controlled by automated atmospheric parameter sensors at set points to direct the generator to start based on favourable ambient conditions.

### **1.5.3 Monitor the microbial and physio-chemical quality of harvested atmospheric water and treatment.**

An analysis and an in-depth determination of atmospheric water quality were done for a year to ensure that all four seasons were recorded. The following sample points were taken for analysis:

- raw water (immediately after condensation from air),
- treated/filtered water (post the three filtration stages of the AWGs),
- the final product (water post UV rays and ozonation treatment).

These analyses were then collated to SANS 241 (South African National Standards, 2015) and they were within specification on raw and final water samples, respectively.

### **1.5.4 Evaluate the cost-effectiveness of atmospheric water harvesting compared to conventional methods and or available technologies.**

Evaluating the cost-effectiveness of atmospheric water harvesting (AWH) compared to conventional methods of obtaining municipal potable water involves considering various factors.

### **1.5.5 Evaluate the acceptability of AW by the community and determine the impact in alleviating water challenges.**

A questionnaire was drafted with a consent form for community engagement. It was submitted for approval by the university’s ethics committee. The committee assessed issues such as the

Protection of Personal Information Act (POPI Act) (South Africa, 2013) on the engagement task and the reliability of the targeted outcomes to ensure the validity of the randomisation. Permission was granted to conduct the community engagement to address this objective.

## **1.6 Motivation of the research**

The availability and security of conventional water supply sources, heavily dependent on seasonal rain and favourable temperatures, have traditionally played a crucial role in alleviating the challenges posed by drought (Steyn *et al.*, 2019). It has become increasingly evident in South Africa and many parts of the world that this traditional reliance on predictable weather patterns is no longer applicable. The year 2022 has been recorded the driest since capturing of records (Piemontese, 2024); environmental changes, including shifts in rainfall patterns, have disrupted the reliability of seasonal rain and temperatures.

Compounding this challenge is the urgent need for maintenance and upgrades to the current water supply network infrastructure in South Africa. The existing infrastructure is facing significant issues and requires attention to ensure its functionality aligns with the ongoing socio-economic requirements of the region, as highlighted in the latest Blue Drop Report of the Department of Water and Sanitation (Blue Drop South Africa, 2023). Without proactive measures to address both environmental changes and infrastructure shortcomings, the resilience and sustainability of water supply systems may be compromised, impacting communities and economic activities. Thus, a comprehensive approach that considers environmental factors, infrastructure upgrades and its governance is crucial for ensuring a secure and reliable water supply in the face of evolving climatic conditions and socio-economic demands.

The challenges posed by power supply interruptions, leading to water supply disruptions to households and businesses, have resulted in decreased profits and increased job losses (Rand Water South Africa, 2023). According to Rand Water Africa, the restoration of water pumping pressure can take up to four hours following the return of power, causing additional inconvenience to communities. Moreover, low-income individuals often struggle to afford the payments required for water services, posing a sustainability challenge for the government in maintaining water infrastructure. In response to these challenges, atmospheric water harvesting (AWH) is proposed as an alternative source of drinking water. The benefits of AWH, among many, include the following:

**a) Climate Resilience:**

AWH can capitalise on high ambient temperatures, where water vapour concentration in the air increases, potentially enhancing harvesting. This is particularly valuable in regions experiencing heat waves that negatively impact traditional water storage due to high evaporation.

**b) Infrastructure Flexibility:**

AWH does not require conventional infrastructure. Due to its simplicity, it can be implemented anywhere, and the number of filtration stages can be adjusted based on the air quality of the targeted location.

**c) Environmental Friendliness:**

The AWH process is environmentally friendly, leaving no by-product footprints such as sludge, which is often associated with traditional water treatment plants.

**d) Energy Alternatives:**

While both traditional water production methods and AWH require electricity, AWH's simplicity allows for alternative power supplies, such as solar energy and inverters, natural or biogas, ensuring greater flexibility and potential returns on investment. It has been acknowledged through observations of this study that AWH is energy-intensive; hence, alternative power supply makes investment sense.

**1.7 Key research questions**

1. Is atmospheric water harvesting technology feasible for South Africa with regard to its accessibility, specifically given the prevailing climate change challenges and water scarcity?
2. Is atmospheric water harvesting quality acceptable when profiled against the South African National Standard for drinking water SANS 241 of 2015?
3. Can atmospheric water harvesting be guaranteed for all seasons, especially in the country's semi-arid, high-altitude region?

### 2.1 Introduction to Atmospheric Water Harvesting (AWH)

Atmospheric water harvesting is a process of harnessing water from the air or the sky, the space above the earth. Water in the atmosphere exists in three forms, namely:

- Clouds in the sky
- Water vapour in the air
- Fog nearer to the earth's surface

The atmospheric water harvesting process occurs through different methods of adsorption-desorption and condensation based on vapour compression.

Tu, Wang, Zhang & Wang (2018) have shown the success of AWH and describes how water is obtained from the air through these methods. The primary purpose of AWH is to provide a sustainable and alternative source of fresh water in areas where traditional water sources are scarce or contaminated. It aims to address water scarcity, reduce dependence on conventional water sources, and improve water security in arid and semi-arid regions. Atmospheric water harvesting captures and condenses water vapour from the air utilizing different techniques, such as natural harvesting and modern technologies, making it available for drinking, agriculture, and other domestic or industrial applications.

### 2.2 Overview of Atmospheric Water Harvesting in South Africa

South Africa is a semi-arid and water-deficient geographical location. The situation has deteriorated recently due to droughts. Therefore, water use should be well regulated and protected from contamination, unregulated use, and waste. A prediction of more water deficits in the future due to drought and increased demand for access to clean water with reference to the National Water Act (South Africa, 1998) was made by Cloete (2020). On these grounds, AWH should be considered one of the resilience options for drinking water purposes for South Africa, now and beyond.

Atmospheric water harvesting (AWH) is the process of extracting water from the atmosphere, which exists in three primary forms: clouds in the sky, water vapour in the air, and fog closer to the Earth's surface. This technique is increasingly critical for addressing water scarcity, particularly in arid and semi-arid regions such as parts of Africa. Fog collection, a significant AWH method, has shown promise for providing sustainable water sources. For example, Elshennawy et al. (2022) reviewed fog collection materials, techniques, and influencing parameters, emphasizing its potential in regions with frequent

fog events (Elshennawy et al., 2022). Additionally, Elshennawy et al. (2023) investigated mesh geometry and shade coefficients for fog harvesting collectors, demonstrating how design optimizations can improve water collection efficiency (Elshennawy et al., 2023). Furthermore, Elshennawy et al. (2024) explored fog collection rates on hydrophobic surfaces and varying mesh inclinations, offering insights into enhancing collector performance (Elshennawy et al., 2024). These studies highlight the applicability of fog collection in African contexts, where environmental conditions often support such technologies, laying the groundwork for further research and implementation in water-scarce regions.

In South Africa, atmospheric water harvesting was initially explored through fog harvesting. Fog is a process where cool and warm, moist air mix over a water surface. The warm, moist air cools, and its temperature drops until the humidity of the moist air reaches 100%. The process of fog formation becomes visible like a smoke upon the surface of the water (National Oceanic and Atmospheric Administration, 2024). Olivier (2002) mentions that the initial discoveries began in the 1960s. Fog was first harvested at Mariepskop in Mpumalanga, South Africa, from 1969 to 1970 (Olivier, 2002). Over 15 months, records indicated a yield of 31 000 L per day or approximately 11 L/m<sup>2</sup> per day of water from fog. The studies do not share much about the literature on fog harvesting at Mariepskop except for the erection of two large fog screens construction, with size, design details, and the compass direction positioning (Olivier, 2002).

In recent years, particularly in 2001 (Olivier, 2002) investigated the possibility of fog harvesting for drinking water purposes on the West Coast in South Africa. The primary motivation for the exploration was the Cape's West Coast water scarcity challenges due to its geographic location factors and the drought, which worsened the availability of drinking water resources due to El Niño, which occurred from 2014 up to 2016. The City of Cape Town continued to struggle with drinking water management a few years after the drought, as the impact was enormous. The City's resources strategy was to explore alternative water supplies to sustain the current and future population, tourism and industrial expansion demands (Rautenbach & Olivier, 2019). The outcome of these studies revealed the following information:

- While the West Coast is dry and experiences most of its annual rainfall only in winter, not exceeding 250 mm, the region does experience high levels of fog (South Africa Department of Forestry, Fisheries and the Environment, 2020).

- The investigation further investigated the behaviour patterns of the fog, including how much fog availability exists in this region and for how long. It was found that Port Nolloth recorded an average of 148 days, Cape Columbine 110 days, and Alexander Bay 67 days per annum.
- These high fog incidence points also referenced altitude, contour line, and wind speed.
- For the duration of the investigation, the highest water harvesting from fog was recorded to be 2.5 L/m<sup>2</sup> of the collecting surface per day.
- The investigation revealed that the highest water yield was harvested at Cape Columbine, which had fewer days of fog incidence compared to Port Nolloth.
- The harvested water was analysed and met the SANS 241 compliance for drinking water quality (SABS, 2015).

The high incidence of fog formation on the West Coast occurs as a result of warm easterly winds that move over the cool West Coastal waters of the Atlantic Ocean (Linder, 2021). The study conclusion highlighted that meteorological studies of fog are the ultimate determinants that forecast which regions may be most suitable for achieving the highest water yield from fog for the most favourable site. Jarimi *et al*, 2020 define atmospheric water technologies in terms of two classifications, namely:

- a) fog harvesting was explained to be visible and
- b) water vapour or dew water harvesting was explained as invisible.

Fog may be harvested using traditional methods, which are “mesh-like” structures. These structures may be hydrophilic or hydrophobic. For this reason, the designer has to understand the construction material to manage the harvest expectations. The efficiency of fog collectors is dependent on the following:

- fog liquid water content,
- wind velocity,
- droplet size distribution, and
- mesh characteristics.

Jarimi *et al.*, 2020 mentions that, unlike fog; water vapour can be harvested anywhere on Earth. However, a cooled condensing surface is required for efficient phase change from vapour to liquid. These authors describe three methods for dew water harvesting, namely:

- passive, which involves a cooling condenser;

- solar regenerated desiccants, which involve metallic-organic frameworks (MOFs); and
- active cooling condensation, which uses a vapour compression cycle.

This author states that the emissivity factor of the material used with passive cooling condensers plays a significant role as it determines if the condensing conditions are hydrophilic or hydrophobic. If the material is hydrophobic by design, this factor shall have a low condensing effect because it will repel water. As such, it prolongs the condensation effect or creates inefficient conditions. Solar regenerated desiccants are highly dependent on solar power for condensation from vapour to liquid. In the evening, when sunlight is not available, desiccants absorb water. When the sun is available, the heat releases the vapour from the desiccant, and the vapour condenses and can be captured.

Studies by Jarimi *et al.* (2020) found that active cooling condensation was based on a vapour compression cycle similar to the AWH method of the dissertation case study (Mkabane *et al.* 2020), which employed atmospheric water generators to harvest water from the atmosphere. Findings by Olivier (2002) provided a successful outcome for the City of Cape Town municipality to invest in this technology as an alternative water source as the scarcity continues to stretch due to changing climate conditions.

Further South African AWH research was conducted by Thisani (2018), focusing on a low-altitude, humid coastal region in KwaZulu Natal. This research assessed the possibility of employing AWG technology to harvest water from the air, particularly during drought in rural areas of the region. These areas were the most affected during the 2014/2015 El Nino drought in South Africa, and people from this area could not afford to buy water. The research focused on assessing the mechanical capabilities of different AWGs, which were pilot studies of those available in the market, to draw conclusions on the most efficient design regarding efficient productivity for a typical coastal region.

The following were the outcomes of Thisani's (2018) study, which were in support of the objectives of the dissertation research study:

1. Air pollution within this location prompted the design of air filters suitable for capturing particulate matter to ensure that the desired water quality can be achieved per legislation (SANS 241, 2015). This particular objective supports the AW quality objective of the case study (Mkabane *et al.*, 2020) report as well as other studies that would wish to solve water shortage challenges by making use of atmospheric conditions of that area as per the activities occurring by day and night; more like a prerequisite for harvesting water from air (Inbar, Gozlan *et al.* 2020).
2. To explore the advantages of the warm ambient conditions provided by the Indian Ocean currents, which produced a high rate of water evaporation from the ground, particularly during

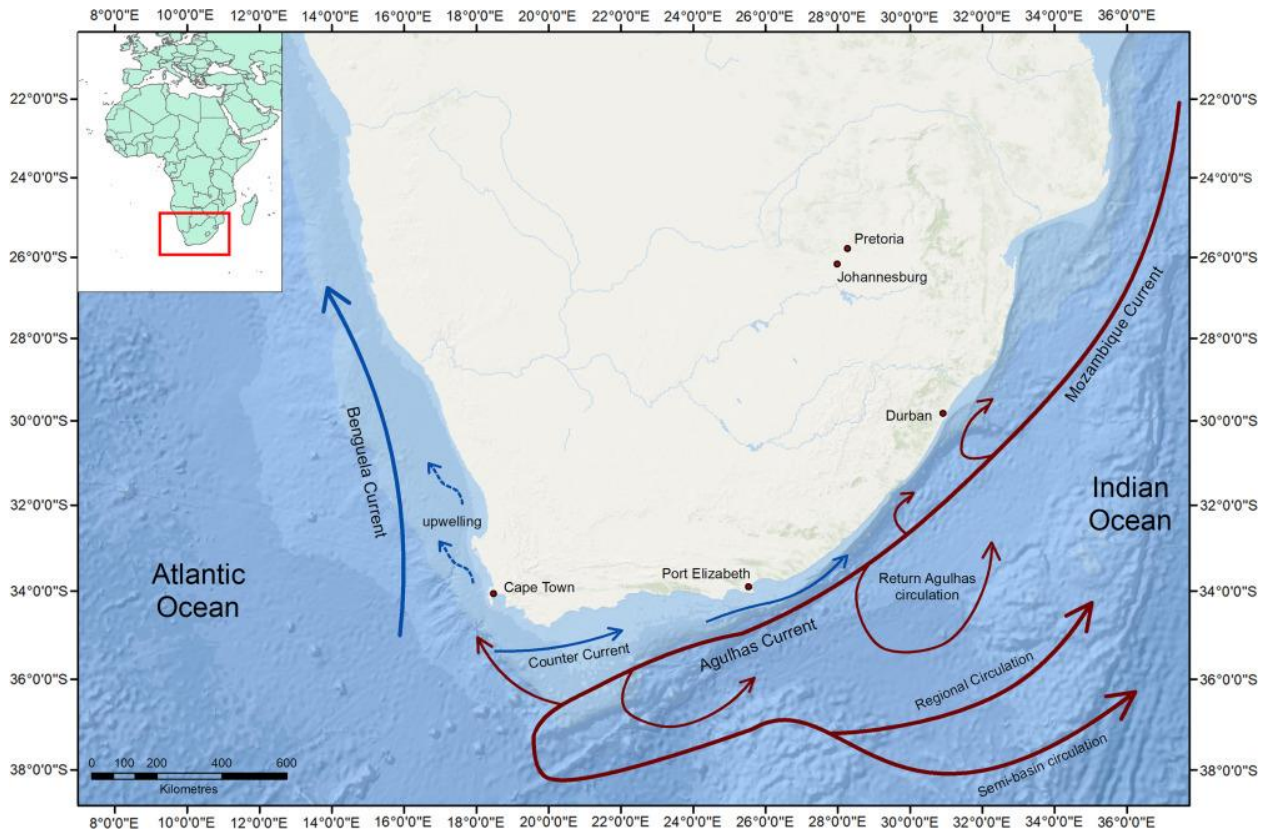
drought, which increased water vapour availability in the atmosphere. When ambient temperatures were high due to heat waves, more ground water evaporated into the atmosphere.

3. Compressor selection assessment was conducted regarding energy efficiency, noise, capacity suitability, maintenance requirements and affordability.
4. Analysis of the overall vapour compression cycle performance in relation to psychometric charts.
5. Overall energy costs on the selected equipment to build a suitable AWG and overall project costs, including labour.

The above findings were critical to the decision-making of the AWG design selection during the feasibility and concept phase for water stakeholders' investment motivation. Due to the favourable east coastal region of South Africa, which provides average annual humidities of above 65% and temperatures above 21°C, research by Thisani (2018) of AWG's water supply project was proven to be a success, particularly for the drought season because of the ocean current and moisture availability.

For this case study report, the Köppen-Geiger classification technique was used as a literature reference to determine the feasibility of AWH in South Africa. The Köppen-Geiger Climate Classification discusses the South African climate, which is crucial for the narration of this study as it explains the operational behaviour of AWG technology observed in the site study. This technique is a continuation of research published originally by the Department of Oceanography at the University of Cape Town in 1990 as revised by Walker and Shillington (2010). The research describes South African weather patterns as distinctive due to how it gets its influence from the east and south; also, by a cold eastern boundary ocean current to the west.

The first current movement, the Agulhas, is the western boundary subtropical spiral of the South Indian Ocean. The current flows south-westward along the east coast of South Africa. The second current, the Benguela, moves huge quantities of heat towards the poles. This movement assists with the redistribution of heat from the tropics to the poles (Figure 2-1). The evaporation rate, which is the latent heat flux and sensible heat flux, varies little from summer to winter due to the existing westerly wind.



**Figure 2.1: South African map with eastern and western ocean currents (Wepener & Degger, 2019).**

The phenomenon further adds an event to the main warm Pacific Ocean, which happened during the years 1982 and 1983, which had an impact on tropical and mid-latitude weather patterns globally and triggered more research into ocean-atmosphere climate. These phenomena were named the El Niño Southern Oscillation (ENSO) and are primarily associated with climate change or global warming effects in South Africa (Walker & Shillington, 2010).

The Köppen-Geiger Climate Classification categorises climate as a constant, and it uses the sparse climatic information available to compile a single static climatic map. It further explains that the climate of a location is affected by its latitude, surrounding water bodies with their currents, and terrain and altitude. The site study observations on climate change's impact on water production have been collated with the Köppen-Geiger Climate Classification. The weather patterns determined when the generators were able to produce water during South Africa's changing seasons in addition to the Uniform Mechanical Code (International Association of Plumbing and Mechanical Officials (IAPMO), 2003.)

which was used where relative humidity of 50%-60% was recommended to be useful for AWH; a tool for heating, ventilation and air conditioning systems.

Atmospheric water harvesting (AWH) is an emerging technology aimed at addressing global water scarcity by extracting water vapor from the air. Recent advancements in materials, system design, and economic feasibility have positioned AWH as a promising solution, particularly in arid and semi-arid regions. This study highlights a key recent publication and an upcoming international summit to contextualize the state of AWH research.

A significant contribution to the field is the study by Safoui et al. (2024), which investigates a desiccant-based solar still for AWH. Published in *Engineering Research Express* (Volume 6, Number 4, 045559), the study experimentally evaluates the performance of a solar-powered system using desiccants to capture atmospheric moisture. The authors demonstrate the system's efficiency in water production under varying environmental conditions and provide an economic analysis to assess its viability for widespread adoption. Their findings suggest that desiccant-based systems offer a scalable, cost-effective approach for AWH, particularly in regions with limited access to traditional water sources. The study emphasizes the importance of optimizing desiccant materials and solar energy integration to enhance system performance.

The broader AWH research landscape is further enriched by collaborative platforms like the 2nd International Atmospheric Water Harvesting Summit, scheduled for February 20-21, 2025. This summit, hosted by the International Atmospheric Water Harvesting Association (IAWHA), serves as a critical forum for researchers, engineers, and policymakers to share abstracts, materials, and innovations in AWH technologies. The event highlights advancements in materials science, such as novel desiccants and hygroscopic materials, and explores practical applications for sustainable water production. By fostering interdisciplinary dialogue, the summit aims to accelerate the development and deployment of AWH systems globally.

Together, these contributions underline the growing potential of AWH to address water scarcity. Safoui et al.'s work provides a practical framework for system design and economic evaluation, while the IAWHA summit facilitates knowledge exchange to drive further innovation. Future research should focus on improving material efficiency, reducing energy requirements, and scaling AWH technologies for diverse environmental and socioeconomic contexts.

The regions illustrated in Figure 2-2 are categorised according to their climate classification categories in South Africa. The regions were identified on a map with altitude and latitude coordinates. The case study location was located between Cwb and Bsh, near Pretoria.

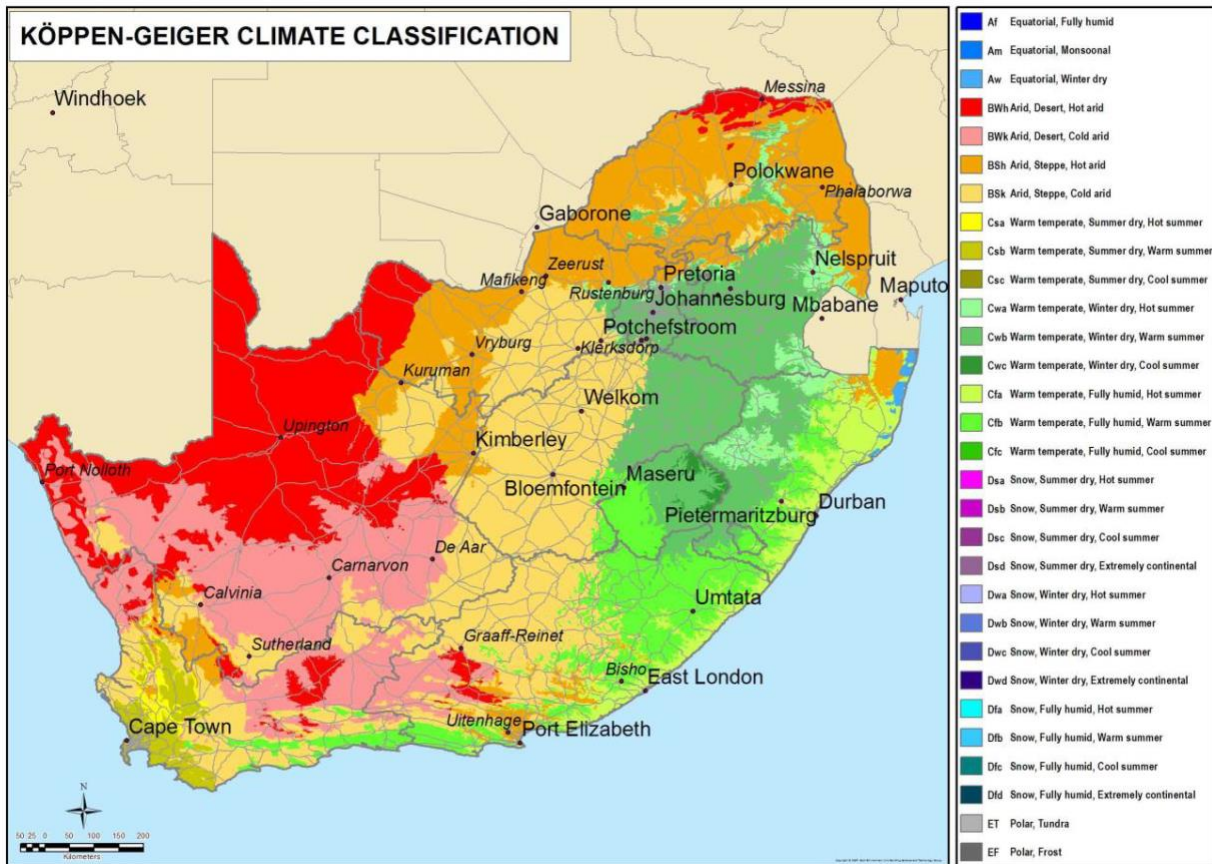


Figure 2.2: CSIR Köppen-Geiger map on a very fine 1 km x 1 km grid (Conradie, 2012).

### 2.3 Current Atmospheric Water Harvesting Research Gaps in South Africa

None of the reviewed literature internationally and in South Africa has investigated the possibility of active atmospheric water harvesting in South Africa's inland, high-altitude, semi-arid region at the time of this study. It is noted that most of these studies have highlighted South Africa as a water-scarce country with a risk of worsening by 2025 (Swatuk *et al.*, 2015). Current available South African AWH harvesting literature focused mostly on solar regenerated desiccants with MOFs piloted and executed with fog collectors on the country's west coast (Olivier, 2002). These fog collectors were made out of hydrophilic mesh material, which acted as desiccants, and they absorbed "moisture" or fog, which was later released through ambient differential temperatures and pressure and harvested as drinking water.

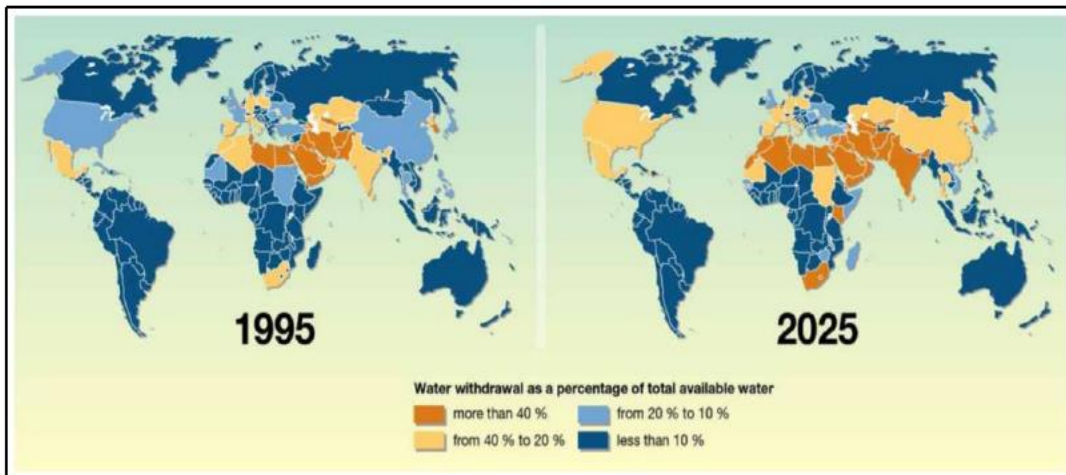
Upon these analyses, the fog collector water harvesting process has been referred to as solar regenerated desiccants.

Additionally, Thisani's South African AWH research (Thisani, 2018) wished to design and execute the best and most cost-effective active AWG to solve water challenges for this particular coastal region. According to Köppen-Geiger Climatic Classification (Conradie, 2012), Thisani's (2018) pilot AWG was placed at the Cfb meteorological point, which is fully humid, warm temperate and warm summer conditions. As such, the AWH throughputs are continually guaranteed at a maximum for this location. Thisani's study did not focus on the daily operation and water quality monitoring of the AWGs, even though the researcher considered filters at a point of air harvesting. It seems the quality was considered, though it was not addressed regarding chemical analysis, which provides an opportunity for the current inland case study project to close this gap and share findings from a region away from a region with ample humidity.

## **2.4 Overview of Atmospheric Water Harvesting Globally**

Literature forecasts that by 2030, the global population may reach nine billion, and domestic, industrial, and agricultural water demands are expected to increase substantially concurrently (McNally *et al.*, 2019). Globally, the number of people lacking access to clean water is 2.1 billion, and the main reasons are water pollution as a consequence of industrialization and the impact of global warming (Jarimi, *et al.*, 2020). Safe drinking water has become scarce for almost 1.1 billion people globally whilst drinking water pollution continues to rise, with recorded hourly deaths of about 400 deaths of children below the age of five. The water pollution chain continues with rainfall erosion, which redirects the polluted water elsewhere, where it ends up mixing with irrigation water or flowing directly onto the crops, consequently creating detrimental diseases for plants and animals (Bullard, 1966). Developing countries' populations usually have a lower ranking in high-quality drinking water and sanitation facilities when compared to developed countries (Gadgil, 1998). Globally, all countries have developed national drinking water standards based on the World Health Organization (WHO), one of the most highly recognised international health organizations.

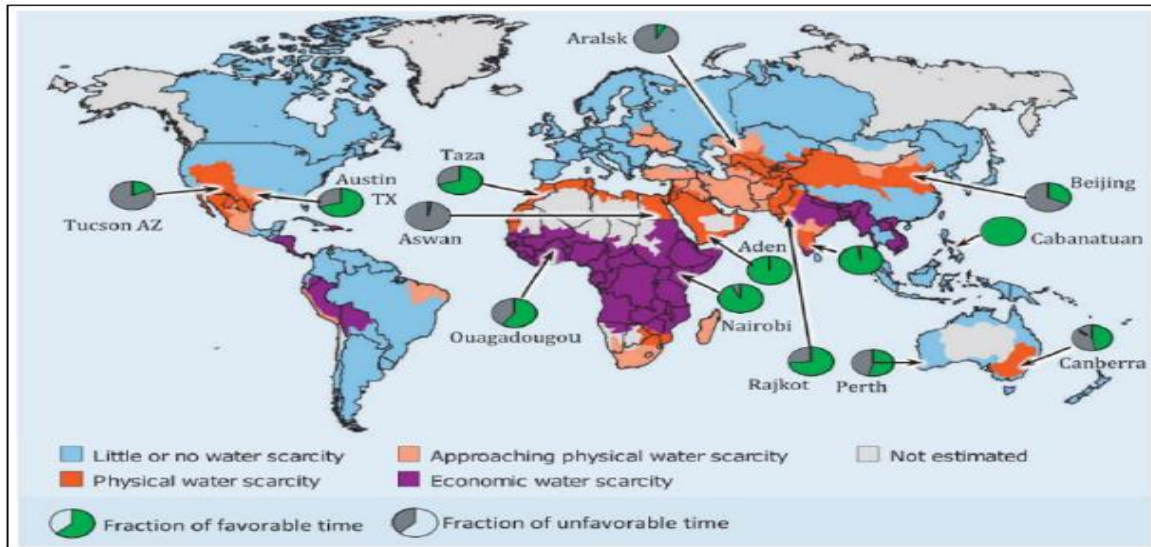
Water supplies continue to shrink because of overuse and pollution, whilst demand continues to increase due to population growth, industrialisation, urbanisation and mechanisation. Water is a source of survival for all living organisms and a central component of the country's economy. Figures 2-3 indicate an increase in water percentage withdrawals, as reflected in colour, from 1995, including a prediction for 2025.



**Figure 2.3: Water withdrawal percentage of total global available water (Swatuk, *et al.*, 2015).**

Globally, access to clean water has become a challenge, especially in areas where natural fresh water is unavailable, and communities rely on processes like desalination for clean drinking water. Methods for producing fresh water must be equal to or more cost-effective than clean drinking water from other sources at the point of use. Atmospheric water generation is one option for producing clean drinking water (Hellberg, 2020).

Research by Zohra *et al.* (2020) explains that AWG studies have come up with the concept of a Moisture Harvesting Index (MHI), which is a tool that can be used by interested parties to assess their feasibility for AWH technology investment. An index determines the feasibility of placing an AWG within a specific area, including the possible water that could be harvested and condensed within that area and the total energy invested within the generator to cool and condense that air from the atmosphere. Additionally, this index has been manipulated to indicate a suitable time for the production window of the Atmospheric Water Generator (AWG) as predicted and calculated from meteorological studies such as the Typical Meteorological Year (TMY) and weather forecasts. Both these tools and their usage are described in this dissertation's case study. MHI suggests that any value that records  $MHI > 0.3$  indicates a suitable production window time, as seen in Figure 2-4. Unfavourable times are also recorded in the same analysis.



**Figure 2.4: Fraction of favourable time for AWG operation based on meteorological data (2005-2014) combined with physical and economic global water scarcity map (Zohra *et al.*, 2020).**

Figure 2-4 does not demonstrate any production window time for South Africa (SA) as per the MHI, even though the colour legends indicate both the “approaching physical water scarcity” and “physical water scarcity” for SA. As such, the study conducted in this dissertation case report encourages further research on AWH for South Africa to identify discoveries from other reviewed studies based on a combination of experiments and experiences and to place them on a global platform and build on them to address water scarcity.

## 2.5 Atmospheric Water Generators: Vapour Compression Cycle

This section provides insights from global literature reviews regarding what AWGs are, their operation, and how this knowledge has further enriched the researcher. Atmospheric water supply can be considered a cleaner resource than traditional streams from dams and rivers. That is mainly because atmospheric air pollution impact depends on the particular area's activities with particulates present within the atmosphere at a particular time (Inbar *et al.*, 2020). One of the main advantages of

atmospheric water harvesting for drinking water is that there is no need to build a water transport infrastructure. AWGs can be erected anywhere, provided the meteorological conditions are suitable.

Many water harvesting methods have been explored that have proven to be effective, such as water desalination, groundwater harvesting and rainwater collection and storage. However, these methods can only be successful when liquid water is already available. During times of droughts and water scarcity, additional methods must be identified. Atmospheric water harvesting (AWH) is one such option (Inbar *et al.*, 2020). The water formation within the air depends on the relative humidity and temperature of the air. This information is derived from studies of climate, allowing one to predict the suitability of the area for atmospheric water harvesting.

The process of extracting water from humid ambient air can be successfully achieved in two methods, namely:

- I. **Vapour compression cycle**- a process that employs a refrigerant, which is circulated by a compressor through a condenser and an evaporator coil, which cools the air surrounding it, lowering the air's dew point (Talib, Khalifa & Mohammed, 2019). The process is also called "active" as it employs energy for phase change of vapour to liquid.
- II. **The adsorption and desorption cycle is a process that allows natural absorption of water vapour at low temperatures**, such as in the evenings. During the day, when the temperatures are warmer, the water desorbs and is removed or condensed from an adsorbent. This process is also known as "passive" due to its natural state of occurrence.

An AWG is a system described in air conditioning or refrigeration in which conditions can employ heat transfer or mass rate changes, where the thermodynamic principle of mass and energy conservation applies (Li, Shi, Wu, Hong & Wang, 2020). It is then derived from energy principles that air and water vapour are assumed to be perfect gases. The air temperature is high relative to its saturation temperature, which is the point where its condensation begins because the water vapour pressure is low relative to its saturation pressure.

Humidity is the measure of the quantity of water vapour present in the air. It is dimensionless in units.

Humidity =  $M_w/M_a$  (where  $M_w$  is the mass of water vapour carried by mass  $M_a$  of dry air) (Shallcross, 2012). Humidity is measured with a *hygrometer* (Underwood, Gardiner, Finlayson, Bell & de Podesta, 2017) and is expressed as an absolute, specific or relative value. In the operational context of AWGs, humidity is expressed as relative humidity, which measures how close the air is to being saturated –

that is, how close the air is to reaching 100% water vapour carrying capacity. The relative humidity of air is defined as the ratio of the partial pressure of water vapour in the air to the saturation vapour pressure of pure water at the same temperature, expressed as a percentage:

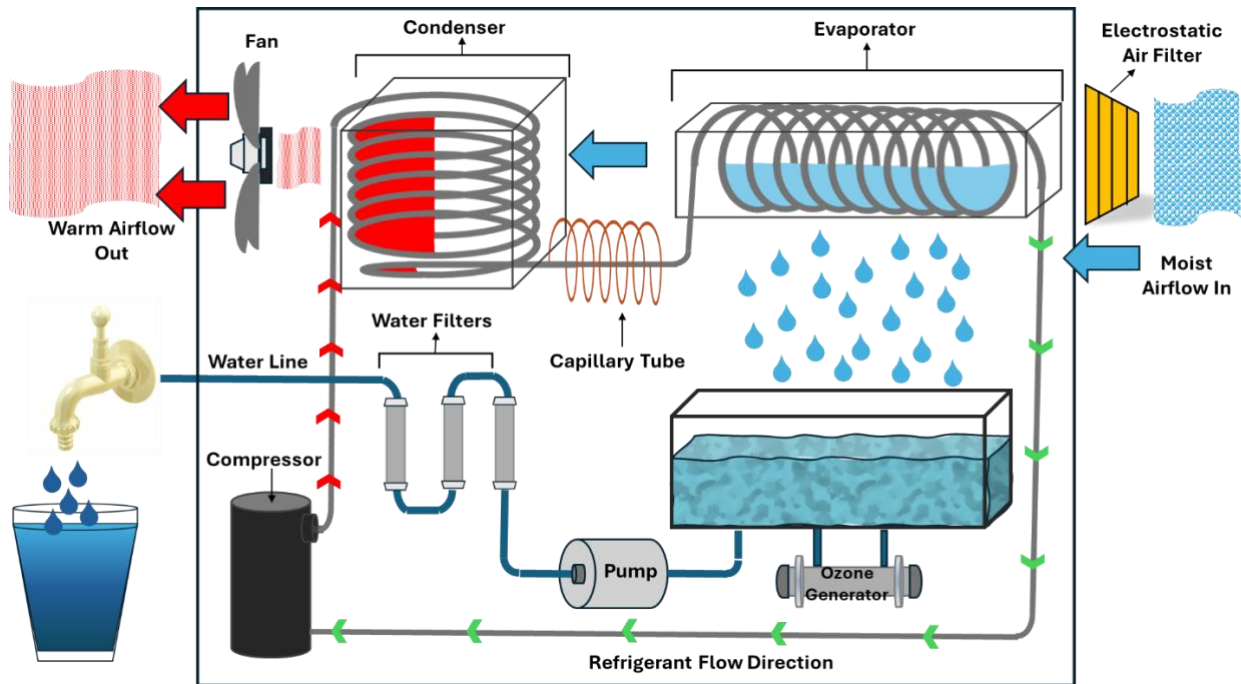
$$RH = \frac{P_W}{P_{SW}} \times 100\% \dots\dots\dots \text{Equation 1}$$

(Source: Kopic *et al*, 2015)

Where:

- **P<sub>w</sub>** is Partial Pressure of Water Vapor
- **P<sub>sw</sub>** is Saturation Vapor Pressure
- **RH** is Relative humidity
  - **RH = 100%**: Air is saturated (e.g., fog, dew formation).
  - **RH < 100%**: Unsaturated air (common in most conditions)

Temperature measures how hot or cold the ambient conditions are and is measured in degrees Celsius (°C). An illustration in Figure 2-5 represents an AWG with its components (evaporator, condenser, fan, water collector, compressor pump, filters, and water output), whereby the air is extracted through air filters, which cleans the air from toxic gases from the atmosphere. The process continues to pass air through the evaporator where it exchanges heat energy with a cold liquid refrigerant. The refrigerant becomes a hot vapour while the air condenses into a liquid. The refrigerant is further compressed into a full gas, and becomes superheated; whilst the water is passed through different filter mediums, including ozone treatment, to ensure that the water produced meets the allowed South African National Standards of drinking water (SANS 241, 2015). Filters require regular maintenance treatment to achieve drinkable, healthy water. Steam tables and psychrometric charts have been used during the design of this AWG to determine all parameters required to achieve an optimal and efficient system, with constants mentioned for the ambient conditions.

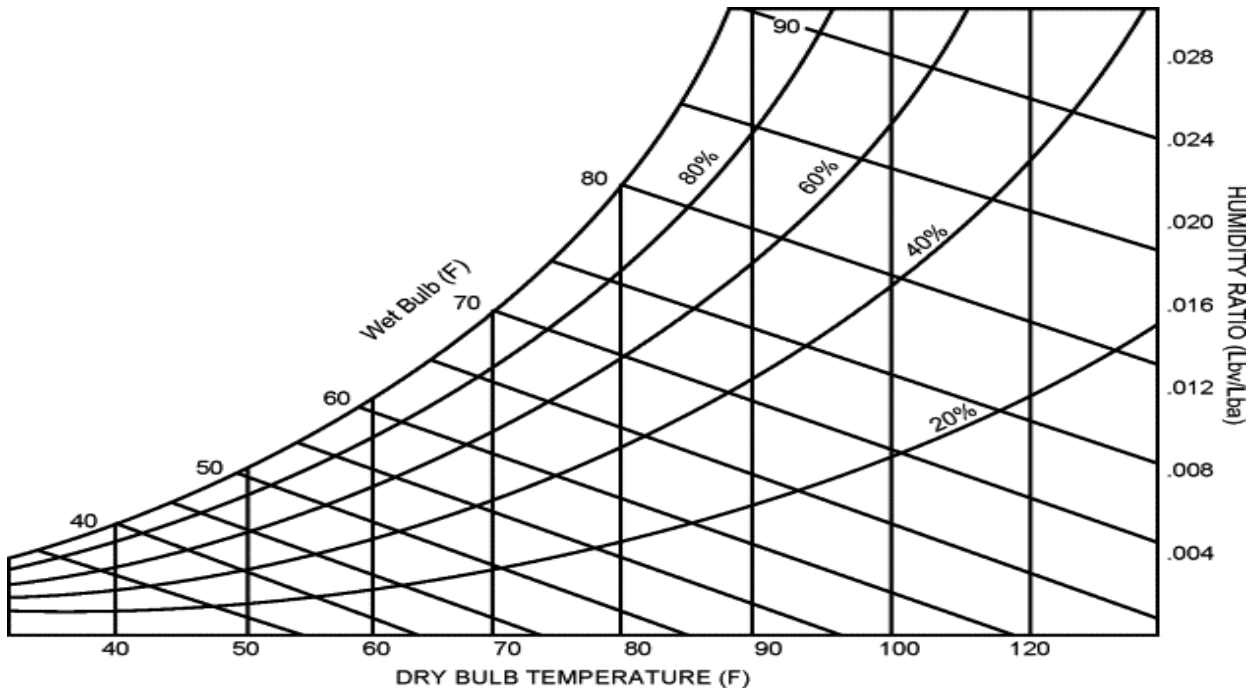


**Figure 2.5: Schematic diagram of an Atmospheric Water Generator (AWG)** (Bodamyalizade, 2018)

The success of the AWGs is based on the principle of phase change from vapour to liquid, whereby the vapour that evaporated into the atmosphere would be harvested and then changed to liquid through condensation. There are four physical processes which occur repeatedly during the dew event (Inbar *et al.*, 2020), namely:

- heterogeneous nucleation,
- self-similar growth,
- re-nucleation and
- droplet removal.

As the ambient temperature increases, the relative humidity decreases while absolute humidity increases (Hyndman, 2004). The original equipment manufacturer (OEM) of these AWGs on the site study stipulated that the temperature conditions of 27 °C and RH of 60% would continuously allow them to perform at their maximum, producing 5000 L per day each. The International Association of Plumbing and Mechanical Officials (IAPMO, 2003) reviewed and reported that the heating, ventilation, and air conditioning (HVAC) system manufacturer would be guided by psychrometric charts to assess their absolute effectiveness.



**Figure 2.6: Psychrometric chart (Zohra et al., 2020).**

Figure 2-6 illustrates a psychrometric chart and displays the humidity ratio on the Y-axis and temperature on the X-axis; the chart provides atmospheric conditions which are most favourable for heating, ventilation and cooling. Dry Bulb Temperature (DBT) is the ambient air temperature as measured by a thermometer, which is not affected by the moisture of the air, whilst Wet Bulb Temperature (WBT) is the temperature reading measured by a thermometer with the bulb wrapped in wet cloth. The WBT lies between the Dry Bulb temperature and the Dew Point. The Dew Point Temperature is the temperature at which water vapour starts to condense out of the air (Al-Azri, 2016). The psychrometric chart is a tool for understanding the relationships between the various parameters of air supply, such as temperature, pressure, enthalpy, and relative humidity. In addition, psychrometric charts are based on standard pressure at sea level. One should consider variability with reference to sea level or consider pressure as constant to simplify the use of the psychrometric chart. Moist air properties vary with pressure because pressure reduces as altitude increases, and the properties of

moist air change with altitude. The psychrometric chart assists in determining the most favourable air conditions for heating, ventilating, and air conditioning (HVAC).

Control of humidity is not required by most HVAC codes ((International Association of Plumbing and Mechanical Officials (IAPMO), 2003.). In most geographic areas however, weather patterns are key to predicting the success and the behaviour of the AWG during the life of its operation. The motivation for an investment in AWG operation would be its ability to deliver the expected water requirements at the lowest cost possible. Hyndman (2004) described a scenario with a warm and humid climate where an air supply can be drawn into a system and then exposed to cooling coils, reducing the air temperature to 7°C (see Figure 2-7). A psychrometric chart indicates that when the relative humidity of the outside air is 80%, and the outside air temperature is 10°C, when the air is cooled to 7°C, water vapour would condense out of the air because the relative humidity would reach 100%.

Psychrometric charts further clarify the relationship between temperature, moisture content, and air energy based on the disclosed temperature. Hyndman (2004) explained that psychrometric charts were built upon two concepts, namely:

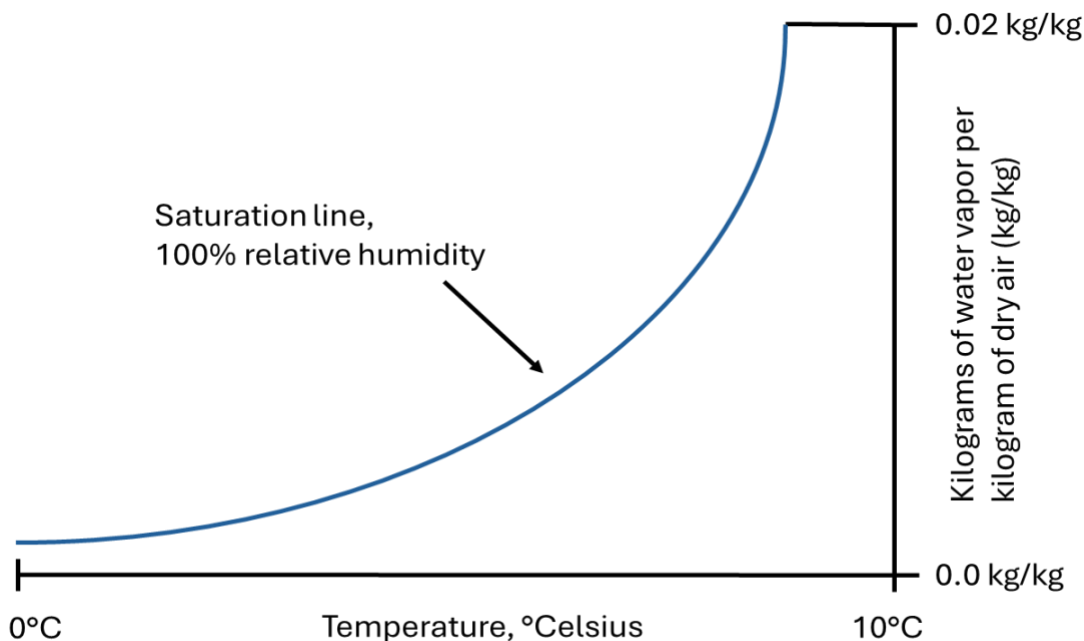
- the definition of indoor air as a mixture of dry air and water vapour, and
- the definition of the specific amount of energy within the air mixture at a specific temperature and pressure.

The water vapour in the air was explained as moisture or humidity, measured as kilograms of water vapour per kilogram of air. This ratio was called the humidity ratio. Moist air properties vary with pressure. Atmospheric pressure is reduced as altitude increases, and the properties of moist air change with altitude.

If the temperature remains constant in an indoor or external environment while the water vapour or moisture within the air increases, there are limits to the volume of water vapour that can be transported or consumed by the air. Once this limit is reached, the air becomes saturated. Any additional water vapour absorbed into this air would be seen as “extra” and would result in the formation of water droplets or ice crystals depending on the temperature of the air (Hyndman, 2004).

Wagner (2019) describes a study of temperature in relation to air and describes what happens when air the temperature drops when it comes into contact with a cooling medium. These are the conditions employed within AWG technology. Water is generated when air is cooled. Air can be cooled continuously until the water reaches saturation point. At this point water vapour condenses out of the air. The temperature at which condensation starts to form is the dew point temperature. Water vapour

is said to be behaving like there is no air presence, the concept was further explained with steam tables where water and air mixture and water in its pure form behave with no difference in pressure at any given temperature. At a specific vapour pressure, condensation occurs in the same way as it would if there was no presence of air. Figure 2-7 illustrates the correlation of air saturation with behaviour water vapour within the relative humidity of air.

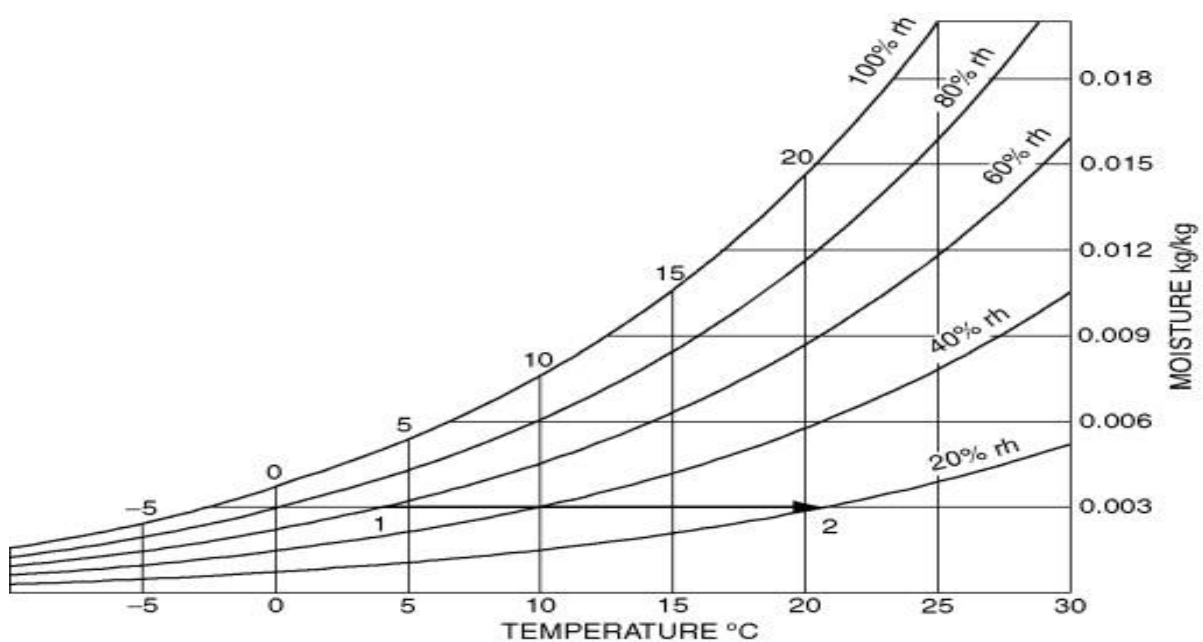


**Figure 2.7: Psychrometric Chart Diagram – Saturation Line. Redrawn from (C Andrade et al. 1999)**

Saturation occurs when the relative humidity (RH) reaches 100%. If the RH is measured as 50%, half of the water vapour within the air has been condensed out when measured in kg of water vapour per kg of dry air, as seen in Figure 2-8. The 50% RH further explains that the air is holding half of the maximum amount of water vapour at that particular temperature.

Another condition of the relationships between the various parameters of air supply, such as temperature, pressure, enthalpy, and relative humidity, is explained by McDowall (2008). When the air temperature increases and the air has high water vapour content, the relative humidity drops, as illustrated in Figure 2-8. Relative humidity is directly proportional to temperature, and thus, the relative humidity was strictly proportional to condensation, but partially proportional to the increase in air

temperature. The warmer the air temperature, the lower the relative humidity (McDowall, 2008). As relative humidity increases, the dry bulb temperature increases to the right of the psychrometric chart while the wet bulb temperature decreases; hence, there was an increase in condensation with an increase in relative humidity. Humidity of the air was the difference measure between dry and wet bulb temperature, the further apart these two temperatures become, the lower the humidity becomes (Razak, 2007).



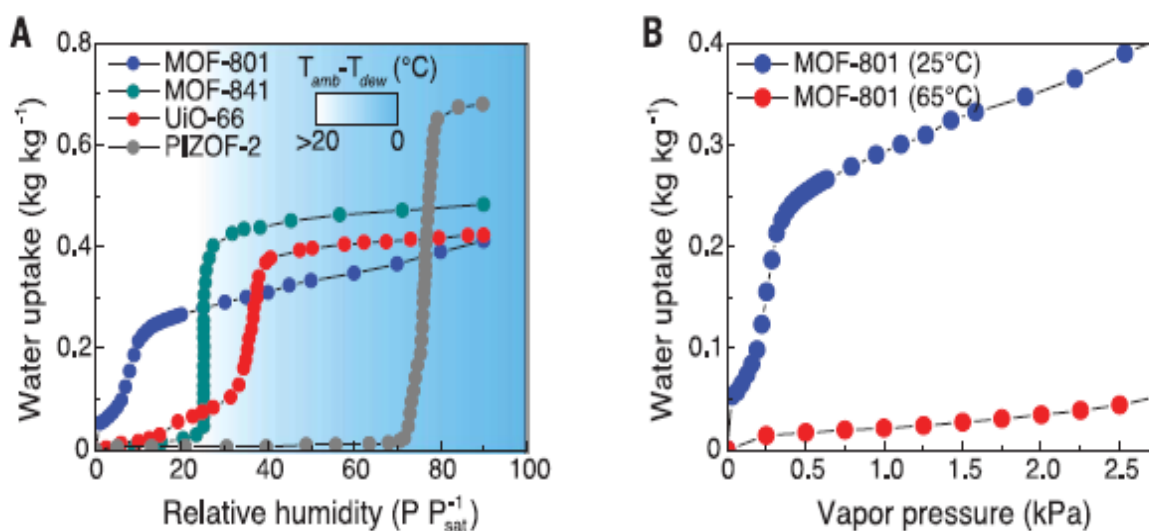
**Figure 2.8: Psychrometric Chart – Change in Relative Humidity with Change in Temperature (C Andrade *et al.*,1999).**

**2.6 Adsorbents Water Harvesters: Adsorption and Desorption Cycle**

An abundance of moisture in the atmosphere can be harvested and captured in different ways to address water scarcity (Asiabanpour, 2017). Fog and dew harvesting has proven successful, but cooling the air below the dew point requires excessive energy, especially in arid conditions. Low humidity conditions in arid geographical areas hinder thriving atmospheric water generation (Xu *et al.*, 2020). Over 25 countries globally are harvesting water from fog and the atmosphere. Most of the studies from these facilities have indicated that consistency in high RH becomes a challenge to maintain the desired continuous water outputs (Li *et al.*, 2018).

Adsorbents employ a process of adsorption-desorption, which uses adsorbents such as desiccants, zeolites and silica gels to absorb vapour and later condense it to access fresh water from them. Literature by Kim *et al.* (2017) describes a method of using adsorbents to fulfil both the purpose of water generation and energy savings, as their experiments used solar energy. Microcrystalline powder from a base of a metal-organic framework (MOF-801,  $[\text{Zr}_6\text{O}_4(\text{OH})_4(\text{fumarate})_6]$ ) was used as an adsorbent. A powder was synthesised and activated at 150°C and under vacuum conditions. Conditions were then maintained for 24 hours for adsorptivity activation. The MOF was coupled to a copper (Cu) plate on one side. The copper is a good heat conductor. The particles absorbed moisture during the day while the solar energy heated the copper plate. The water was then released when temperatures dropped in the evening using a low-grade solar heat-driven pump to desorb the water from the MOF. The MOF was placed in a chamber for controlled conditions. Water vapour was introduced by diffusion with temperatures ranging from 25°C to 65°C, and the relative humidity (RH) conditions were controlled.

The device was reported to have harvested and delivered 2.8 L of water per kg of MOF adsorbent per day at a RH of 20% with solar flux energy of 1  $\text{kw}/\text{m}^2$ . These results become a supporting reference to the current AWG project used for this research case study because they require RH of 30% and a temperature (T) higher than 15°C to be able to generate water. These conditions were similar to those of the Kim *et al.* (2017) experiment. AWGs use a refrigeration vapour compression cycle and grid power. An option of having these AWGs connected to a solar panel, as mentioned in literature by Kim *et al.* (2017), exists and can be explored further as an alternative. Figure 2-9 demonstrates temperature swings from lower temperatures to 65°C whereby an adsorbent can harvest water volume of greater than 0.25 kg water/kg adsorbent at vapour pressure greater than 0.6 kPa (reference of 20% RH at 25°C). As described by McDowall (2008), moist air properties vary with vapour pressure. Vapour pressure is reduced at higher altitudes, while the properties of moist air change with altitude. The Second Law of thermodynamics applies to air molecules in the atmosphere. This principle states that “for a spontaneous process to occur, the entropy of the universe increases” (Witkowski, 2009).

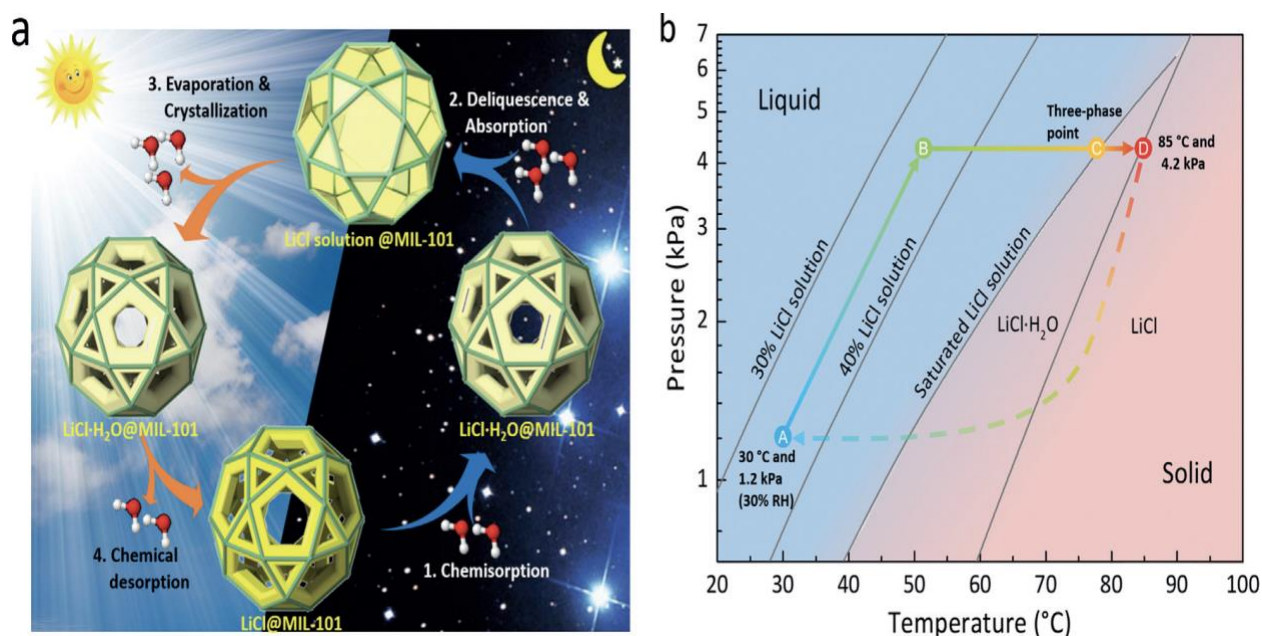


**Figure 2.9: Water adsorption isotherms of MOF-801, measured at 25°C and 65°C (Kim *et al.*, 2017).**

Another adsorption-desorption cycle study method was conducted by Xu *et al.* (2020), which explains the use of a metal-organic framework matrix, LiCl MIL-101 (Cr), with a hygroscopic salt and a natural sunlight environment baseline. Interestingly, the study mentions that certain cohesive forces exist between sorbents and water vapour. Sorption interactions are divided into two categories: physical and chemical sorption. It is mentioned that for most porous absorbents such as zeolites and silica gels, their physical properties result in high regeneration temperature when they interact with water vapour; hence, it becomes difficult for the process to be successful under solar power. On the contrary, chemical absorbents, such as hygroscopic salts, have a higher water intake capacity or absorptivity and lower regeneration temperatures for water harvesting than physical sorbents. While chemical sorbents are advantageous, they have disadvantages such as swelling, agglomeration and being corrosive.

Experiments conducted by Xu *et al.* (2020) used a range of salts to study conditions simulated by Kim *et al.* (2017) for sunlight support. The composite sorbent indicated 0.77 g/g (gram water per gram sorbet surface) water sorption capacity at 1.2 kPa vapour pressure (30% RH at a temperature of 30°C) by integrating the multi-step integrating of salt chemisorption, deliquescence, and solution absorption sorption processes. The conditions had to be monitored with repetitive adsorption-desorption cycles. A highly efficient AWH prototype was demonstrated with LiCl@MIL-101(Cr) that enabled the harvesting of 0.45–0.7 kg water per kg of material under laboratory and outdoor ambient conditions powered by natural sunlight, as illustrated in Fig 2-10. All the adsorption-desorption dynamics were witnessed after

several cycles. A composite salt in a porous matrix (CSPM) was used to solve agglomeration experienced in chemical sorbents.



**Figure 2.10: a. Steps in water adsorption-desorption cycles of LiCl@MIL-101(Cr). b. Different salt solutions of LiCl@MIL-101(Cr) indicating adsorption-desorption cycles (Xu *et al.*, 2020).**

An experiment was conducted by Li *et al.* (2018). Three fibrous adsorbent materials were loaded with three anhydrous salts, respectively: copper chloride (CuCl<sub>2</sub>), copper sulphate (CuSO<sub>4</sub>) and magnesium sulphate (MgSO<sub>4</sub>). Each adsorbent material was fitted with a top layer of photothermal material, which absorbed heat energy from the sun. A total of 14 salts were screened: iron(III) chloride (FeCl<sub>3</sub>), zinc nitrate (Zn(NO<sub>3</sub>)<sub>2</sub>), copper(II) nitrate (Cu(NO<sub>3</sub>)<sub>2</sub>), calcium chloride (CaCl<sub>2</sub>), nickel(II) nitrate (Ni(NO<sub>3</sub>)<sub>2</sub>), iron(III) nitrate (Fe(NO<sub>3</sub>)<sub>3</sub>), iron(II) sulphate (FeSO<sub>4</sub>), lithium sulphate (Li<sub>2</sub>SO<sub>4</sub>), sodium carbonate (Na<sub>2</sub>CO<sub>3</sub>), sodium sulphate (Na<sub>2</sub>SO<sub>4</sub>), copper(II) chloride (CuCl<sub>2</sub>), nickel(II) acetate ((CH<sub>3</sub>COO)<sub>2</sub>Ni), copper(II) sulphate (CuSO<sub>4</sub>), and magnesium sulphate (MgSO<sub>4</sub>). It should be noted that calcium chloride was the salt used by Xu *et al.* (2020). It had a lower but successful water uptake of 1g/g at 28% RH and 28°C. Three salts were selected for their high water absorption and release capabilities, along with strong chemical and physical stability. Copper chloride (CuCl<sub>2</sub>) performs best in low relative humidity (RH) environments, functioning effectively down to 10–15% RH. It releases water at 39.5°C, making it suitable for solar-driven applications. Additionally, it demonstrates excellent durability,

retaining 92.3% of its water capacity after 10 hydration and dehydration cycles. Copper sulfate ( $\text{CuSO}_4$ ) is effective at RH levels of 35% and above, releasing water at  $32.5^\circ\text{C}$ . It maintains full water absorption capacity even after 10 cycles, making it ideal for use in humid regions with weaker sunlight, such as islands. Magnesium sulfate ( $\text{MgSO}_4$ ) shows the highest water uptake capacity among the three, with an absorption rate of 0.45 grams of water per gram of salt. It also operates effectively at RH levels of 35% and higher, releasing water at  $34.5^\circ\text{C}$ . While chemically stable,  $\text{MgSO}_4$  may form mixed hydrates, such as  $\text{MgSO}_4 \cdot 4\text{H}_2\text{O}$  and  $\text{MgSO}_4 \cdot 6\text{H}_2\text{O}$ , under certain conditions. The following table summarizing the salts screened in the experiment, highlighting the three selected salts ( $\text{CuCl}_2$ ,  $\text{CuSO}_4$ , and  $\text{MgSO}_4$ ) along with the other eleven salts and the one used by Xu *et al.* (2020):

**Table 2.1: Summarizing the salts screened in the experiment, highlighting the three selected salts**

Salt	Water Uptake (g/g)	Minimum RH for Absorption	Dehydration Onset Temp. ( $^\circ\text{C}$ )	Available Water Capacity (g/g)	Key Properties
$\text{CuCl}_2$	0.27	10% RH (onset at 15%)	39.5	0.27 (salt) / 0.21 (device)	Best for low-RH regions (deserts); high photothermal efficiency ( $75\text{--}87^\circ\text{C}$ under 1 sun).
$\text{CuSO}_4$	0.4	35% RH	32.5	0.40 (salt) / 0.30 (device)	Suitable for moderate RH; fast water release at $>50^\circ\text{C}$ ( $0.7\text{ kW/m}^2$ sunlight).
$\text{MgSO}_4$	0.45	35% RH	34.5	0.45 (salt) / 0.35 (device)	Highest water capacity; needs higher RH but works at weaker sunlight ( $0.7\text{ kW/m}^2$ ).
$\text{CaCl}_2$	-	Deliquesces at 60% RH	-	-	Excluded due to deliquescence (forms liquid).
$\text{FeCl}_3$	-	Deliquesces at 60% RH	-	-	Excluded (chemically unstable).
Nitrates	-	Deliquesce at 60% RH	-	-	Excluded (e.g., $\text{Zn}(\text{NO}_3)_2$ , $\text{Cu}(\text{NO}_3)_2$ , $\text{Ni}(\text{NO}_3)_2$ ).

An experiment on the adsorption-desorption cycle was also conducted by Mittal *et al.* (2020), who employed a solid desiccant material composed of a super porous hydrogel (SPHs) of polyacrylamide (PAM) and AQSOA-Z02 zeolite which were fabricated to capture water vapour from moist air. The study explains the benefits of using the zeolite with the polymer, which benefited the experiment by increasing the water vapour absorptivity on the desiccant from  $0.77\text{ g/g}$  within the hydrogel to up to  $0.89\text{ g/g}$ . The water vapour absorptivity decreased with an increase in temperature, similar to studies referenced by Xu *et al.* (2020). The physical properties of most porous absorbents such as zeolites, result in high regeneration temperatures when they interact with water vapour.

Mittal *et al.* (2020) found that the high adsorption capacity of SPHC occurs due to capillary condensation and the presence of hydrophilic Lap-RD particles within the polymer matrix. The concept supports similar insights in a literature study of a MOF with hygroscopic salt adsorption and a natural sunlight environment (Xu *et al.*, 2020). Xu *et al.* (2020) mentions that cohesive forces exist between sorbents and water vapour when capillary condensation occurs.

## 2.7 Legislation Relating to Atmospheric Drinking Water Quality

All drinking water should be sampled and analysed, including atmospheric water, to ensure that it is free of contaminants that may be detrimental to a human being's health in accordance with the guidelines of the World Health Organisation (WHO) (2022). This analysis provides further information about water sources and how they are impacted by external factors such as humans, industrials, and animals concerning quality. It is a requirement by the WHO that the public have safe drinking water and that water is managed well to ensure economic security. The following parameters are the key requirements regarding drinking water quality as stipulated by both WHO and The South African National Standard for Drinking Water 241(SANS 241, 2015):

- **pH:** is a degree of how acidic or alkaline water is and it is represented on a scale of 0 to 14. Water with a pH of 7 is neutral,  $\text{pH} < 7$  is acidic,  $\text{pH} = 0$  being highly acidic. Water  $\text{pH} > 7$  is alkaline, with pH 14 being the most alkaline. Alkaline water is favourable to digestive health and promotes acidic pH balance. According to the United States Environmental Protection Agency (EPA) (2018) and the WHO's Guidelines for Drinking Water Quality (GDWQ) (World Health Organization, 2022) pH has no direct impact on the health and safety of consumers (Hansen TH, 2018). It remains crucial to monitor drinking water quality as its pH affects the way water interacts with its environment such as piping and holding tanks, including human bodies. SANS 241 (2015) provides limits of  $> 5.0 - < 9.7$  for operational risk monitoring.
- **Turbidity:** indicates the cloudiness of water due to suspended particles and organic matter (WHO, 2022); it is expressed in nephelometric turbidity units (NTU). Poor water source or treatment quality is the root cause of turbidity presence. WHO (2022) provides a guide of NTU of  $< 4$  whereas SANS 241 (2015) has a limit of 1 NTU for aesthetic and 5 NTU maximum for drinking water operational systems.
- **Total Dissolved Solids (TDS):** indicates water containing more dissolved solids, which can influence taste. The WHO (2022) recommends levels below 600 mg/l (millito be generally good, while SANS 241 (2015) provides a limit of 1200 mg/l for aesthetics.

- **Electrical Conductivity (EC):** is an expression of the saltiness of water. It is measured in a range from 0 to 50,000 uS/cm. It is also related to TDS presence. SANS 241 (2015) gives the limit of 170 mS/m.
- **Metals:** some metals exist in water naturally as deposition of metals from rocks that come in contact with water; however, most metals in water have been a result of pollution directly or indirectly by humans through socio-economic activities. SANS 241 (2015) provides limits for metals in drinking water.
- **Cations:** naturally form part of water as the water flows from sources under and above the ground. They result mainly from the weathering of silicate and evaporite rocks. The most common cations in water are calcium ( $\text{Ca}^{2+}$ ), magnesium ( $\text{Mg}^{2+}$ ), sodium ( $\text{Na}^+$ ), and potassium ( $\text{K}^+$ ). SANS 241 (2015) provides limits for cations in drinking water.
- **Anions:** form part of water in the same way as cations. They originate mainly from the dissolution of evaporite rock (Liu *et al.*, 2019). The most common anions in water are bicarbonate ( $\text{HCO}_3^-$ ), chloride ( $\text{Cl}^-$ ), and sulphate ( $\text{SO}_4^{2-}$ ). SANS 241 (2015) provides limits for anions in drinking water.
- **Microbiology:** An analysis was conducted on microorganisms commonly found in water, including bacteria (*Escherichia coli*, *Enterobacter spp.*), yeasts (*Candida albicans*), fungi (*Aspergillus spp.*), viruses (e.g., *Norovirus*), algae (*Chlorella spp.*), and protozoa (*Giardia lamblia*). These organisms typically proliferate when a water system becomes septic or is contaminated. In this study, microbial presence is assessed using heterotrophic plate count (HPC), total coliform bacteria (TCB), and *Escherichia coli* (*E-coli*) as key indicators. SANS 241 (2015) provides limits for microbiological contaminants in drinking water.

A study was conducted by the United States Environmental Protection Agency (EPA) (2018) to research and explore the use of AWGs in different States' needs. Whilst energy efficiency and cost of AWGs were being assessed; the quality of the generated water was at the forefront of the research, particularly the microbiology of the immediate, raw harvested water. The research was done over three months, and analysis indicated the absence of opportunistic pathogens on samples collected weekly; however, high levels of heterotrophic bacteria were detected using heterotrophic plate counts (HPC) of treated water. HPC denotes inadequacy of disinfection and/or microbial reoccurrence post-disinfection (EPA, 2018). While research mentions that the presence of heterotrophic bacteria does not represent a human health risk, it has been found that it does threaten those with a compromised immune system, such as

cancer and AIDS patients (Pavlov, 2004). EPA research and development (EPA, 2018) recommends the chlorination and or ozonation process of the AWGs to ensure that the water is HPC free.

Inbar *et al.* (2020) share the outcomes of a study conducted in an urban area in Tel Aviv, Israel; of AW quality on organic and inorganic compounds, metals, ions and ammonium, including volatile and semi-volatile organic compounds. About 64 water samples were collected and analysed from the AWG from June 2019 to March 2020 under different climatic conditions and seasons. AWH analysis results were then compared to the WHO (2022) drinking water guidelines as well as Israeli drinking water standards (IDWS) (Israeli Ministry Regulations, 2020). It was found that none of the results exceeded either of these drinking water standards. There was also a concern about detecting some chemical elements that form part of the AWG equipment, such as iron, chromium, molybdenum, and aluminium, but these were not present. Occasionally, these were detected in the dew water or raw harvested (before filtration) in extremely small quantities of less than 5 µg/L.

Metal analysis of the atmospheric water from the Israel study was conducted with a total of 24 samples focusing on the common metals; namely aluminium, zinc and copper. They were found to be lower than the drinking water standards. A higher Zinc count was detected many times, but this still did not exceed the standard. The review found that the source of zinc came from pollution caused by the abrasion of vehicle tyres. Earlier information reported that several long-range transport processes resulted in a characteristic aerosol over Israel, resulting in a high level of zinc being detected in the atmosphere. Even though metals are essential to human health, excessive amounts of these metals may have a severe adverse health effect on humans. Hence, their quantity must be monitored.

In addition, copper (Cu) was detected in all AW samples but in lower amounts when compared to the WHO (2022) and Israeli Drinking Water standards. It was mentioned that its existence originates from metal industrial production, industrial combustion of lubricants, coal combustion and abrasion of vehicle parts. Nickel was detected higher than the limits within the Israeli Water standard and was the only metal out of range; its origin was traced from fuel oil combustion through vehicle emissions in the city (Heo *et al.*, 2017). Furthermore, calcium (Ca<sup>2+</sup>), magnesium (Mg<sup>2+</sup>), sodium (Na<sup>+</sup>) and potassium (K<sup>+</sup>) ions were detected in low concentrations. These are considered important in water geochemistry. These metal ions do not have limits in either WHO (2022) or IDWS standards. Mg<sup>2+</sup> and Ca<sup>2+</sup> deficiency in drinking water can cause various health deficiencies. As such, the review recommends that AW should be supplemented with these essential minerals to a concentration of 25–50 mg/L as recommended for desalinated water (WHO, 2022). This study suggests that AW has excellent quality compared to recommendations of regulations and can be accessed for human consumption.

## 2.8 Energy efficiency of AWG and success factors

The case study conducted within this dissertation supports AWH as an alternative source to the current drinking water because air is available everywhere, whilst conventional drinking water has to come from sources such as dams, rivers and the sea. Without these sources, it would be impossible to produce potable water. For this reason, extensive infrastructure investment in pipework, extensive structural supports, pumps and valves would be needed to ensure that water reaches its destination for treatment and distribution. Tu (2018) mentions that in order for an AWH process to be deemed successful, it has to meet the following criteria:

- It should be efficient;
- It should be affordable when compared to other similar technologies;
- It has to be viable for scalability;
- It should be wide-band in operations; and
- It should be efficient to operate throughout all seasons in a year.

The literature indicates that “b” and “e” above have proved to be the limitations to AWH technology. **Criterion b** becomes a challenge with regard to energy intensity. The technology derives vapour (air) into liquid (water), which requires an extensive amount of energy. As such, the process becomes highly costly in energy billing. Bui (2017) states that the energy consumption of AWH is highly dependent on the particular system design. Upon analysing a few commercial vapour compression cycle systems on AWGs the author found that they employ conventional air-conditioning technology to generate water, and most of them have tested efficiency rates of around 250 W/h of electricity per kilogram of water produced. Researchers have begun coupling solar energy drives to AWGs and adsorbent operations to reduce the electricity energy costs for this operation. Such operations combine vapour compression and adsorption-desorption cycles.

Further findings of the same literature reveal that energy efficiency in atmospheric water harvesters was calculated as the specific energy consumption (SEC) to assess possible investment in this technology. It was reported that the SEC was highly dependent on ambient relative humidity (RH), ambient temperature (T), and recovery ratio (RR). The recovery ratio is the fraction of the water vapour within the air stream harvested as liquid water. SEC was calculated as follows using equation 2 to 6:

$$\frac{RR}{RH} \times T_{\text{ambient}} = \text{SEC in kWh/m}^3 \quad \text{Equation 2}$$

$$\text{SEC} = \frac{Q_{\text{condenser}}}{m_{\text{water}}} = C_p \frac{T_{2,i} - T_{\text{condenser}}}{d_{2,0} - d_{\text{condenser}}} + hfg \quad \text{Equation 3}$$

$$m_{\text{water}} = \rho_1 V_1 t_1 (d_{2,0} - d_{\text{condenser}}) \quad \text{Equation 4}$$

$$m_{\text{water}} = \rho_2 V_2 t_2 (d_{2,0} - d_{2,i}) \quad \text{Equation 5}$$

- The subscripts 1, 2 stand for the sorption and desorption process.
- The subscripts i, o, stand for the inlet and outlet.
- $\rho$  represents the vapour density ( $\text{kg}/\text{m}^3$ ).
- $V$  represents the vapour flow ( $\text{m}^3/\text{h}$ ).
- $t$  is the time taken in hours (h).
- $d$  is the humidity ratio ( $\text{kg H}_2\text{O}/\text{kg dry air}$ ).
- $C_p$  is the wet air's specific heat capacity ( $\text{J}/\text{kg } ^\circ\text{C}$ ).
- $Q_{\text{condenser}}$  is the entire cooling load.
- $h_{fg}$  is the enthalpy of condensation.
- RR is the Recovery Ratio (a measure of efficiency in separation or desalination processes, often defined as the ratio of product water to feed water).
- RH is the Relative Humidity (a percentage representing the amount of moisture in the air compared to its maximum capacity at a given temperature).

Energy efficiency limitations in direct cooling, such as AWGs, have been found to be highly impacted by the energy input that unnecessarily cools the air, and it continues to deteriorate when ambient RH decreases. Additionally, SEC can be derived from the coefficient of performance (COP) below (Equation 6) of the cooling system calculation, which is as follows (Kim *et al.*, 2017):

$$\text{COP} = \frac{\text{Total Cooling Load}}{\text{Input Power}} \quad \text{Equation 6}$$

A study by Kim *et al.* (2017) explains that desiccants should work in cycles of two heat-rejection steps and condensation, plus one heating step for regenerating the desiccant. Although sorption and condensation do not require sub-ambient cooling temperatures, high efficiency mandates externally driven active cooling, translating into non-negligible energy input for the cooling steps. Although the sorption heat is desiccant-dependent, its minimum value was water's latent heat of vaporization, which was independent of RR. The desiccant regeneration heat is non-negligibly higher than the water sorption heat. The energy input to solar heating increases  $\text{SEC}_{\text{min}}$  by a factor of about two because mass-produced stationary solar thermal systems have a solar-to-heat efficiency of about 50% for the temperature range of interest. The experiment described in this literature (Kim *et al.*, 2017) states that energy efficiency improves upon the SEC of desiccants by combining them with active solar-powered cooling (electricity from photovoltaics and heat from solar thermal collectors).

Upon analysis of the work of Tu (2018) with regards to **critterion 'e'** on atmospheric water harvesting technology being able to operate efficiently throughout all seasons in a year, Section 2.1 of the dissertation discusses the importance of climatic condition analysis or a feasibility study of the identified location to harvest water from the air prior to the implementation of the investment. To assess water harvesting productivity for all seasons of the year, the Köppen-Geiger Climate Classification (Conradie, 2012), in conjunction with the use of psychrometric charts in Section 2.6, and a typical meteorological year (TMY), have been referenced for the feasibility study evaluation of a selected location. Though the Köppen-Geiger Climate Classification has been designed for a South African context, psychrometric charts and TMY apply globally. In addition, **critterion 'e'** analysis has been supported in Section 5.5 of the dissertation dealing with energy analysis of the AWG used within the case study for a cost-effective overview of the technology compared to municipal potable water. The energy costs supported by Moghimi *et al* (2019) were as follows:

- Atmospheric Water Harvesting (AWH) energu costs: R24 per kilolitre (R24/kL)
- Municipal Water energy costs: R2 per kilolitre (R2/kL)

The above costs have indicated that AWGs were not energy-efficient equipment because a phase change process would occur from the vapour from air into liquid water through condensation. The case study recommends using an alternative energy source, such as solar energy. This has to be explored in detail for future studies, particularly in the South African context. Additionally, a thorough costing analysis of the following parameters has to be conducted together with energy analysis to create a holistic business case between AWH and Municipal Water:

- Chemical usage of a typical municipal plant;
- Municipal by-product environmental clean-up and
- Overall plant maintenance.

AWH has proven to be successful at higher humidities of  $RH > 40\%$ , while fog harvesting has its best performance when super-saturated conditions exist (Li, 2024). It is further recommended that equipment used in AWH, such as condensers, evaporators, and vacuum pumps, be evaluated for efficiency improvement to improve or obtain more productivity from the technology.

## 2.9 Chapter Summary

Chapter 2 explores Atmospheric Water Harvesting (AWH) as a sustainable solution for extracting freshwater from atmospheric sources such as clouds, fog, and water vapor. It highlights two main

technologies: fog harvesting and atmospheric water generators (AWGs); which utilise mechanisms like mesh-based collection and vapor condensation through adsorption-desorption or vapor compression.

The chapter emphasises AWH's relevance in water-scarce areas, especially in arid and semi-arid regions like South Africa, which has historically suffered from droughts and increasing water demand. Fog harvesting has been explored since the 1960s, with early success at Mariepskop and more recent promising results in coastal areas like Cape Columbine (up to 2.5 L/m<sup>2</sup>/day). The favourable fog conditions are due to the interplay of warm easterly winds and cold Atlantic waters. Additionally, AWGs have been tested in KwaZulu-Natal's humid coastal climate, benefiting from warm Indian Ocean currents, and demonstrating effectiveness during drought conditions.

Globally, AWH is crucial for over 2.1 billion people facing water scarcity. The chapter notes that fog harvesting is passive and low-cost, while AWGs offer more control but require significant energy; often limiting widespread use. Innovations such as solar-powered desiccants and advanced materials like metal-organic frameworks (MOFs) are being developed to reduce energy consumption and increase efficiency. However, operational efficiency depends heavily on climate factors like relative humidity (typically >30%), temperature, and recovery ratios.

Cost remains a major barrier with AWH water costing around R24/kL, compared to municipal supply at R2/kL. Seasonal and climatic variability further complicate deployment, necessitating robust climate assessments using tools like psychrometric charts and the Köppen-Geiger classification.

The quality of harvested water does meet WHO and SANS 241 standards. While AWG water generally complies, urban pollution can introduce contaminants such as zinc, requiring treatment and mineral supplementation to ensure potability.

In conclusion, AWH shows strong potential, especially in South Africa's fog-rich coastal zones. However, to scale effectively; further research is needed on energy cost reduction and alternatives (e.g. solar integration), and long-term performance assessments across different climate zones.



### 3.1 Case Study Location

The case study site was situated on a global positioning system (GPS) indicated by a purple-coloured pin location  $25.5864^{\circ}$  S,  $27.9876^{\circ}$  E (Figure 3-1), Pretoria North, Gauteng Province in South Africa.



**Figure 3.1: Case study area indicated as “site area”.**

The Köppen-Geiger Climate Classification categorised the case study region as a high-altitude location with a combination of Cwb being warm temperate, winter dry, warm summer, and Bsh being steppe climate, hot steppe or desert. These classifications are further explained by concatenating a maximum of three alphabetic characters, describing the main climatic category, temperature, and precipitation characteristics. The high altitude, semi-arid region in South Africa has at least 4  $T_{\min}$  (monthly mean lowest temperature)  $\geq +10^{\circ}\text{C}$  with  $P_{\min}$  (lowest precipitation in winter)  $< P_s$  (summer precipitation) and  $P_{\max}$  (highest precipitation in summer)  $> 10 P_{\min}$  as well as  $T_{\text{ann}}$  (annual mean temperature)  $< +18^{\circ}\text{C}$  and  $P_{\text{ann}}$  (annual accumulated precipitation)  $> 5 P_{\text{th}}$  (dryness threshold precipitation) hence the rain pattern only exists in spring and summer with a dry autumn and winter.

## 3.2 Material and Apparatus Used During the Study

### 3.2.1 Atmospheric Water Generators

Atmospheric water generators were the heart of the study as they were the leading equipment employed for harvesting water. These AWGs employed a vapour compression cycle to condense water vapour from the atmosphere by cooling atmospheric air below its dew point temperature. Water passes through multiple stages of filtration within the AWG to satisfy the South African National Standards for Drinking Water (SANS 241, 2015) (SABS, 2015). These AWGs were designed to produce 10 000 L of pure drinking water per day, following a process illustrated in Figure 3-2. They were powered by the national electricity grid and consumed 105 kW per hour when on maximum production. The AWGs generated no by-product except for the exhaust air after dehumidification.

**Table 3.1: Site AWGs specifications.**

Mode No.	BWT-A5000-38	
Power Supply	3/N/PE AC 380V 50Hz three-phase voltage	
Input Power	64kw	
Water Production (Litres/24Hr)@ 30°C & RH- 80%	5000 litres @ 30°C & RH @ 80%	
Compressor	Compressor Type	Enclosed vortex compressor
	Compressor Qty	4
	Phase Protection	- Phase-sequence Protection - Delay Protection - High & Low Pressure Protection - Overheat & Overload Protection
Refrigerant	Gas Type	R407C
	Control Type	External balance type Thermal expansion valve
	Gas charge amount	4×9kg
Air volume	Circulating air volume	31000 m3/h
	Heat exhaust air volume	39000 m3/h

Fan	Recycle Fan (High efficient centrifugal fan)	8 pcs
	Heat Removal Fan (Efficient axial flow fan)	8pcs
Air Filter (G3 non-woven filter)	450*2200*360mm x2set 450*2200*600mm x2set	
Filtration System	PPF+CTO+UDF+UF+UV+Mineralization	
Machine Dimension (L*W*H) (mm)	2200*5650*2130	
Machine Weight (kgs)	3900kgs	
Working condition	Temperature	Standard working temperature:15°C – 45°C In case the temp below 15°C or higher 45°C, System needs to be customized
	Humidity	30% - 100%
Control system	PLC	

\*Supply voltage: 400V, Maximum output current: 1000A, 750kVA, Power factor : 0.9, Silent type



Figure 3.2: Site study AWGs front view (as per the GPS location).



**Figure 3.3: Site study AWGs back view (as per the GPS location).**

The AWGs were designed with temperature and RH measuring instruments to measure and display these variables on the human-machine interface (HMI) mounted on them it is listed in Figure 3-4. The AWGs had no HMI storage memory to save data and trends. Data had to be collected manually daily on an hourly basis for record keeping and operational event traceability. The AWGs had flowmeters as part of their critical measuring equipment from which their water production readings were collected. The collected water from the condenser was passed through activated carbon and reverse osmosis (RO) filters to ensure conformance of drinking water quality with SANS 241 (SABS, 2015).



**Figure 3.4: HMI mounted on the site study AWGs.**

### **3.2.2 Methods of data capturing**

Each day of the week readings were taken and captured manually from AWGs and tabulated along with the figures from South African Weather Services (SAWS) (South Africa Department of Forestry, Fisheries and the Environment, 2020); a weather forecast tool which was used as a forecast, reference and verification tool. Discrepancies between forecasted data and what AWGs would measure were recorded as temperature (T), relative humidity (RH) and actual water production. The design table of AWGs from the original equipment manufacturer (OEM) was used as an added advantage to monitor the outcomes of the tabled parameters against water production to see if the AWGs were producing as per the design.

The collected data and the water chemistry quality data were recorded and saved on a spreadsheet. Each week, SAWS was checked for the weather forecast for the week ahead for seven days. The temperature and RH values and water production predictions from those values were tabulated per the OEM's design table of AWG performance, as illustrated in Figures 3-5 and 3-6.

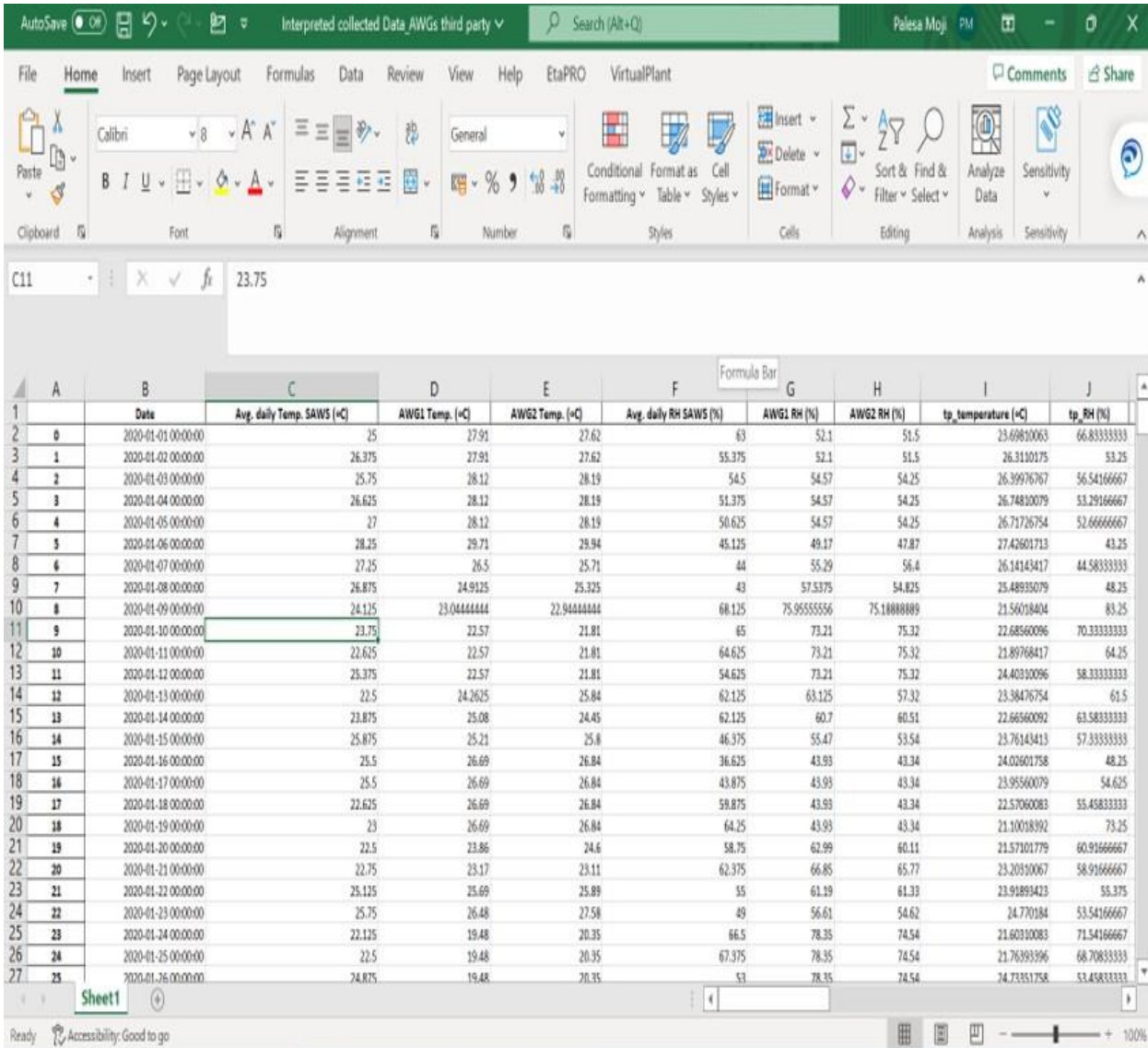
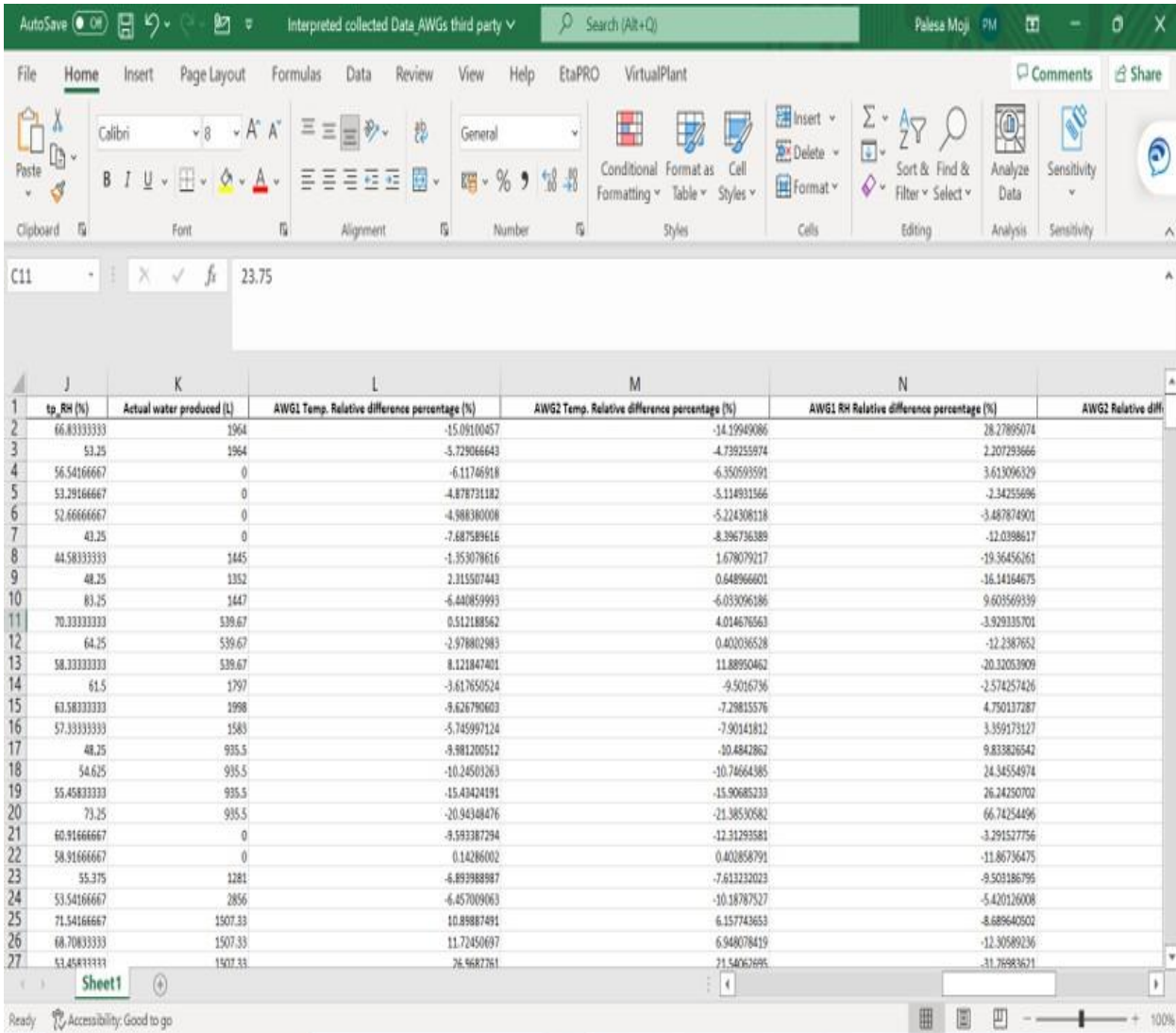


Figure 3.5: Site recorded data.



**Figure 3.6: Site recorded data continued.**

SAWS has a limitation of a seven-day weather forecast and provides daily average readings in a 24-hour period. Any data beyond these days was not available at the time of this data collection. Another source of reference and data verification was obtained from Meteoblue (2020), which was operated under a license. This provided more confidence in the precision of the data. Meteoblue data is displayed in Figures 3-5 and 3-6 as third-party temperature (tp\_T) and third-party relative humidity (tp\_RH). This third-party platform had the advantage of forecasting data up to 14 days ahead, as well as hourly forecasts instead of daily averages, as was the case with SAWS. The use of this third-party weather forecast tool was not obtained at the beginning of the research. It was identified in October 2020 after several online research efforts to find a solution that could provide a complete ambient weather forecast,

including hourly changes, to meet productivity business expectations for current and future investments. The tool also provided the additional advantage of a maintenance watch. If the AWGs were scheduled to be in service and were not operating, the site Operations team would be alerted that something might be defective with the generators. A comprehensive model has been designed, which consists of all collected site data of all recordings done during the study. This simulates the conditions that favour atmospheric water harvesting in this particular region. The information is presented in the next chapter of results and discussions.

### 3.2.3 Equipment additional to site atmospheric water generators

#### a) Hygrometers

Hygrometers are instruments used to measure the humidity of air or another gas to indicate how much water vapour is present within the air or the gas (Figure 3-7). Hygrometers were procured and mounted on the site AWGs in November 2020 to verify the generator’s relative humidity readings. They also recorded the temperature. It was to the researcher’s advantage that many options were available, including the operating manual from AWGs OEM, weather forecast online tools, and hygrometers.

Detailed results are discussed in section 4.2 of the next Chapter. It was expected that the AWGs would be commissioned, but they would not start as per their set point design. This alerted the operations team of a defect. Corrective maintenance of control and instrumentation equipment of AWGs was linked to the internal thermometer and hygrometer. These externally mounted hygrometers were kept as an added verifier of hourly data recordings during the remainder of the research year and beyond as part of business operational instruments.

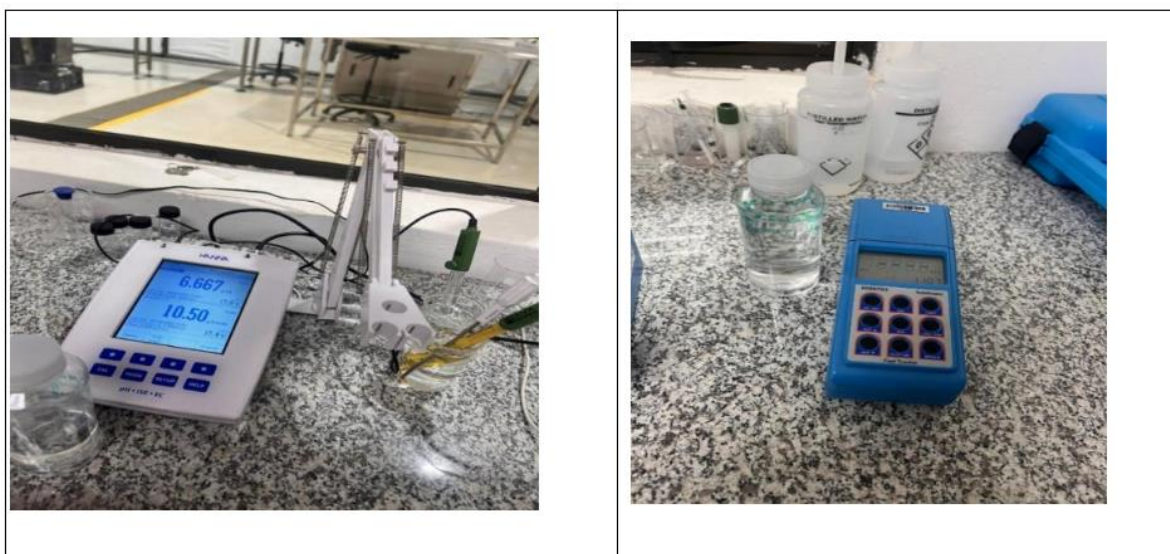


Figure 3.7: Site hygrometer, monitor (left) and display (right).

## b) Site chemical analyses

Every batch of the atmospheric water (AW) produced was analysed in triplicate at the site laboratory for pH, turbidity, and electrical conductivity to ensure precision and repeatability (Figure 3.8). Cotton wool swabs, collected in duplicate from each stage of the filtration and ozonation process; including final product piping and storage tanks—were submitted to a specialised microbiological laboratory for the detection of any microbial contamination. Turbidity and conductivity measurements served as indicators of treatment efficacy, while the swab analyses were used to assess microbial growth within the system.

In addition, all sampled batches were sent to accredited external laboratories for comprehensive analysis of ionic composition and microbiological parameters. A monthly cleaning-in-process (CIP) procedure was performed across the entire plant to maintain aseptic conditions and prevent bacterial growth.



**Figure 3-8: pH and conductivity meter (left) and turbidity meter (right) at site laboratory.**

### 3.3 Data analysis

The data collected from the atmospheric water generators (AWGs), meteorological instruments, and laboratory analyses were processed through a systematic and quality-assured workflow to ensure reliability and accuracy.

All temperature, relative humidity (RH), and water production readings were recorded manually on an hourly basis and entered into a structured Microsoft Excel spreadsheet for each day of operation. These datasets were then cross-referenced against forecasted ambient conditions obtained from the South African Weather Services (SAWS) and Meteoblue. The third-party Meteoblue dataset, which provided up to 14-day hourly forecasts, served as a validation and verification tool to enhance confidence in the ambient data records. Any significant deviations between site measurements and forecasted values were flagged for investigation.

Weekly comparisons were made between actual site production values and the AWG design performance table from the original equipment manufacturer (OEM) to assess machine efficiency under prevailing environmental conditions. Discrepancies informed both predictive maintenance planning and operational optimisation strategies.

The water quality data, including pH, turbidity, and electrical conductivity, were analysed in triplicate, and microbiological swab samples were analysed in duplicate to ensure data repeatability and consistency. These results were compiled and statistically evaluated using basic descriptive analysis (mean, standard deviation, range) to determine treatment efficiency and detect potential contamination points in the system. All outliers or abnormal readings were subjected to root cause analysis by the operations team.

Furthermore, data from the site laboratory and external accredited laboratories were collated to form a comprehensive dataset of ionic and microbial water quality, which was used to benchmark system performance against SANS 241:2015 Standards for Drinking Water. These datasets formed the basis for trend analysis and were later used in developing the site simulation model discussed in Chapter 4.

### **3.4. Environmental Impact of the Method Used**

The study employed Atmospheric Water Generators (AWGs) as the core technology for water harvesting. While AWGs provide a decentralized and innovative solution to water scarcity, especially in semi-arid, high-altitude regions like Pretoria North, their environmental impact depends on several key factors:

#### **Positive Environmental Aspects:**

##### **1. Water Security Without Groundwater Extraction:**

- AWGs do not deplete groundwater or surface water resources, which is especially crucial in water-stressed environments.
- This method supports sustainable water access independent of rainfall or aquifers.

2. Minimal Waste Generation:

- The only by-product from AWG operation is filtered exhaust air with no liquid discharge or chemical waste, reducing pollution risk.

3. Microbial Safety and Reusability:

- The reusable filtration system, including RO and UV, ensures high water quality with minimal environmental contamination.

**Environmental Concerns:**

1. High Energy Consumption (105 kWh per hour at full capacity):

- The system relies heavily on the national electricity grid, which in South Africa is largely coal-based.
- This contributes significantly to carbon emissions unless offset by renewable energy sources (e.g., solar integration).

2. Use of Refrigerants (R407C):

- Though R407C is less ozone-depleting than older refrigerants, it is still a hydrofluorocarbon (HFC) with a high global warming potential (GWP  $\approx$  1770).
- Leakage during operation or maintenance could contribute to climate change unless carefully managed.

3. Noise and Heat Emissions:

- The AWGs operate using multiple fans and compressors, resulting in thermal and acoustic emissions, which may impact surrounding environments, especially in residential zones.

**Mitigation Opportunities:**

- Integrating solar PV or hybrid energy sources can reduce grid dependency and lower the carbon footprint.
- Regular monitoring of refrigerant integrity and safe disposal protocols can minimize GHG emissions.
- Smart scheduling of operation based on ambient RH and temperature trends (as done via Meteoblue) can optimize runtime and save energy.

### 4.1 Value of Collected Data

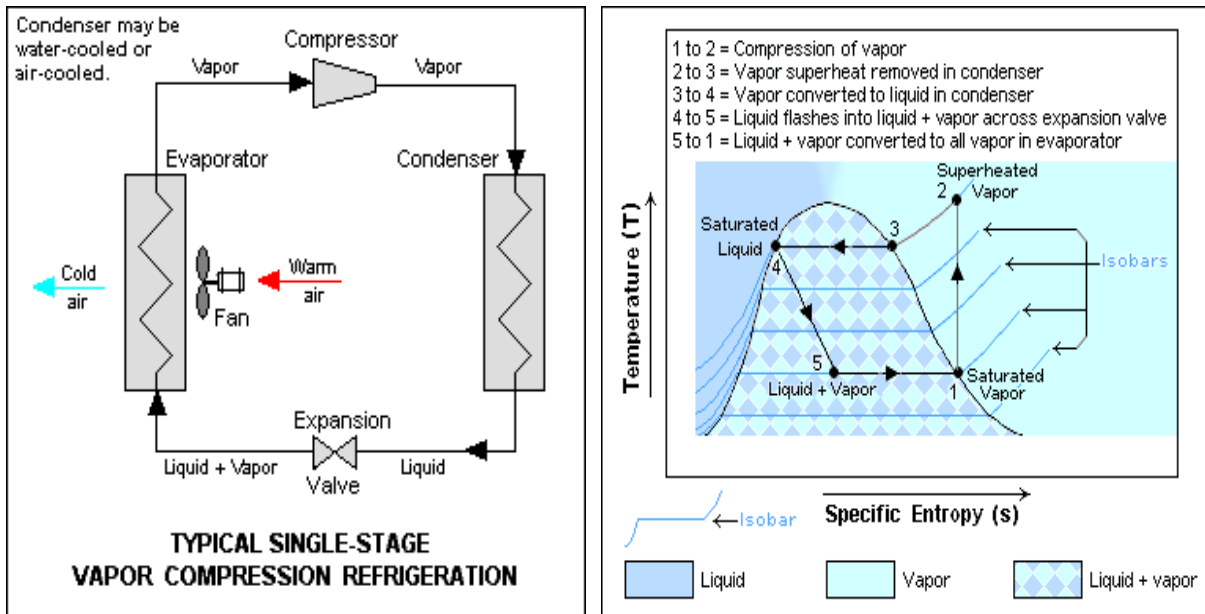
On-site data from the AWGs was recorded daily and hourly during the study, focusing on the main parameters that affected water formation, such as air, temperature, and RH. These records confirmed the feasibility of water harvesting from the atmosphere from a semi-arid region with a high altitude in South Africa (SA). It was the first of its kind research at the time of this publication. The research set out to study the feasibility of moisture harvesting in the region. This chapter highlights the successes and challenges experienced during the study to demonstrate that semi-arid regions within the continent and globally, similar to the one in South Africa, can undertake AWH for water security. The study aimed to answer a call by the United Nations' Sustainable Development Goal No. 6 to address water and sanitation challenges.

The results from site data support the findings of the literature reviewed, that atmospheric water harvesting has higher success in warm, lower altitude and high humidity regions than in semi-arid, high-altitude regions. While many initiatives support drinking water sustainability, such as wastewater or contaminated water treatment, recycling and re-use, these conventional water supply resources have declined significantly in semi-arid regions due to climate change and pollution, which leaves some communities vulnerable to inadequate drinking water supply. It would, therefore, be beneficial for atmospheric water harvesting to be added to these limited and overloaded fresh and recycled water resources to ensure that human needs are continuously being addressed. Additionally, approximately 12,900 km<sup>3</sup> of water vapour is available in the atmosphere (Schneider, 1996), which can be accessed to minimise drinking water challenges globally. The data reported herein demonstrates the feasibility of accessing water vapour for semi-arid regions during different seasons of the year. The report includes the strengths and weaknesses of such locations.

### 4.2 Results of the collected data

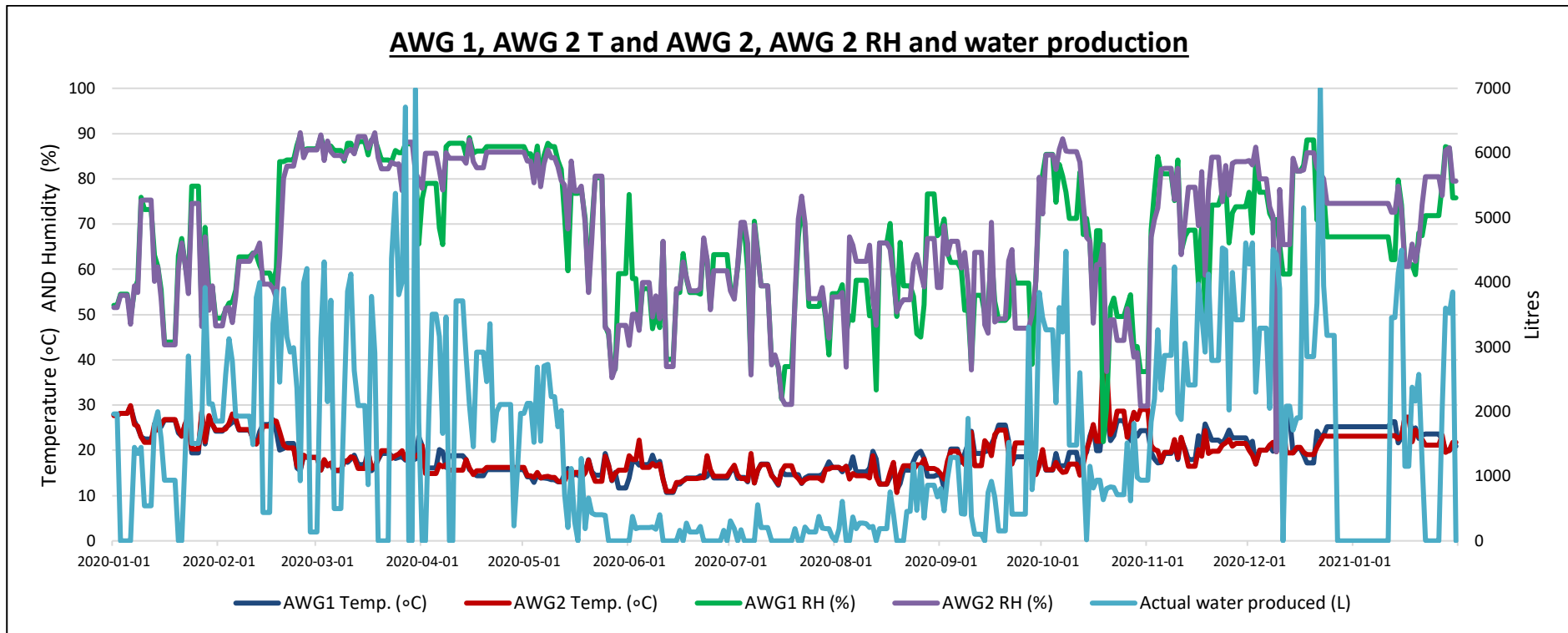
The following results were obtained for the seasonal variation impact on water production and the performance of AWG in a high-altitude, semi-arid region in South Africa. The amount of water vapour in the air is measured by the relative humidity (Meteoblue, 2020). The relative humidity can be used to predict the suitability for atmospheric water harvesting. The mechanism of atmospheric water harvesting is an example of the second law of thermodynamics applied to the active cooling and condensation of vapour compression. This describes the relationship between energy, enthalpy, entropy, and temperature resulting from changes in pressure, relative humidity, density, and volume of

matter. An illustration of the vapour compression cycle used in this process is shown in Figure 4.1 (Boles and Cengel, 2008,).



**Figure 4.1: Illustration of vapour compression cycle (Boles and Cengel, 2008)**

The AWGs used in this study employ a vapour compression cycle process, which formed water with ambient temperature ( $T$ ) of  $15\text{ }^{\circ}\text{C}$  and relative air humidity ( $RH$ ) of 30% and above. The performance of the AWGs was assessed by plotting water harvested vs the  $T$  and the  $RH$ . These parameters were recorded over one year in order to consider the results during all four seasons. The seasonal changes had a considerable influence on the water production. Figure 4-2 displays the raw data collected on-site for a period of one year (Jan to Dec 2020). The graph displays the temperature and relative humidity of both site AWGs and the total actual water produced.



**Figure 4.2: AWGs 1 and 2 Ts and RHs with water production from Jan 2020 to Jan 2021.**

The information displayed in Figure 4-2 illustrate that water production peaked in January 2020 and there was a downward trend from the 1<sup>st</sup> May 2020. There was minimal to no water production between mid-May until the end of August 2020 which is winter season in South Africa. This pattern follows the explanation of the Köppen-Geiger Climate Classification model explained in chapter 2. The location of this study has a combination of warm temperate, winter dry, warm summer and steppe climate, hot steppe or dessert. These weather patterns have high precipitation in spring and summer and experience extreme dry conditions in winter resulting in high water production during these times. Water productivity had a improved continuously through summer months until the end of April as seen in Figure 4-2.

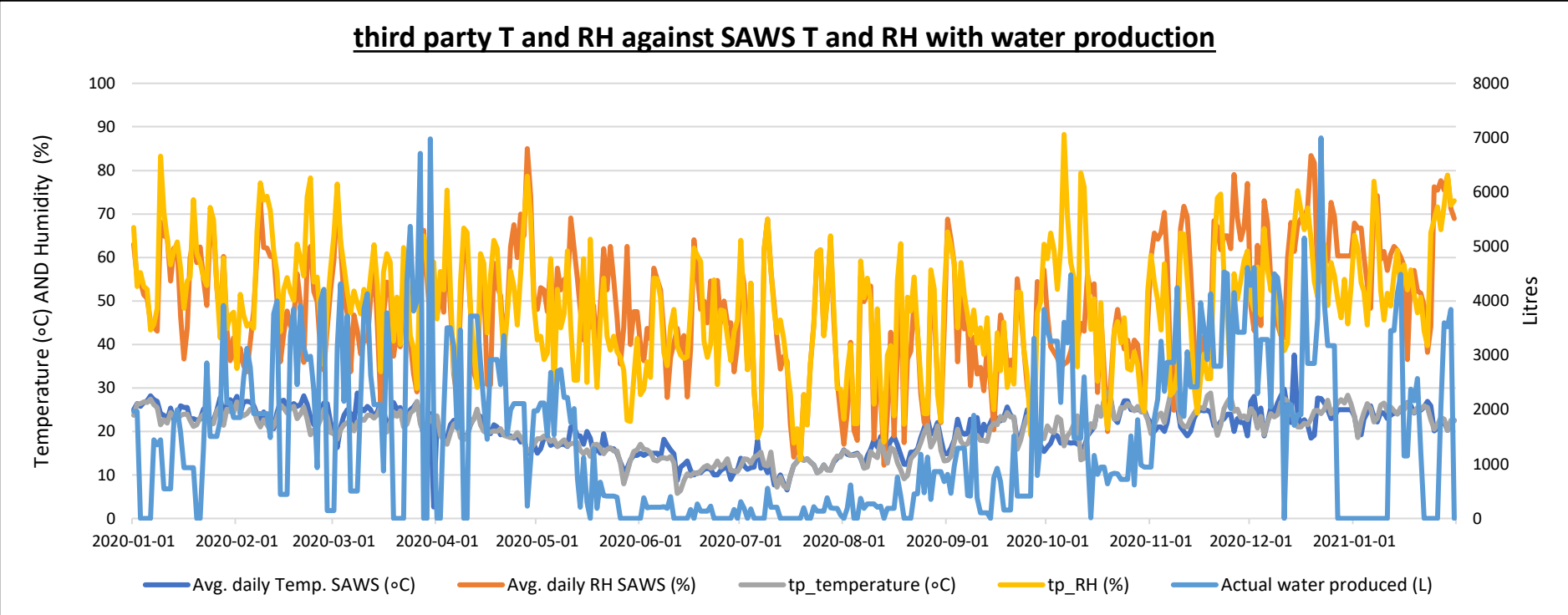


Figure 4.3: Third party (Meteoblue) Ts and RH; and SAWS Ts and RH with water production.

The trends in Figure 4-3 indicates that both Meteoblue and SAWS weather data were similar. SAWS provides a summary of averages for the day while Meteoblue gave hourly details. The AWGs adequately mimicked the temperature profile of the third-party temperature data (Meteoblue, 2020) when analysing both Figure 4-2 and 4-3 respectively; though there were a few missing data points from the AWGs due to the following operational challenges experienced on site:

- Planned and unplanned maintenance downtime of the AWGs, and
- Power outages due to the country's electricity load-shedding challenges.

The main motivation for searching for an alternative weather forecast tool was that SAWS did not provide hourly figures. Consequently, a water production window would be missed. For example, on the 2<sup>nd</sup> and 3<sup>rd</sup> of October 2020 and on the 10<sup>th</sup> and 11<sup>th</sup> of October 2020, it was observed that AWGs did not start as per their design set point parameters, that is  $T = 15^{\circ}\text{C}$  and  $\text{RH} = 30\%$ , whilst the forecasted ambient conditions were favourable for water production. This deficiency was noticed during manual hourly data capturing on the AWGs, whereby the AWGs displayed parameters of a higher humidity of 38% at temperatures of 14 C. The SAWS forecast tool had already provided forecast figures for the day, but these values were not those seen and read in the AWG's HMI. As such, the AWGs skipped this operational window.

Because of such occurrences, it was motivated to buy and install hygrometers to assist the research and the operational business by verifying in support of the weather forecast tool. Additionally, such events prompted a search for an alternative weather forecast tool, which Meteoblue was then discovered. The AWGs offered control and instrumentation maintenance, including testing and calibrating the instrumentation on these generators.

Figure 4-4 reflects the relative humidity (RH) on the AWGs profiled with the third-party RH. It was observed that during autumn, i.e. a season from March to May in South Africa, AWGs RH was not within the range when compared to the third-party data (Meteoblue, 2020) during the period between 1<sup>st</sup> March 2020 and the 13<sup>th</sup> May 2020. AWGs RH followed the same trend with third-party RH for the remainder of the other months within the year, as well as SAWS, as shown in Figure 4-5.

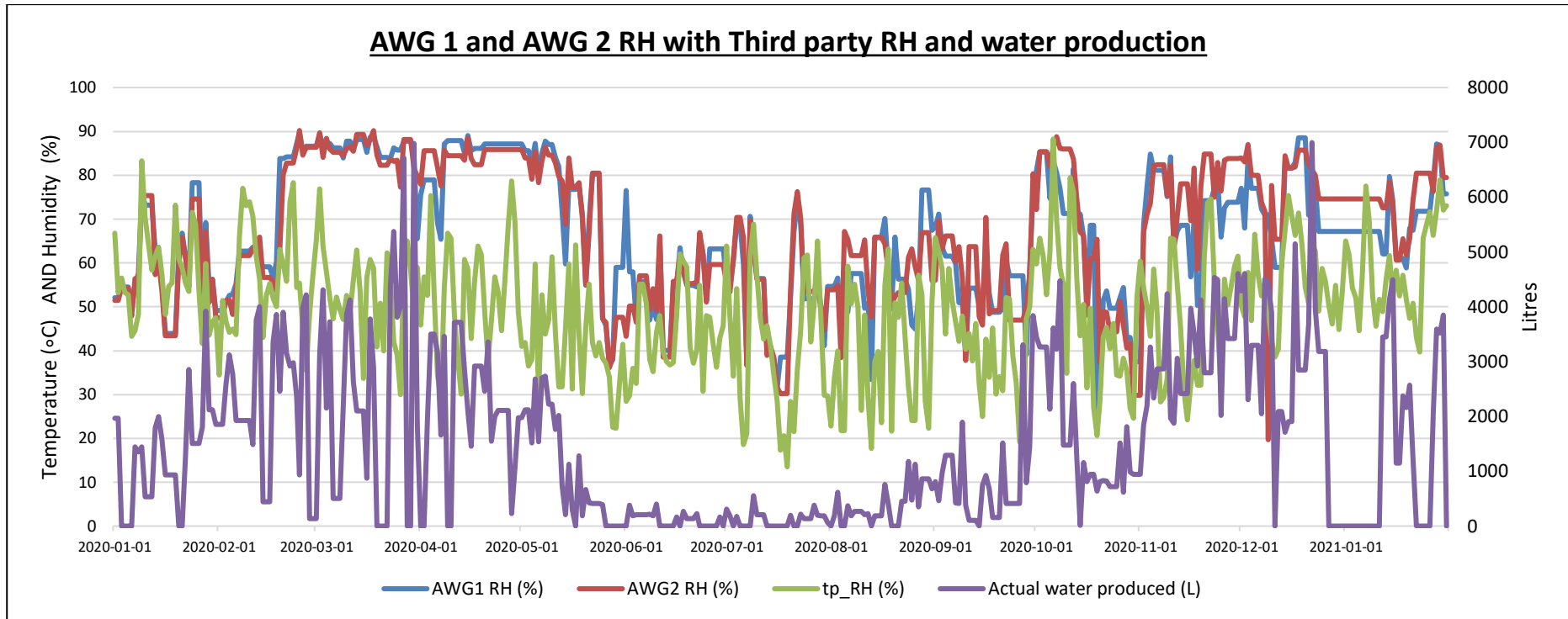


Figure 4.4: AWGs RH with third party (Meteoblu) RH; and water production.

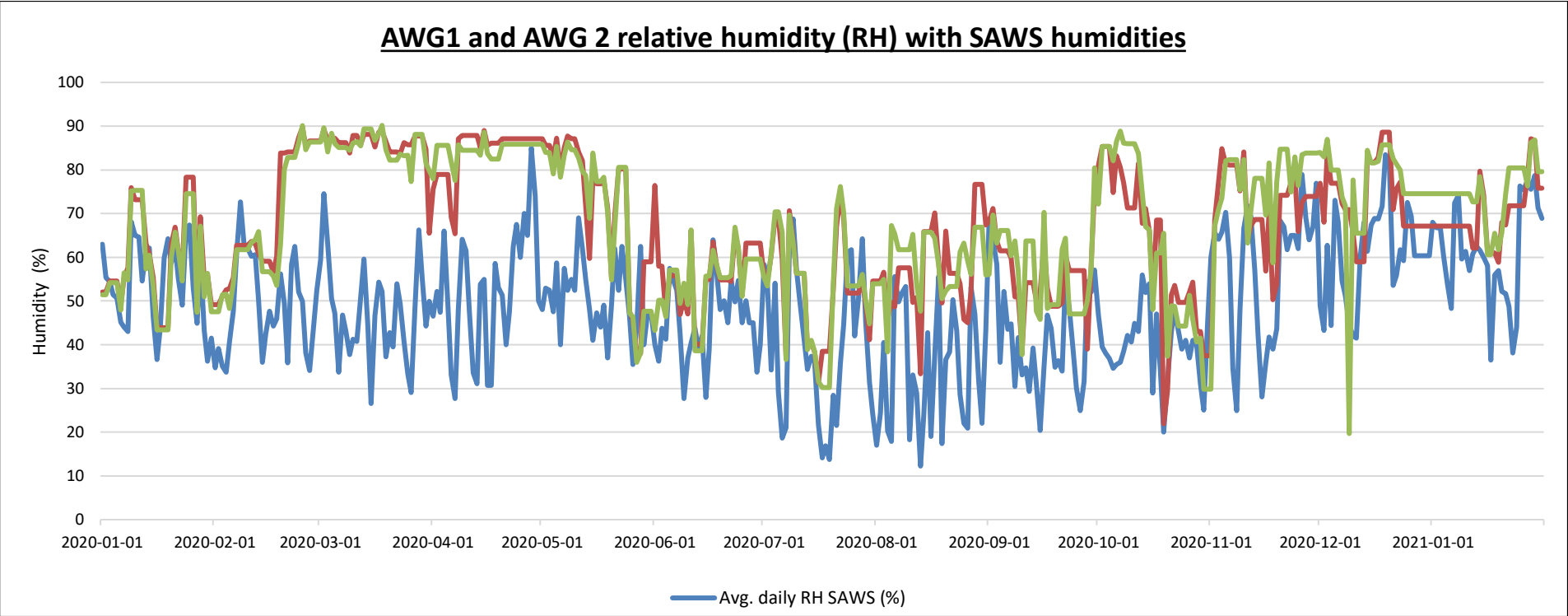


Figure 4.5: AWGs RH shown with the SAWS RH.

The trends in Figure 4-6 show an extrapolated version of the raw data obtained from AWGs. The data was extrapolated using forward and backward filling to highlight outliers. This was done to ascertain whether the AWGs were calibrated correctly. The forecasted relative humidity (RH) profile depicts a significant difference in RH patterns compared to the third-party data.

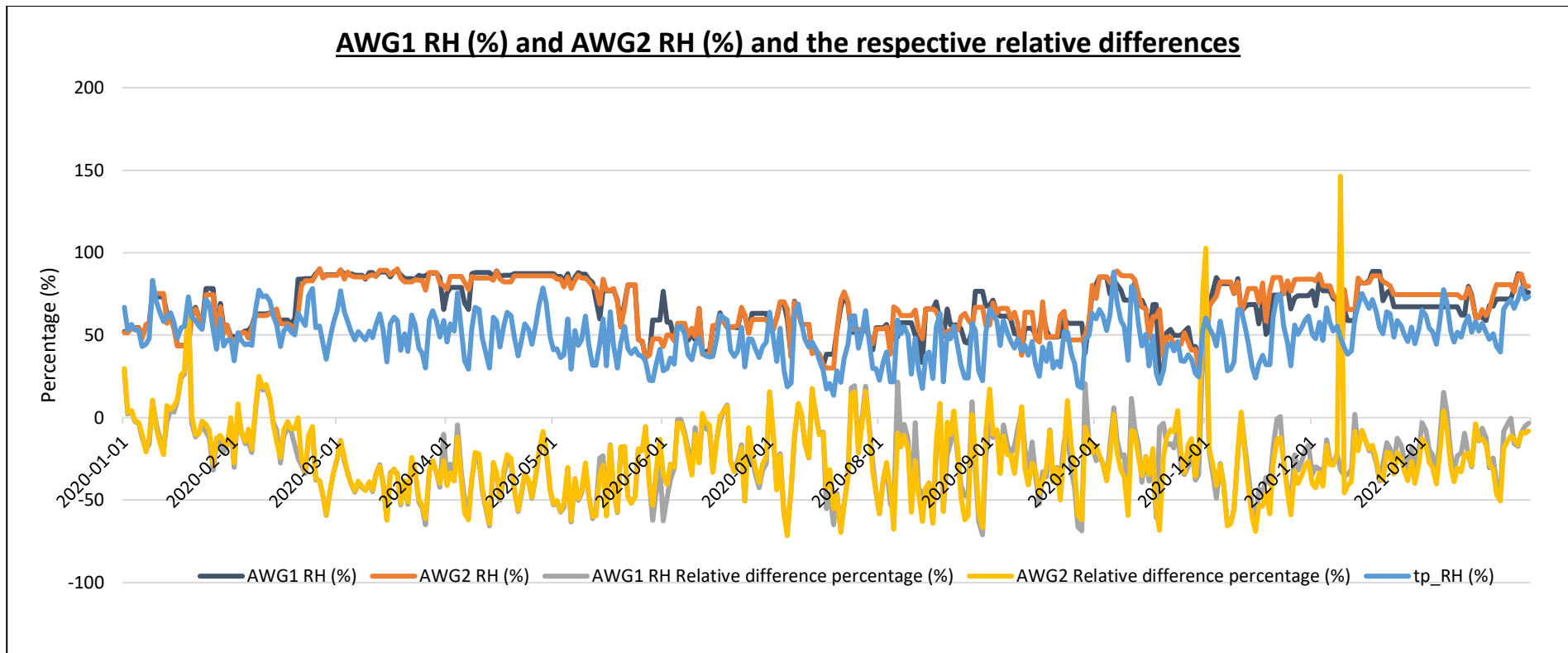
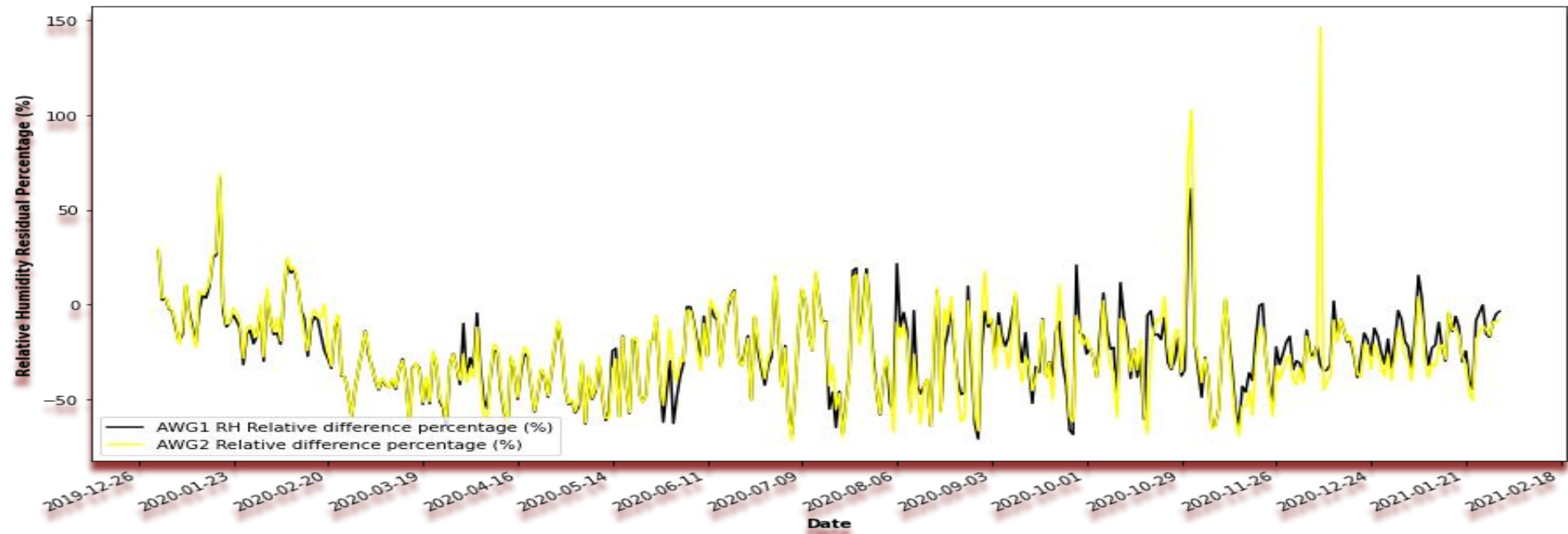
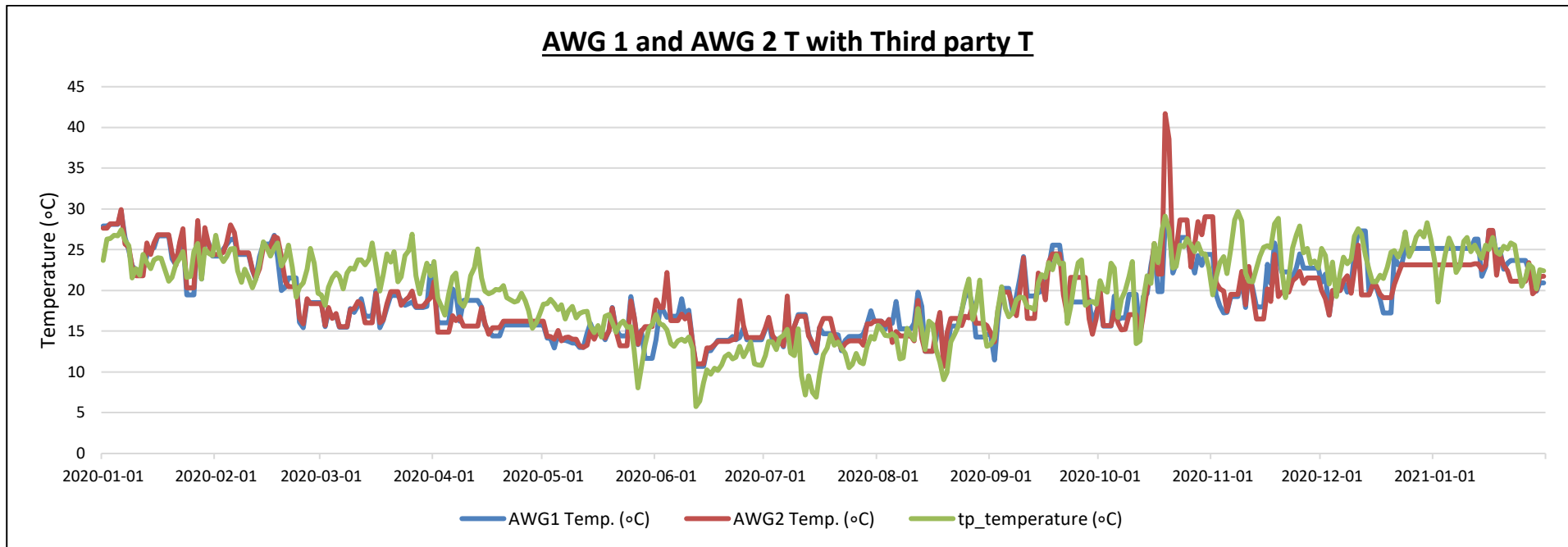


Figure 4.6: AWGs RHs with their relative difference against the third-party RH.



**Figure 4.7: Percentage difference of AWGs relative humidity data.**

The percentage difference for the RH of the two AWGs is illustrated in Figure 4-7, which indicates the accuracy between the two AWGs. However, the RH figures showed significant differences from the third-party data.



**Figure 4.8: AWGs Ts shown against the third-party Ts.**

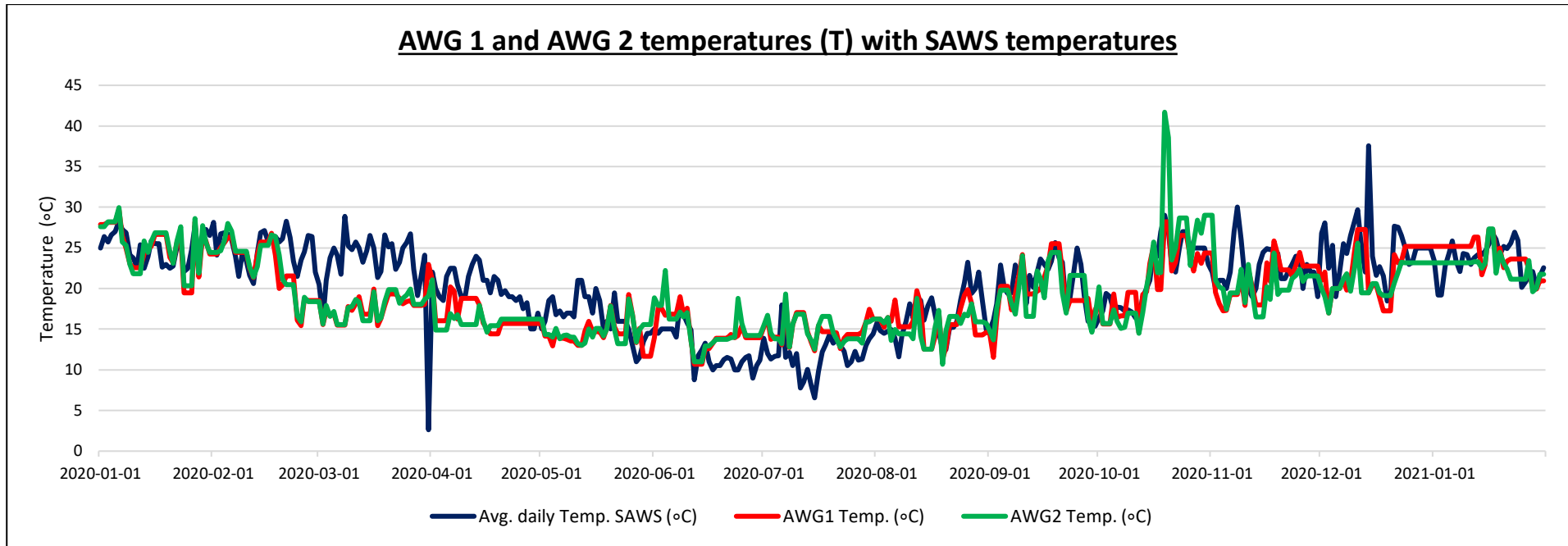
Data in Figure 4-8 illustrates On **19 October 2020**, **AWG 2** recorded an abnormal temperature spike exceeding **40 °C**, unlike AWG 1 and SAWS data. This outlier was caused by a **temporary sensor error** linked to the **instrument calibration** process conducted during that period. As part of the scheduled maintenance, the temperature transmitters were cleaned, realigned, and recalibrated. The brief spike was

not reflective of actual ambient conditions but rather a result of **transmitter drift or electronic interference** during the calibration. The issue was resolved shortly after and no long-term impact on data integrity occurred.

The Figure 4.9 shows a line chart titled "AWG 1 and AWG 2 temperatures (T) with SAWS temperatures," which compares temperature data over a period from January 2020 to January 2021. The chart includes three data series, each represented by a different colored line:

- **Average Daily Temperature (SAWS) (blue line):** This represents the daily average temperature recorded by the South African Weather Service (SAWS). The data fluctuates between approximately 10°C and 40°C, with notable peaks and dips, indicating seasonal and daily variations. A significant drop is observed around April 2020, followed by a sharp rise later in the year.
- **AWG1 Temperature (red line):** This line tracks the temperature readings from AWG1 (likely an Atmospheric Water Generator unit). The values range from about 15°C to 35°C, showing a pattern similar to the SAWS data but with some deviations, suggesting differences in measurement conditions or equipment sensitivity.
- **AWG2 Temperature (green line):** This represents the temperature data from AWG2, another unit. The green line also varies between approximately 15°C and 40°C, with a notable peak around October 2020, indicating a higher temperature reading compared to the other two series at that point.

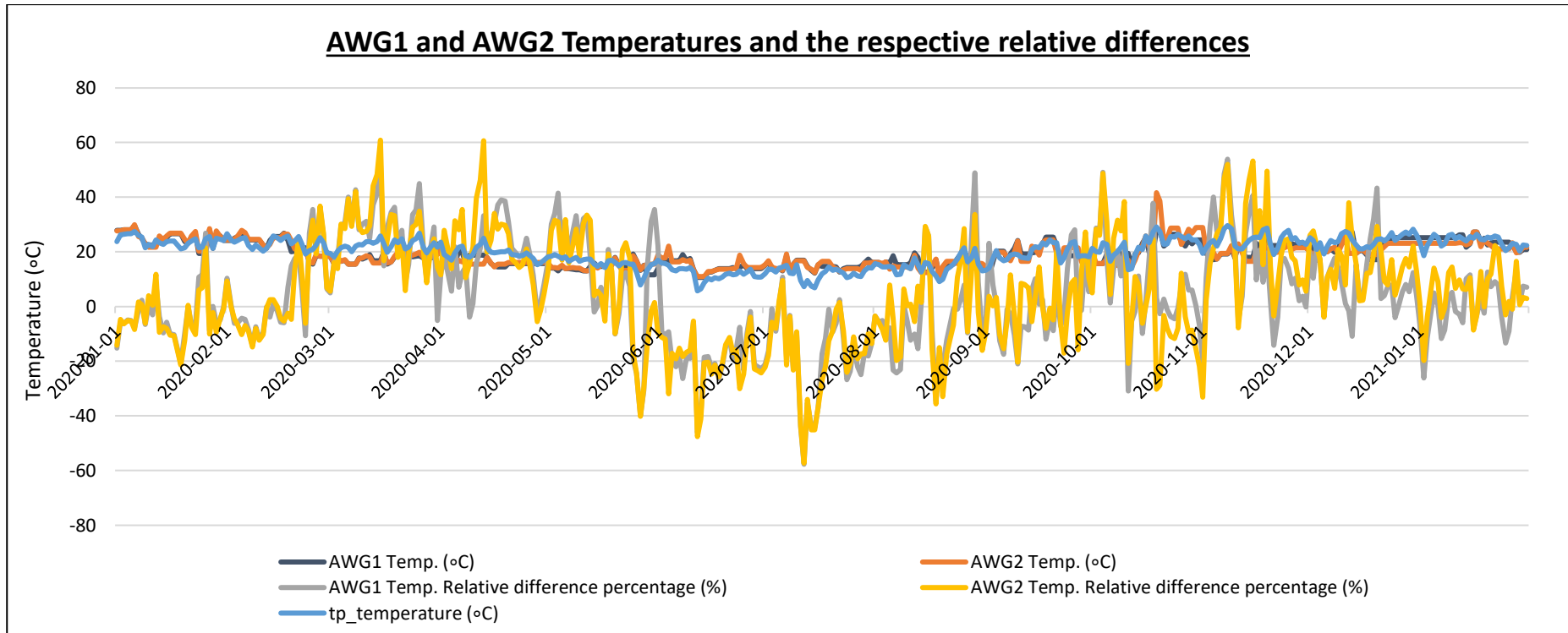
The chart highlights how the temperatures from the two AWG units (AWG1 and AWG2) align with or diverge from the SAWS average daily temperatures, potentially indicating the performance or calibration of the AWG units relative to official weather data. Seasonal trends, such as warmer temperatures in the Southern Hemisphere's summer (December-February) and cooler temperatures in winter (June-August), are visible across all three datasets.



**Figure 4.9: AWGs Ts shown against the SAWS Ts.**

Figure 4.10, titled "AWG1 and AWG2 Temperatures and the respective relative differences," presents a line chart that compares temperature data from two Atmospheric Water Generator units (AWG1 and AWG2) over the period from January 2020 to January 2021, alongside their respective relative differences from a reference temperature ( $tp\_temperature$ ). AWG1 temperature (blue line) remains relatively stable, fluctuating between approximately 15°C and 25°C throughout the year, while AWG2 temperature (orange line) displays greater variability, ranging from 0°C to 60°C, with notable spikes in early and late 2020. The relative difference percentages, represented by grey and yellow

lines for AWG1 and AWG2 respectively, show that AWG1 oscillates between -60% and +60%, whereas AWG2 exhibits sharper fluctuations from -80% to +80%, indicating larger deviations from the reference. The stark contrast between the stability of AWG1 and the volatility of AWG2 suggests potential issues such as environmental sensitivity, calibration discrepancies, or measurement errors affecting AWG2. Overall, the figure highlights the more consistent performance of AWG1 and raises concerns about AWG2's reliability, emphasizing the importance of calibration and accuracy in temperature-sensitive applications.



**Figure 4.10: Extrapolated AWG Ts shown against the third-party Ts.**

Figure 4.11 presents a line chart comparing the residual percentage differences in temperature readings from two Atmospheric Water Generator units, AWG1 (red line) and AWG2 (orange line), over a shared time period, illustrating how each unit's recorded temperature deviates from a reference or predicted value. Both units follow a broadly similar trend, indicating exposure to common external influences,

but AWG2 exhibits more pronounced fluctuations, with sharp negative spikes and greater overall volatility, especially in the middle of the timeline. AWG1 demonstrates relatively smoother and more stable residuals, suggesting better calibration or operational consistency. The synchronized peaks and troughs across both units suggest environmental or systemic factors impacting performance simultaneously. However, AWG2's larger deviations point to possible sensor drift, calibration errors, or mechanical instability that warrant further investigation. The chart's temporal segmentation shows early stability, mid-period volatility, and late-stage minor fluctuations, highlighting distinct performance phases. Overall, the figure underscores AWG1's superior reliability and the need for closer monitoring or adjustment of AWG2 to ensure accurate and consistent temperature control in atmospheric water generation.

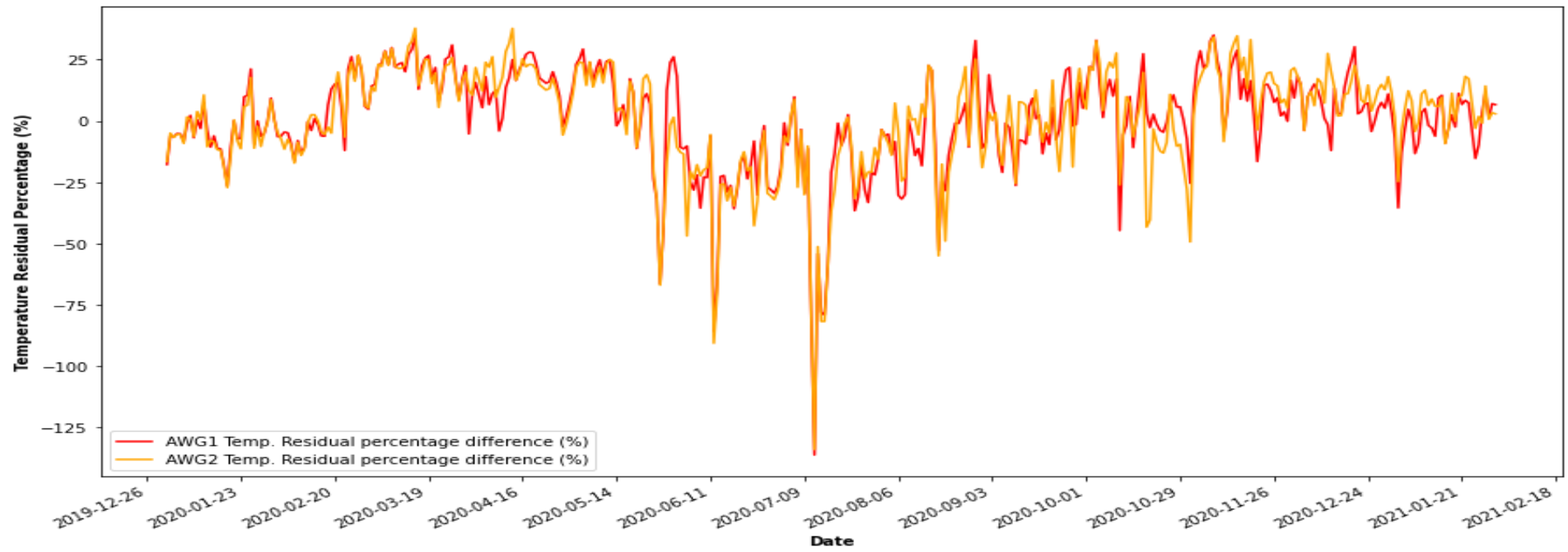
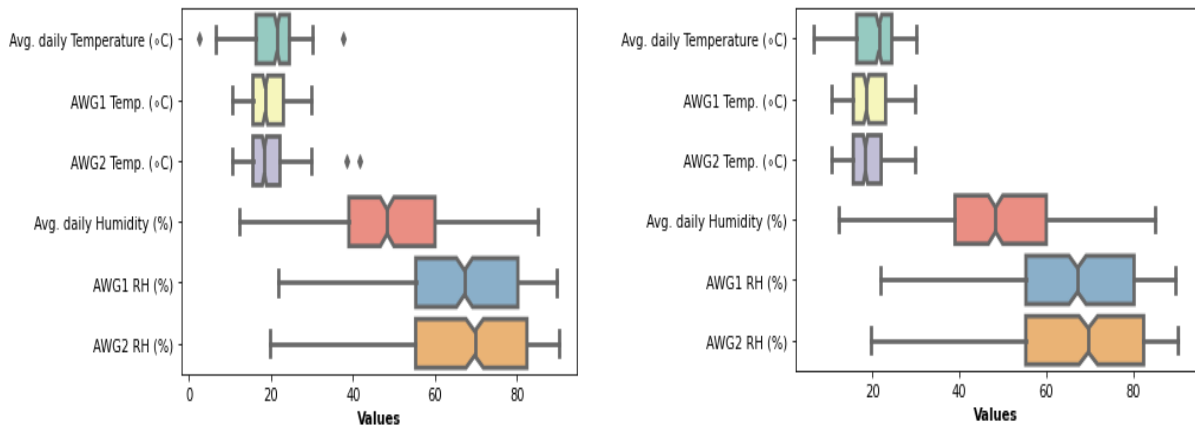


Figure 4.11: Temperature residual percentage time series

Figure 4-12 is a boxplots analysis of atmospheric water production drivers before and after the replacement of outliers. The boxplots indicate the shape of the data distribution, the variability and the central values. During early fall, a pilot test of humidifiers was done, and these were mounted on the AWGs to assist in humidity inflation due to low humid conditions measured as observed from the collected data.



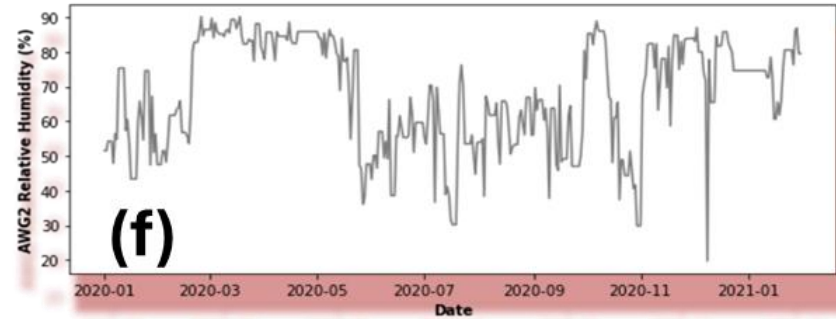
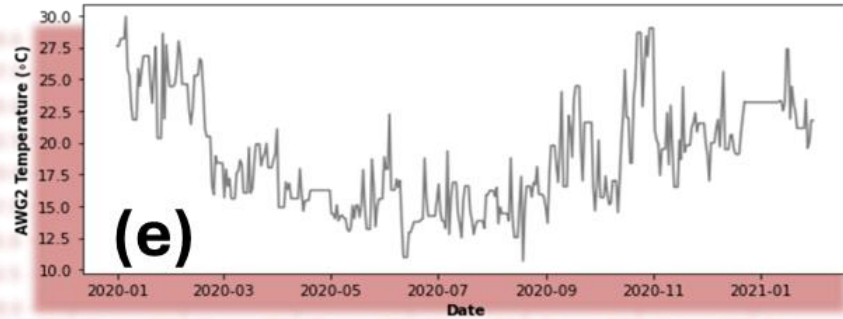
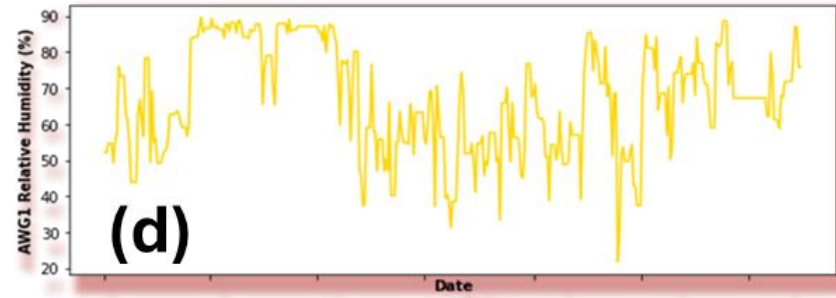
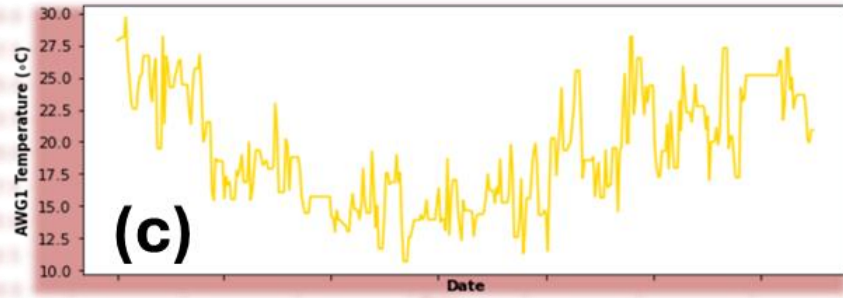
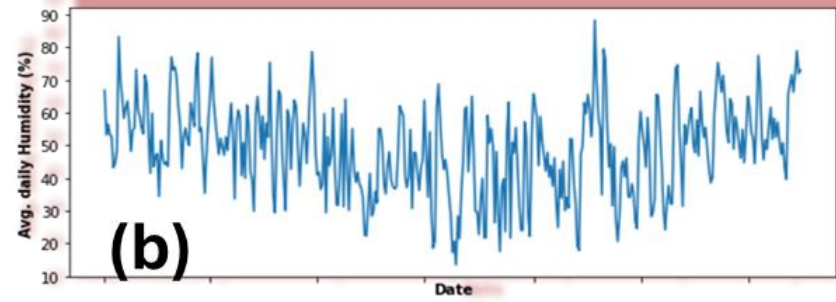
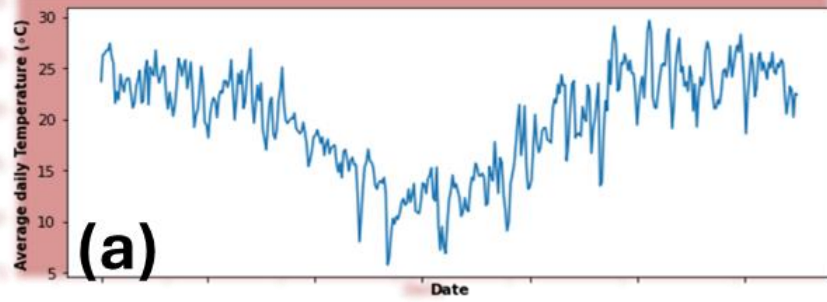
a) Boxplots of the parameters before the replacement of outliers

b) Boxplots of the parameters after the replacement of outliers.

Figure 4.12: Boxplots of the atmospheric water production drivers before and after the replacement of outliers.

Following the implementation of an extrapolation methodology to further minimise the outliers, differences in RH trends for the fall season were persistent, as shown in Figure 4-6. At this stage, these variations were explored to uncover the specific reasons for the differences observed in the RH trends.

Figure 4.13 presents six subplots (a–f) comparing the average daily temperature and relative humidity for two Atmospheric Water Generator units (AWG1 and AWG2) from January 2020 to January 2021. Subplot (a) shows AWG1’s temperature ranging from 10°C to 30°C, exhibiting a seasonal decline toward the end of 2020, while (b) displays AWG1’s relative humidity fluctuating between 0% and 100% with irregular spikes. Subplot (c) illustrates AWG2’s temperature between 15°C and 27.5°C, showing a relatively stable trend with occasional peaks, and (d) presents AWG2’s humidity varying between 0% and 80%, with more pronounced peaks than AWG1, indicating greater variability. The zoomed-in views in (e) and (f) provide detailed insights into AWG2’s short-term fluctuations in temperature (10°C–27.5°C) and humidity (0%–80%), respectively. The comparison highlights that while both units experience similar temperature ranges, AWG1 shows a steadier decline, and AWG2 demonstrates more frequent temperature peaks and heightened humidity sensitivity. These variations suggest AWG2 may be more influenced by localized environmental factors, potentially affecting its water generation efficiency. The zoomed subplots reinforce AWG2’s responsiveness to rapid environmental shifts, emphasizing the need to assess its placement, calibration, or design for optimized performance.



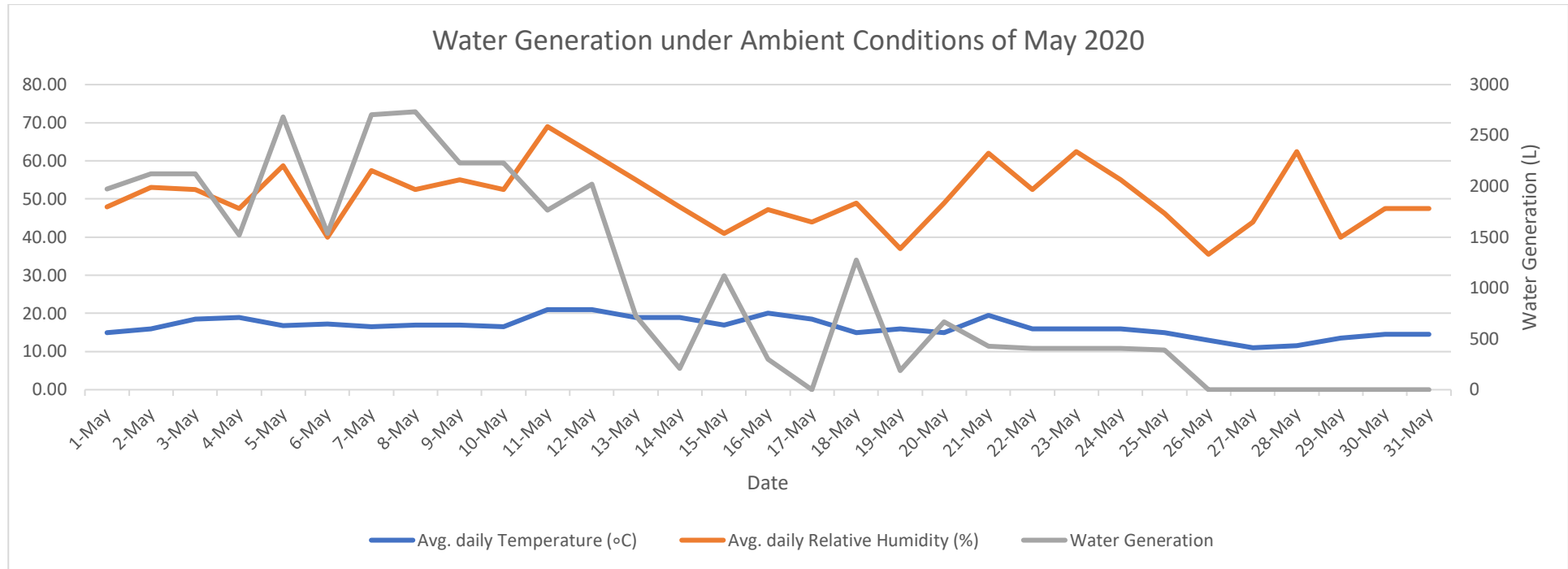
**Figure 4.13: A comparative analysis of average daily temperature and relative humidity for AWG1 and AWG2 across six subplots: (a) shows the average daily temperature for AWG1, (b) displays the corresponding average daily humidity for AWG1, (c) and (d) present the same parameters, temperature and humidity, for AWG2, while (e) and (f) offer zoomed-in views of AWG2's temperature and humidity data, respectively (See next page.)**

**Top left and top right-hand side - average daily temperature and humidity.**

**Middle left and middle right - average temperature and Relative humidity data recorded from AWGs.**

**Bottom left and right hand side - average temperature and Relative humidity data recorded from AWGs without outliers.**

Figure 4-13 illustrates a strong correlation between the site-recorded AWG data and the third-party (Meteoblue) data from late summer until the start of winter. Although there were differences in the recorded RH data of AWGs, trends are similar in the middle and bottom right-hand side data. However, they do not follow the third-party data shown on the top right-hand side. When comparing the individual units AWG 1 and 2, significant outliers were observed during mid-spring (October), with T being different in the individual AWG units. Such variations started in early spring, culminating in variations in stop and start-up times on the generators, albeit initially with a small variation despite the units having similar operating set points and conditions as per their design. As such, calibration processes were initiated to address this defect, as explained following Figure 4-3. A certified local service provider calibrated and tested the generators' controls and instrumentation, which feeds into the HMI. This ensured that data values were valid. The manufacturer's guide information provided with the manual stated that an ambient air temperature below 15°C and a RH below 30%, would result in minimal to no moisture harvesting from the AWGs. The minimal water production occurred between the first of May and the twentieth of August 2020, as seen in Figure 4-14.

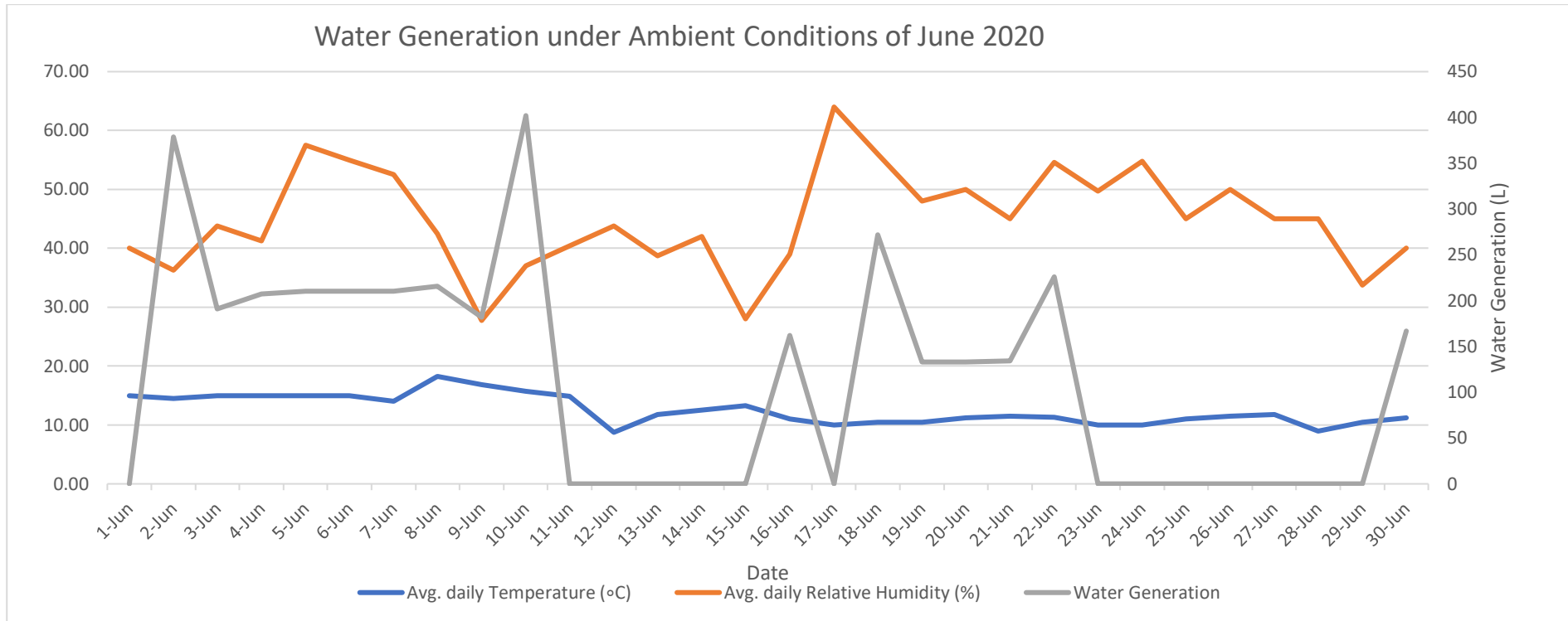


**Figure 4.14: Site Study AWGs Water Generation**

Figure 4-14 presents the relationship between water generation, average daily temperature (blue line), and average daily relative humidity (orange line) under the ambient conditions of May 2020. While the focus was initially placed on water generation decline starting around 26 May, the roles of temperature and humidity are also clearly evident in this figure. Throughout May, the average daily temperature remains relatively stable, fluctuating between 15°C and 20°C, suggesting that temperature alone did not drastically influence the decline. However, the relative humidity shows significant variability, with notable dips observed between 13–19 May and again from 24 May onward. These dips in humidity coincide with a marked decrease in water generation output (grey line), especially after 26 May when generation dropped below 500 L/day. This

correlation strongly indicates that **relative humidity is the dominant environmental factor** affecting AWG performance during this period. Even with relatively consistent temperatures, low RH limits moisture availability in the air, reducing condensation efficiency. Therefore, the integration of temperature and RH trends in this figure emphasizes their combined impact on AWG productivity and supports the conclusion that **seasonal variations in humidity**, more than temperature, directly influence water output.

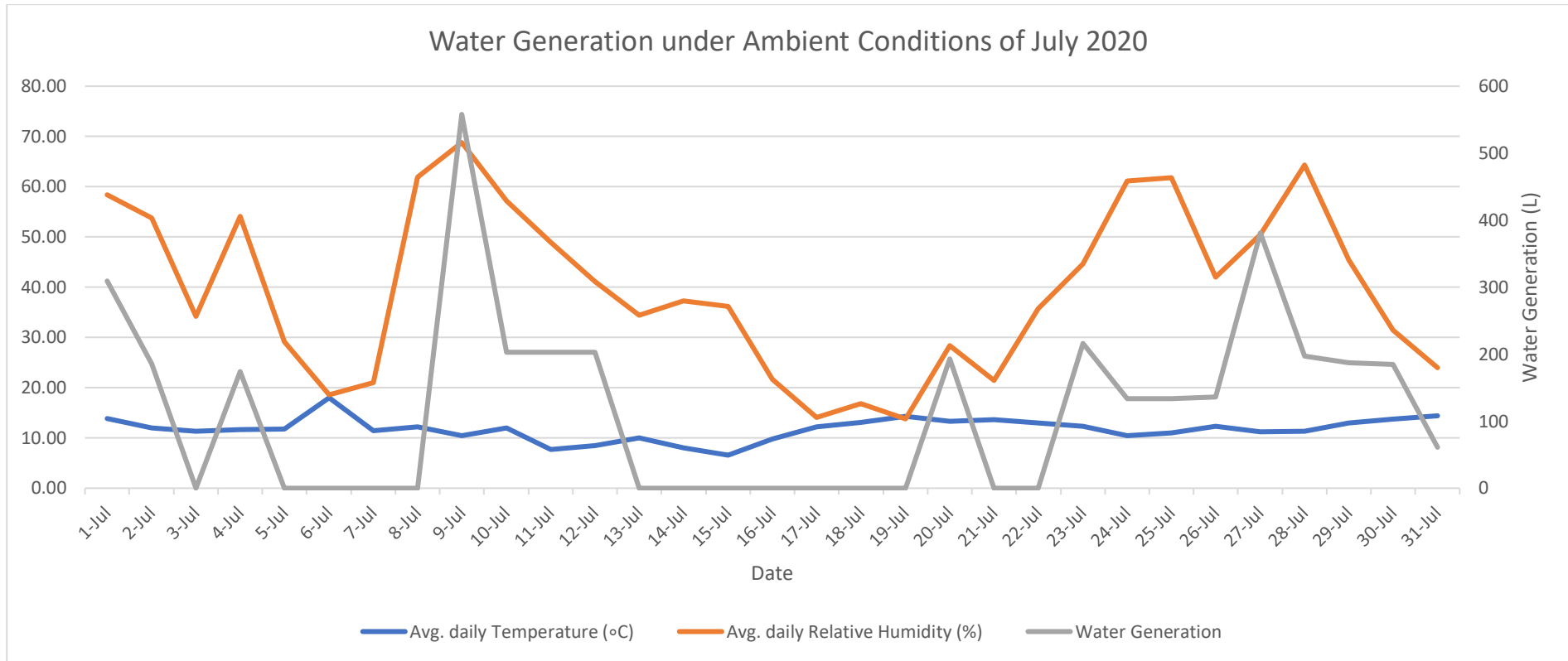
Figure 4-15 shows average daily temperature (11–18°C), relative humidity (30–65%), and water generation (L) for June 2020. Cool temperatures remained below AWG optimal range (~20–30°C), limiting performance. Humidity fluctuated, with peaks on 5–6, 16–17, and 24–26 June, but never reached summer levels (>70%), causing sporadic water output. Water generation was intermittent, with zero output during low humidity/temperature periods, except a peak over 400 L/day on 10 June linked to moderate humidity and higher temperature. Overall, suboptimal and variable winter conditions restricted AWG productivity, highlighting their reliance on warm, humid climates for consistent performance.



**Figure 4.15: Site Study AWGs continual decline of water generation for June 2020.**

It can be seen in Figure 4-15 that from May to June 2020, water production declined below 500 L per day compared to the design capacity of 5000 L per day. The maximum design productivity was never achieved during the year. Figure 4-14 records the extreme conditions on the 11<sup>th</sup> of June 2020, when there was no water production. Only five days later, on the 15<sup>th</sup> June 2020, 150 L of water was collected.

Figure 4.16 illustrates the relationship between ambient conditions and water generation for July 2020, showing that peak water output around July 8–10 coincided with the highest temperature (up to 20°C) and relative humidity (up to 70%), highlighting optimal conditions for Atmospheric Water Generator (AWG) performance. However, a steady decline in water generation followed despite intermittent rises in humidity and temperature, suggesting possible equipment-related issues such as reduced efficiency or maintenance needs. A minor recovery in output around July 25–28 during another humidity peak confirms AWG responsiveness to improved conditions, though overall performance remained lower. The figure emphasizes relative humidity as the primary driver of water generation, with temperature playing a secondary role within the observed range, and underscores the need for continuous monitoring and upkeep to sustain AWG efficiency during fluctuating winter conditions.

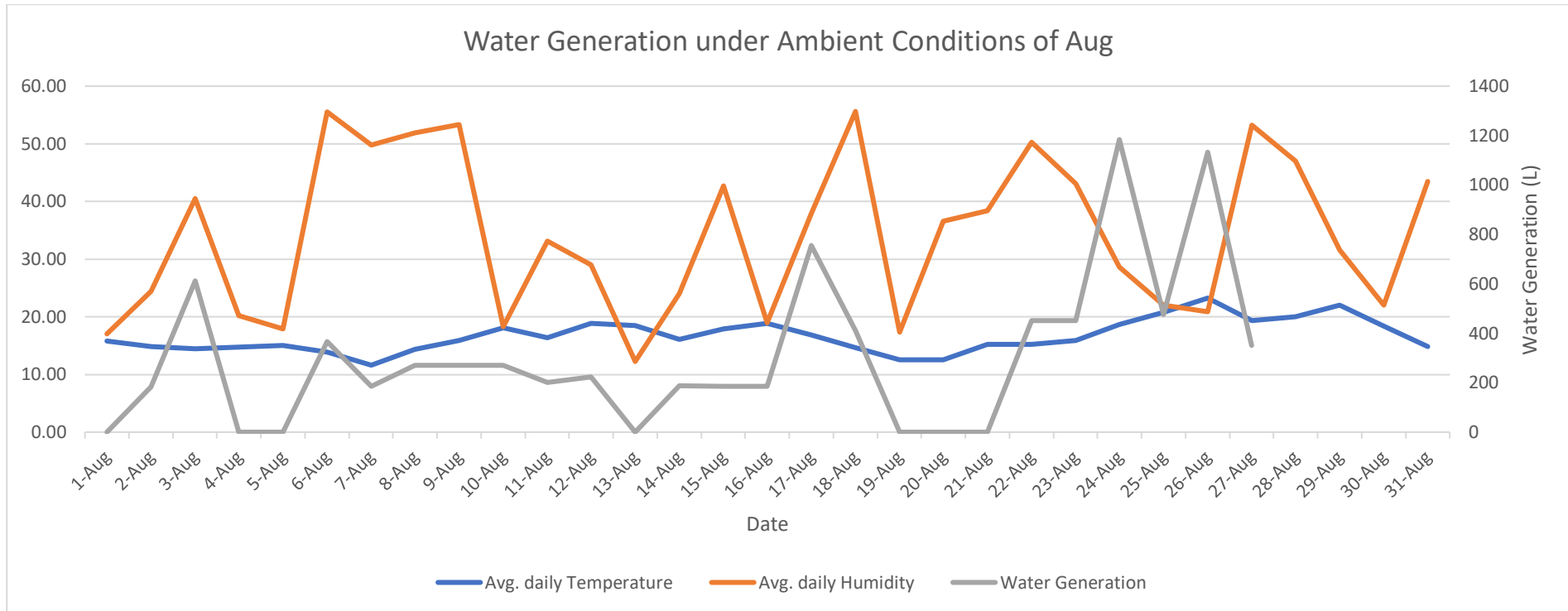


**Figure 4.16: Site Study AWGs continual decline of water generation for July 2020.**

On the 9<sup>th</sup> of July 2020, ambient conditions improved. RH rose to 69%, and the average temperature reached 20 °C. Daily water production increased from the previous one recorded in June of 150 L to 558 L. These conditions, however, did not last long as it was still mid-winter in South Africa. Water production declined drastically soon afterwards for four days with no water formation on the 13<sup>th</sup> July 2020.

Figure 4.17 illustrates a marked improvement in Atmospheric Water Generator (AWG) performance during August 2020, with water generation steadily increasing in response to ambient conditions. While average daily temperatures remained stable between 10°C and 20°C, relative humidity showed several notable peaks, particularly around August 5–7, 12–14, and 25–27, which aligned with significant increases in water output. Starting from low levels in early August (200–400 L/day), production rose sharply to peak around 1200 L/day toward the end of the month, marking the first sustained incline in productivity observed during the winter period. This correlation suggests that relative humidity, more than temperature, played a pivotal role in enhancing AWG efficiency during this transitional month from winter to early spring.

The overall trend indicates a recovery from the declining performance seen in July (Figure 4.16), likely due to improved ambient conditions, potential equipment servicing, or operational adjustments. The repeated alignment of water generation spikes with humidity peaks reinforces the critical influence of moisture availability on AWG output. These findings highlight the importance of monitoring and responding to climatic variables, particularly relative humidity, to optimize water production. August 2020 serves as a reference point for effective AWG operation in similar settings, suggesting that strategic planning around seasonal changes can significantly improve productivity.

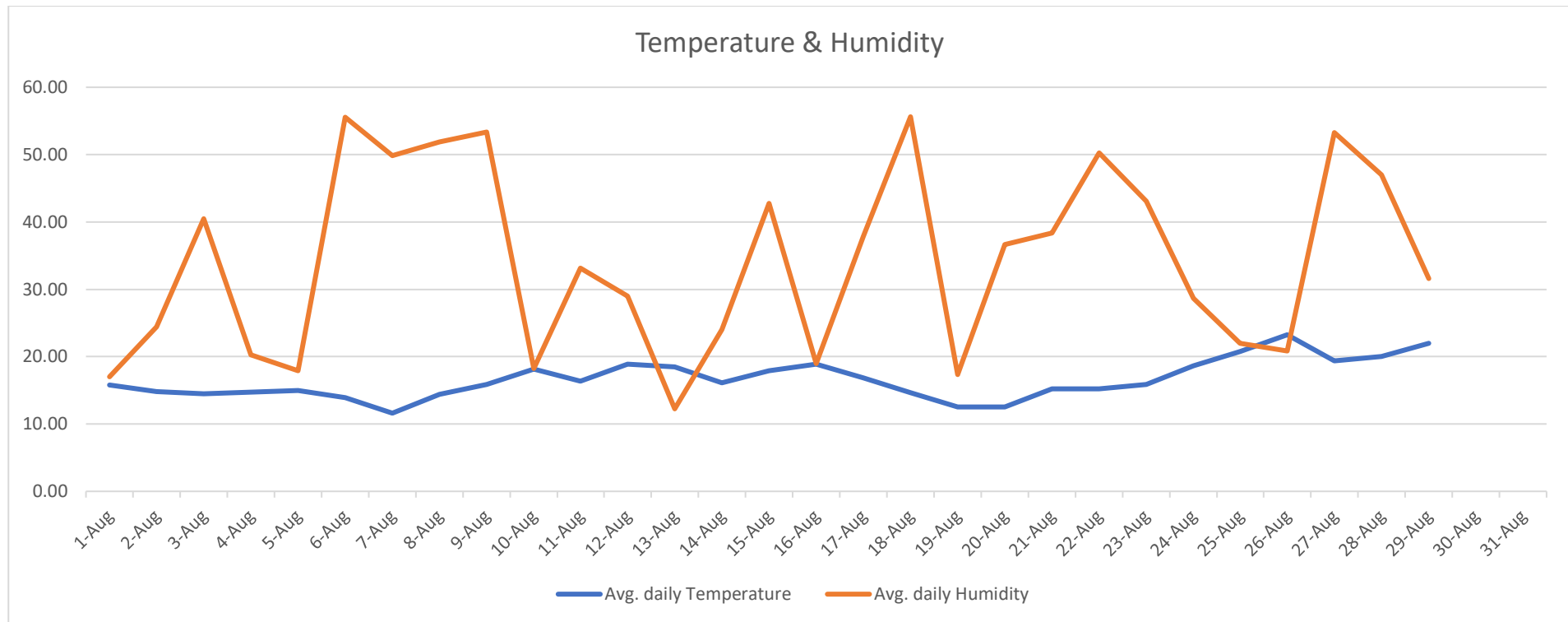


**Figure 4.17: Site Study AWGs first water productivity incline in August 2020.**

On the 3<sup>rd</sup> of August 2020, water generation increased to 612 L per day for the first time since winter began in May 2020. The production went up and down as the climatic conditions changed from cold to warm until the 25<sup>th</sup> of August 2020, when water levels reached 1184 L per day, as seen in Figure 4-17.

Figure 4.18 presents the average daily temperature and relative humidity recorded by Atmospheric Water Generators (AWGs) during August 2020, capturing the environmental conditions under which the systems operated. The temperature remained relatively stable between 10°C and 20°C with a slight upward trend, reflecting the seasonal transition from winter to early spring. In contrast, relative humidity fluctuated significantly between 20% and 60%, with notable peaks around August 5–7, 12–14, 19–21, and 25–27. These variations indicate intermittent periods of increased atmospheric moisture, likely influenced by local weather patterns.

The temperature's stability provided a consistent operational baseline for the AWGs, while the more dynamic humidity pattern played a larger role in determining water generation potential. The lack of a strong correlation between temperature and humidity suggests that changes in humidity were largely independent of temperature shifts. These findings reinforce the importance of tracking relative humidity to optimize AWG performance. The identified humidity peaks align with increased water productivity seen in Figure 4.17, emphasizing the need for responsive system calibration and maintenance to capitalize on favorable moisture conditions.

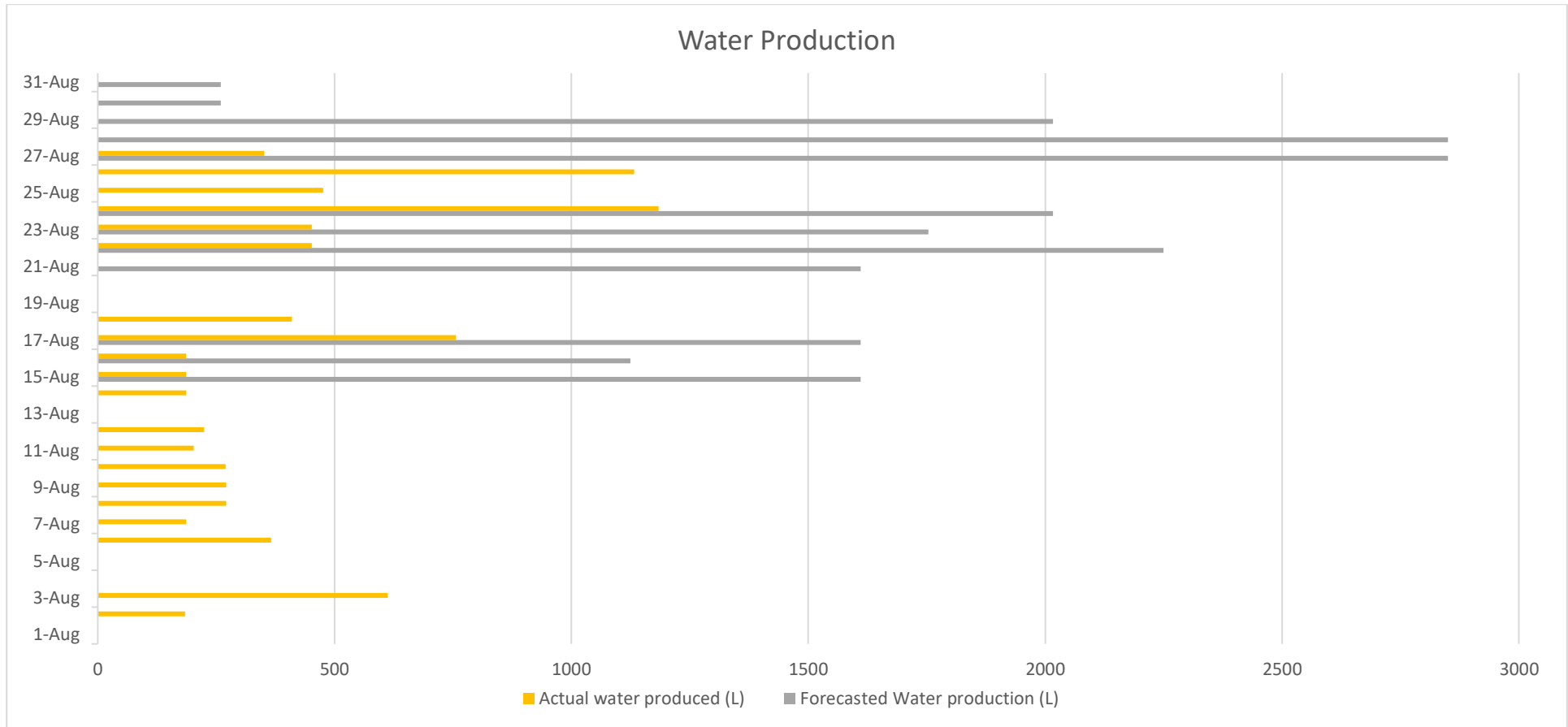


**Figure 4.18: Site Study AWGs average T's and RH's as recorded by AWGs in August 2020.**

A closer look at ambient climate condition improvement is illustrated in Figure 4-18. At this time, winter was transitioning into spring. It was observed that the first day when relative humidities picked up to 56 % was on the 6<sup>th</sup> of August 2020, while on the 1<sup>st</sup> of August 2020, the average temperature was 17%. On the first day of the month, the average ambient temperature was recorded at 16 °C, whilst on the 6<sup>th</sup> of August 2020, the average temperature was 14 °C.

Figure 4.19 compares the forecasted and actual daily water production by Atmospheric Water Generators (AWGs) during August 2020, revealing a consistent underperformance relative to expectations. Forecasted values, shown as grey bars, range from 500 L to over 2500 L per day and remain relatively high throughout the month. In contrast, actual production, depicted by yellow bars, starts low (200–300 L/day), increases gradually to a peak of about 1000 L around August 17–25, and then declines again toward the end of the month. The most significant discrepancies appear in early and mid-August, where actual output reaches only 10–20% of forecasted values, indicating early operational challenges and a forecasting model that may have failed to account for real-time system limitations or fluctuating environmental conditions.

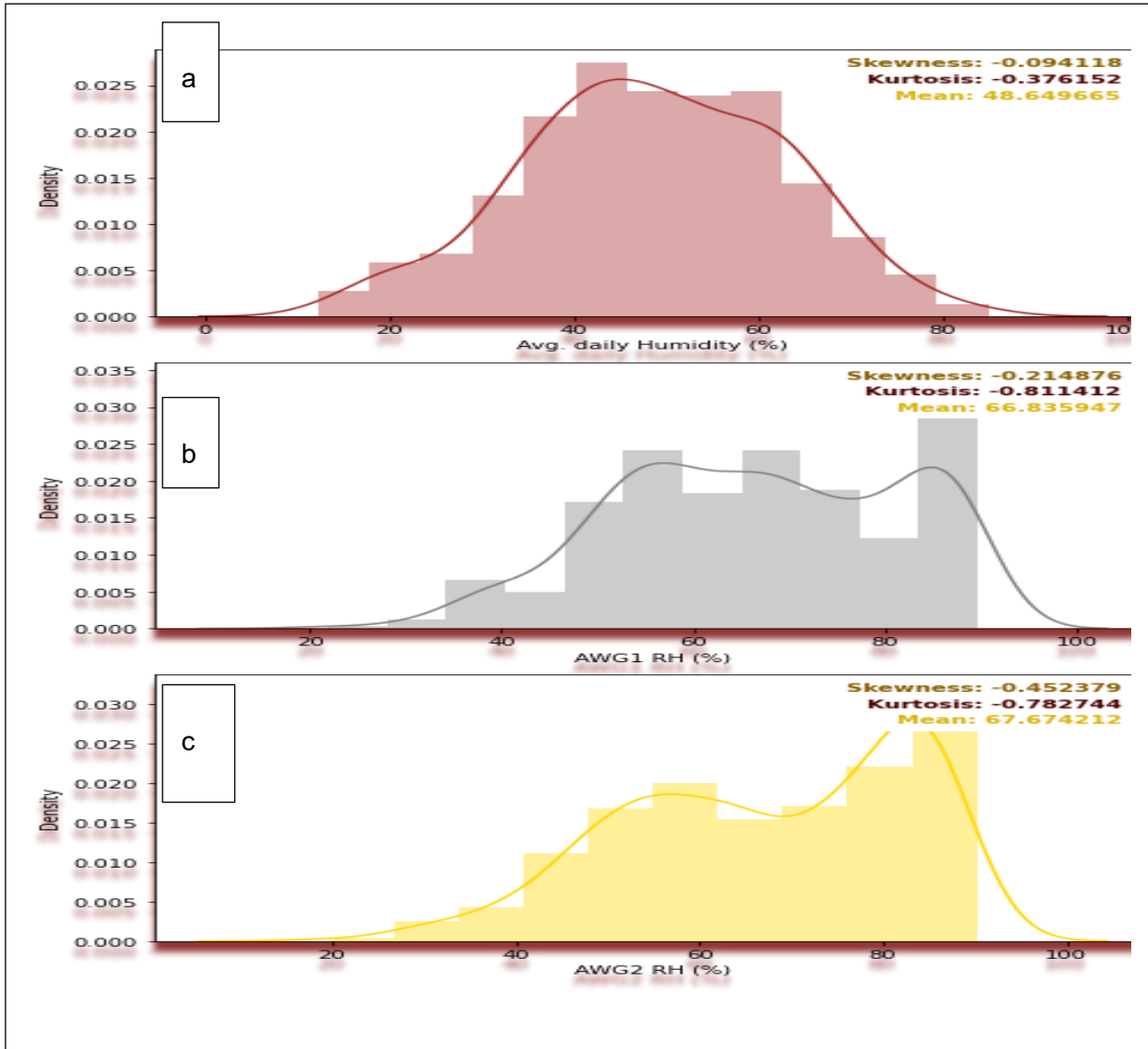
Despite the underperformance, the gradual mid-month rise in actual water production aligns with observed humidity peaks (Figure 4.18), confirming the AWGs' sensitivity to atmospheric moisture. However, even during these favorable periods, actual output remained well below predictions, suggesting over-optimism in the model or unaddressed system inefficiencies. The sharp drop in actual production at the end of August, while forecasted values remain high, further emphasizes a mismatch between expectations and operational realities. This highlights the need to recalibrate forecasting models using on-site performance data and to investigate operational issues such as maintenance practices, equipment degradation, or localised environmental influences. Such adjustments are critical for improving future predictions, optimizing water generation, and ensuring more accurate planning and resource management.



**Figure 4.19: Forecasted water production and the actual water produced by the AWGs**

It may be observed from Figure 4-19 that there was a huge difference between the forecasted water production and the actual water produced during August 2020. This was the first month of production after a dry winter season. The forecasted figures were obtained from SAWS (2020-2021), while the AWGs production was stop-start and not associated with their input set point ranges and design specification, as described previously in terms of their calibration requirements.

Upon investigations by the researcher and the calibration service provider, it was found that the physical transmitters had been bent and had accumulated dust. This damage impacted the set point values which the AWGs were recording. These were supposed to trigger the generators to start automatically. It was also noticed that the generators deviated from starting at expected times. The forecast values would provide information that suitable ambient conditions would commence at a specific time of the day. It was then observed that the AWGs would not switch on at those times. They would start much later on in the day, and the production windows would be missed. This explains the deviations illustrated in Figure 4-19.

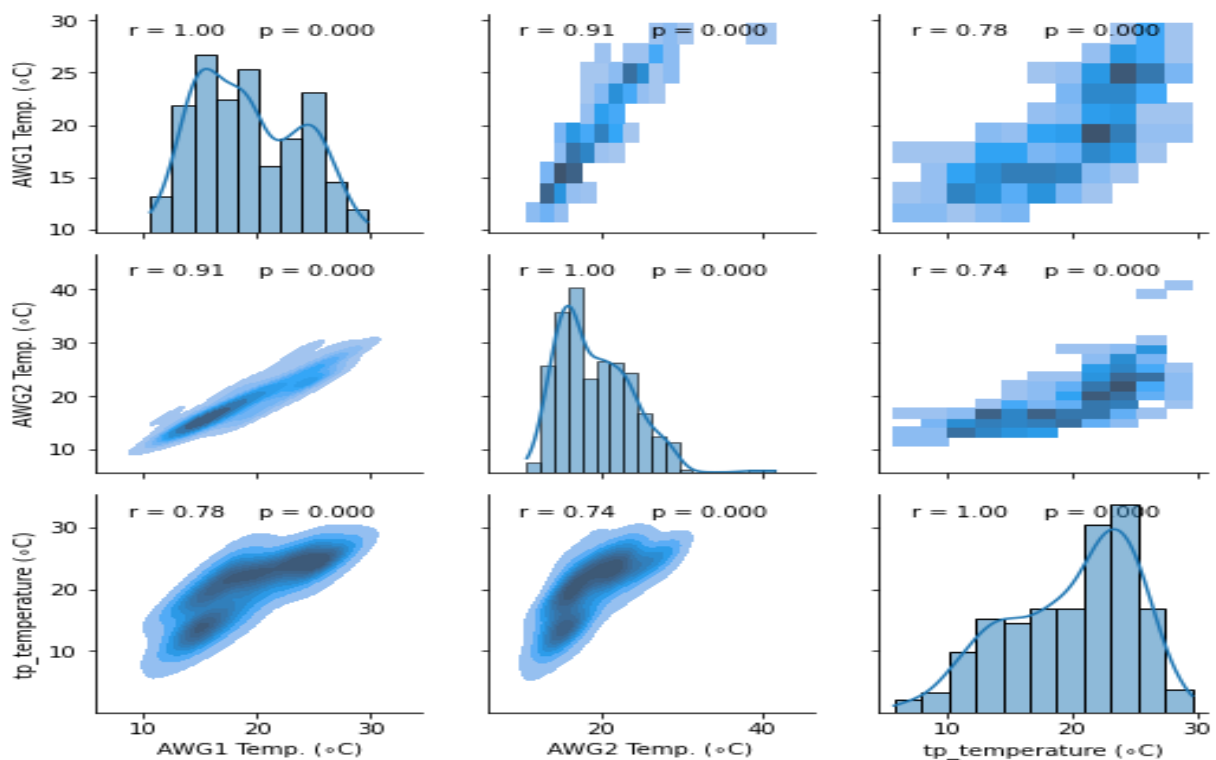


**Figure 4.20: Presents the distribution of daily relative humidity (%) recorded individually by three Atmospheric Water Generators (AWGs) during August 2020, with subfigures (a), (b), and (c) representing AWG1, AWG1H, and AWG2 respectively.**

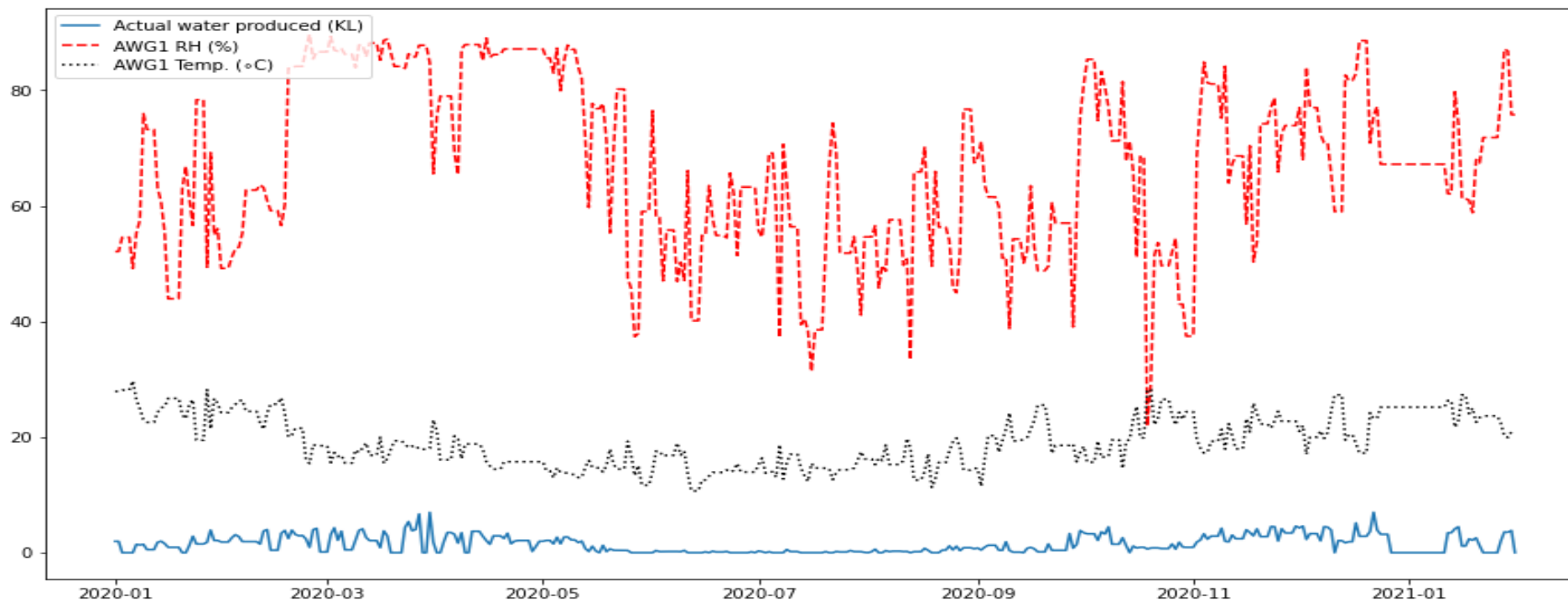
The data in Figure 4-20 illustrates the density distribution, the skewness, the kurtosis, and the mean value of each relative humidity data distribution. It can be observed that the distribution of the average daily humidity data collected from the weather history was less tailed than the distribution of the relative humidity data collected from the hygrometers. Furthermore, the mean value of the distribution from the weather history was significantly lower, with 49 %, than the ones provided by the first and second hygrometers, which were 67% and 68%, respectively. This again highlighted a significant difference between the two means of the collected data.

A similar analysis was done for the average daily temperature data from the weather history and the hygrometers' measurements, as illustrated in Figure 4-21; the correlation of these parameters was evaluated using a correlation matrix that also provides the values of the Pearson correlation coefficient between the parameters, and the corresponding p-value of each correlation to reject or confirm the null hypothesis. A strong correlation was observed between the values measured by the two hygrometers ( $r = 0.91$  and  $p\text{-value} = 0.00$ ). The correlation coefficient was not as strong between the weather history data and the first hygrometer values ( $0.72$ ), and the weather history data and the second hygrometer ( $0.69$ ).

However, though the distribution of these values had different skewness and kurtosis (see Figure 4-20), the mean of each distribution of the values from the hygrometers differed by  $1^{\circ}\text{C}$  from the one of the weather history data, which indicated that the data collected from the AWGs was not far off from the values gathered by the weather stations.

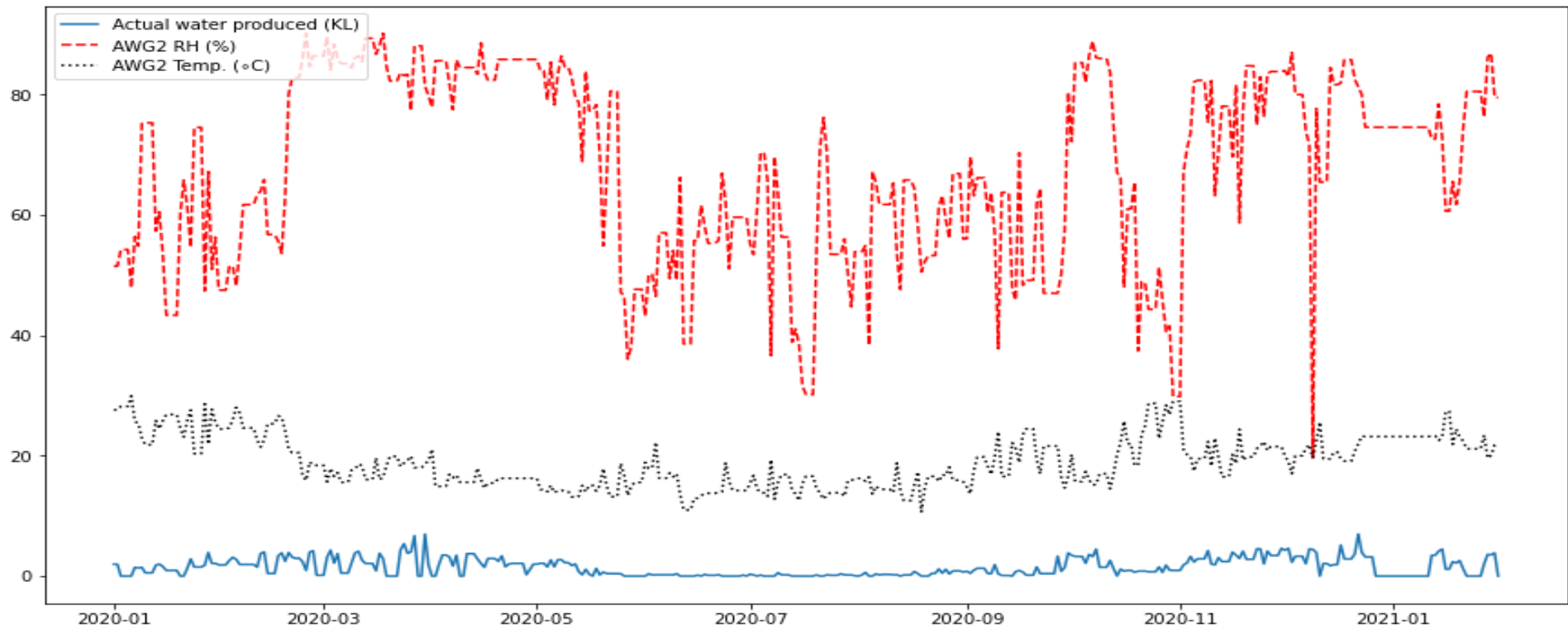


**Figure 4.21: Correlation matrix between the average temperatures recorded from the AWGs and those from the weather history data (Meteoblu)**



**Figure 4.22: Time series of the water produced throughout the study with T and RH of AWG1.**

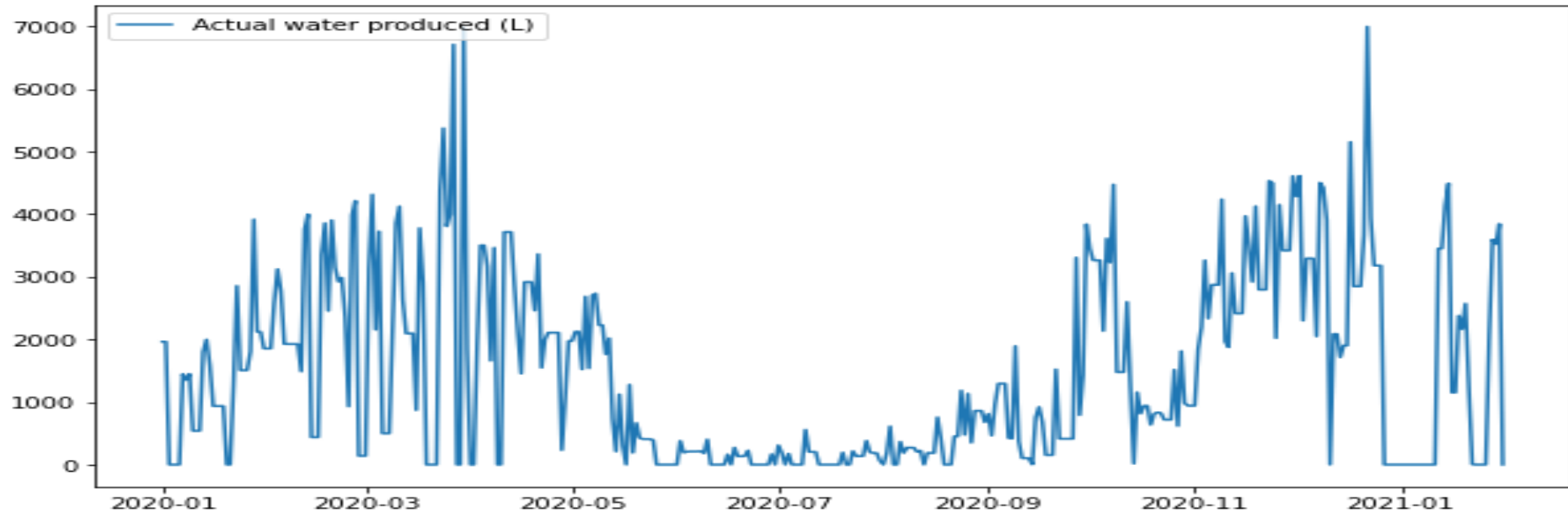
Figures 4-22 and 4-23 show that less water was harvested from the atmosphere during the winter season, from mid-May 2020 until mid-August 2020, where the lowest average T was 9°C with RH being around 17%, as observed and summarised in Figure 4-2 to Figure 4-9. A total of almost **60 000L** of water was recorded for the production year period.



**Figure 4.23: Time series of the water produced throughout the study with T and RH of AWG2.**

The highest water production was observed on the first day of fall, and from mid- to early-summer, with 6983 and 6997 L/day, respectively, as depicted on both time series data. Both graphs highlight a summary of the yearly T and RH of the AWGs with water produced, as observed during the study. These two parameters are the basis of water formation in the atmosphere. Overall, less water was harvested from the

atmosphere during the winter season, where the lowest average temperature was at  $T = 9^{\circ}\text{C}$  and  $\text{RH} = 17\%$  on the 11th of June 2020, while the highest volume generated in one day was 6997 L at  $20^{\circ}\text{C}$  and  $70\% \text{RH}$  on 31st March 2020. The annual water productivity trend has been summarised below in Figure 4-24.

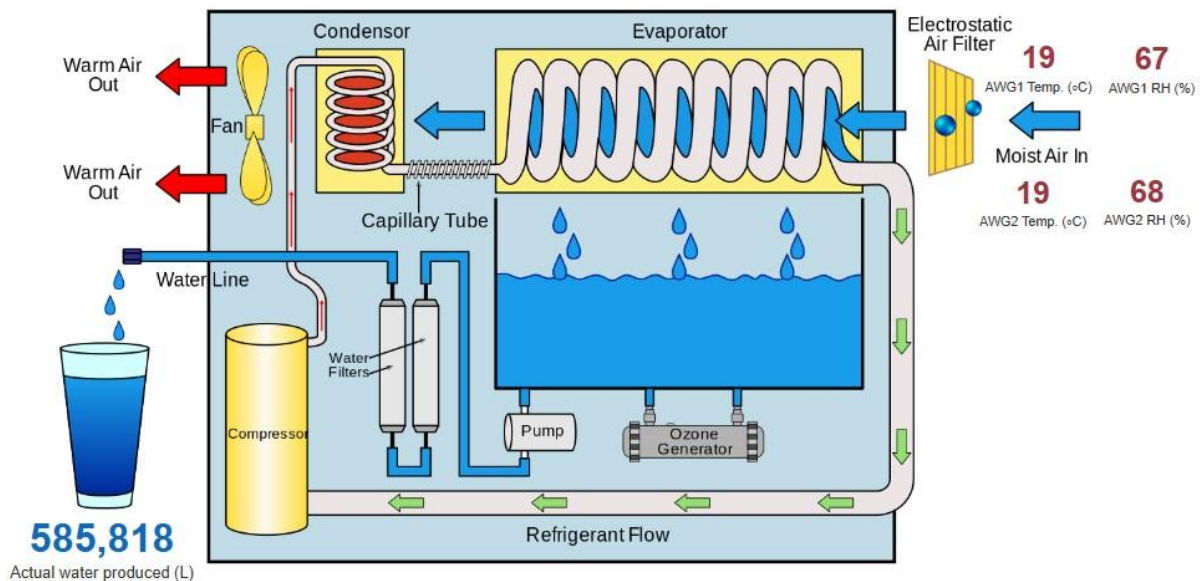


**Figure 4.24: Time series of water produced throughout the study**

**Table 4.1: Highest water production days within a year as indicated with peaks reference to Figure 4-24.**

Date	30 March 2020	22 December 2020
AWG 1 temp (°C)	18	23
AWG 2 temp (°C)	18	22
AWG 1 RH (%)	84	76
AWG 2 RH (%)	81	81

All ambient conditions, including temperature and relative humidity data recorded during the study, were incorporated into the simulation presented below. The image used in the simulation is adapted from the study by Ahmad *et al.* (2022), and the full model can be accessed via the following link below:



**Figure 4.25: Illustration of the simulation for atmospheric water generator performance, sourced from (Ahmad, et al. 2022).** Performance analysis of atmospheric water generator under hot and humid climate conditions: drinkable water production and system energy consumption. Case Studies in Chemical and Environmental Engineering, 6, p.100270. Available at: <https://doi.org/10.1016/j.cscee.2022.100270>

The simulation provides a useful tool for current and future decisions on possible investment in this technology, as it can be manipulated to indicate favourable productivity conditions, which will predict the project's viability.

#### **4.3 Site Atmospheric Water Quality on Microbial and Physio-Chemical Properties and Treatment Requirement**

This section shares the chemical parameters of atmospheric water harvested at the site study between 1 January 2020 and 31 January 2021. Parameters such as turbidity, conductivity and pH were analysed on-site at the organisation's water laboratory. A complete chemical and microbiological analysis of the water was done at the laboratories of Water Lab and Nvirotech, accredited by the South African National Accreditation System (SANAS) in South Africa, as third-party verifiers of analysis. All analyses conducted were compared to the regulation conformation of the South African National Standard for Drinking Water 241(SANS 241) (SABS, 2015). (See Appendix 1.)

Water generated from the AWGs was sampled post filtration processes as "final product" and post-ozonation as the "final ozonated product". The researcher arranged for a special sample for full organic and inorganic analysis on raw harvested water post condensation (air to water phase), prior filtration being sediment filter, carbon filter, plus ultraviolet (UV) disinfection seen in Appendix 2 and final ozonated product water shown on Appendix 3.

As reported in Appendix 2, none of the analyses were out of specification compared to SANS 241 limits except for free saline ammonia as N, which was **1,9 mg/l** whilst the limit is **< or = 1,5 mg/l**. The site study location was near an industrial area with a chicken farm about 500 metres away, where ammonia may have been generated. Literature shares that chemical properties from AWH largely reflect the local environment from which the air was extracted (Tomaszkiewicz *et al.*, 2015), while other studies have reported that contaminants were more efficiently transferred under unstable anticyclone conditions, allowing the harvested water to indicate long-range reality within the atmosphere (Inbar *et al.*, 2020).

The final analysis of the product reported in Appendix 3 showed that all the parameters were well below the specification limits by up to 80% on average. Such analysis reflects the purity of the water harvested from the air with impurities at lower levels prior to

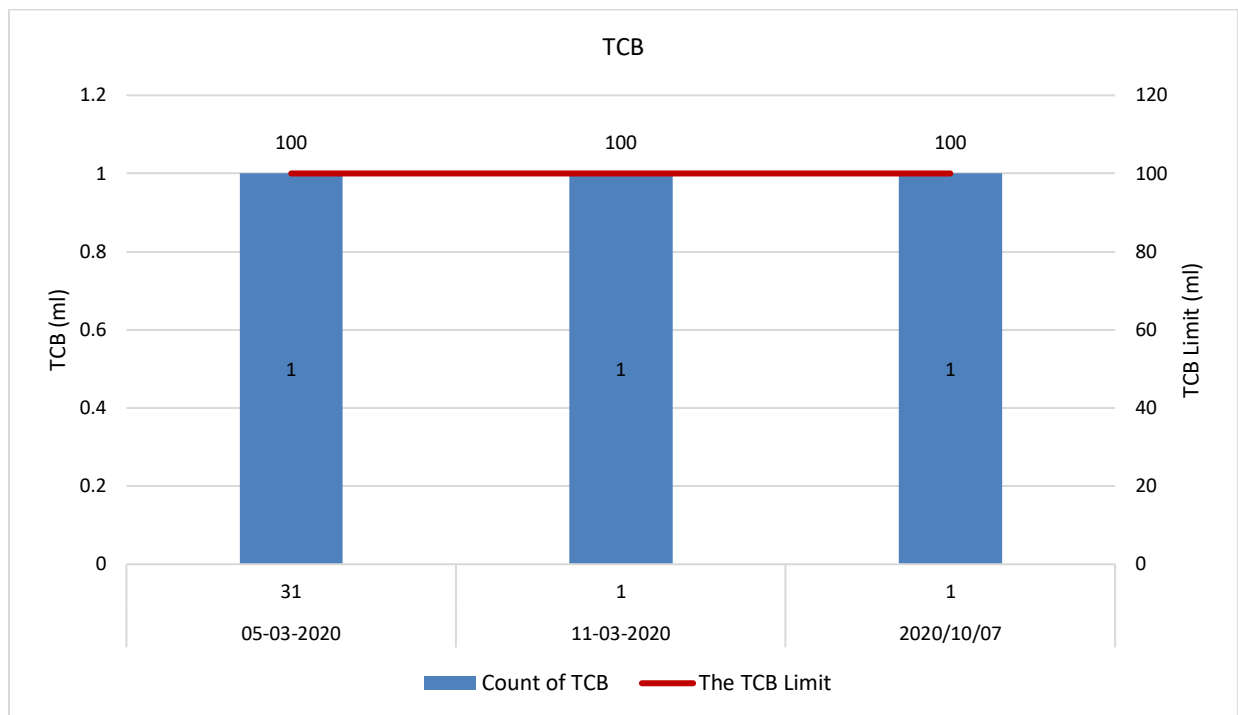
filtration and at excellent levels following filtration with over 400% difference from SANS 241 drinking water standard limits (SABS, 2015). It was a standard procedure to conduct a “cleaning in place” (CIP) process of all the equipment of the AWG plant, comprised of valves and piping with bends, as well as holding tanks from filtration processes, every month. The top filter bags, which extracted air from the atmosphere, were replaced as per the maintenance procedure provided by the manufacturer’s guide based on the generators' running hours

The microbiology in drinking water is of utmost importance as per the World Health Organisation (WHO), as it protects consumers against detrimental health effects which may occur as a result of bacteria and viruses from under-treated or unmonitored drinking water as per the quality standards and regulations such as SANS 241 (SABS, 2015). An external accredited laboratory analysed parameters such as heterotrophic plate count (HPC), total coliform bacteria (TCB) and *Escherichia coli* once every three weeks and with every change of season. This particular routine was developed due to the non-existent to low detection of microbiology within the AW.

Sample analysis of AWH as a final product post-filtration, non-ozonated on HPC, is shown in Figure 4-26. Each batch of water produced on site was taken away for third-party analysis. A batch consisted of a full final production tank of 2000 L. Many batches would occur when there was a high ambient humidity level and favourable temperatures for AWGs to produce water. During the study, almost 2279 samples were sent away for analysis of HPC, TCB and *Escherichia coli*. Of these, about **40** samples were out of HPC specification. This was almost **2%** of 100% samples. Only **3** samples detected some low levels of TCB, whilst E-coli was never detected. The highest value of HPC detected was > 100 000 cfu/ml, with the standard limit being 1000 cfu/ml, whilst TCB detected the highest value of **31** cfu/ml against the standard limit of 100 cfu/ml. The other values were **1** cfu/ml on TCB during March and October 2020 (see Figure 4-24). The HPC detection occurred during winter when the AWGs were not in service for almost a month due to the absence of humidity in this region. The sample was collected from water harvested over a four-week period. TCB was detected during the high humidity season, during which there was a lot of AWH.

The EPA (2018) stated that surface water treatment systems may use HPC measurements as an alternative indicator for disinfectant residual. It further stated that systems exceeding 500 cfu/ml limit in more than 5% of samples over a period of two

months were contravening the regulatory requirements. SANS 241 (SABS, 2015) has a higher limit than the EPA standard of 1000 cfu/ml. Only 2% of the samples were out of specification, even every two months of the AWGs' operation. The primary purpose of HPC measurements was to send an alarm of microbial instability of water and provide proof of inadequate system disinfection, even though it is not directly associated with human health risks.



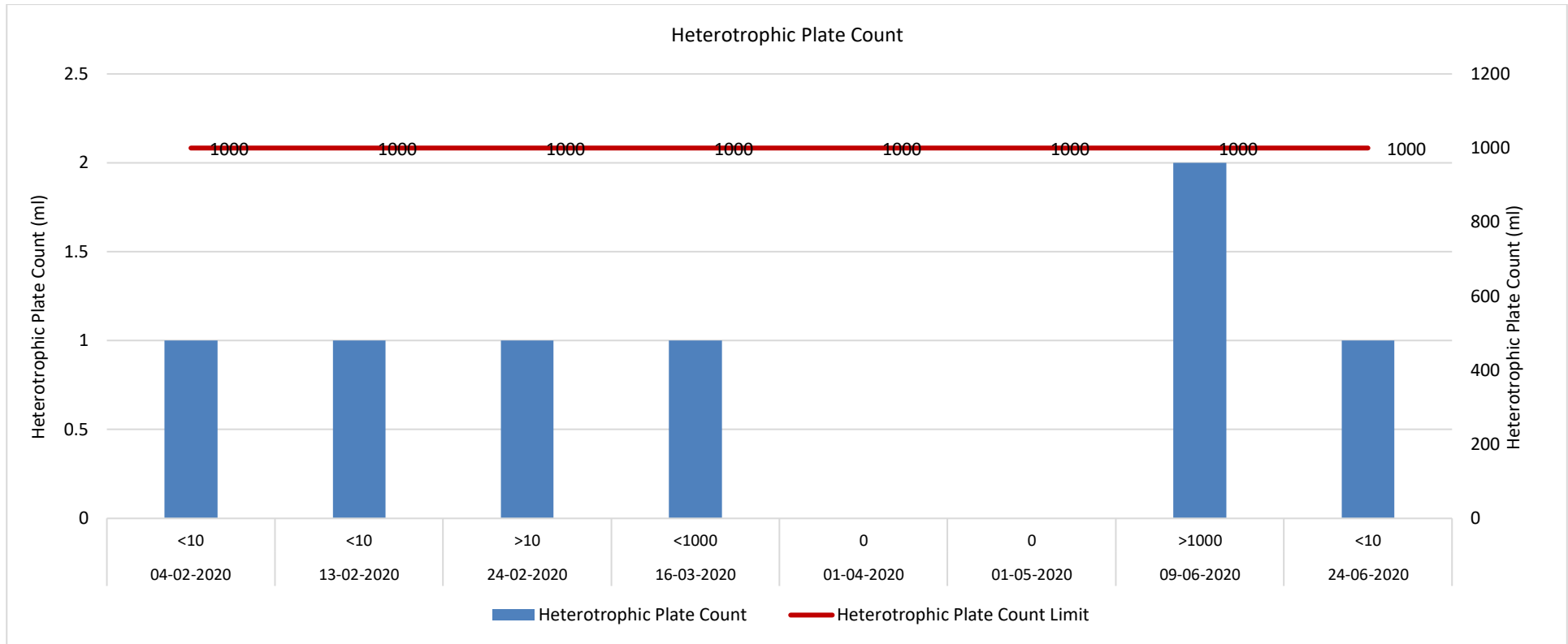
**Figure 4.26: Total Coliform Bacteria detected on final water product non-ozonated samples analysed during the cause of the study.**

The site production team took advantage of the high humidity in the atmosphere during the summer season to harvest more water as the CIP process was postponed. Unfortunately, harvested water quality analysis detected 31 cfu/ml on a sample taken on the 5<sup>th</sup> March 2020. Each time TCB or HPC was detected, the CIP process had to be enriched with disinfectant as a basic agent for safe conditions against TCB or HPC. This particular agent was suitable within these generators because atmospheric water had no salts. The disinfection process was not extremely costly. In the post-disinfection process, an adenosine triphosphate (ATP) test with sterile cotton swabs would be conducted on

every pipe bend, between valves, tanks, before and after the filtration systems and the UV and ozonation system within the AWGs.

ATP indicates microbiological activity as it is an energy molecule found in all living cells. It was used to indicate how successful the disinfection process was. On the 11<sup>th</sup> of March 2020, a count of TCB with a value of 1 was detected. Another disinfection dose was executed on the plant, which lasted for six months with normal three-weekly CIP cleaning. Disinfection was conducted again on site post the TCB detection on the sample analysis of the 7<sup>th</sup> October 2020 (see Figure 4-27). A new disinfection regime was then established from the outcome of this study as to when to conduct disinfection on the plant after winter and when the plant would be out of operation for many weeks to prevent septicity.





**Figure 4.28: Heterotrophic Plate Count on final ozonated water product samples analysed for the first semester of the study.**

It can be observed in Figure 4-28 that only two samples out of the 1140 taken during the first half of the year were above 1000 cfu/ml. These results prove the effectiveness of ultraviolet rays (UV) and ozonation disinfection. This is a significant decrease from 40 previous out-of-specification samples displayed in Figure 4-27. In addition, no *Escherichia coli* was detected in any samples reported in Appendices 2 and 3.

### pH Values Over Time with pH Limit

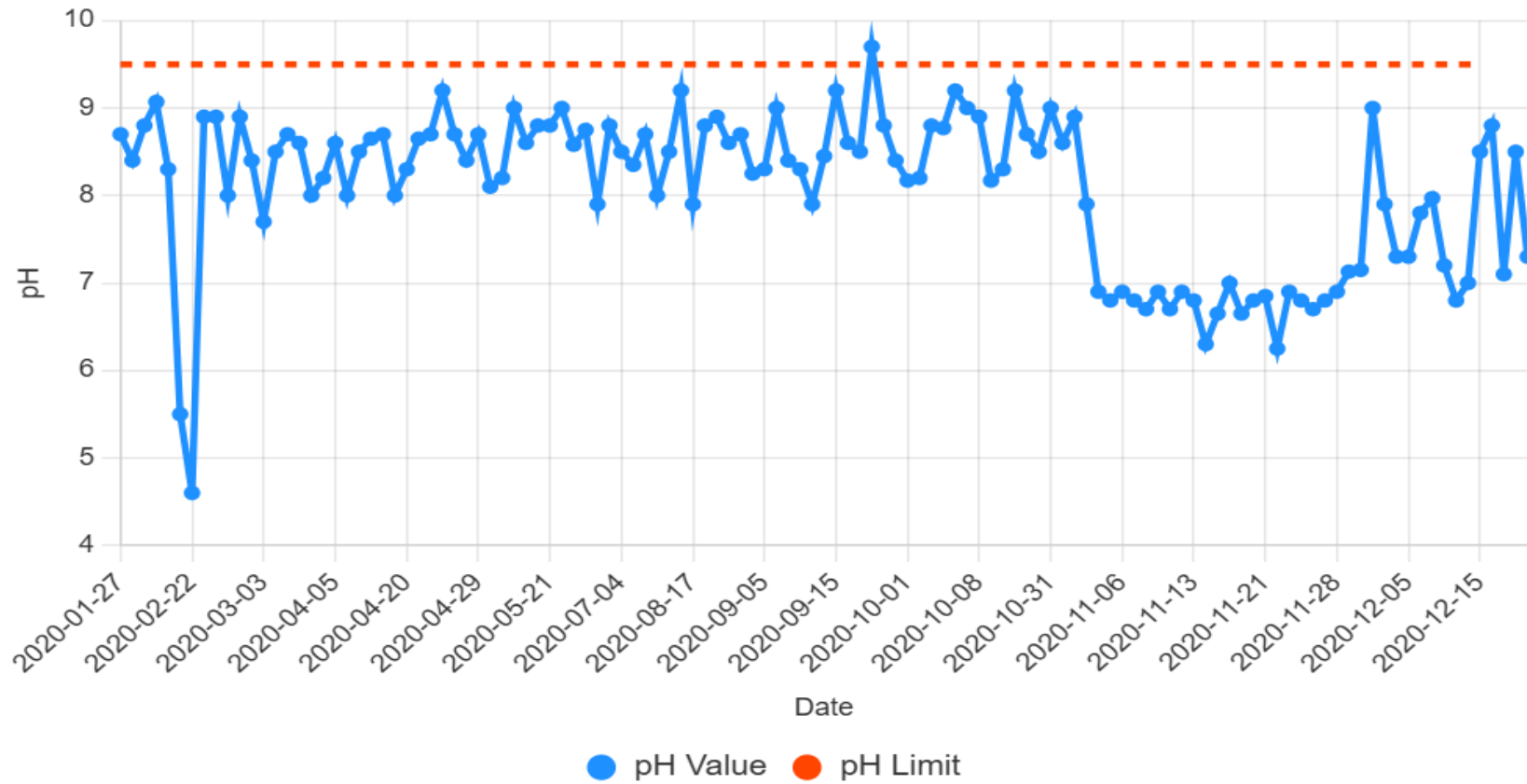
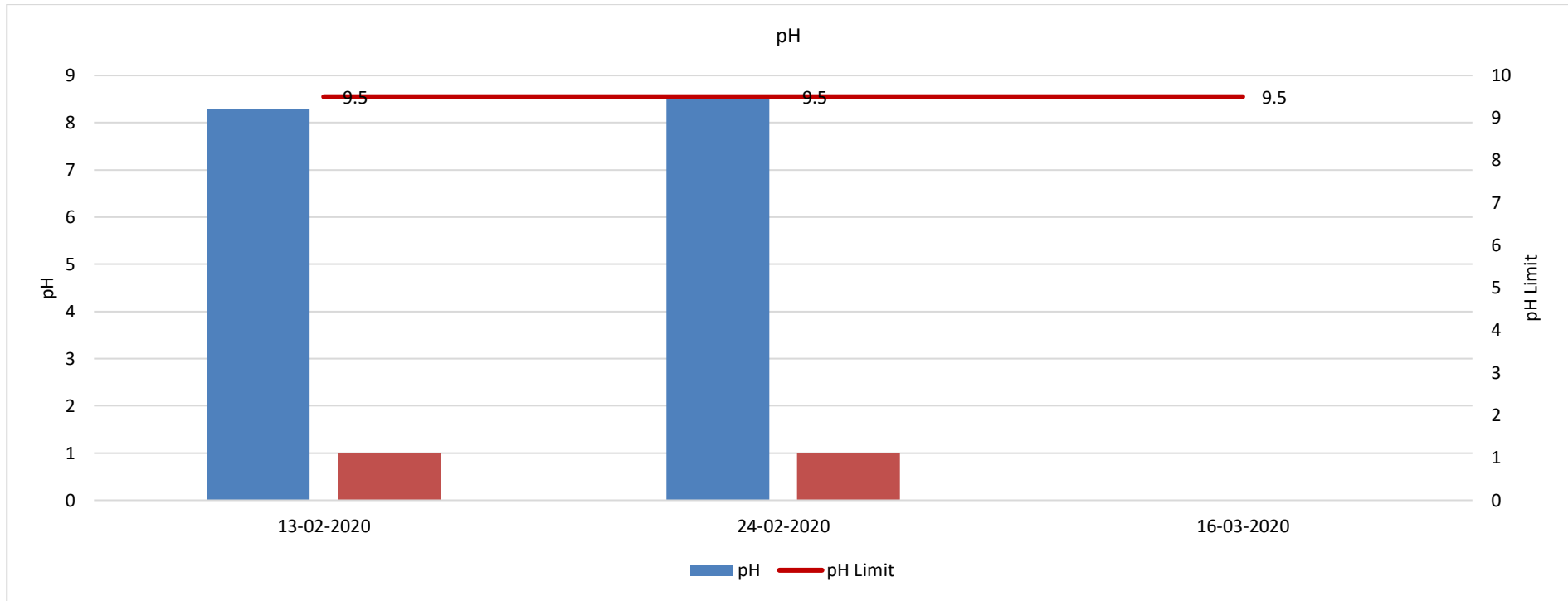


Figure 4.29: pH analysis done on final non-ozonated water product upon duration of the study.

The average acidity of the water harvested on the final non-ozonated water product observed in Figure 4-29 was pH 9 (alkaline). It demonstrates that water is alkaline and that it will not corrode the generator's equipment. It is also safe for human consumption. Lal (2022) discusses the benefits of consuming alkaline water versus acidic water for humans. They are less likely to get diseases such as ulcers and cancer as these thrive in an acidic environment in the body. The pH continued to stabilise between 8.5 and 9 even in final ozonated water in a few captured samples which indicated that ozonation did not have any impact on the pH as displayed in Figure 4-30.

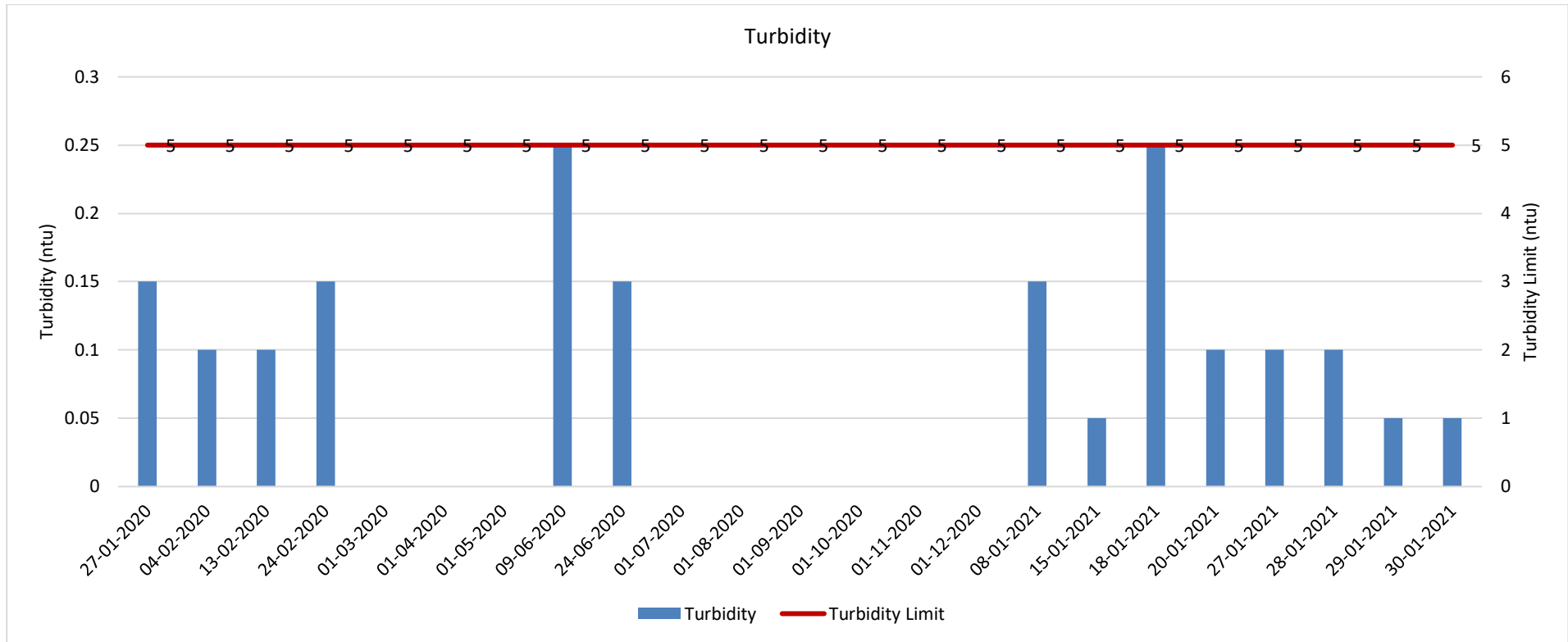


**Figure 4.30: pH analysis done on final ozonated water product**

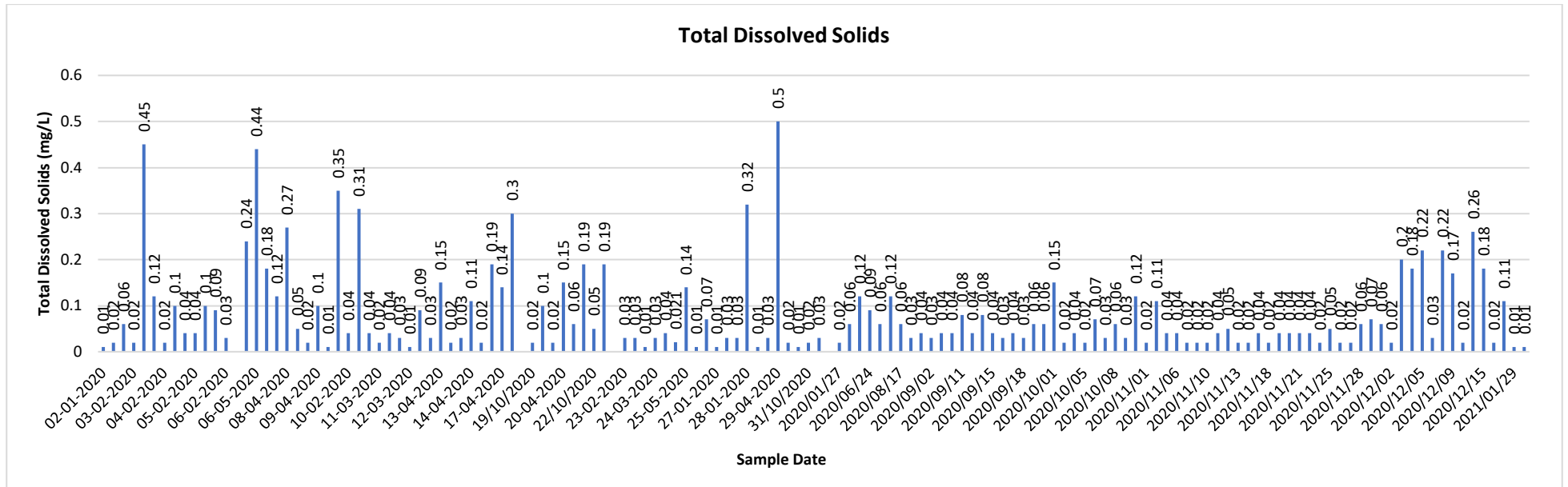
Turbidity analysis results from tests done on site are presented in Figure 4-31. Tomaszekiewicz *et al.* (2015) mentioned that high turbidity interrupts the effectiveness of disinfection, ozonation, and ultraviolet rays (UV). The World Health Organisation (WHO, 2022) recommends that the mean turbidity of water being treated with these disinfection methods should be below 1 NTU, with no single sample having turbidity exceeding 5 NTUs. The turbidity analysis on the final water products shown in Figure 4-31 shows that only one sample from the analysis results recorded on the 9<sup>th</sup> of March 2020 had a value of 2,4 NTU, which was out of this specification.



Figure 4-32 shows the turbidity analysis of samples post ozonation disinfection which their values are reflecting at the base of the graph. These results do not indicate the sample described in Figure 4-30, which was out of specification. There were no turbidity results above 1 NTU, confirming the disinfection process's success.

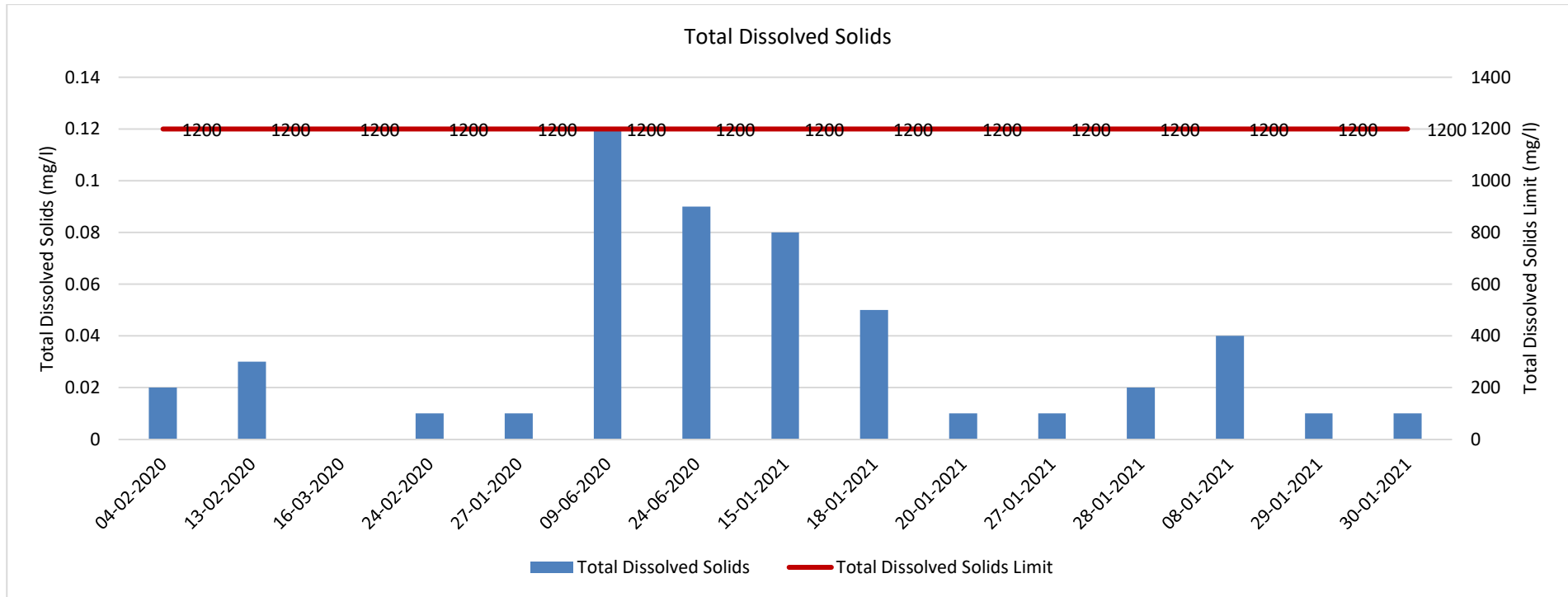


**Figure 4.32: Turbidity analysis done on the final ozonated water product during the study duration.**



**Figure 4.33: Total Dissolved Solids analysis done on final non-ozonated water product upon the study duration.**

The analysis of total dissolved solids (TDS) (Figure 4-33) indicates no value above 1 mg/l in the final non-ozonated product from AWGs. The raw water sample in Appendix 2 indicated analysis results of 14 mg/l. This sample was taken immediately after condensation but before the filtration process. These analyses showed the purity levels of water from the air, and these levels continued to improve to values below one mg/l after the filtration treatment, as seen in Figure 4-34.



**Figure 4.34: Total dissolved solids analysis done on final ozonated water product upon the study duration.**

Figure 4-34 shows TDS analyses of final ozonated water. There was a peak on the 9<sup>th</sup> June 2020, with analysis results of 0,12 mg/l TDS. This was well below the SANS 241 specifications limit of 1200 mg/l following the ozonation process.

The results for electrical conductivity (EC) of water illustrated below in Figure 4-35 depict the number of ions present in water. When these ions are at high levels, they may contribute negatively to the water system with chemical scaling and affect water quality and the water plant's or generators' longevity. EC represents how effective the water treatment process is at removing heavy ions. The EC value was expected to trend at lower ranges with AWGs because the analysis of the raw AW, sampled during the winter season, was 2,6 mS/m, as indicated in Appendix 2. The drinking water standard SANS 241 (SABS, 2015) recommends a limit of 170 mS/m of EC for drinking water. The highest value of EC was measured after filtration, as recorded in Figure 4-35, was on the 22<sup>nd</sup> of October 2020. All other parameters were within specification for this particular day, and a re-sample was taken for re-analysis at a third-party laboratory. The outcomes were the same, as displayed in Figure 4-36.

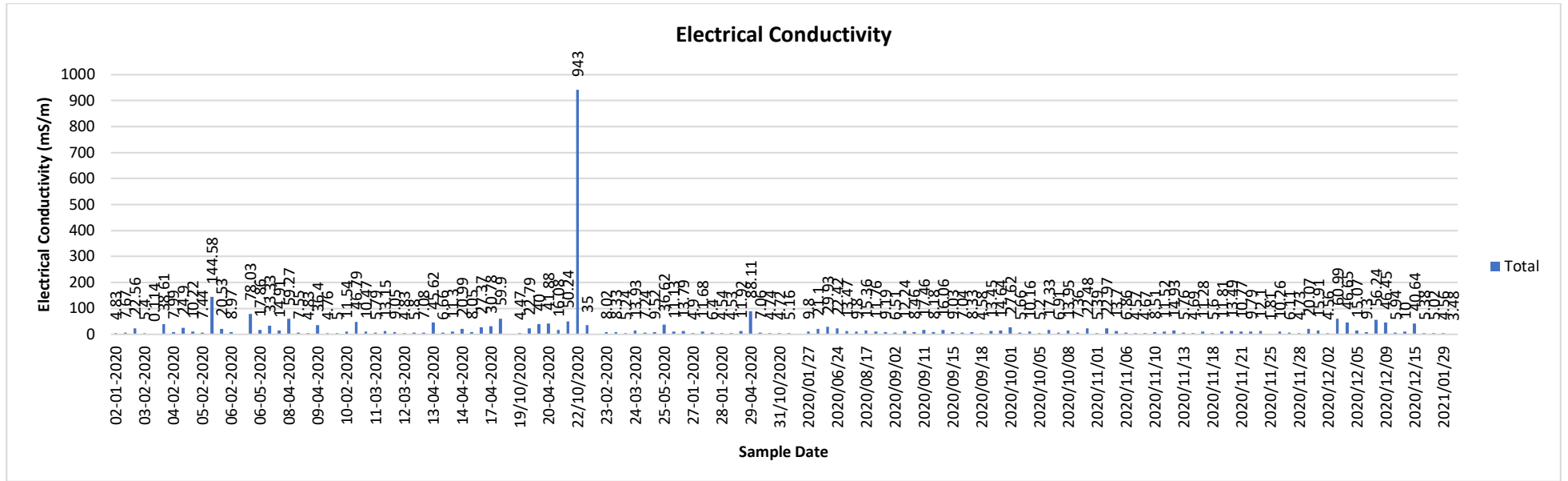
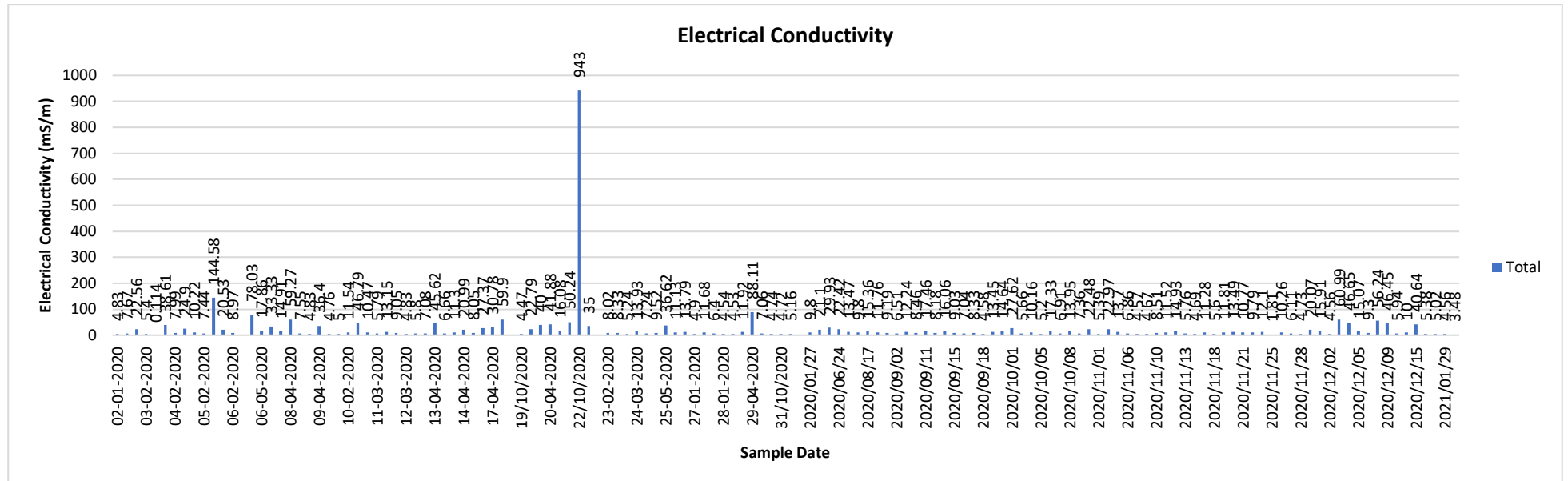
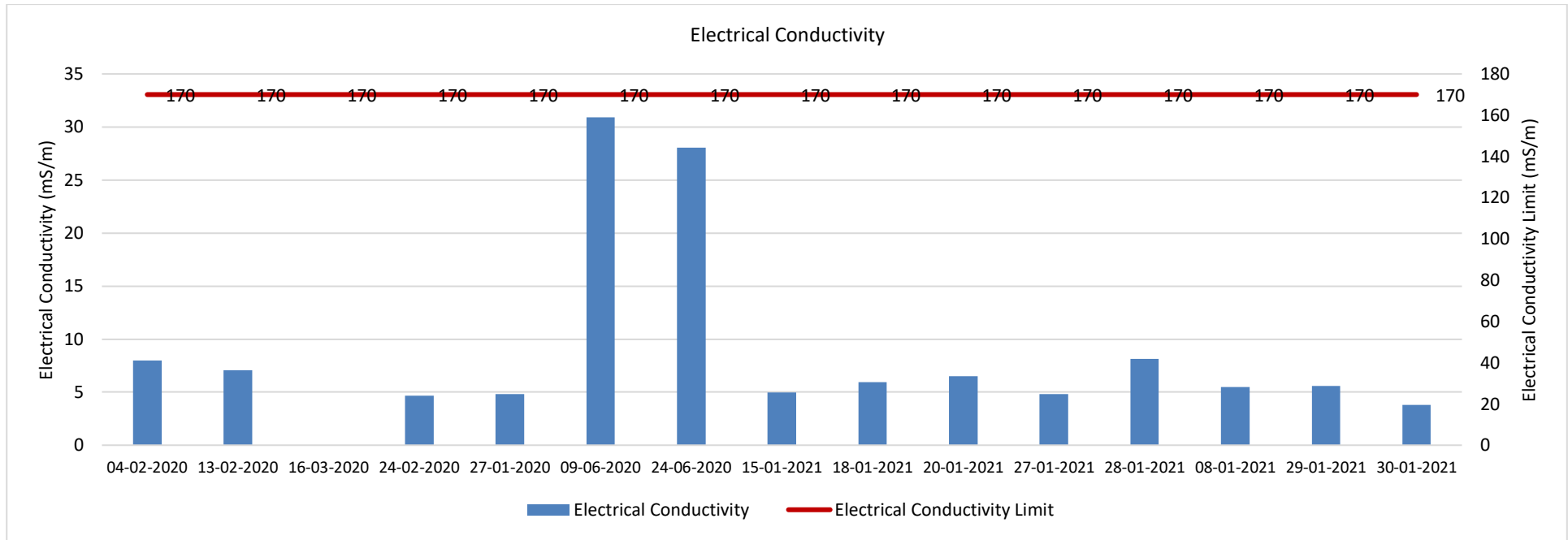


Figure 4.35: Electrical conductivity analysis done on final non-ozonated water product.



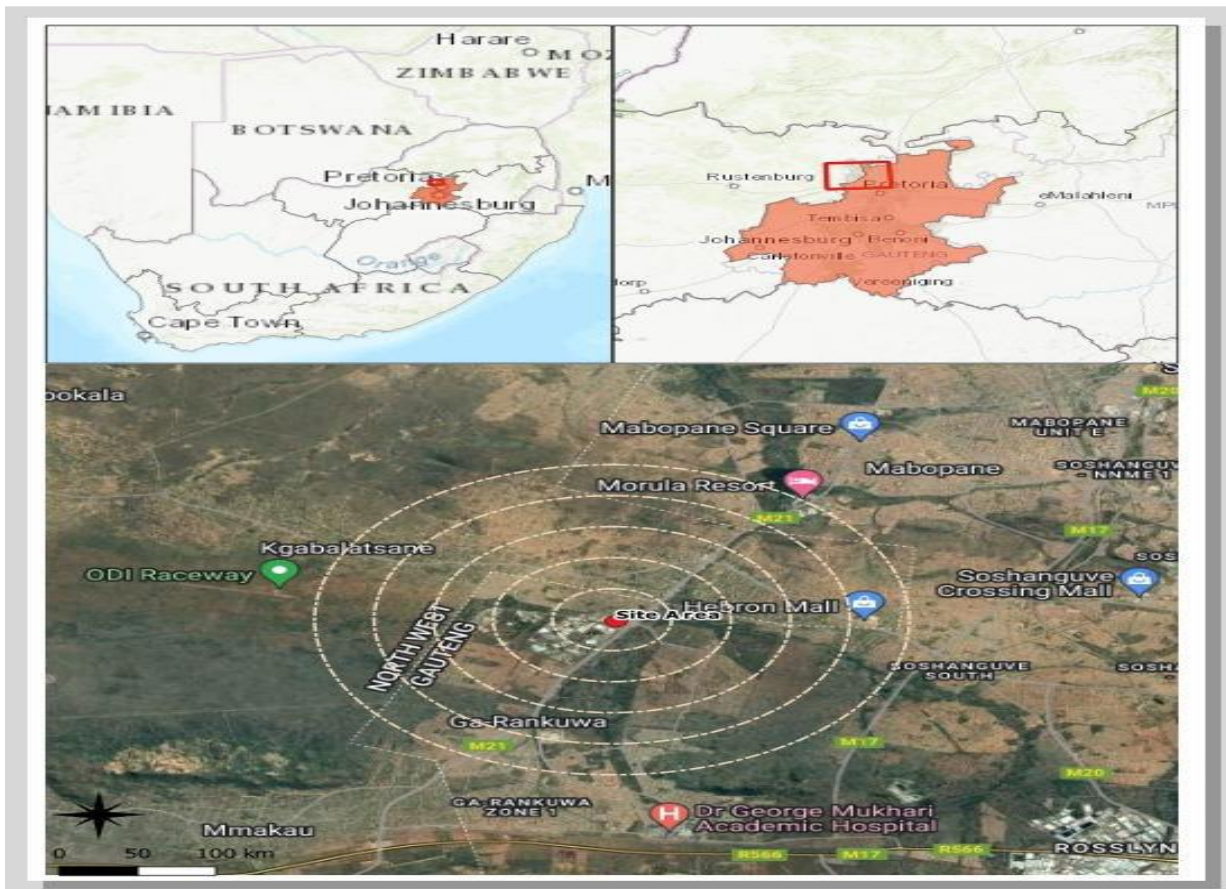
**Figure 4.36: Electrical Conductivity analysis done on final non-ozonated water product by a third-party water laboratory (re-sample).**

Ozonated final water trends shown in Figure 4-37 illustrate EC values of below 10 mS/m, except four sample values, one recorded at 20 mS/m, another at 28 mS/m, followed by two at 30 mS/m and the highest being at 63 mS/m. The latter was alarming as it stood out from the rest. Even though this sample was still within the standard’s limit, the TDS of the same analysis was also recorded at a high range. Rusydi (2018) stated that ions that would raise TDS values would increase the EC values. This correlation is described in the equation  $TDS = k EC$ ; where k is a constant at 25 °C. This analysis of the final ozonated water illustrated the power of ozone as an oxidising agent that disinfected and attacked bacteria, as reflected in the results.



**Figure 4.37: Electrical conductivity analysis done on final ozonated water product.**

#### 4.4 Community Engagement Interviews to Assess Acceptability of AW by the Community and Determine the Impact in The Alleviation of Water Challenges



**Figure 4.38: Case study area indicated as “site area” and 5 km radius indicated by circular mapping coverage.**

A community survey was conducted through interviews for over a month within a five km radius of the case study location. The research survey aimed to assess how much people in the community knew about atmospheric water harvesting and to create awareness about the technology.

The surveyed community consisted of an industrial area on one side and a residential area on the other. The two groups used most of the water. After being told that the survey was about research into drinking water, the participants contributed voluntarily to the survey as water was vital for human lives and socio-economic growth. The survey evaluated whether people cared about water quality and its impact on their health. It also attempted to

determine if the participants understood the tariff costs associated with drinking water. Water rates in South Africa are calculated on a sliding scale, meaning the more one consumes water, the higher the cost. In this regard, the issue of quality versus tariff cost was highlighted in the survey while also noting that usage must be monitored. South African municipal billing highlights different water usage brackets. In the **City of Tshwane Metropolitan Municipality**, water billing begins at a usage range of 0 to 9 kilolitres (kL), charged at a rate of R16 per kL (Municipality, 2020). Each month, a municipal official from the City of Tshwane records water meter readings from residential and business premises on a predetermined date.

The survey applied a method of quantitative engagement (Nel, 2017) using mathematical or numerical data. In order to ensure that the Protection of Personal Information Act (POPI) (South Africa, 2013) has been adhered to; the researcher presented the community engagement plan to the university for approval from the institution's ethics committee. The committee assessed the following information:

- the type of the survey, if it posed a risk to humans or the environment,
- the benefits of the survey,
- the criteria for participation recruitment,
- privacy and confidentiality of both data and participants,
- facilities or places where the survey took place,
- if there were incentives or not for the participants.

The researcher further submitted the prepared questionnaire and consent form to the ethics committee and research department for approval. The consent form highlighted the following information for the participant:

- that participation was voluntary, and the participant could withdraw at any given time without any prejudice,
- that the participation was solely for research purposes,
- that there was no remuneration attached to participation,
- that there was no personal identification, sex, or race except for age to distinguish between an adult and a child for survey information validity,
- that the survey would be done twice for validity purposes.

Questionnaires and consent forms were provided to anyone who agreed to participate in the survey interview. No name, race or identity of a participant was captured. A consent form was attached, with a number to track people's involvement for validity and randomization. Randomization was ensured by following Ronald Fisher's principle (DasGupta, 2011). Two people engaged a participant twice with the same questionnaire on the same day. The bias among participants depicted an error in the survey based on characteristics such as gender, age, social class, and beliefs of those who voluntarily participated in the survey compared with those who did not. The literature highlights the fact that it is challenging to achieve outcome rates of more than 80%. However, higher outcome rates have sometimes been observed in developing countries (Fenton *et al.* 2001).

Three meetings occurred between the researcher and her field worker to ensure they did a "dry run" for the preparations ahead of the survey. The main agenda points were the friendly approach to the targeted participant; she/he should agree first to be interviewed, then confirm if the participant was an adult, followed by taking the participant through the consent form, then through the questionnaire and finally, to communicate that another similar interview would follow in a few minutes. Kabir (2018) states that when engaging with human beings, friendliness should be paramount, and one should be humble and respectful while maximising the benefit of the time given for the engagement. The researcher had undergone ethics training with the university and completed an international academic ethics training programme, which equipped her with tools, concepts, and methods to conduct this survey efficiently.

The researcher prompted the appointed field worker to survey her to prepare her mind for the actual community engagements. The researcher also covered extensive literature on data collection during this time in preparation for any unforeseen circumstances that could arise during the survey. The researcher stood a few meters from the appointed field worker to keep track of the person being interviewed, whilst the researcher informed the participant through the consent form that she/he would be interviewed by another person shortly after they were done with the particular interview.

The Ronald Fisher method (DasGupta, 2011) explained how the researcher can get quality statistical outcomes from their random surveys without being biased through the distribution surveys from participant s' feedback, that any difference spotted from the surveys can be explained and seen by the researcher. Additionally, the method explains

that only age may be recorded for opinion validity purposes, as any person above eighteen years old would be considered an adult in South Africa (South Africa, 2005). The survey tested and validated the opinions and what people understood about drinking water challenges in South Africa and atmospheric water (AW). It was crucial to get feedback on their understanding of the difference between AW and the usual potable water, and if people would use AW as an alternative source versus the regular potable water they were used to or not, or if they would use both these sources.

Age was used as a criterion in the questionnaire as data analysis distinguished between the opinions of adults using the following criteria:

- Comparisons: conventional supply of drinking water versus atmospheric water supply.
- Comparisons: water quality versus water costs.

The researcher conducted the first set of interviews, whilst the person appointed by the researcher did the second set. Kabir (2018) mentioned that fieldworkers had to be highly vigilant during engagements with participants and had to be equipped with all necessary knowledge of how to interact with participants to ensure they earned their cooperation. The researcher chose a master's student studying a similar topic as a fieldworker to conduct the survey. The advantage was that the student already understood the importance of information and the ethics involved in conducting such a survey. The survey was conducted during the day between 8h00 and 16h00 between Monday and Friday.

Engagements took place at the taxi ranks and bus stops. These places were found to be suitable as people could be asked questions while queuing for transport. Other places were a community hall on the day where government grants were being paid, on industrial sites during lunch times where people would be in and out of their workplaces to get food, at mall entrances, and a few times near the church. The questionnaire had the following summary of questions to assess the acceptability of AW by the community and determine AWH's impact in the alleviation of water challenges:

- Do all South Africans have access to clean drinking water?
- Is drinking water supply infrastructure adequate in South Africa to ensure that drinking water reaches all intended places safely?

- Is the drinking water supply infrastructure always available and reliable in South Africa?
- Does the South African climate always allow enough rain during the rainy season?
- Have severe droughts been experienced in South Africa?
- Are most water sources contaminated and polluted in South Africa?
- Can rain, fog and atmosphere be harvested as an alternative drinking water source to assist water challenges gaps?
- Are drinking water tariffs at a lower rate in South Africa than in other countries?
- Is drinking water quality more important than its cost?
- Should the cost of drinking water be relative to the quality? Can more be charged for high-quality water than for poor-quality water?

The results in Tables 4-2 and 4-3 show that most of the people who participated in the survey (40%) were in the 30-39 age group. Most of the people in this group were found on the industrial sites and the malls, suggesting that the most influential group was from the working class. The group had buying power regarding changes to the water supply or even considering AWH as an alternative to what they were currently provided.

**Table 4.2: Overall survey population participation**

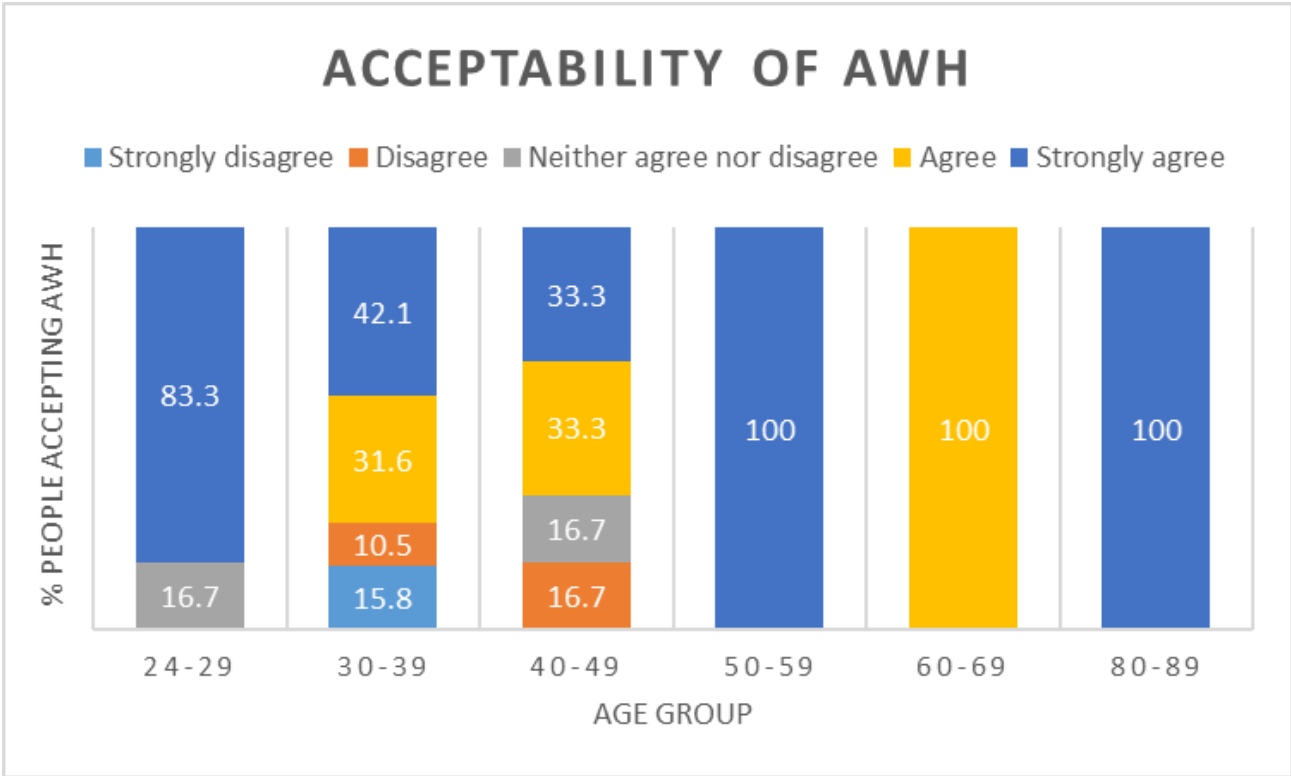
<b>Age group</b>	<b>Survey contribution %</b>
24 - 29	20
30 - 39	40
40 - 49	20
50 - 59	7
60 - 69	3
80 - 89	3

**Table 4.3: Overall survey outcome results**

<b>Scoring</b>	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>5</b>

Question	Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
1.	42%	32%	3%	13%	10%
2.	32%	51%	11%	3%	3%
3.	33%	44%	6%	7%	10%
4.	33%	23%	7%	23%	14%
5.	8%	11%	12%	42%	27%
6.	3%	13%	7%	38%	39%
7.	6%	7%	7%	22%	58%
8.	21%	27%	20%	12%	20%
9.	3%	3%	7%	27%	60%
10.	17%	10%	16%	30%	27%

Figure 4-39 focuses on the reality of the outcome of the assessment of AWH acceptability by the community. It highlights the perception of age groups regarding an alternative water source, AWH, as an alternative to the current source supplied by the government. Although the number of participants varies per age group, it was important to notice that, in general, at least 66.6% of participants per group favoured an alternative water source, in this case AWH. The negative answers were recorded from two age groups, the 30-39 year old and the 40-49 year old. This was understandable as the participants from these age groups have just started families and might be afraid of any possible instability. Alternative water sources represented, for them, an unknown source which they still had to discover, whilst most of them assumed high costs associated with it. Kabir (2018) states that any number lower than 50% is less than the majority. In this case, one could say that AWH was accepted as an alternative source of drinking water.



**Figure 4.39: Percentage of acceptance per age group interviewed (Q7 reflection)**

## CHAPTER 5: CONCLUSIONS

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Globally, in many countries, drinking water boards, agencies, private supplies, research hubs and innovators are the designated institutions tasked with drinking water resources and supplies. It is, therefore, beneficial for such institutions to have access to the type of data compiled within this dissertation. This information may assist in mitigating challenges related to the unavailability or inconsistency of drinking water associated with ageing infrastructure, natural disasters such as droughts or hurricanes, and temporary shutdowns. The data further motivates investment in atmospheric water harvesting for semi-arid regions, which illustrates the reality of adequate water productivity and economic returns. About 2.1 billion people globally lack access to clean water, while 4.5 billion people have inadequate sanitation. This challenge is perpetuated by climate change and water pollution activities due to industrialisation (Jarimi *et al.*, 2020).

In 2015, the United Nations (UN) promulgated sustainable development goals (SDGs) to address global impact challenges of, amongst others, water and sanitation, which had negatively impacted global communities due to pollution and overpopulation. Sustainable Goal 6 (Gaffney, 2014) clearly indicates that clean water access continuity should be ensured to support economic prosperity and environmental sustainability, particularly in developing economies. Atmospheric water harvesting can be one of the solutions to address water challenges due to the effects of global warming, as supported by this case study. The water vapour trapped in the atmosphere due to heat or warming from the earth could be harvested and utilised for drinking water.

This dissertation shares data collected from a high-altitude, semi-arid region. First-hand information and materials could empower individuals and organisations of interest for alternative water solutions while responding to the SDGs for a sustainable future of global existence. Another benefit of AWH highlighted was that no byproduct footprint was created during its operation. It may be regarded as a sustainable technology for the environment. The only byproduct was the exhaust air released during the operation, from which water had been harvested.

The study's main aim was to assess the viability and acceptability of atmospheric water harvesting in South Africa's semi-arid region as an alternative water source to the currently available potable water from treated sources, particularly in areas that have difficulty receiving fresh water. AWH requires minimal infrastructure and can be erected anywhere

it may be needed, provided the meteorological conditions allow it to be effective. The development observed in this case study was that the technology comprised the harvester equipment and the container for the harvested water. It became evident that the turnaround time for implementation is minimal and would require lower capital expenditure, too; this advantage supports the technology's viability.

### **5.1 Conclusion relating to Objective 1: Monitor the Microbial and Physio-Chemical Quality of Harvested Atmospheric Water**

Most samples analysed during the study were within specification for critical drinking water chemical and microbial parameters defined by the SANS 241 drinking water standard (SANS, 2015). It can be concluded that the filtration system of the AWG does not employ extensive work regarding purifying the water because of the quality parameter ranges compared to the drinking water standard. As such, AWGs would have long-term plant health. About 2% of the samples analysed for microbiology on HPC did not conform to the standard. It was discussed in Chapter 4 that the root cause of non-conformance was the plant standing for an extended period during the winter season due to low humidity in the atmosphere. The generator equipment developed waterborne bacteria because there was no water movement for the entire water season. Disinfection conducted after the detection of the bacteria was a successful solution. The cleaning routine was done up to three times until the ATP swabs showed contamination as close as possible to zero. Nisar (2020) mentions the importance of testing for both the presence of bacteria and the success of the disinfection process after every step, as some waterborne bacteria might not respond to a particular treatment. This ensures the proper treatment has been used to treat the identified bacteria.

Another point of note was the turbidity of the final water, which was detected only once above the regulation limit for the duration of the study. The sample was at a value of 2,4 NTU, when the global and local drinking water standards for turbidity is 1 NTU. The turbidity value was reduced after the ozonation process, indicating the ozonation's power to eliminate the taste and odour. This significantly impacted the turbidity, ensuring that this parameter was maintained within limits. The purpose of ozonation was to disinfect water from any impurities remaining, irrespective of water pH levels, as seen from the pH analysis conducted during the study, as reported in Chapter 4 (Sensorex, 2020).

A sample's Electrical Conductivity (EC) was at higher levels, as recorded in Chapter 4, Figure 4-35 on the 22<sup>nd</sup> October 2020. It was the only time during the study that EC was detected above the stipulated SANS 241 limits. Almost twelve days later, the TCB detection triggered the disinfection process to be conducted. Horiguchi *et al.* (2022) stated that there was a high correlation between EC and TCB because the presence of bacteria could result from an ineffective water treatment process, resulting in a high EC reading.

Based on the above analysis, it is concluded that AWH produces water of high quality compared to municipal water, as seen within the chemical parameters from the AW generated during this case study. The country's potable drinking water quality has been reported in the South African municipal drinking water audits (Department of Water and Sanitation, 2023). It is concluded that on a few occasions within the study where the AW parameters were not within specification, the generators were overwhelmed with high production during the high humidity season, and the disinfection regime was not executed timeously. The researcher experienced challenges regarding continual sampling at times, as seen by the absence of data on ozonated turbidity. She had appointed operators and laboratory analysts on site to assist with these duties, particularly during some weekends and or night shifts, but people sometimes fell short.

## **5.2 Conclusion Relating to Objective 2: Assessing the Production Impact of Seasonal Variation**

When assessing the impact of seasonal variation on the performance of AWG at a high altitude, a semi-arid region in South Africa, it is concluded, based on literature by Köppen-Geiger as reported in Chapter 2 (Conradie, 2012), that a high altitude, semi-arid region in South Africa becomes humid during the spring season, which commences in September as per the region's geographical characteristics. The Climate Classification states that this region's humidity peaks in the summer season from December until February. More water was harvested from the atmosphere during this time. However, less water was harvested by the AWGs, as shown in the productivity records in Chapter 4, Figure 4-2. During winter, the lowest average temperature (T) was 9°C, with relative humidity (RH) at around 17%. According to the literature (Conradie, 2012) and the AWG's manufacturer's guide, no water will form under such conditions, and indeed this was the case.

The low-temperature season, typified by minimal rain in SA, is from late fall, during winter and the beginning of spring for high altitude areas, while the rainy season is from mid-

spring through summer until mid-fall. Daily water production was, therefore, guaranteed. However, daily water production volumes would differ depending on the ambient T and RH conditions. These climatic conditions have been described by the Köppen-Geiger Climate Classification as a climate between arid and warm temperate, with a combination of 16,59% and 12,11% between the two categories (Conradie, 2012). The Classification of these numbers states that the climate of an area is an averaging effect of weather conditions that have existed in that area over a long period of time i.e. over 30 years (Kalogirou, 2014). This particular knowledge led the researcher to use an additional tool, a Typical Meteorological Year (TMY), for the location of the case study to calculate the psychrometric chart of the area. The outcome has been shared in Appendix 3. In the 1900s, climate researchers did not have the technological luxury to research gradual climate changes. Currently, climate researchers and meteorologists use a similar analogy of a typical meteorological year (TMY). The TMY contains a summary of a 30-year cycle of complete characteristics of solar irradiation, hurricanes and cyclones for a particular region to predict or forecast weather patterns for the future. The TMY includes all other parameters, such as wind speed, precipitation, humidity and dry bulb temperatures (Vignola, 2013).

It has been concluded that AWH cannot be an ideal investment as a primary drinking water solution at a high altitude, semi-arid region in South Africa, primarily because the technology provides water only during select seasons in a year. However, the technology can be utilised during municipal water infrastructure outages. These can be planned for peak humidity seasons, which favour AWH. Similarly, AWH technology may be utilised during droughts or hurricane episodes when meteorological predictions through TMY can provide precise forecasts of when weather conditions can favour AWH. The technology can be employed in low-altitude, humid regions per the Köppen-Geiger Climate Classification. The simulation data model developed through this study may be customised to suit any South African location to predict the success of the AWH technology for any particular region.

### **5.3 Conclusion Relating to Objective 3: Optimize the Performance of the AWG**

Based on seasonal variation (South African Context), site AWGs' performance was optimised using a “smart” control system. The manufacturer had already designed generators with “ALWAYS ON!” narrative when ambient conditions were  $T \geq 15$  °C and  $RH \geq 30\%$ . The program was considered “smart” as it saves unnecessary energy usage of the generators, which may run at any ambient conditions, even though not all weather conditions would yield water as predicted by the Köppen-Geiger Climate Classification (Conradie, 2012).

Zohra *et al.* (2020) mention the benefits of having such optimised designs during the feasibility phase of generators to ensure that the AWH investment will provide a return. It may be seen as additional costs to have a “smart” control and instrumentation system which needs to be wired and cabled electrically; however, the investment return will be worth the initial budget as such a mechanism saves energy and ensures that no production time would be missed thanks to an automatic mode of operation.

In addition, human errors could be avoided, as seen during this case study when specific data collection was missed, particularly weather sampling records, due to plant operators not adhering to the researcher's requests to collect the data continuously. It can be concluded that the performance of these site AWGs was optimal as they could start and stop as per the sensors incorporated within them to detect atmospheric conditions. The only time information was missed was when these instruments were not triggered due to the necessary calibration and cleaning maintenance. Furthermore, additional equipment such as hygrometers and weather forecasts provides prompt operational analysis assistance to the generator owner to assess if the operations remained optimal when the correlations or deviations would be evident.

#### **5.4 Conclusion relating to Objective 4: Evaluate the Acceptability of AW by the Community**

As described in Chapter 4, Section 4.4, the community was consulted to evaluate AW's acceptability and determine the impact on alleviating water challenges. This was guided by the writing of Das Gupta (2011). Ronald Fisher's ethics governance and randomization principles were applied to ensure the survey's quality outcomes. The questions prepared for the survey are described In Section 4.4. The researcher set out to identify how people were likely to embrace or reject the new AWH technology as a source of drinking water of

choice or as an alternative source during municipal water supply downtimes or natural disasters.

The survey found that at least 66.6% of participants in each of the six age groups favoured an alternative source of water, which in the case of the study was AWH (see Figure 4-38). The responses to questions 7 and 9 (Section 4.4 of Chapter 4) proved to be central in assessing the community's acceptance of the new technology as a source of drinking water. The most positive response was on the issue of water quality (question 9), which was rated higher than the cost of paying for the water (question 7). These results illustrated that people were concerned more about their health and the impact of drinking water on their lives than about the cost of buying water. The average selling price of municipal water was R16 per kL at the time of this research, and the selling price of AW was about twice as much. People appeared to value quality over cost.

It is therefore concluded that communities will accept AWH as an alternative source of drinking water, or even water of choice, as it meets all the quality requirements even though it is more costly than the usual potable water. AWH costing can be minimised when the generation process is coupled with solar energy. Most of the costs came from the cost of electricity.

## **5.5 Conclusion Relating to Objective 5: Evaluating the Cost-Effectiveness of Atmospheric Water Harvesting (AWH) Compared to Conventional Methods**

AWH is considered cost-effective regarding infrastructure, particularly for decentralised applications or regions with favourable atmospheric conditions because water productivity would be guaranteed throughout all seasons. Cerro (2018) refers to AWH technology as "Urban Acupuncture", which defines a small-scale solution created to produce large-scale social change. AWGs can be as small as 500 L a day and can easily be scaled up to meet any demand without major infrastructure requirements. The narrative of acupuncture has been analysed as a solution that can provide small-scale relief to the already overburdened clean water supply networks and bring about huge alleviation for humanity, particularly where funding is a limitation and agile solutions are desperately needed.

Table 5-1 was formulated to assess the cost-effectiveness of AWH compared to municipal water supply. Most importantly, energy consumption was calculated to validate the economic model. Ahmad *et al.* (2022) found that the electrical energy consumption of the

AWG would be calculated as the energy consumed by the AWG to produce 1 L of drinking water.

**Table 5.1: Overall economic analysis overview for AWH and Municipal Water.**

Source	AWH	Municipal Water
Treatment/Operations	No chemicals for operations. Only scheduled cleaning is required for control of septicity as and when required.	Pretreatment chemicals and filtration requirements. Additional cleaning chemicals required.
Environmental Impact	None	Sludge byproduct.
Design	Erected anywhere as per the climate classification tools, requires generators, filtration as per atmospheric quality conditions, and final holding tank.	Requires water source and water plant equipment.
Quality	Turbidity: average 0.6 NTU Conductivity: average 6.5 mS/m Total Dissolved Solids: average 1mg/L No chlorine	Turbidity: average 1.2 NTU Conductivity: average 21.5 mS/m Total Dissolved Solids: Chlorine presence
Electricity Costs	R25/kL	R2/kL
Cost of Production	R0	R7/kL
Cost of Sales	R19/kL	R12/kL

\*all municipal information obtained from Magalies Water Board in July 2023.

\*quality municipal results obtained from (Spies, 2023).

The following was the energy consumption per AWG machine on site:

Energy= 105kW/hr

Industrial Power Utility Electrical Charge (cost)= R50.06 per hour (at peak hours: Eskom Tariff Booklet, 2020/2021)

Industrial Energy Consumption per day per AWG = R109.09 × 24 hours  
= R1 201.44 per day  
= R37 244.64 per month per AWG

AWG produced approximately 2000 L per hour.

The national electricity utility, Eskom, applies a stepped tariff system for power users, where higher electricity consumption results in increased rates per kilowatt-hour. During the study period, the atmospheric water generation (AWG) units recorded higher energy usage in the spring and summer months due to favourable meteorological conditions that enhanced water production. A total of 585,818 litres of water was harvested during the active fieldwork phase, while only 2,070 litres were collected over a four-month period spanning the autumn and winter seasons.

This observation suggests that in high-altitude, semi-arid regions, AWGs consume more energy during warmer seasons, while in low-altitude, coastal, and humid areas, energy demand is likely to remain consistently high throughout the year, as the units can operate at full capacity year-round.

The cost-effectiveness of deploying AWG systems should be established during the feasibility study phase. This involves evaluating water production output relative to potential profit margins, after deducting operational costs—particularly energy consumption. A suitable financial performance indicator for this is the Net Profit Margin (NPM), calculated as follows:

$$NPM = \frac{(R - CGS - OPE - OTE - I - TR)}{R} \times 100 \quad \text{Equation 7}$$

Where:

**NPM** = Net Profit Margin of the operations

**R** = Revenue generated (monthly or annually)

**CGS** = Cost of Goods Sold (water)

**OPE** = Operating Expenses (e.g., maintenance, technology, human resources)

**OTE** = Other Expenses (e.g., office supplies, administrative costs)

**I** = Interest on capital or operational costs

**TR** = Tax-related deductions or liabilities

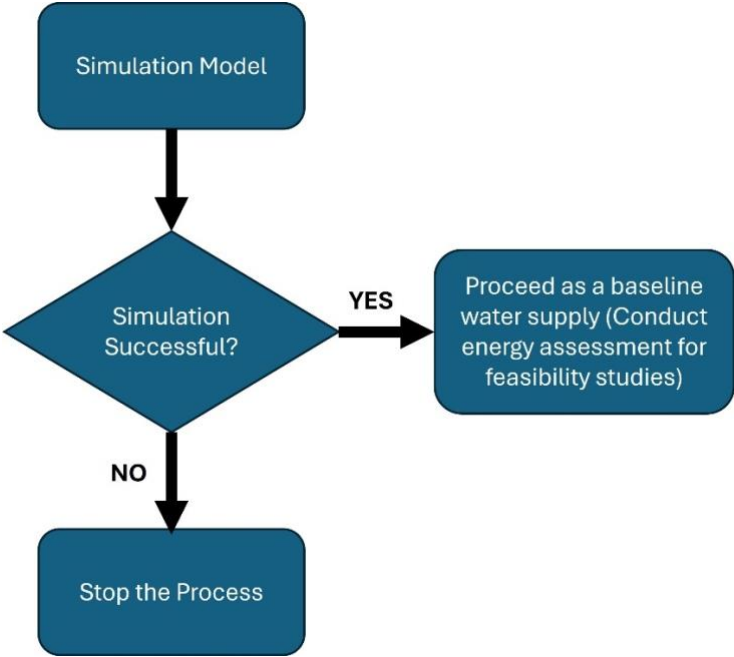
Finally, the research reported in this dissertation continued the work of Thisani (2018), as described below:

- Thisani (2018) assessed AWGs mechanically to determine which generator design performed best with regard to its vapour compression cycle to harvest water from the atmosphere. The study aimed to explore alternative water sources for rural areas in KwaZulu-Natal (KZN). Though the purpose was similar, Thisani's study did not explore the parameters influencing the success of AWH based on meteorological limitations such as altitude, ambient temperature, relative humidity and wind speed, even though the region's climatic conditions favoured the study due to easterly coastal KZN location, hence the success of the designed AWG. Tomaszewicz *et al.* (2015) emphasised that the success in such regions was due to the large diurnal temperature differentials with high atmospheric moisture content from the ocean's wind circulation.
- The KZN project did not consider seasonal variations, including how the AWG would perform through different seasons, and whether its performance would still guarantee water production to meet the expectations of the rural community and potential investors.
- Thisani's research did not evaluate the range of the water quality from the AWG. However, it briefly mentioned that the water produced had conformed to the South African Drinking Water Standard (SABS, 2015).
- None of the operational costs were shared with the community to establish the feasibility of such a water supply and if the community could afford such a water generator continually supplying them with water

## **5.6 The Concluding Success Story of the Dissertation**

The case study managed to answer all the objectives set at the commencement of the research whilst breaking new ground in South Africa for the country to be better prepared

for climate change and to be resilient regarding drinking water availability. The study simulated a model catering for all water users, including communities and businesses. It provides them with the power of choice. In turn, they are provided with knowledge of the technology that may or may not be efficient in any location of choice. Figure 5-1 provides a roadmap illustration of a guide upon using the simulation.



**Figure 5.1: Roadmap illustration for using the productivity simulation.**

The case study closed the loop of AWH as practical research was available in South Africa for the East and West of the country based on AWG and fog harvesting, respectively. The case study provides practical information based on an inland study.

The community engagement conducted as part of the case study provides a model for water authorities and investors for community involvement in alternative drinking water solutions, particularly regarding water tariffs. The data illustrates that AWGs for “in-land” South Africa can be used successfully during spring and summer as defined by the Köppen-Geiger climatic classification tool. The ideas developed in this research study can be extrapolated to test the success or failure of the technology when AWGs are placed in any other region with any climatic condition.

A fact of note in the case study was that the generators were designed for 5000 L per day maximum capacity. However, the maximum capacity was never achieved due to the limitation of the region's meteorological conditions. Additionally, during the warm summer season, hot wind blows from the South-East and North-East, so there is more humidity from October to March, resulting in rain in this region. During cold seasons, air blows from one direction, southeast, hence the drop in humidity from April to July.

## CHAPTER 6: RECOMMENDATIONS

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Due to changing climatic conditions globally, freshwater availability and inadequate treatment processes, particularly in developing countries, continue to pressure humanity. It is, therefore, necessary to explore new drinking water solutions to ensure a fulfilling existence for future generations. The outcome of this study has proven, in addition to previous global research about AWH technology, that it can be employed as an alternative and or primary source of drinking water, including during natural disasters and or downtime of available water supply systems. The two water supply systems can co-exist or be integrated such that when one is unavailable, the other can “kick in” automatically. The following are recommendations based on the learnings experienced during this research study:

- 6.1 AWH has proven a successful technology for water stakeholders and investors to consider as an alternative source to the currently available water supply or a co-existing solution to add to the water supply mix. It is recommended that interested parties utilise pointers shared in this research to identify viable sites for harvesting water from the air to avoid operating such systems at a loss, as observed with the underperformance and under-utilisation of 10 000 L capacity AWGs. The site AWGs only achieved their highest productivity of 6999 L in one month of the humid peak season in the entire year due to the meteorological and climatic conditions.
- 6.2 It is recommended that data obtained from this study be used to test the performance of AWGs in other regions as part of feasibility studies to assess the success of the investment prior to execution in support of point 6.1 above. The simulation can accommodate all altitudes using a similar methodology incorporating temperatures and relative humidity in forecasting models for atmospheric water harvesting. This can be tested under varying weather conditions as long as the required combination of these parameters can be optimised to produce drinking water from the atmosphere using AWGs at different locations.
- 6.3 It is recommended that automated water analysers be installed with AWH to ensure a 24-hour quality assurance for the operations to prevent challenges of human errors experienced during the case study, as mentioned in Section 5.1. As

such, any operations may create credible standards for themselves, which would be positive for the business or the intent.

- 6.4 Similarly, it is recommended that these automated water analysers and control instruments be calibrated according to the manufacturer's set maintenance regime to avoid unplanned production downtimes narrated in section 4.2.
- 6.5 Different AWGs consume different amounts of energy based on their design capacity and ambient climatic conditions. Future research is recommended to ensure that energy usage from AWGs is gauged and measured separately from all other elements consuming energy from the same facility so that a compelling energy model for AWH investments for communities and business investment may be established, particularly in South Africa. The manufacturer rated the case study AWGs at **105 kW/hr** maximum usage whilst the power utility charged the site business **R50.06/hr**. This is costly compared to the municipal drinking water rates even though AWH has environmental, infrastructure and quality benefits, providing more support for the technology. It is recommended that solar energy be explored to assess energy savings coupled with AWH technology, as suggested by Kim *et al.* (2017). Lin and Hubbard (2004) state that environmental radiance measurements developed with TMY data would be crucial for solar panel selection studies to reduce the vapour compression energy consumption of AWGs. It is evident from the literature that energy usage costs could be kept extremely low because the source would be the sun. There would eventually be a return on investment (ROI) for solar panels.
- 6.6 It is recommended that an efficient mechanical maintenance strategy regime be followed for AWG operations, either provided by the OEM or from lessons learned in this dissertation from the start and throughout the life of the plant, to avoid challenges resulting from deviations in parameters as observed from this case study. This happened when AWGs were no longer triggered to start and stop automatically as per their design set points due to mechanical defects resulting in them being out of range. Consequently, major production windows were missed, particularly at the start of spring when these defects occurred, and the loss of production resulted in a loss of revenue.
- 6.7 It is recommended that quality maintenance, including disinfecting and cleaning in place (CIP), be executed for AWGs before the winter season, every time the plant was inactive for more than three days and during the high production season. It was observed from the harvested water quality parameters that Total Coliform

Bacteria (TCB) was detected, as described in Section 4.3. During a season of high productivity, the business wished to harvest as much water as possible in the time available. Such a quality maintenance regime is recommended to prevent the formation of any harmful bacteria and to prevent septicity. The detection methods have been described in the same section in Chapter 4.

- 6.8 It is recommended for future AWH studies in South Africa to explore a combination of adsorbents arranged in a mega array for adsorption-desorption blended with AWGs to assess the possibility of high absorptivity to achieve high water productivity similar to AWGs. Both adsorbents and AWGs in parallel with each other may be used to assess the water productivity from both.
- 6.9 It is recommended that accredited laboratory analysis be financially planned for in AWH budgets to ensure that all water harvested is adequately analysed to avoid missing data, as was reported in Section 4.3. TDS analysis within the study created challenges in ensuring the chemical quality of the water.

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## **APPENDICES**

### **Appendix 1: South African National Standards for Drinking Water (Africa, 2015).**

SOUTH AFRICAN NATIONAL STANDARD  
Drinking water ( SANS 241 :2015)

Parameter	Unit	Risk	Standard limit
pH at 25 ° C	pH Unit	Operational	≥ 5.0 - ≤ 9.7
Conductivity at 25 0 C	mS/m	Aesthetic	170
Turbidity	NTU	Operational	1
		Aesthetic	5
Free Chlorine	mg/L	Chronic Health	5
Colour	mg/L	Aesthetic	15
Calcium as Ca	mg/L	Aesthetic/Operational	150
Magnesium as Mg	mg/L	Aesthetic/Health	70
Sodium as Na	mg/L	Aesthetic	200
Potassium as K	mg/L	Operational / Health	50
Zinc as Zn	mg/L	Aesthetic	5
Chloride as Cl	mg/L	Aesthetic	300
Fluoride as F	mg/L	Chronic Health	1.5
Sulphate as SO <sub>4</sub> <sup>2-</sup>	mg/L	Acute Health Chemical	500
		Aesthetic	250
Total Dissolved Solids	mg/L	Aesthetic	1,200
Nitrate and Nitrite Nitrogen as N	mg/L	Acute Health Chemical	12
Ammonia Nitrogen as N	mg/L	Aesthetic	1.5
Iron as Fe	µg/L	Chronic Health	2,000
		Aesthetic	300
Manganese as Mn	µg/L	Chronic Health	400
		Aesthetic	100
Aluminium as Al	µg/L	Operational	300
Total Coliforms count	cfu/100mL	Operational	10
E.Coli (<1 taken as 0)	cfu/100mL	Acute Health Micro	0
Heterotrophic Plate Count	cfu/ mL	Operational	1,000
Cytopathogenic Viruses	cfu/10 L	Acute Health Micro	0
Cryptosporidium Species	cfu/10 L	Acute Health Micro	0
Gardia Species	cfu/10 L	Acute Health Micro	0
Chloroform	mg/L	Chronic Health	0.3
Bromodichloromethane	mg/L	Chronic Health	0.06
Dibromochloromethane	mg/L	Chronic Health	0.1
Bromoform	mg/L	Chronic Health	0.1
Combined Trihalomethanes	mg/L	Chronic Health	1
Phenols	µg/L	Aesthetic	10
Nitrate as N	mg/L	Acute Health Chemical	11
Nitrite as N	mg/L	Acute Health Chemical	0.9
Antimony as Sb	µg/L	Chronic Health	20
Arsenic as As	µg/L	Chronic Health	10
Cadmium as Cd	µg/L	Chronic Health	3
Chromium as Cr	µg/L	Chronic Health	50
Cobalt as Co	µg/L	Chronic Health	500
Copper as Cu	µg/L	Chronic Health	2,000
Lead as Pb	µg/L	Chronic Health	10
Mercury as Hg	µg/L	Chronic Health	6
Nickel as Ni	µg/L	Chronic Health	70
Selenium as Se	µg/L	Chronic Health	40
Vanadium as V	µg/L	Chronic Health	200
Cyanide	µg/L	Acute Health Chemical	200
Total Organic Carbon as C	mg/L	Chronic Health	10

**Appendix 2: Full anion and cation analysis of raw water sample post condensation from air.**



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T0391

**CERTIFICATE OF ANALYSES**

**GENERAL WATER QUALITY PARAMETERS**

Date received: 2020-06-26	Project number: 1000	Report number: 92594_02	Date completed: 2020-07-09	Order number:
Client name: <del>Aqua Air Africa</del>		Contact person: Ms. O. Majatladi		
Address: <del>101 Veale Street, Sandton, Johannesburg</del>		e-mail: <del>tsf@aquair.co.za</del>		
Telephone: <del>012 664 7200</del>		Facsimile:		Mobile: <del>084 822 4873</del>

Analyses in mg/l (Unless specified otherwise)	Method Identification	Risk	SANS 241 : 2015 Limits	Sample Identification
				Sample 6 24/06/2020
Sample Number				098016
Date/Time Sampled				N/A
pH - Value @ 25 °C	A WLAB065	Operational	≥5 to ≤ 9.7	6.3
Electrical Conductivity in mS/m @ 25°C	A WLAB002	Aesthetic	≤170	2.6
Total Dissolved Solids @ 180°C	A WLAB027	Aesthetic	≤1200	14
Colour in PtCo Units	N WLAB006	Aesthetic	≤15	3
Turbidity in N.T.U	A WLAB005	Operational/Aest	≤1 / ≤5	0.8
Total Alkalinity as CaCO <sub>3</sub>	A WLAB007	---	---	<5
Langlier Index at 25°C	A WLAB053	---	---	-4.3
Chloride as Cl	A WLAB046	Aesthetic	≤300	2
Sulphate as SO <sub>4</sub>	A WLAB046	Acute health/Aest	≤500 / ≤250	6
Fluoride as F	A WLAB014	Chronic health	≤1.5	<0.2
Nitrate as N	A WLAB046	Acute health	≤11	0.2
Nitrite as N	A WLAB046	Acute health	≤0.9	0.07
Combined Nitrate & Nitrite	A WLAB046	Acute health	≤1	0.1
Silica as SiO <sub>2</sub>	N WLAB046	---	---	0.4
Total Organic Carbon as C	N WLAB060	Chronic health	≤10	2.1
Free and Saline Ammonia as N	A WLAB046	Aesthetic	≤1.5	1.9
Sodium as Na	A WLAB015	Aesthetic	≤200	<1
Potassium as K	A WLAB015	---	---	<0.5
Calcium as Ca	A WLAB015	---	---	2
Magnesium as Mg	A WLAB015	---	---	<1
Aluminium as Al (µg/l)	A WLAB015	Operational	≤300	<100
Antimony as Sb (µg/l)	A WLAB050	Chronic health	≤20	1
Arsenic as As (µg/l)	A WLAB050	Chronic health	≤10	<1
Barium as Ba (µg/l)	A WLAB015	Chronic health	≤700	<25
Boron as B (µg/l)	A WLAB015	Chronic health	≤2400	<25
Cadmium as Cd (µg/l)	A WLAB015	Chronic health	≤3	<1
Total Chromium as Cr (µg/l)	A WLAB015	Chronic health	≤50	<25
Copper as Cu (µg/l)	A WLAB015	Chronic health	≤2000	45
Iron as Fe (µg/l)	A WLAB015	Chronic health/Aest	≤ 2000 / ≤300	<25

J. Ngobeza - Chemical Technical Signatory

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**CERTIFICATE OF ANALYSES**

**GENERAL WATER QUALITY PARAMETERS**

**Date received:** 2020-06-26 **Project number:** 1000 **Report number:** 92594\_02 **Date completed:** 2020-07-09 **Order number:**

**Client name:** ~~Aqua Air Africa~~ **Contact person:** ~~Ms. S. Majath~~  
**Address:** ~~101 Yeats Street, Brooklyn, FTA~~ **e-mail:** ~~jelele@aquair.co.za~~  
**Telephone:** ~~012 664 1204~~ **Facsimile:** **Mobile:** ~~064 999 4679~~

Analyses in mg/l (Unless specified otherwise)	Method Identification	Risk	SANS 241 : 2015 Limits	Sample Identification	
				Sample Number	Date/Time Sampled
				Sample 6 24/06/2020	
				098016	
				N/A	
Lead as Pb (µg/l)	A	WLAB015	Chronic health	≤10	<1
Manganese as Mn (µg/l)	A	WLAB015	Chronic health/Aest	≤ 400 / ≤100	32
Mercury as Hg (µg/l)	A	WLAB047	Chronic health	≤6	<1
Nickel as Ni (µg/l)	A	WLAB015	Chronic health	≤70	<25
Selenium as Se (µg/l)	A	WLAB050	Chronic health	≤40	<1
Uranium as U (µg/l)	A	WLAB050	Chronic health	≤ 30	<1
Zinc as Zn	A	WLAB015	Aesthetic	≤5	0.140
% Balancing	N	---	---	---	91.0

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Client name: ~~Aqua Air Africa~~

Address: ~~484 Veele Street, Brooklyn, DTA~~

Telephone: ~~012 004 1204~~

Facsimile:

Contact person: ~~Ms. S. Majatadi~~

e-mail: ~~tsisi@equinox.co.za~~

Mobile: ~~001 822 1070~~

Information regarding accredited analyses

Analysis	Method Identification	Reporting limit	Average Uncertainty
pH Value	WLAB001	0.6	21%
Electrical Conductivity	WLAB002	0.1 mS/m	7%
Total Alkalinity	WLAB007	5 mg/L	10%
Chemical Oxygen Demand	WLAB018	10 mg/L	16%
Sulphate	WLAB046	2 mg/L	14%
Free & Saline Ammonia	WLAB046	0.1 mg/L	14%
Nitrate	WLAB046	0.1 mg/L	6.2%
Nitrite	WLAB046	0.05 mg/L	10%
Ortho Phosphate	WLAB046	0.1 mg/L	26%
Chloride	WLAB046	2 mg/L	10%
Fluoride	WLAB014	0.2 mg/L	7%
Turbidity	WLAB005	0.1 NTU	8%
Sodium	WLAB015	2 mg/L	13%
Potassium	WLAB015	1.0 mg/L	7.3%
Calcium	WLAB015	2 mg/L	7.8%
Magnesium	WLAB015	2 mg/L	8.0%
Aluminium	WLAB015	0.100 mg/L	7.2%
Cadmium	WLAB015	0.003 mg/L	9.1%
Cobalt	WLAB015	0.025 mg/L	4.6%
Chromium	WLAB015	0.025 mg/L	6.8%
Copper	WLAB015	0.025 mg/L	36%
Iron	WLAB015	0.025 mg/L	3.8%
Manganese	WLAB015	0.025 mg/L	4.4%
Nickel	WLAB015	0.025 mg/L	14%
Lead	WLAB015	0.010 mg/L	7.7%
Zinc	WLAB015	0.025 mg/L	23%
Total Coliform Bacteria	WLAB021	0 CFU/100 mL	6.1%
E. coli	WLAB021	0 CFU/100 mL	23%

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Test	Unit	Results	Limit	Method
Heterotrophic Plate Count*	count/ml	5.1	<= 1 000	WIN 042

**NOTAS / NOTES:**

**Verslag goedgekeur deur / Report approved by:**

Courtney Johnson  
courtney.johnson@nviroteklabs.co.za  
TS: WIN 014, 041

**Verslag / Report**  
**Water**

Nviro Business Hub unit 6, Ou Wapad road, Ifafi, Hartbeespoort, 0260 | Tel: 012 252 7588 | www.nviroteklabs.co.za

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  - \*\* Results marked with \*\* are Subcontracted Tests and are not included in the Schedule of Accreditation for this laboratory.
  - < Where a result is reported as less than (<) a value, the result obtained is below the limit of detection for the specific analyte.
1. This test report shall not be reproduced except in full, without written approval of the laboratory. These results are only applicable to the tests performed on the sample as received.
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**Limit column: values are derived from the SANS 241-1:2015 standard and are provided in the absence of client specified limits.****Irrigation Classification** done according to US Agriculture Handbook 60 - Diagnosis and Improvement of Saline and Alkali Soils (Cert 2018-086).**SAR:** Due to the uncertainty of measurement for Calcium and Magnesium at very low levels, the SAR calculation will not be performed when the sum of Calcium and Magnesium is less than 0.5 mg/l. When evaluating this water sample for use on soil, the Sodium content should be considered carefully as Sodium in water at any level can negatively impact certain soils if Calcium and Magnesium is absent in the water source.**Total Hardness Classification:** Soft (0-17.1), Slightly Hard (17.1-60), Moderately Hard (60-120), Hard (120-180)

End of Report

Appendix 4: Case study psychrometric chart simulated for the period January 2020 to December 2020.

File:C:\Users\HumanDC\Desktop\Palesa\_graphs.EES 2020/08/27 02:09:18 PM Page 1  
EES Ver. 9.457: #1514: For use only by Mohamed Shaker, Ginza, Cairo, Egypt

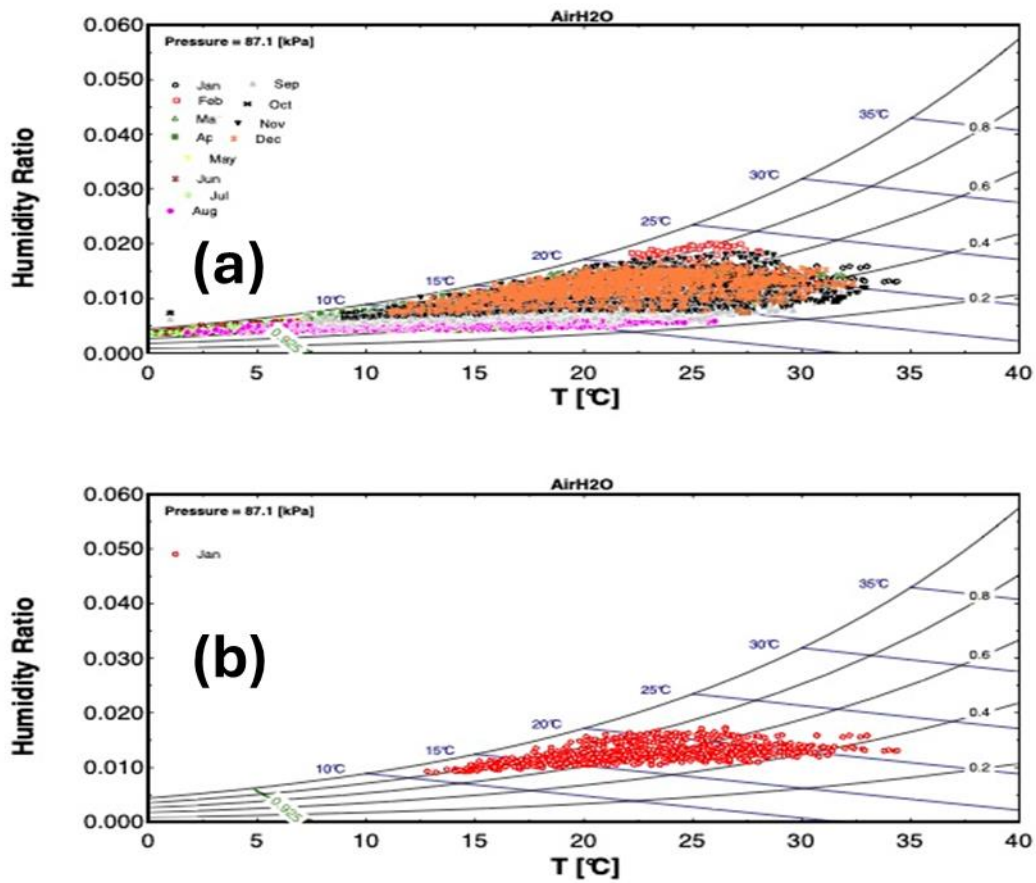


Figure A4.1: (a) Psychrometric chart simulated for the period January 2020 to December 2020 (b) Psychrometric Chart for January 2020

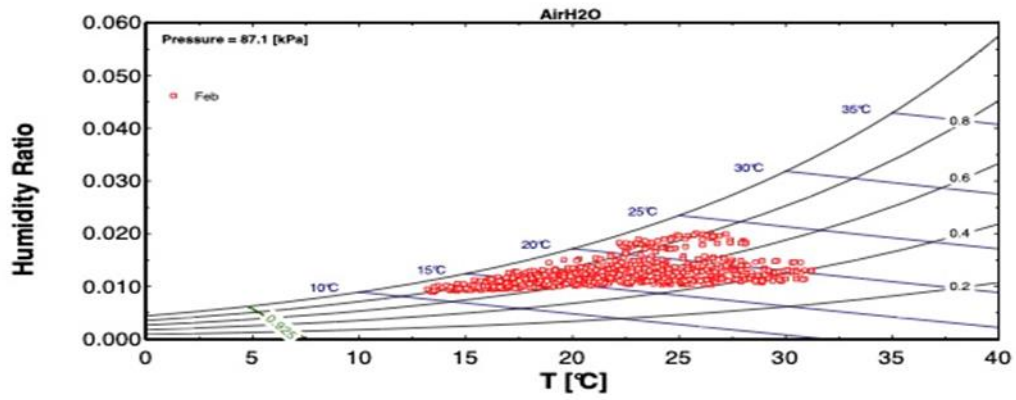


Figure A4.2: Psychrometric Chart for February 2020

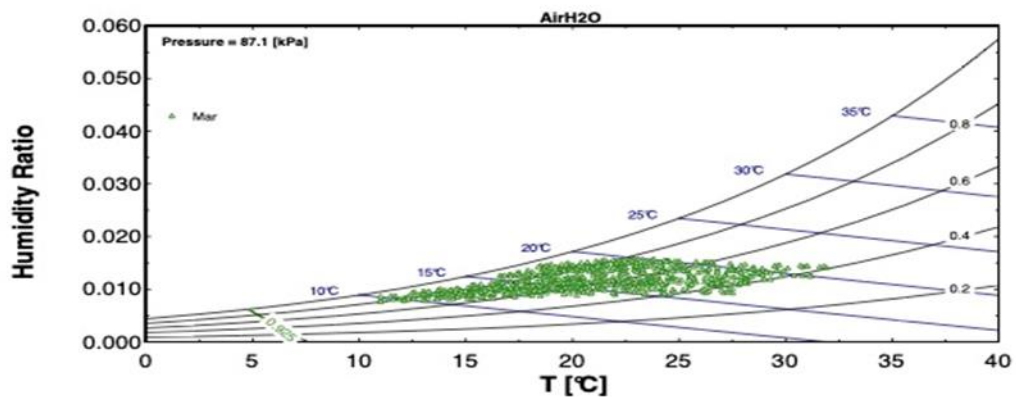


Figure A4.3: Psychrometric Chart for March 2020

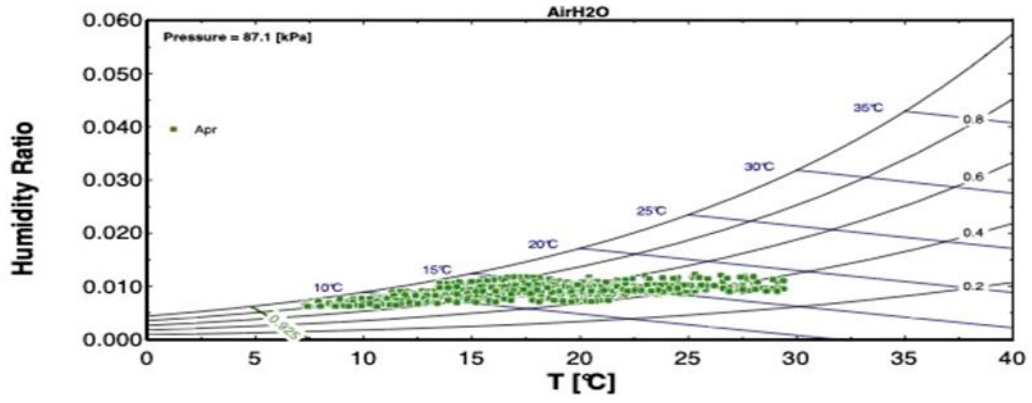


Figure A4.4: Psychrometric Chart for April 2020

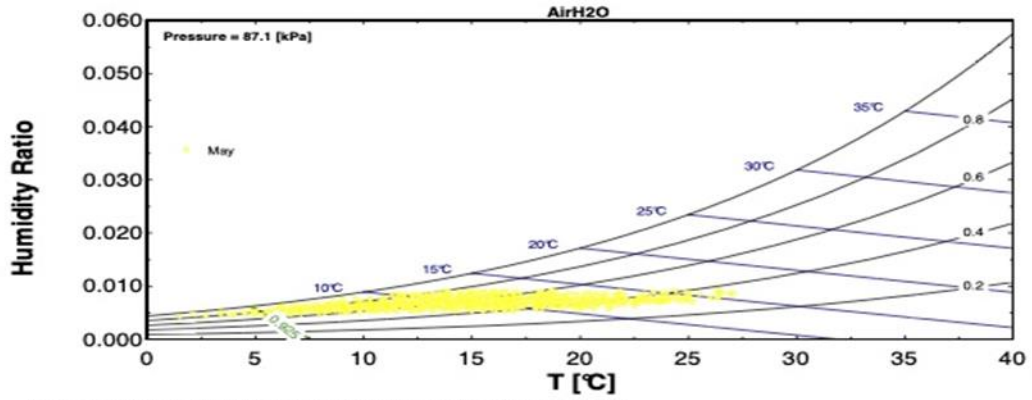


Figure A4.5: Psychrometric Chart for May 2020

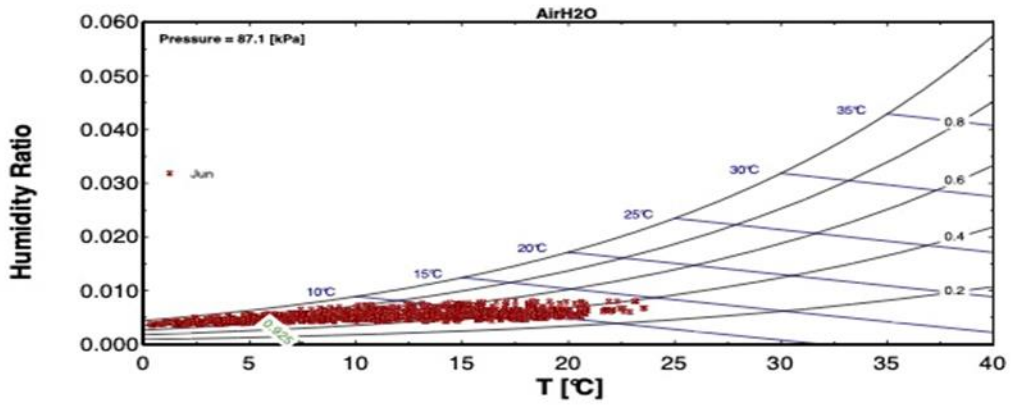


Figure A4.6: Psychrometric Chart for June 2020

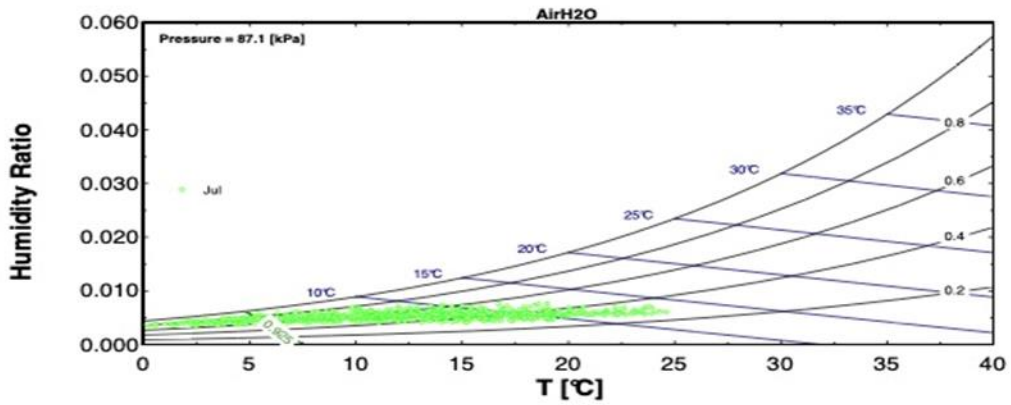


Figure A4.7: Psychrometric Chart for July 2020

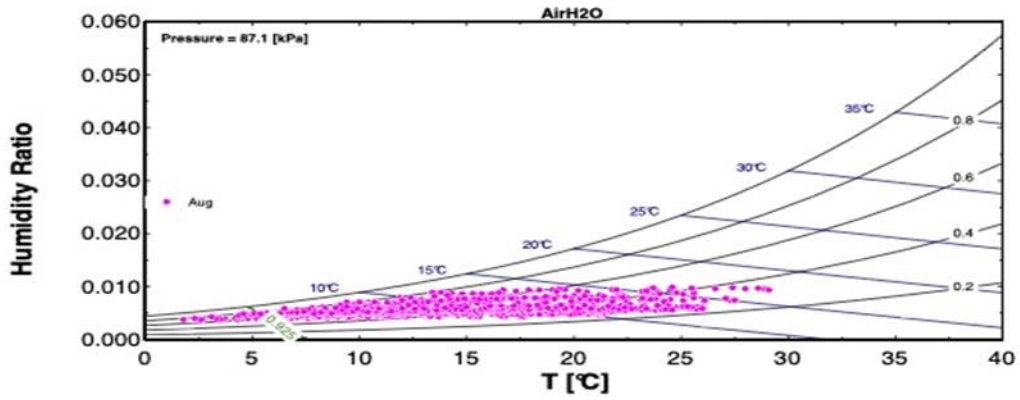


Figure A4.8: Psychrometric Chart for August 2020

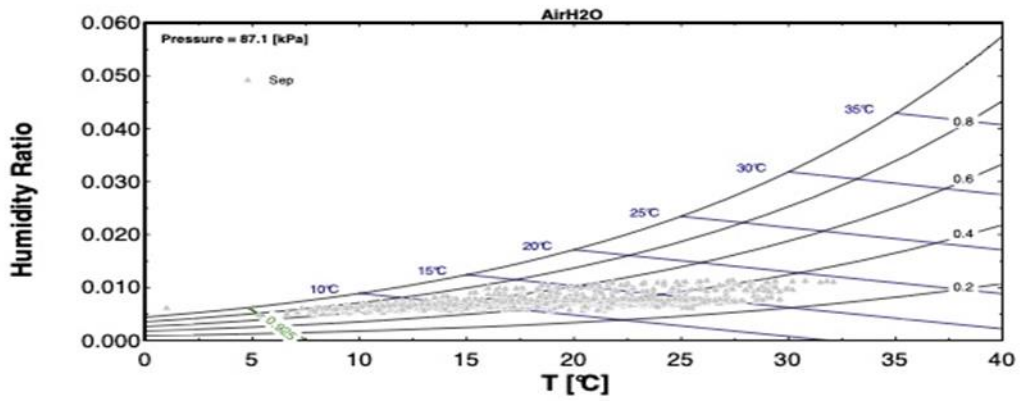


Figure A4.9: Psychrometric Chart for September 2020

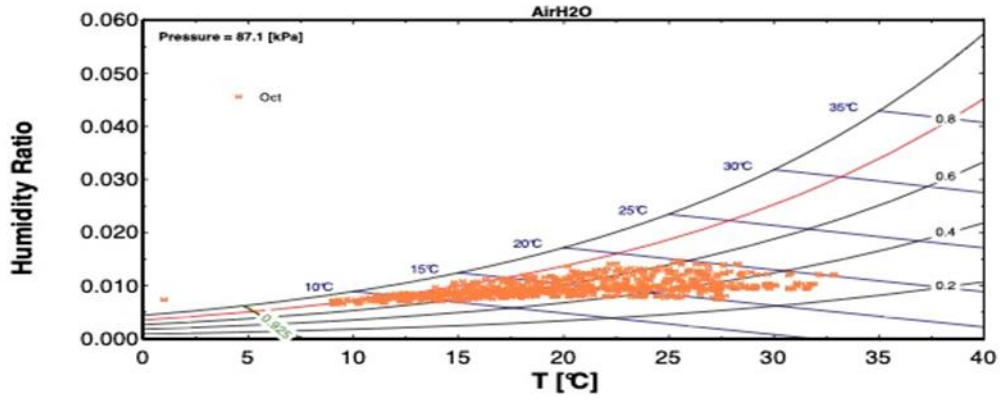


Figure A4.10: Psychrometric Chart for October 2020

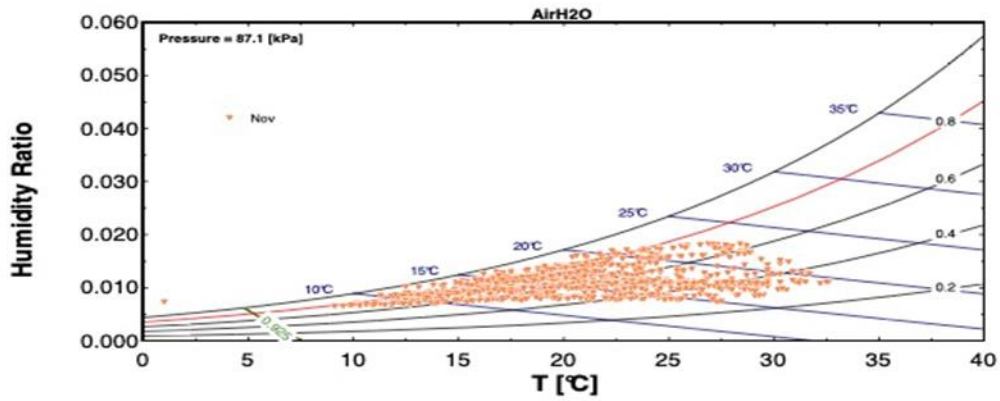


Figure A4.11: Psychrometric Chart for November 2020

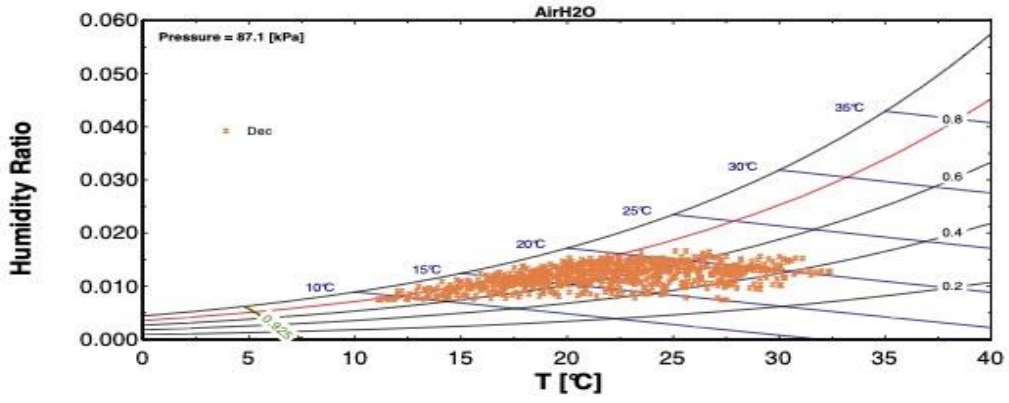


Figure A4.12: Psychrometric Chart for December 2020