FUTURE STRESS ON WATER QUALITY DUE TO CLIMATE CHANGE AND HUMAN RELATED ACTIVITIES IN THE OKAVANGO DELTA, BOTSWANA USING WEAP

A thesis submitted to the College of Science and Engineering, Flinders University in partial fulfilment of the requirement for the degree of Master's in Water Resources Management

By

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DECLARATION

I certify that this thesis does not incorporate without acknowledgement any material previously submitted for a degree or diploma in any university; and that to the best of my knowledge and belief, does not contain any material previously published or written by another person except where due reference is made in the text.

Signature: Segametsi Pholo Date: 22/10/2018

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ABBREVIATIONS

ANZECC- Australian and New Zealand Environment and Conservation Council

AWP- Australian Water Partnerships

BNWMPR- Botswana National Water Master Plan Review

BoBS- Botswana Bureau of Standards

CSO- Central Statistics Office

DWA- Department of Water Affairs

EAR- Environmental Assessment Report

EFA- Environmental Flow Assessment

EIA- Environmental Impact Assessment

GDP- Gross Domestic Product

GEF- Global Environmental Fund

IPCC- Intergovernmental Panel on Climate Change

MDB- Murray-Darling Basin

ODMP- Okavango Delta Management Plan

OKACOM- Okavango River Commission

ORASECOM- Orange-Senqu River Commission

ORI- Okavango Research Institute

RBOs- River Basin Organizations

SADC- Southern African Development Community

SB- Statistics Botswana

SIDA- Swedish International Development Cooperation

UN- United Nations

UNDP- United Nations Development Program

UNESCO-United Nations Educational, Scientific and Cultural Organization

USAID- United States Agency for International Development

WEAP- Water Evaluation and Planning

WHO- World Health Organization

WMO- World Meteorological Organization

WTTC- World Travel and Tourism Council

WUC- Water Utilities Corporation

ZAMCOM- Zambezi Watercourse Commission

ABSTRACT

Water is of immense value to all life on earth. The value of water is defined in its availability for irrigation, domestic, industrial, environmental flows as well as the benefits that the future generation will enjoy with the availability of water in the years to come. Healthy and unpolluted water systems drive the economy and important in alleviating poverty. Research has shown that the world surface temperatures are set to increase by 2℃ due to climate change. This increase in temperature will impact water availability as well as water quality. Freshwater ecosystems such as wetlands are expected to be impacted more through high evaporation rates and pollution. Similarly, human-induced factors in irrigation, urbanization and population growth are expected to put more pressure on the limited water resources. The effects of climate change will be severe in arid and semi-arid developing countries because of high evaporation rates and low precipitation that will cause repeated droughts. The UN reports that more than 2 million people reside in regions that are water stressed.

Botswana is one of the driest countries in Southern Africa and is home to the iconic Okavango Delta. The Okavango Delta is the world's largest inland delta that was listed under the UNESCO World Heritage site in 2014. The delta is formed when the Okavango River splits into different channels forming permanent swamps and islands over an area of about 12 000 square kilometres. The delta is popular tourist attraction site and sustains the communities that reside in the area through an endless supply of water, food and raw material. Just like all other regions, water in the Okavango Delta will be impacted by climate and human induced factors. To obtain an insight of the impacts of climate change and human activities on water quality in the Okavango River, WEAP was used to simulate future changes to water quality. Temperature, pH and EC for 2015 was used as the baseline data and 2030 was set as the target year. Although the catchment is relatively undeveloped, the planned construction of a hydro-power plant in Angola and a water carrier pipeline in Namibia, water flow in the Okavango catchment will decline and thereby impacting water quality. The results from the model indicate that water quality for temperature, EC and pH will be affected, especially pH levels at

the lower channels. Continuous monitoring and research is necessary to keep track of further water quality changes that may occur in the system so that timely decisions could be made to protect the vulnerable water resources of the Okavango River Basin.

1.0 INTRODUCTION

A healthy and unpolluted natural environment and ecosystem can sustain life and drive economic goals. Wetland ecosystems are of particular interest as they contribute an irreplaceable resources base that are fundamental to the alleviation of poverty and fueling of economic development (Finlayson, et al., 2015). With the global prevailing changes in climatic patterns, population growth and urban development, traditional water resources management in groundwater and surface water are no longer sufficient because of availability and quality issues (IWA, 2016). Since the industrial revolution, human activities have released large volumes of greenhouse gases into the atmosphere at a rate which the ocean waters cannot absorb resulting in sea level rise, frequent storms, prolonged drought periods, fluctuations in rainfall patterns and reduced agricultural productivity (Falkner, 2013). These changes impact hydrological processes which in turn affect stream flow patterns and water quality. Wetland ecosystems are likely to be impacted more especially in water stressed areas where there is irrigated agriculture and tourism activities (Pham, et al., 2017). Rivers are particularly important because they provide an endless supply of water to replenish and sustain freshwater ecosystems. There are over 200 river basins that support about 2.67 billion people but their carrying capacity has declined by 71% during the 20th century because of channel diversions and pollution (Matthews, 2016). Fresh water from river systems is of immense value to all life on earth with several socio-economic uses including sustenance of farming, maintenance of wetlands, community uses and industrial purposes. These values also include the benefits that future generations will continue to enjoy with the availability of water in the years to come.

Wetlands account for about 6% of the earth's land surface and are vulnerable to hydrological and ecological changes because of the impacts of climate change and anthropogenic activities (Milzow, et al., 2010). They regulate climate and serve as sinks for carbon and other nutrients. They provide nutrients to downstream tributaries, dilute polluted waters, recharge aquifers, provide an endless supply of fish and other plant food materials, while also providing revenue through tourism (Hamandawana & Chanda, 2010). To prepare for the future, water resources planners and managers need to intensify research to find new planning methods that consider the effects of climate change at regional and local levels for proper management and preservation of wetland systems. These sustained research efforts are crucial to understanding how different water demand areas could be affected and thereby develop appropriate strategies to control demand. Additionally, decisions on proper water allocation, development of emergency supply schemes during drought and flood events is based on understanding the dynamics of water resources including water quality in response to climate change and human interventions (Herrera-Pantoja & Hiscock, 2015).

In many regions of the world, water allocation is influenced by high-level decisions about how water is to be distributed and shared optimally among the competing demands in hydro-power generation, agriculture, industry, domestic supply as well as for replenishing ecosystems (Pohlner, et al., 2016). Authorities are aware of the impacts of climate change on water resources and therefore, it is up to water managers to review the current acts and policies and make them flexible enough to accommodate the envisaged water demand, the changes in water quality and the possibilities of unreliable water supply in the future (Herrera-Pantoja & Hiscock, 2015).

The challenges to water resources vary from one region to another. In some regions where water resources is limited, there are problems with its quality and it becomes unsafe for use. Rapid population growth, economic diversification, urban development and climate change put enormous pressure on the world's water resources as well as the ecosystems that surround them. These factors impact the water availability and quality, with potential global impact (Kumar, et al., 2018). Kumar et.al explained that water resources in India, Pakistan and Afghanistan started showing signs of degradation in the 1960's and have since reached stress levels in 2015 resulting in a challenge to the smooth delivery of food, energy and water for human and industrial consumption. The Kingdom of Bahrain is in a severe arid region and consequently, it is deemed a water stressed country (Al-Zubari, et al., 2018). Al-Zubari et al (2008) purports that although the country has invested more on modern infrastructural development for water supply services, the projected trends in population growth coupled with the impacts of climate change, freshwater accounts are feared to drop drastically in the next two decades. The forest climate change impacts will further exert more damage to the water resources and thereby giving water planners and managers an uneasy task of allocating the little resources that are available. In 2015, the United Nations adopted the Sustainable Development Goals to bring all countries on-board to address the issues of water security.

Of importance to this study is Goal 6 that points out that “access to safe water and sanitation and sound management of freshwater ecosystems are essential to human health and to environmental sustainability and economic prosperity” (UN, n.d.). The report further explains that more than 2 million people in the world reside in countries that are water stressed particularly in Northern Africa and Western Asia where over 60% of the population have inadequate fresh water. This is an indication of possible future water crisis. In many arid and semi-arid developing countries, the effects of climate change are severe on water resources as precipitation is lowered while at the same time, temperatures increase resulting in prolonged drought periods. Africa, Middle East, South Asia, Northern China, Mexico, North East Brazil and western South America have experienced severe drought periods that impacted the economies, ecosystem health, food and energy production in these regions (Herrera-Pantoja & Hiscock, 2015).

Botswana is one of the driest countries in Southern Africa. It is the same size as Kenya and France with a population of just over 2 million people on an area of 582 000 square kilometers (CSO, 2009). It shares borders with Zimbabwe, Zambia, Namibia and the Republic of South Africa. Since attaining independence in 1966, Botswana’s economy has been growing steadily and transformed from being an underdeveloped country to a middle-income country mainly from tourism, mining and beef export (NDP10, 2009). As a diamond-rich country, the mining and sale of diamonds has been the principal contributor to infrastructural development in terms of road networks, health care, communication as well as education facilities (DWA, 2013). A portion of the country’s revenue has been injected in infrastructural development to improve water reticulation and supply services to match supply and demand throughout the country. However, the move towards a supply-driven approach has shifted attention to water efficient use and conservation, deterioration of water quality and the overall increase in the total costs of water production and distribution. In line with the United Nations Millennium Development Goal 7, at least 97% of the population of Botswana had access to safe drinking water in 2013, a figure that was considered to be above the average 93% for the upper middle-income countries as well as being above the targeted figure for Sub-Saharan Africa (DWA, 2013).

The current infrastructural development as well as the effects of climate change are already having consequences on water resources as evidenced by the drying of water supply boreholes and increasing levels of pollutants in surface water resources (AllAfrica.com, 2015). The direct and indirect impacts of climate change show signs through hot temperatures that increase evaporation rates and ultimately drying of surface water resources. Prolonged and recurrent drought periods as a result of decreased rainfall are a threat to the already limited water resources. On the other hand, pollution remains a major challenge as polluted water resources are costly to maintain and as a result, some water-rich groundwater resources like the Ramotswa wellfield had to be abandoned due to elevated levels of nitrites pollution (Setlhogile, et al., 2016). With the already limited water resources, recurrent droughts and pollution, the country is often faced with acute water shortages especially in urban centers where most people reside. In the mid 1990's, there was severe drought throughout the country, which was further aggravated by high water demand. There was little rainfall and most surface water supplies had minimal or no flows resulting in the drying up of major water supply dams like Gaborone dam. This compelled water authorities to embark on massive water transfer schemes to transport water from areas where water was plenty to areas where the resource was in high demand. As a water demand management strategy, the government injected US$42 million in a project to install an underground water pipeline that runs over 400 kilometers from Letsibogo Dam to Gaborone to meet water demands in the capital city (INTEM, 2003). At the same time, water restrictions were imposed to contain the situation, but they were of little help. Although the Kingdom of Bahrain has the same geographical setting and limited water resources like Botswana, Bahrain has invested greatly on constructing desalination plants and the expansion of wastewater treatment facilities to improve per capita water accounts and currently, water supply stands at 100% while sanitation services are at 97% (Al-Zubari, et al., 2018). In Botswana, there is low uptake and re-use of wastewater. This is because most wastewater treatment facilities are not designed to treat wastewater to a re-usable state and consequently, wastewater is flushed into the environment and some of it end up causing pollution problems at the receiving waters (DWA, 2013). Large volumes of waste water are discharged into rivers and this increase pollution levels of the available water resources.

The Okavango River Basin is an importance water resource for the countries it traverses. Although in Angola the basin is less developed, there are minimal water withdrawals for domestic use and irrigation purposes, but the planned expansion of irrigation schemes and hydropower generation is likely to impact the downstream users in Namibia and Botswana (Hughes, et al., 2011). Hughes et al. (2012) further asserts that in Namibia, there are plans to expand the irrigation industry to improve food security, and to construct a pipeline that will transfer water to Windhoek. For Botswana, the main concern is to maintain the ecological integrity of the basin as it is an important source of tourism revenue (Andersson, et al., 2006; Kgathi, et al., 2006; Mbaiwa, 2003). With increased economic activities, improved livelihoods and the improved peace process in Angola after the civil wars, pressure on the natural resources in the Okavango River basin is expected to mount. Hence a coordinated approach to the management of the water resources among the countries sharing the basin is crucial for sustainability (Kgathi, et al., 2006). The issues surrounding the water resources of the Okavango River Basin has prompted this research investigation on the impacts of climate change and human related activities on water quality of the basin at the panhandle from Mohembo to Etsatsa villages.

1.1 Impacts of climate change on wetlands and water resources

The world's temperatures have increased by 0.85ºC during the last decade and this was followed by the repeated occurrence of extreme weather events such as flooding, prolonged droughts, severe hot and cold temperatures throughout all regions of the world (Mal, et al., 2018; NASA, 2018). NASA reveals that since 2010, five warmest years were recorded with 2016 been exceptionally warm across the twelve months. The long-term effects of climate change manifest themselves through rising sea-levels, modification of freshwater ecosystems, soil erosion and sediment deposition leading to pollution. Due to flooding, fertile soils have been eroded, leaving behind barren and unproductive soils which do not produce good yields leading to food shortages. Hot temperatures increase evaporation rates and thereby leading to the drying of surface water resources. Elevated temperatures predicted will not only increase evaporation rates from surface water resources but will also result in decreased global water stocks. Other impacts include the inability of water systems to transport pollutants and to dilute them as they move along the water ways. While some dry-land areas will experience severe water shortages, water-rich areas in the tropical regions will be required to take extra measures to capture, purify and utilize polluted water sources. In areas that usually experience flooding, groundwater tables are set to rise leading to damages to infrastructure and water logging in irrigated areas as was the case for the Murray-Darling Basin (AWP, 2016). Figure 1 below shows the increasing levels of accumulation of CO_2 concentration in the atmosphere since the industrial revolution.

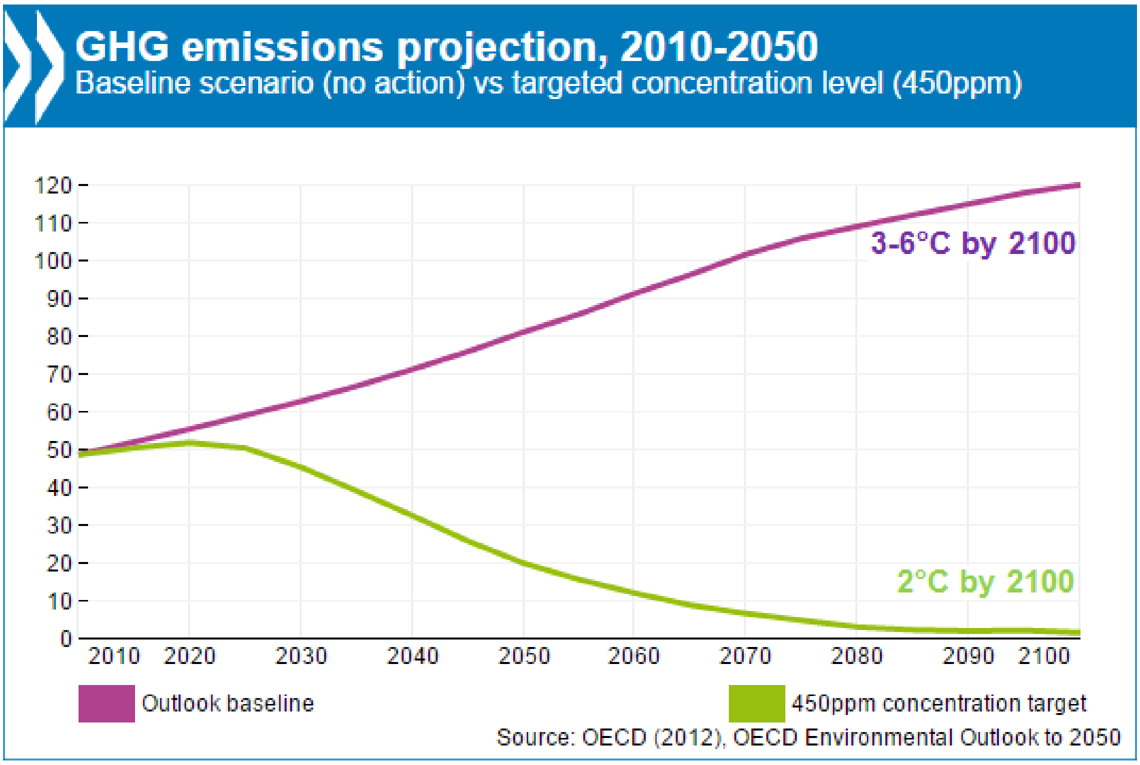

Figure 1: Global greenhouse gas emission projections, (EOCD, 2018)

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The IPCC report (2007) indicates that there is the good news as well as the sad news concerning the world's water resources. The report concludes that due to climate change, regions that usually get more rainfall may experience water shortages while flooding could be a problem in other areas. This phenomenon is supported by climate change projections that indicate that the amount of rainfall in the Murray Darling Basin in Australia will be lowered by 2% in the north and 5% in the south (Potter, Chiew and Frost, 2010). The Murray-Darling Basin is the largest basin in Australia that is shared among 3 states namely, New South Wales, South Australia and Victoria. It covers an area of approximately 1.06 million km² which is almost the size of the Republic of South Africa (Galeano, 2015). Galeano (2015) explains that the basin is the food basket of Australia that provides ¾ of water for irrigation and livestock farming across the 3 states that share the water resources. The basin is the main source of water supply to Australia and any changes in it leaves a significant impact on water supply as well as the ecology of the basin.

In 2015, world leaders met at the United Nations forum and adopted the 2030 agenda for Sustainable Development Goals and developed 17 targets that serve as guidelines to ensure people's lives are improved by 2030 target year. Of importance to this study is Goal 6 that is aimed to "ensure availability and sustainable management of water and sanitation for all" (UN, 2017). The report indicates that over 2 billion people in the world live in water stressed regions, with North America and Asia experiencing water stress levels above 60%. This is a sign that adverse future water scarcity is eminent. Individual countries have set their own targets that are aimed at preserving and restoring fresh water ecosystems. The European Union Water Framework Directive was developed to ensure there is sufficient water of acceptable quality for the people and the environment. Under the directive, all EU member states were required to achieve good ecological and acceptable surface water quality by 2015 (Molina-Navarro, et al., 2018). According to Molina-Navarro, the stipulated targets were not met and as a result, a new deadline was set to 2027.

Climate change knows no boundaries. Transboundary water resources are ecologically connected and thus, if one country becomes water stressed, the problems are transferred to another. There are several cross-boundary water resources in the world with which the countries that share the resources are governed by treaties and protocols to ensure equitable and sustainable allocation of water resources across boundaries and to avoid future conflicts over water. One such transboundary river is the Mekong River Basin that is shared among Vietnam, Thailand, China, Lao PDR, Cambodia and Myanmar. In response to increased demand in energy, large-scale hydro-power dams are being developed in the Mekong River Basin to meet energy demand and export surplus to neighboring countries for revenue collection. China is already ahead with the construction of a series of large hydropower projects in the upper Mekong while 11 are planned in the lower stream in Lao PDR, Thailand and Vietnam (Lee & Scurrah, 2009). Hydropower in the region is a major source of revenue and supply of renewable energy and as a result, a series of tributary and mainstream dams are either under construction, approved or planned in the lower stream while several other projects are on-going in the upper channels (Gerlark & Haefner, 2017). The dams pose threats to the ecological integrity of the basin and the local communities that depend on the river and its resources for their livelihoods. (Lee & Scurrah, 2009) Attest that the Mekong River Commission agreement was signed by Cambodia, Lao PDR, Thailand and Vietnam in 1995 to protect natural resources, preserve aquatic ecosystems and to maintain an ecological balance of the whole river system especially at the lower stream of the river. The commission recognizes that although the development of hydropower dams is crucial to the economies of the countries, other water users in fishing and tourism must be considered during allocations of the resource in the basin.

Similarly, within the Southern African Development Community (SADC) region, there are several river basin management organizations that serve as links between the different countries that share river basins. SADC, founded in 1992, is made up of 16 countries in Southern Africa including Seychelles. Under the SADC Protocol on Shared Watercourses, river basin organizations and shared river basin management plans have been developed to ensure regional cooperation for water resources. Most of Botswana's perennial surface water resources come from shared international water courses including the Okavango, Limpopo and Chobe River systems and these are subject to International Water Protocols (World Bank Group, 2014). Botswana shares 4 major rivers namely Limpopo, Zambezi, Okavango and Orange-Senqu Rivers with other countries and these rivers have river basin management plans that serve and govern them (DWA, 2013). DWA explains that the Zambezi Watercourse Commission (ZAMCOM) is the largest watercourse in terms of riparian states that share it and Zambia has the largest share of 40.7% while Namibia enjoys only 1.2% of the benefits of the river basin. The Orange-Senqu River Commission (ORASECOM) is an agreement between Botswana, Namibia, Lesotho and the Republic of South Africa for the Orange-Senqu River water resources that are shared among these bordering countries.

1.2 Human related impacts on water quality

The effects of humans on water resources is experienced in both developing and developed countries. Developed nations, such as Australia, have financial and human resources to restore damaged water resources. After the environmental damage to the Murray-Darling Basin in 2008, the government of Australia committed AUD13 Billion to fund initiatives that were geared towards improving the balance between environmental water and water for irrigation in the basin (AWP, 2016). This was achieved by funding irrigation schemes to switch from traditional methods to modern irrigation techniques that minimize water demand and loss and at the same time, all diversions of surface water resources were closed. This was a milestone achievement for the states that share the MDB. Unlike the developed world, developing nations allocate little to no funding for environmental restoration but rely on international donor organizations for funding. The Swedish International Development Cooperation (SIDA), United States Agency for International Development (USAID) and Global Environmental Fund (GEF) provide monetary support and technical expertise through RBOs to build adaptation ad resilience strategies to communities residing in shared watercourses (Blumstein, 2017). USAID and WMO have worked together to draw a strategy for a basin-wide flood forecasting and early warning systems in the Zambezi River Basin (Salman, 2004). Urbanization and related activities can impact water resources the same way as climate change does. Compaction of surface soil material and the removal of vegetation to pave way for buildings, roads and sidewalks alter the natural water pathways and hence water flow movements. During storm water runoff, running water may transport contaminants as well as contaminated material into surface water resources thus impacting water quality (Carlson et.al, 2011).

Rapid economic growth is associated with higher per capita income and a change from traditional to modern lifestyles. There is an increase in demand for manufactured goods and consequently, waste generated from these products has changed from biodegradable agricultural waste to non-biodegradable types in the form of packaging materials, hazardous waste, waste water and construction debris that end up in water channels thus causing pollution (Moleele & Ntsabane, 2002). In Denmark, water bodies showed high levels of nitrogen and phosphorus, primarily from intensive agricultural activities, and action had to be taken to lower the levels down by 43% (Molina-Navarro, et al., 2018). Forests are being cleared to pave way for developments, and when this happens, human settlements encroach on wetlands and reduce the overall space for water resources. The long-term impacts are felt on water resources as well as the economy of the country. Socio-economic pressures such as over-abstraction and pollution of surface water on the Okavango River Basin are expected to cause irreversible environmental damage that would lead to the loss of its local and international benefits (Kgathi, et al., 2006; Moleele & Ntsabane, 2002).

1.3 Problem statement

The projected demand for food and fresh water resources is expected to weigh heavily on wetlands leading to declines in biodiversity and the ecological ecosystems they support. The rate of damage to wetlands by humans and climate change is greater than the concerted efforts the international world is making to rehabilitate and restore them (Finlayson, et al., 2015). Despite the challenges to wetlands, clean water remains crucial for both human and animal life. Polluted water is the main source of some fatal diseases such as diarrhoea, malaria and typhoid fever. In most developing and less developed countries, many people have no access to safe drinking water as much of the water that is available is polluted largely because there are limited resources to purify it to usable state (IWA, 2016). Without adequate water supply of adequate and acceptable quality, public health and economic development remain at risk.

Increasing human exploitation and modification of the natural environment has degraded wetlands ecosystems and there is evidence of drying up of water channels, toxic pollutants continue to poison humans and fish causing endemic diseases and the overall environmental degradation is growing (Finlayson, et al., 2015). Water quality of the Okavango Delta is compromised by both climatic and human related activities. The delta shows signs of overgrazing, mostly from a large population of elephants that roam the area and pollution from agrochemicals and wastewater (Hamandawana & Chanda, 2010). Hamandawana and Chanda opined that the threats to surface water resources of the Okavango Delta are worsened by the planned construction of 7 hydropower plants and an undisclosed number of irrigation dams in Angola as well as the planned Eastern National Water Carrier project that will abstract some water in the river in Namibia. These projects will reduce the amount of water that flows through the system and the supply of silt and nutrients to downstream users. In addition to these threats, there is lack of agreement between Namibia, Zambia and Botswana on the amount of water that each state must abstract, which is particularly a problem for Botswana on the downstream end of the system (DWA, 2013). Rapid population growth, intensive agricultural activities, uncontrolled water withdrawals, eutrophication, algal blooms and the disappearance of seabed vegetation are matters of concern that need to be addressed to protect the waters of the Okavango Delta. Apart from pollution and other factors, invasive aquatic weeds are a problem in wetlands systems in Botswana. Salvinia is an aquatic weed that poses a threat at the lower Okavango Delta where the water is rich with nitrates and phosphate that is associated with eutrophication (Kurugundla, et al., 2016).

Although the government of Botswana regards pollution of water resources as a major threat, preventive measures on the ground are limited as evidenced by the lack of separation of waste from the source (Moleele & Ntsabane, 2002) and lack of capacity to enforce the polluter-pays-principle (DWA, 2013). The threats to surface waters of the Okavango Delta are pronounced but little research has been done to investigate the long-term impacts of human and natural factors on the overall functioning of the wetland. The limitations to these studies prompted this study to investigate the impacts of climate change and human activities on water quality of the Okavango Delta using the WEAP model. Information on water quality along the Okavango River is an important guide to water planning, management, monitoring and protection of water resources. Due to the large surface area that the delta covers, it is almost impossible to conserve it but there is need for proper management and constant monitoring of changes in the upstream channels as all the changes that occur impacts the downstream users (West, et al., 2015).

Unlike Australia, Botswana is a developing country that still lacks resources to reverse the impacts of environmental damage especially to water resources. Australia is proactive on matters that concern the environment as evidenced by the billions of dollars that was injected for the restoration of the MDB to a state that the basin is in today. Additionally, the laws such as Water Act of 1968 are outdated and need reviewing if they are aimed at protecting Botswana's vulnerable water resources. The Waste Management Act does not have capacity to enforce the polluter-pays-principle and as a result, it is only fair to protect Botswana's water resources through constant research. Information on water quality and water use along the Okavango Delta is an important component of water resources management and planning.

1.4 Research objectives

As previously highlighted, climate change and human related activities are expected to impact the availability and the quality of the world's water resources. The primary objective of this study is to predict how climate change and human-related activities will influence the changes in water quality for pH, EC and temperature of the Okavango Delta panhandle in 2030 using the WEAP model. This study forms the basis to the understanding of whether the overall ecological integrity of the Okavango River Basin system will be affected. The results of this study are aimed at giving signals to water resources managers to either review the current laws and policies or to continue using them in preparation for the projected future changes in water quality.

2.0 STUDY AREA

2.1 Description of the area

The Okavango River passes through riparian states of Angola and Namibia and after entering Botswana, it splits into numerous small tributaries forming a continuous swampy marsh. The river is formed by Cuito and Cubango as they join and pass through Namibia and Angola into Botswana to form Okavango River before spreading out to form an alluvial fan of the Okavango Delta. The delta covers an area of 5 537 400 ha and it is the world's largest Ramsar site with a numerous diverse complex habitat (West, et al., 2015). Sediment deposition in the delta is active at the panhandle and at the lower tributaries. Chemical processes occur on surface water due to evapotranspiration that occurs on surface water at the rate of 1580mm/year, a rate that is three times the rate of precipitation (Kgathi, et al., 2006). This results in the accumulation of pollutants on surface water as there is less water available for dilution. Figure 2 below is an illustration of the study area with reference to the position in Botswana and Africa.

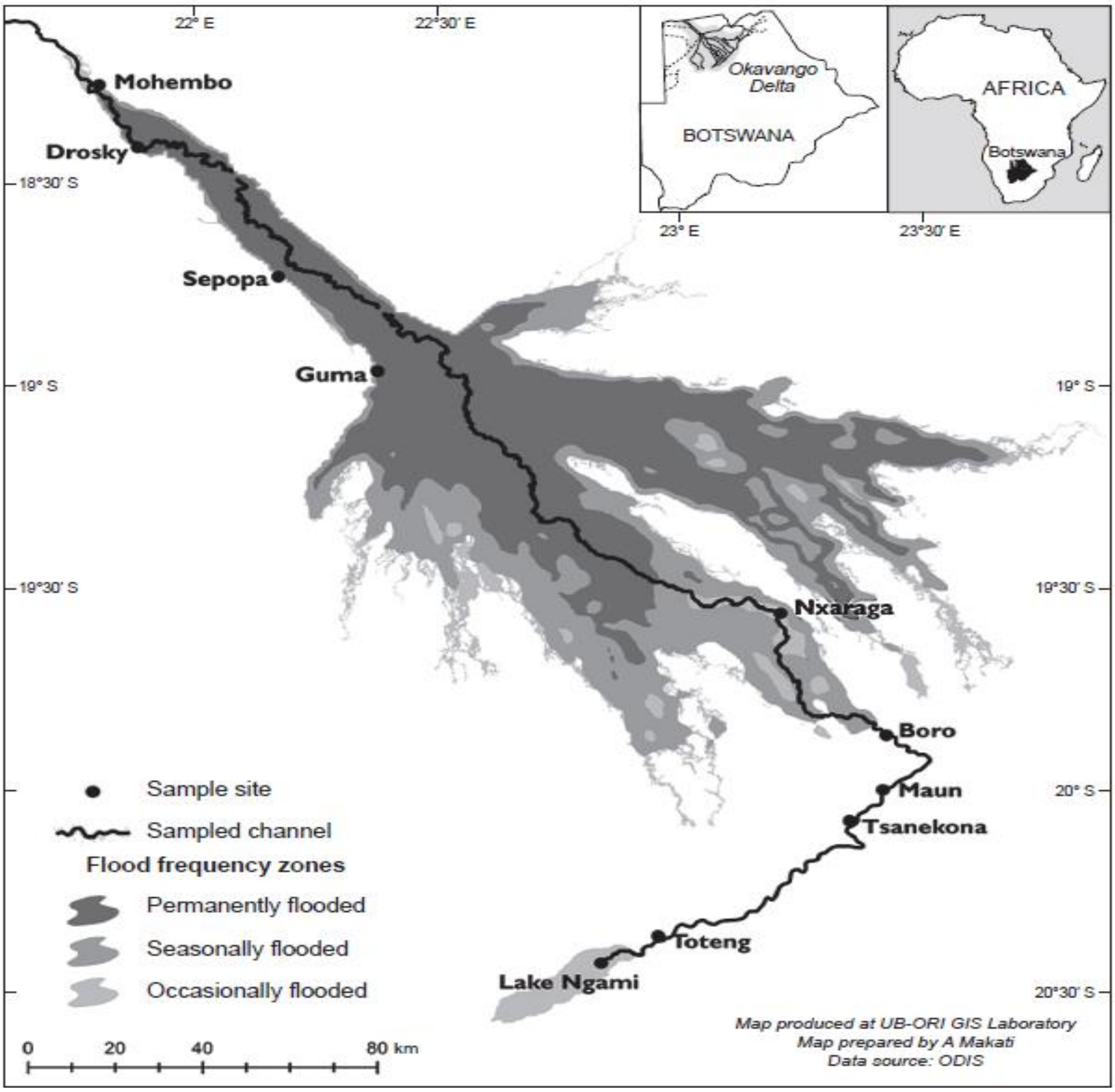

Figure 2: Map of the study area (Gondwe & Masamba, 2016).

2.2 Demography

The Okavango Delta is suited in Ngamiland District in north west Botswana. The district has 3 main population centres namely Maun, Gumare and Shakawe. The Okavango River basin supports fourteen major ethnic groups with diverse cultural beliefs, among them the marginalized San tribe who have never been to school, live below the poverty datum line and depend on the natural resources that are freely available in the area (Kgathi, et al., 2006). During the past years, human population has increased and so did the number of livestock in the area. Statistics indicate that the population of Ngamiland grew from 124,712 in 2001 to 164,104 people in 2011 (DWA, 2013). Of this total, the 2011 Population and Housing Census report indicates that 59 421 people reside in Ngamiland West Sub-District, an area where the study area falls in at the upper Okavango River panhandle (SB, 2015). The report projects that at an annual growth rate of 2.1%, the population in the sub-district is expected to increase to 75 116 in 2026. Using a 2.1% annual growth rate, a summary of the projected population trends is shown in figure 3 below. d

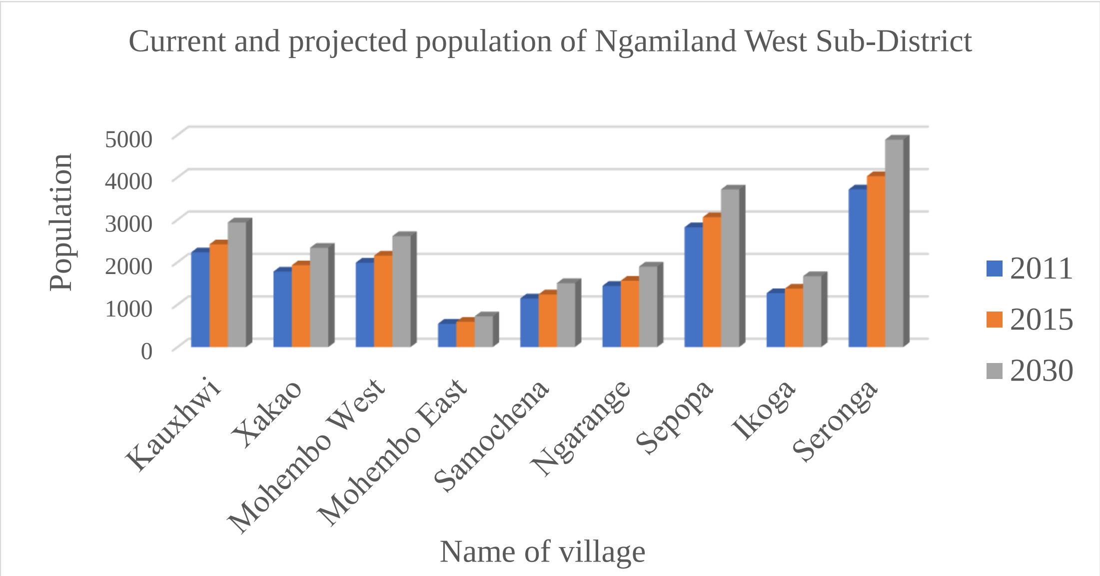

Figure 3: Current and projected population growth for Ngamiland West Sub-District.

2.3 Land use and distribution

There are 3 land tenure systems in Botswana. These are tribal, commonly known as communal land, state land that includes protected areas and forest reserves and lastly, the freehold land. A larger portion of the land in the study area falls under communal land. The Tawana Land Board Authority is the legal custodian of the land and is responsible for land allocation and management priorities in the study area in accordance with the laws of Botswana (ODMP, 2008). Although the Okavango Delta is a sensitive area, only a small portion of the system at Moremi Game Reserve falls under protected management areas. This is because the area around the delta is underdeveloped except for several lodges and campsites that target tourists that visit the area.

2.4 Economic activities

The economy of Botswana is heavily reliant on the country’s natural resources base in mining, agriculture and tourism. In 2010, the mining and tourism industry contributed 19.2 and 15.1% to the GDP respectively (SB, 2017). Statistics Botswana state that five years later in 2015, mining contributed 17.7% while tourism stood at 16.2% and the figures for tourism are expected to rise by 5.2% per annum between 2017 and 2027, with a total contribution of about USD2 941.3 million to the country’s GDP (WTTC, 2017).

The area around the Okavango Delta is relatively underdeveloped. Most people live below the poverty datum line and as a result, they depend on the basin’s freely available natural resources such for fishing, hunting and gathering and subsistence farming to sustain their livelihoods (Kgathi, et al., 2006). The delta provides surface water to human population and an abundant number of wildlife species that frequent the Okavango River for watering when small water pools within the area have dried up. Apart from being a source of water to the local community, the catchment derives its value from the diverse biodiversity and the income brought about by the tourism industry (Mbaiwa, 2003).

The delta is situated in the north-western part of Botswana in a less populated area except for a large variety of wildlife species and therefore, it is a pristine and undisturbed natural ecosystem. However, there are fears that the resettlement of communities that were displaced during the Angolan civil war during the period 1975-2002 may have impact on the total integrity of the system downstream on Botswana side (Wilk, et al., 2006). With the rate of recovery of the economy of Angola after the civil unrest, changes in land-use, deforestation and the use of fertilizers, the hydrology and water quality in the upstream channels is expected to change and therefore more research work must be done to investigate any possible changes that may occur (Milzow, et al., 2010). Milzow et al state that many farmers in the catchment area still use the traditional method of flood irrigation that is very water intensive and consequently, there are signs of a decrease in inflow of water at the upstream channels.

The Okavango Delta is the largest Ramsar Site that was added to the United Nations Educational, Scientific and Cultural Organization’s (UNESCO) list of World Heritage Sites in Doha in 2014 (West, et al., 2015). The listing of the delta as a heritage site means that it has attracted international attention, putting pressure on Botswana to closely monitor all activities in the system. In the past, the delta was used as a source of food, water and material for shelter and cooking. Over the years, there has been an increase in population, farming as well increased interest in the tourism industry and thereby impacting negatively on water resources in the area. It is estimated that the delta supports some 1,300 species of plants, 70 species of fishes, 30 species of amphibians, 65 species of reptiles, 445 species of birds and 120 species of mammals (Africa News Service, 2013). Water demand in the area is largely for small irrigation purposes.

2.5 Climate

Rainfall in Botswana varies between 650mm and 250mm in the north eastern and extreme south eastern part of Kgalagadi District including the study area (DWA, 2013). Rainfall distribution is highly variable and unpredictable over most parts of the country and climate change is expected to increase variability over time. Even though the country is classified as having a semi-arid climate, it can receive considerable amounts of rainfall during the wet periods between October and April. The study area is semi-arid with summer rainfalls that fall between November and March which (Hughes, et al., 2011) defines as a single wet season that has precipitation averages of 6mm/day. Since rainfall occurs in summer when the temperatures are at peak, most of the water does not penetrate the ground but it is immediately lost through evaporation and transpiration. The mean monthly temperatures range between 16ºC and 26ºC in June and October respectively (ODMP, 2008) with light easterly winds and occasional heat waves can raise the temperatures to over 42 ºC in some areas (Nkemelang, et al., 2018). The winter season, between May and August, it is extremely dry. During the winter season, during the day it is usually sunny and cool but nighttime temperatures can drop below the freezing point especially in areas in southeast of the country. The mornings in summer are humid with humidity ranges between 60 and 80% while the winter mornings are considerably less humid. Figure 4 shows the minimum, maximum and the mean monthly temperatures recorded in Shakawe in 2015.

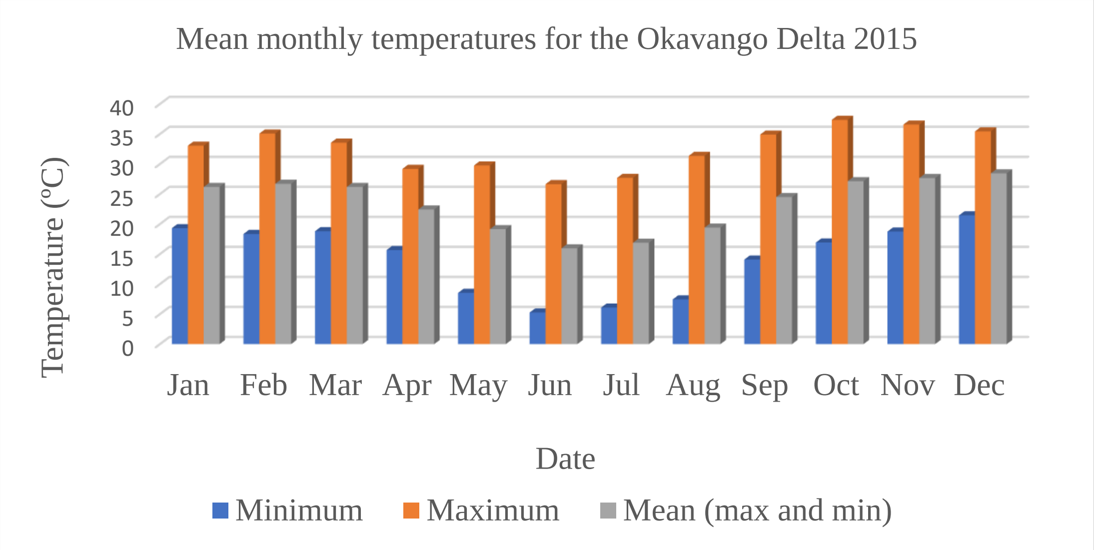

Figure 4: Monthly maximum, minimum and mean temperatures for Shakawe.

Figure 5 below is a graph of the daily rainfall amounts in Shakawe between 2014 and 2016. The graph shows low rainfall amounts recorded in the dry winter months between May and August. The wet season is stands out with high peaks in precipitation amounts as seen on the graph. The dry season is the longest and during this period, most months of the year have minimum or no precipitation at all.

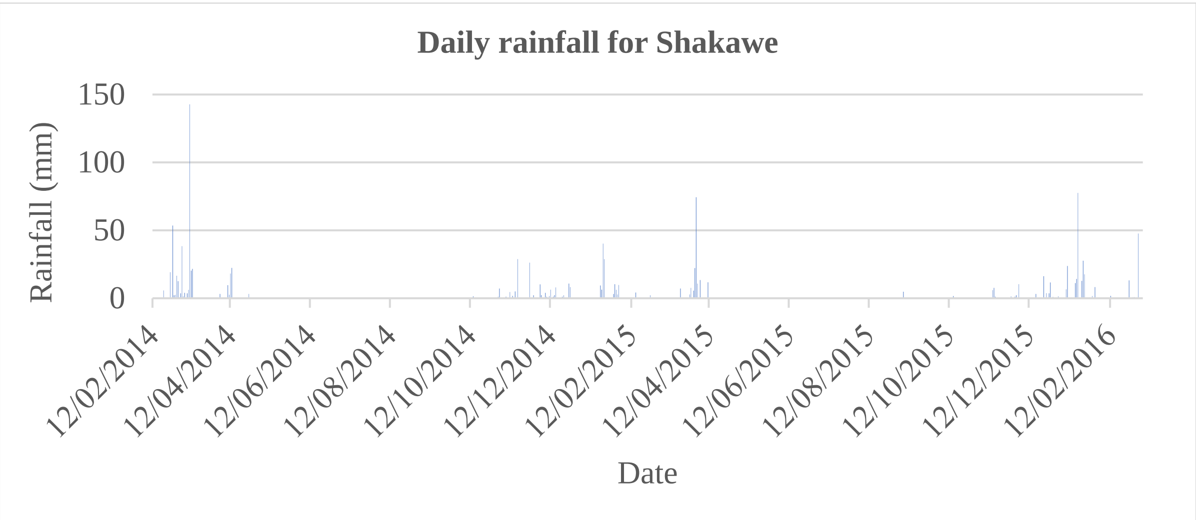

Figure 5: Recorded daily rainfall amounts for Shakawe between 2014 and 2015.

2.6 Water resources

2.6.1 Surface water resources

There are 2 perennial rivers in Botswana and these are Okavango and Chobe Rivers whose sources are outside the boundaries of the country. Surface water resources account for about 34% of water supplies (ODMP, 2008) and this figure includes 9 dams that have been developed in the country. The Okavango drainage basin covers an area of approximately 97 000 km² that is divide into the panhandle, permanent swamp, seasonal swamp and areas of drier sand-dominated islands (Hart, 1997; Ramberg, et al., 2006). At the panhandle, the main river channel is approximately 200 metres wide while at the delta inlet the other channels are between 20-30 metres wide (Wolski & Murray-Hudson, 2006). At the end of the panhandle, the Okavango River splits into Thaoge, Jao and Nqoga tributaries that share water from the main river and eventually leak the water to feed the permanent swamps within the system (McCarthy & Ellery, 1998). McCarthy and Ellery explain that because water is not confined to the channels, it flows through gentle slopes creating regions of sheet flooding. During periods of exceptional flooding, water from the Okavango River travels through the delta and eventually reach the lowest discharge points in Boteti River and Makgadikgadi pans where it is eventually lost through evaporation (McCarthy, et al., 2003).

There is no significant amount of water withdrawals from Okavango River as well as from the delta due to low population density and industrial development in the area. A larger portion of the water in the river is used by wildlife and for boat cruising to entertain the tourists that what to have the Okavango experience. The Botswana National Water Master Plan Report of 2006 indicates that there is a lot of potential for the use of water in the basin, but the use must be restricted to the villages at the panhandle such as Mohembo and Shakawe (DWA, 2013). Currently, there are no restrictions to the amount of river water withdrawals by the community living within the vicinity of the river channel.

2.6.2 Groundwater resources

Groundwater resources make 66% of the total water supply in Botswana. However, due to pollution of some high yielding aquifers, the resources are greatly reduced in terms of quantity and quality. The use of groundwater resources is declining as a result of high operation and maintenance costs, low yields, degraded water quality and some aquifers are located far away from demand areas (DWA, 2013; Setlhogile, et al., 2016). There is little demand for groundwater resources in the study area because the area is less developed has low population density. Additionally, there is an abundant supply of surface water from the Okavango River. At the lower areas of the delta, groundwater is not fully exploited because of high salinity levels in the shallow groundwater resources (Linn, et al., 2003). Since the study area is an area of permanent swamps, it has a shallow water table. Water level along the main river channel fluctuates by less than 0.2 metres while at the swamps the variations are 1.5 metres (Ellery, et al., 2003). Figure 6 below shows a summary of sources of drinking water supplies in Ngamiland Sub-District, a region where the study area is located.

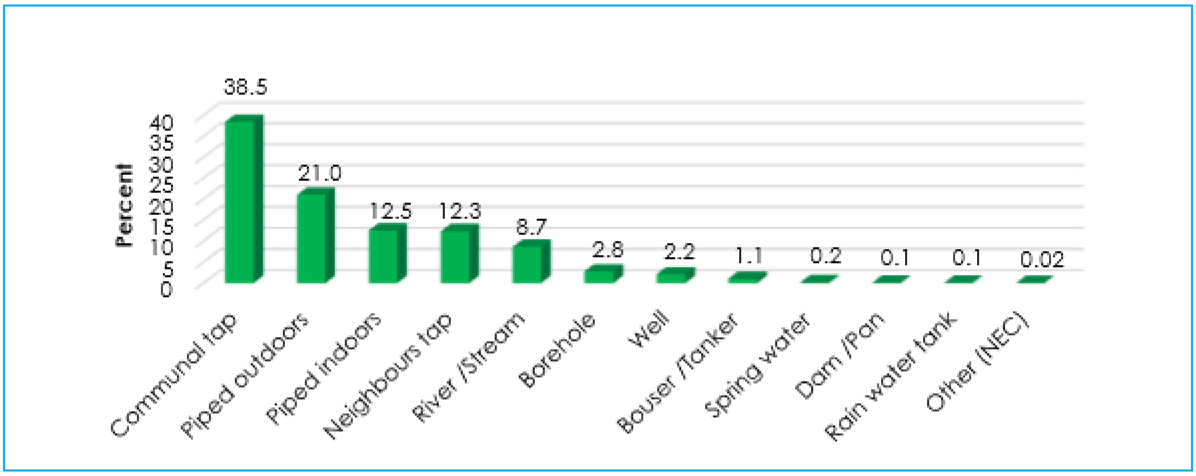

Figure 6: Sources of drinking water supplies in Ngamiland Sub-District (CSO, 2009).

2.7 Geology and hydrogeology

There is a possibility that the Congo Craton extends into Botswana in the north-western part and is overlain by a folded bed of sedimentary rocks (Key & Ayres, 2000). The geology of the area has been studied by (Bufford, et al., 2012) who suggest that the Okavango Rift Zone lies between the Congo Crafton at the northwest and the Kalahari Craton at the east of southeast end. Key and Ayres explain that Craton has some ferruginous quartzites that are exposed and visible at Shakawe as well as some remnants of weakly metamorphosed sili-clastic rocks and fine-grained marbles that extend up to Nxau-xau Valley. Although the age of the Okavango Rift Zone remains unknown, Bufford et.al state that the paleo-environmental modelling of the Ngami sub-basin sediments show that the current direction of the river channels of the Okavango and Kwando flowed to the southeast into the Makgadikgadi pans. The Okavango Delta lies on an area consisting of unconsolidated sediments with small fragments of calcrete and silcrete of the Kalahari Beds with a thickness of between 100m to the east of Thamalakane fault and 500 metres at the north-west of Kunyere fault (Linn, et al., 2003) as shown in figure 7 below. Kalahari Beds are characterized by fine sand, silt, clay sand and clay materials. Groundwater levels range between 1 and 10 metres near the river valleys while in other areas it is in the range 10 and 15 metres.

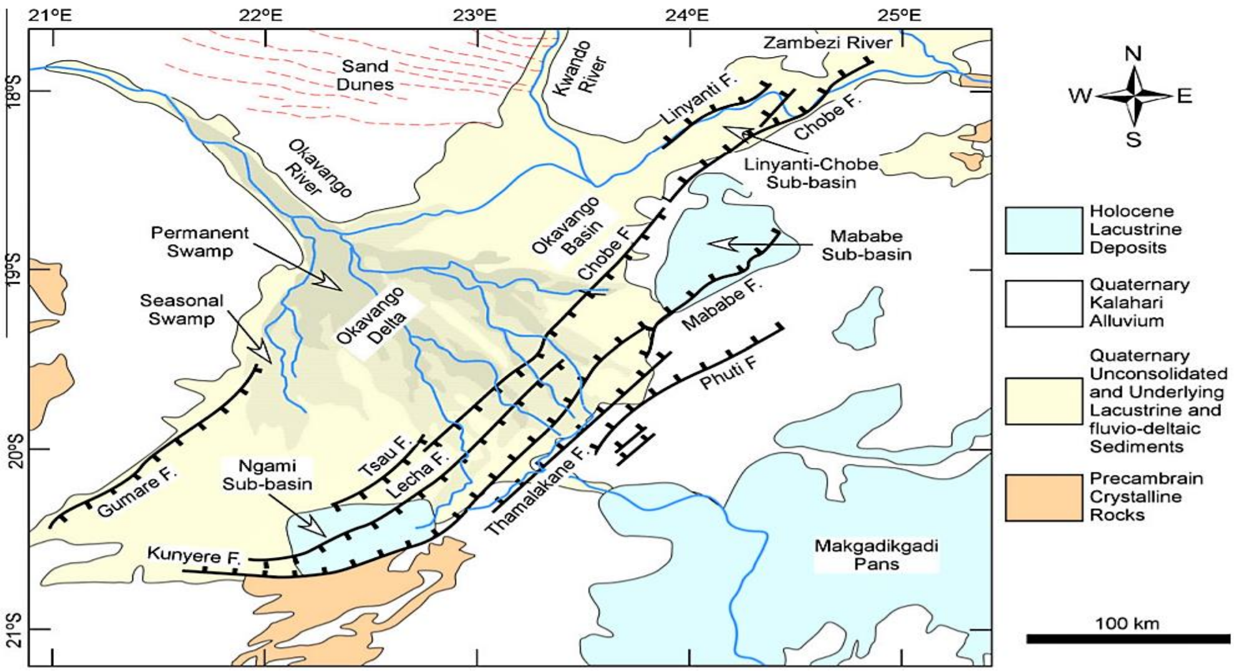

Figure 7: Surface geology and hydrology of the Okavango Delta (Bufford, et al., 2012)

3.0 LITERATURE REVIEW

This chapter is an analysis of the literature related to the concept of WEAP and the success stories behind the model across the globe. Additionally, the section considers the current laws, policies and protocols at national, regional and international level that related to the wetlands, and, the Okavango Delta. There have not been extensive investigations on the impacts of climate change and human interventions on the dynamics of wetlands in semi-arid and arid environments especially with regard to water quality (Milzow, et al., 2010) but some studies (Pantoja-Herrera & Hiscock, 2015; Murray-Hudson, et al., 2006) have been done to predict changes on the hydrological and hydro-ecological effects of climate change on water resources, not only on the Okavango Delta but other water systems that are similar to the wetland under study.

3.1 Current national laws and policies related to the study

3.1.1 Water Act, 1968

Under the Water Act of Botswana, the state owns all public water resources, but everyone has the right to use water for cooking, drinking and hygiene purposes. Although it is outdated, the act has not been reviewed and is still being used to date. The Okavango Delta exists because of the continuous flow of water from Angola and Namibia. The use and management of the water resources in the delta influences the overall balance of the system. The Water Act of Botswana was enacted in 1968 shortly after the country attained independence in 1966. The act was established to define and control the ownership of all rights to the use of water through the provision of water rights and the terms and conditions that govern them in Botswana (WaterAct, 1968).

An applicant of water rights is entitled to withdraw 22 750 litres of water per day at any public water source for personal or other uses that they had applied the water right for. However, the amount of withdrawals is unknown as the users have not installed water metres at their withdrawal points and at the same time, the issuing authority does not have capacity in terms of personnel and equipment to do ground-truthing of all activities to enforce compliance (DWA, 2013). Consequently, some water users withdraw more than the specified limits and thereby leading to over-abstractions and misuse of water. In addition, water quality issues are not fully addressed in the act. Before the 1998 Water Law in South Africa, water users were free to use water to the full advantage of their water requirements because there was no enforcement of the law on the ground (Levite, et al., 2003). Levite et. el explain that, currently, water users are required to register although they do not know how much they require and abstract due to lack of water metering and data collection. Uncontrolled water withdrawals coupled with high evaporation rates have an impact on the overall flow and water quality of surface water bodies.

The Water prohibits the privatization of any public water entitles the public to have equal access to public water for essential purposes in hygiene, cooking and drinking. Water rights holders have an obligation to protect the water resources and must not introduce any pollutants that may be detrimental to human, animal and plant life (CSO, 2009). When the act was implemented in 1968, the charge for pollution of public water resources was set at BWP 1,000.00 or USD 94.31 (WaterAct, 1968). Since the act has not been reviewed, the penalty is applicable today. Considering the magnitude of environmental damage some pollutants cause, and the challenges to water resources in Botswana, the charge is extremely low, does not motivate the public to protect water resources and needs reviewing.

3.1.2 Botswana Water Policy

Although it is not fully implemented, the Botswana Water Policy was approved by an act of parliament in 2016. The policy was developed following the recommendations made by Botswana National Water Master Plan Review (BNWMPR) of 2006 that revealed that there were too many players in the water sector in Botswana, and therefore, water sector reforms were necessary (DWA, 2013). There was the District Councils supplying water at the rural centres, DWA at major villages and then WUC delivering water services in urban centres and this, according to BNWMPR report, resulted in the duplication and confused roles among the three water service providers. After the reforms, the water policy was developed to classify the roles and responsibilities in the water sector into water resources management, water regulation and water service delivery. DWA was mandated to plan, manage, assess and protect

Botswana's water resources, WUC was tasked to provide water service delivery while district councils were relieved their role and removed from the water sector (Setlhogile, et al., 2016).

The Botswana Water Policy is guided by the principles of water resources management being equity, efficiency and sustainability. The guiding principle of equity recognizes water as a basic human need essential for daily use in cooking, drinking and hygiene. This notion is supported by (Cahil, 2005; Priscoli, 2004). Priscoli contends that human dignity is fully met when people have access to water and that, denying people water is basically denying them the right to live. Similarly, Cahil indicates that the people's individual water needs are their rights to water and as a result, those rights cannot be taken away from them. In line with this, the water policy aims to ensure that all Batswana have access to water of adequate quality for economic growth, diversification and poverty eradication (DWA, 2013). Although the legal frameworks that guide the policy such the Water Act of 1968 and the Boreholes Act of 1956, the policy aims to allocate water in order of priority starting with human consumption, environments, agriculture and lastly, industry. Contrary to what the policy highlights in priority of water allocation, environmental flow requirements are not met as some river channels have signs of stress from over-abstraction and pollution (CSO, 2009).

3.1.3 Environmental Impact Assessment (EIA) Act, 2011

The Okavango Delta is a complex and sensitive ecosystem that attracts international attention. As a result, any planned development within the parameters of the delta are subject to assessment through the EIA process to ensure minimal disturbance to the system and for sustainable resource management (EIA, 2011). The wetland system falls under a list of environmentally sensitive areas that are protected under the Environmental Assessment Regulation legislation of 2012, and all developmental projects in the area are required to have a full EIA report indicating all the potential effects and the mitigation measures to be undertaken (EAR, 2012). The process also includes monitoring and evaluation plans of the long-term effects of such projects. Unless authorization is granted by the minister responsible, no developmental activity shall be undertaken. Any developer who contravenes the environmental law is liable to fines or imprisonment as stipulated in the act (EIA, 2011). Due to strict environmental regulations and the environmental sensitivity of the Okavango Delta, the area remains relatively un-disturbed, and some conservation areas such as the Moremi Game Reserve have been demarcated within the area.

3.1.4 Waste Management Act, 1998

The deals with the control and management of waste from household, industry, government premises as well as hazardous waste. Each district, town or city in Botswana is required by the law to prepare and follow waste management plans in their area of jurisdiction. The Department of Waste Management and Pollution Control is responsible for the issuance of waste management licences and carry regular pollution inspections of waste management facilities to ensure compliance and maintain a waste-free environment (DWA, 2013). Improper management of waste and uncontrolled waste disposal are a source of water pollution.

3.1.5 Tourism Act 1992

The act controls tourism activities and tourism operation companies are required to register and licence with the Department of Tourism and all tourism activities are expected to incorporate water conservation measures (ODMP, 2008). The Okavango Delta is a popular tourist attraction site. A large crowd of tourists frequent the area for leisure and to experience both the traditional and modern boat cruises on the waters of the delta. Some visit the area to view a wide variety of wildlife and plant species the area is commonly known to host. When this happens, there is continuous disturbance of the natural environment in terms of littering and pollution that may be a result of oil leakages from the boats.

3.2 Current regional protocols related to the study

3.2.1 SADC Protocol on Shared Watercourse, 2001

International River Basin Organizations (RBOs) have been established to address problems of water availability, water quality and the loss of aquatic ecosystems caused by population growth, infrastructural developments and climate change (Blumstein, 2017). The SADC Protocol aims to encourage cooperation and sustainable management, protection and efficient use of shared waters including Limpopo, Zambezi and Okavango Rivers in the SADC region. Its main target also includes the improvement of regional integration and the reduction of poverty through the wise use of shared water resources among member states. Each riparian state is required to prevent pollution of shared waters and take timely decisions to eliminate or compensate for any harm that might occur to water (DWA, 2013). SADC member states are obliged to obtain permits to use shared watercourses for uses that are not intended for domestic purposes and to ensure that any waste discharged into the water systems does not pose any adverse environmental effects to the downstream users (Salman, 2004). Salman adds that riparian states must notify other member states of any activities they intend to undertake within the watercourses. However, this move does not mean that disputes do not exist. River diversions and dam constructions in the upstream channels are the main causes of water disputes.

3.2.2 The Permanent Okavango River Basin Water Commission (OKACOM)

OKACOM was established in 1994 between Angola, Botswana and Namibia and is made up of a steering committee with representatives from member states countries. Member states are committed to the use, management and conservation of the Okavango River basin and the resources that surround the basin in a coordinated and sustainable manner (DWA, 2013; ODMP, 2008). The social, economic and environmental needs of each riparian state are considered during allocation of the resources. Currently, member countries are working together to implement the integrated management plan for the basin. OKACOM is concerned with the modifications to the basin as result of future developments that are likely to modify the flow regimes within the basin. There is inadequate information about the physical, chemical, ecological and socio-economic implications that are expected to come along with developmental projects within the basin and therefore, OKACOM recommends that an Environmental Flow Assessment (EFA) be done to predict the possible effects on the overall performance of the Okavango River system (EPSMO-Biokavango, 2009).

3.3 Current international laws and policies related to the study

3.3.1 United Nations (UN)

By virtue of Botswana being a member of the United Nations, the country is bound by the 2015 Paris Agreement in which member states are expected to work together to reduce greenhouse gas emissions in order to lower global temperatures by 1.5 ºC (Nkemelang, et al., 2018). Research work predicts increases by 2 ºC on global surface temperatures that will cause climate extremes such as wildfires and an exchange between extreme dry and wet conditions. At the 16th Conference of the Parties to the UNFCCC, (COP), developed countries committed to invest USD 100 Billion per year to finance developing countries to develop climate change mitigation and adaptation plans (OECD, 2017). Although Sub-Saharan Africa contributes less to the global greenhouse gas emissions, the region is more vulnerable to the impacts of climate due to lack of resources such infrastructure, finance and human capital to collect and interpret climate data. Environmentally sensitive sectors such as water, will be impacted more due to global changes in precipitation patterns, temperature, humidity. During the UN 17th Conference of the Parties (COP) in Durban, South Africa, SADC ministers responsible for water agreed that, as a vulnerable resource, water must be put as a stand-alone agenda item at the UNFCCC deliberations (Busani, 2011).

Just like other developing countries, Botswana has benefited from international donor organizations such GEF, Green Climate Fund and as well as capacity building programmes to develop innovative strategies that reduce greenhouse gas emissions and adapt to climate change (DWA, 2013). The water sector, in particular, has shifted from being supply driven to water resources management through the assistance from Stockholm Water Institute. Every year, Botswana joins the international community to commemorate the UN World Water Day as recognition of the benefits that come with the availability of water.

3.3.2 Ramsar Convention on Wetlands

The Ramsar Convention on Wetlands was established in 1971 in Ramsar, Iran as an international framework that calls for the wise use of wetlands and their related resources through national land-use planning, laws and policies, management and public education (EPSMO-Biokavango, 2009). The convention classifies wetlands to include swamps, lakes, rivers, deltas, reservoirs and salt pans that make up part of the natural environment in Botswana and the Okavango River and its supporting systems falls under the definition. Wetlands are conserved because of the endless benefits they provide to the environment and the local communities. They are a source of economic development, scientific research, support cultural norms and are a source of recreation through the tourism industry and they are also climate regulators as they act as carbon sinks to mitigate the effects of climate change (IWA, 2016). The environmental damage to wetlands could be irreversible and very costly and therefore, wetlands must be conserved, restored and rehabilitated whenever the need arises (ODMP, 2008). Through the Ramsar Convention, countries can apply for funding to conduct research or establish conservation activities through the Ramsar Small Grants Fund.

3.4 Water quality

Water quality monitoring is useful in decision making about water resources management. It helps to track the physical, chemical and biological characteristics of water such as temperature, dissolved oxygen, pH and turbidity. Understanding water quality of ecosystems is important to appreciate how the parameters behave as well as how their effects can be properly managed for the sustenance of aquatic life, proper water management and for the social and economic services they provide to the local communities (ANZECC, 2000). Water quality of any water system is influenced by environmental factors and human related activities. Invasive aquatic weeds such as Salvinia and water hyacinth have been found to contribute to water quality issues in open water systems in the Okavango Delta by decreasing DO and pH and at the same time, increasing CO_2 levels (Kurugundla, et al., 2016). This impact nutrient balance in water. Water quality data is useful for the development and management of water strategies during allocation of water for domestic use, recreation, commercial and to understand the conditions necessary to sustain aquatic ecosystems services. Due to data availability constraints, this study focuses on water quality indicators for pH, temperature, EC.

3.4.1 pH

pH is the amount of the strength of hydrogen ions in a given water body. It indicates how acidic or basic a water system is. The mathematical expression of pH is as follows:

pH= $-log_{10}[H^{+}]$, where H^{+} is the strength of the hydrogen ion (DWAF, 1996).

DWAF notes that the pH of pure water or water that does not contain any pollutants is 7.0 at 24°C. It is pH 7.0 that the number of H^{+} and the number of OH^{-} ions are in equal quantities and the water is classified as neutral. When the concentration of H^{+} ions increases, the pH decreases, and the water is termed acidic and when the H^{+} decreases, water becomes alkaline (ANZECC, 2000). Most chemical reactions in aquatic organisms require narrow changes in the pH range. At both ends of the pH scale is either acidic or alkaline and it is at these ends that most aquatic organisms die. pH signals that the chemical contents of the water are changing. Pollution can alter the pH in water and thereby making it unsuitable for plants and animals living in the water.

3.4.2 EC

Solids can be found in water in a dissolved form. Salts that are soluble in water break into negative and positive ions and these ions are conductors that carry an electrical current. Positively charged ions are Na^{+}, Ca^{+2}, K^{+} and Mg^{+2} while negatively charged ions include Cl^{-}, SO_4^{-2}, CO_3^{-2}, HCO_3^{-}, NO_3^{-2} and PO_4^{-3} (ANZECC, 2000).

3.4.3 Temperature

Although temperature is not an important measure of water quality, it influences the type of organisms that can survive in different aquatic ecosystems. Fish, insects and phytoplankton have different tolerance levels of temperature ranges. Apart from impacting aquatic life, temperature influences chemical reactions in water. At high temperatures, the rate at which chemical reactions occur is rapid and ions dissolve more (ANZECC, 2000). ANZECC states that in groundwater, high temperatures aid the dissolution of minerals and as a result, EC levels are increased. Temperature also influences the amount of oxygen that can be dissolved in water in that at warmer temperatures, more oxygen gets dissolved. It controls the rate of photosynthesis in aquatic plants and the rate of metabolism of some organisms. Water temperature is affected by the surrounding air temperature, stormwater discharge, turbidity and groundwater inflows. Increase in water temperature increases the solubility of ionic pollutants which results in an increase in pollution loads on surface waters (Gray, 2008). In natural ecosystems such as the Okavango Delta, aquatic plants and animals have developed adaptive mechanisms to cope with the continuous changes in temperature (DWAF, 1996). Temperature does not change abruptly, unless human-induced pollutants are introduced into the water.

3.5 Previous research

WEAP was used by (McCartney & Arranz, 2010; Pham, et al., 2017; Metobwa, et al., 2018) to investigate different scenarios of water demand in the Olifants River in South Africa, Thac Mo Catchment in Vietnam and the Mara River Basin in Kenya respectively. McCartney and Arranz study used estimates of water demand in 1995 to predict different scenarios of future water demand to project water use in the year 2025. The results of this study indicate that the predicted water demand resulting from population growth, changes in water use patterns and government policies will put greater stress on the Olifants River Catchment water resources. Pham et al. show that annual temperatures, rainfall and stream-flows are predicted to increase as predicted by the IPCC report of 2007. IPPC indicate a predicted increase in stream-flow patterns in South East Asia because of climate change. The study also reveals that the combined impacts of climate change and socio-economic development will exuberate water shortage during the period 2046-2064 and hence tripling the year 2000 baseline data that was used. In the Mara River Basin in Kenya, Metobwa et.al, after conducting a study to investigate water demand, concluded that major demands in the study area are human consumption and irrigation, citing that demand will increase from 0.03 billion cubic litres in 2013 to 2.65 billion cubic litres in 2045.

In a densely populated Steelpoort sub-basin in the Olifants River catchment, South Africa, WEAP was used to answer water demand allocation questions by testing water demand management scenarios (Levite, et al., 2003). Levite et. al explain that the study area was selected because, although it is water-stressed, it is a simple basin that has not been dammed and has no inter-basin transfers except for the 33 demand sites in irrigation, mining, domestic and stock watering. The study established data for water demand allocations and sites, water flow requirements and river head-flows in a 74-year old observation period that ran between 1920 to 1995. It was discovered that out of the 33 demand sites being studied, 15 had unmet demands and that there was the likelihood of the situation worsening if no corrective measures are not taken. Since minor water uses were neglected in the study, the results could have shown even severe water shortages. Additionally, the study did not include water quality of the system, a critical component that determines the availability of water. This is because when water is of inadequate quality, it is as good as not being available as it cannot be used. A similar study was carried out to assess the situation of water supply and demand and how precipitation and temperature changes impact crop yields in a 30-year period between 2009 and 2040 in Gediz Basin (Yilmaz, 2015). Yilmaz describes the basin as being water stressed and the results indicate an even increased water demand issues that will greatly impact the agriculture sector. The study recommends the use of efficient water saving techniques such as drip irrigation as well as a change in the current management policies for better sustainable solutions.

Just like the Okavango Delta, the Indus Delta in Pakistan is also listed under the Ramsar Convention on wetlands (Salik, et al., 2016). Salik et.al state that during the 19th and the 20th Century, water in the Indus River has been over-abstracted for irrigation, power generation, industrial use and for domestic consumption and as a result, the volume of water that feeds the Indus Delta has been greatly reduced. Another threat to the Indus Delta is pollution from untreated effluent from industrial waste with an annual amount of 20 000 tons of oil making way into the beaches, harbours and fishing areas (Khuhawar, et al., 2018). Khuhawar et. al explain that there has been little research done about water quality status and the effects of pollution on water resources in Pakistan including the Indus Delta, and as a result, conducted a study to examine the physical and chemical water quality of the Indus River Basin. The study concluded that the results of the tested parameters were above the recommended limits and there were signs of microbiological contamination from human induced pollution.

The Okavango Delta has been studied by (West, et al., 2015) to investigate if the changes in human activities had influenced the water quality of the system and if the changes had an impact on the ecological integrity of the system. The study involved conducting water quality sampling at the panhandle in 159 sampling sites in December 2006, October and November 2007, July and December 2008 and January 2009 covering all areas with varying water depth during the daylight. The study indicates that microbiological results were above the set targets for human consumption and recommended proper treatment of water before use. However, the physical and chemical parameters showed slight changes except for a pH of 9.20 that was recorded in an isolated pool that is used by cattle for drinking. In conclusion, the study states that the overall water quality of the Okavango Delta has not been affected by human interventions but frequent follow-up monitoring at the panhandle is necessary to detect early changes in water quality along the channel. The results of West et al. were almost similar to those obtained by (Hart, 1997) between January and February in 1986 in the same study area except for a much lower pH of 5.7 recorded at Seronga.

The concept of integrated water resources management requires water planners to be knowledgeable about the quantity and quality of water resources under their jurisdictions. Although the Okavango Delta is less developed and is a wildlife management area, the effects of human activities on water quality at the downstream channels is not known but there has been indications of water pollution from industrial, agricultural and urban development in Maun, a village downstream outlet of the Okavango Delta (Masamba & Mazvimavi, 2008). In light of this, Masamba and Mazvimavi conducted a study to determine how human activities impact water quality of the Thamalakane River around the village of Maun. The study involved water quality sampling and analysis for both the physical and chemical parameters along the river channel covering 75 kilometres between June 2005 and January 2006. The Thamalakane River is a river that drains from the Okavango Delta and therefore, it is part of the larger basin. Since the study is located downstream, all activities along the stream channel and at the point of study have a combined effect on water quality of the system. The study indicates that, on average, the activities occurring along the study area had little impact on water quality and the tested parameters were within the acceptable range set by Botswana Bureau of Standards. Masamba and Mazvimavi notes that although the results indicate that water in the study area is of acceptable quality, there are signs of human interference that manifest in the results of pH, lead, EC and DO especially in areas where the river passes through built-up areas. seasonal flooding influenced water quality since during peak floods, concentrations of water quality parameters were high and decreased during the rainy season.

(Andersson, et al., 2006) conducted a study in the Okavango Delta to assess the impact of urbanization and climate change scenarios on the overall flow of water of the delta using a Pitman monthly rainfall-runoff model. The study used recent and historical rainfall data and the ongoing developments and climate changes. A similar study was conducted by (Hughes, et al., 2011) to investigate the effects of climate change on the overall water budget of the Okavango River Basin using the Pitman hydrological model. The model was set to create simulations of hydrological responses to future climate change using mean monthly runoff data in 7 GCM that were set to perform at the predicted 2℃ increases in global temperatures. The result of estimates of Hughes et.al show that there will be noticeable changes in the hydrology of the wetland during the 21st century although the degree of confidence to the changes was not immediately known by the researchers. Although Hughes et.al and Andersson et.al studies are similar, Hughes et.al state that the magnitude and the range of projected changes are greater than those obtained by Andersson et.al and recommends that further studies must focus on establishing relationships between hydro-climate change and ecological wellbeing in the upstream channels of the delta.

During 2009 to 2011, the Okavango River Basin experienced flooding that damaged infrastructure and most settlements around the area were flooded leading to economic loss. At the same period, Pakistan and other areas in the region had flood events that were more destructive and this phenomenon prompted (Wolski, et al., 2014) to carry out a study to investigate if the flooding events in Pakistan and the Okavango Basin were a result of climate change. The study was aimed to answer questions of whether the threshold of emitted greenhouses into the atmosphere had been exceeded and if similar flooding events may occur in the future using climate models applied in the real world and non-GHG world. The results of the study indicate that human-related greenhouse gas emissions had minimal effects on rainfall patterns, instead, the resultant higher temperatures lead to high evaporation rates and thereby reduced the risk of flooding in the study area. The study concluded that without anthropogenic greenhouse gases, the flooding events that occurred during 2009-2011 would have been of lower magnitude and recommends climate change adaptation planning in the basin for informed decision making.

(Hamandawana & Chanda, 2010) conducted a study in the Okavango Delta at the panhandle in Namibia and Botswana. The study used satellite imagery for 1967, 1989, 1994 and 2001 to investigate the impacts of natural and human activities on the environment in the proximity of the water systems and the results indicate that grassland cover and woody vegetation decreased close to perennial water supplies due to overgrazing and unsustainable use of natural resources in the study area. The results also point out that there is human-wildlife and wildlife-livestock conflicts and recommends that farmers must shift from livestock farming to tourism to reduce the number of animals that cause overgrazing in the area.

4.0 MATERIALS AND METHODS

As already outlined in the description of the study area section, the Okavango Delta is a world class iconic sight that attracts multitudes of tourists every year. Consequently, the tourism industry is booming with an influx of accommodation facilities and boat cruise activities to keep up with the growing number of tourists that visit the area. This impacts water quality as well as water that flows through the delta. Since the delta system covers a huge area, only the upper basin that is commonly known as the panhandle, was used as the study area. The study covers an area of 3460 square kilometres from Mohembo to Etsatsa including Sepopa, Guma and Cresent Island. The was done to create a closed system that the model can easily run on. The total length of the system is 122 kilometres.

4.1 Sources of data

The data used in this study was obtained from several sources. Data for water quality, climate and sampling locations was obtained from ORI. ORI is a centre for research with the focus on natural resources management. Although the institution is based in Maun, Botswana, it conducts research in river basins and watersheds in Southern Africa with the aim of informing and influencing policy makers to make the right decisions to tackle the region's most pressing environmental issues.

DWA provided data for water discharge at Mohembo and Etsatsa. In addition to water discharge, data for the total number of water rights permits issued by the department in the study area was availed. However, it should be noted that the daily water abstraction rates were not available because the permits do not enforce gauging of river water at abstraction points.

Journal articles and all online reports were obtained from Flinders University library portal. The download of WEAP and ArcGIS software licences was made possible by the university.

4.2 Methods

4.2.1 WEAP model

WEAP is a user-friendly and free for academic use model that was developed by the SEI to serve as a guide to water resources planners and managers rather than to substitute the skilled personnel (SEI, 2011). It is a water balance model that recognizes water supply sources as rivers, groundwater, lakes and water demand areas that include withdrawals for irrigation, industry, domestic and for ecosystem services. WEAP is a water accounting tool that can be used to solve water demand issues, priority of water rights allocation and pollution tracking for any given water system. WEAP works in 3 different forms. It is a database for storing water demand and supply information. Secondly, it acts as a forecasting tool to estimate future water demand, supply, storage, sources of pollution including treatment and discharge. Lastly, it a policy analysis tool that informs future water allocation strategies for a range of multiple competing water users.

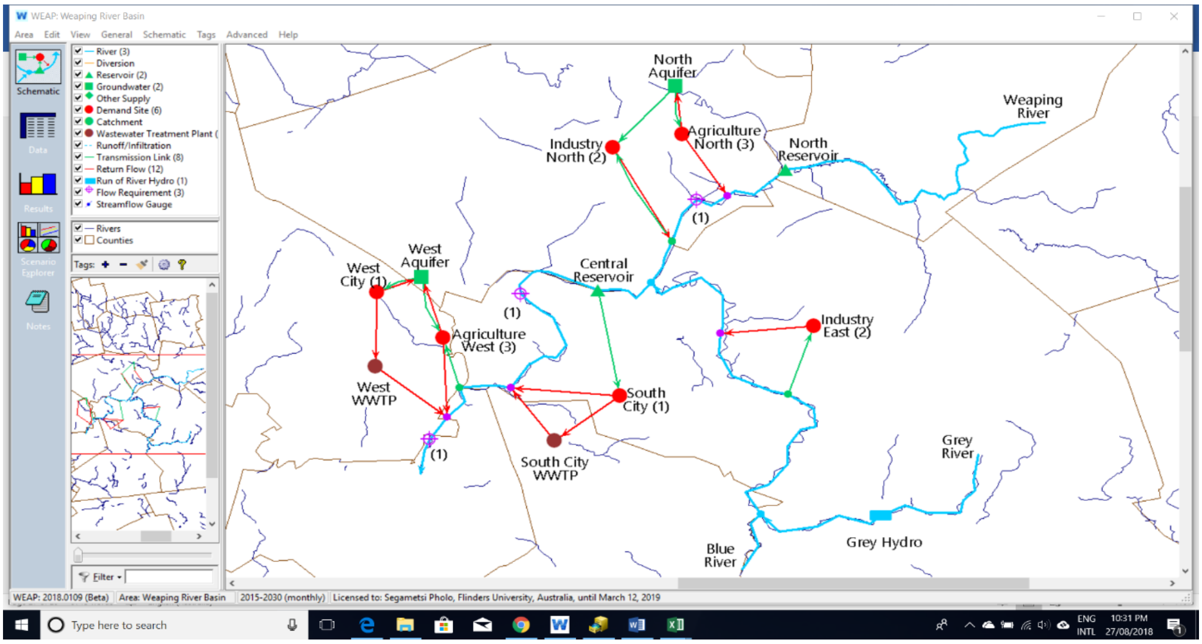

Figure 8: The WEAP model interface (SEI, 2018).

For this study, the WEAP model requires several input variables to run. Data for rainfall, temperature, daily average stream-flow measurements, water quality indicators for point and non-point sources (Kumar, et al., 2018), and information on waste water treatment facilities was used. WEAP is preloaded with global layers that cover major rivers, countries as well as oceans and for this study, the Okavango Delta layer will be selected. The model is used to investigate the extent of pollution at Mohembo in the upstream and at Etsatsa at the downstream channels which in this case define the spatial boundary of the study area. This is precisely 122 kilometres stretch of the study area and 3460 square kilometres in size. The model is also used to establish demand sites as per the allocated water rights issued by DWA office and to investigate if the rate of abstractions has an impact on the overall flow of water through the delta. The model has well defined priority areas for water allocation that are classified as supply and demand sites. These include water for irrigation, hydropower generation, and groundwater recharge. Data required for this study is water quality of five basic water quality parameters measured at the upstream in Mohembo and downstream at Etsatsa. In this study, water demand is mainly for agriculture through irrigation and livestock. The year 2015 is used as baseline year to establish current accounts data that the model requires, and the future demand projections are set at 2030 to coincide the UN Sustainable Development Goals target year.

4.2.2 Water quality measurements

Although there are several water quality parameters that can be modelled, this study focuses on EC, temperature and pH that were measured in the Okavango Delta panhandle in 2015 to simulate changes that may occur in water quality in 2030. The data for water quality was collected by ORI between January and December 2015. The water samples were collected at Mohembo, Sepopa, Guma Lagoon, Cresent Island and Etsatsa sampling sites in the study area. Mohembo is at the upstream while Etsatsa is at the downstream end of the river channel. The distance between the upstream and downstream points is 122 kilometres. Water quality for Sepopa, Guma and Crescent Island were used for comparison purposes as these sites also form part of the panhandle and fall within the study area. Table 4.1 below shows the coordinates of the sampling sites where the water quality parameters under investigation were measured during January to December 2015.

Table 4. 1: Water quality sampling sites for the panhandle.

	Coordinates	
Sampling Sites	Longitudes (S)	Latitudes [E]
Mohembo	21°48'21.774" S	18°15'37.46" E
Sepopa	22°10'30.972" S	18°43'59.075" E
Guma Lagoon	22°22'47.257" S	18°57'58.15" E
Crescent Island	22°23'28.14" S	18°52'42.44" E
Etsatsa	22°'25'26.67" S	18°51'17.43" E

4.2.3 Water balance of the study area

Water discharge is impacted by different activities along the river channel. As water flows along the channels, it is diverted and used for different purposes such as irrigation, wildlife and some of it is evaporated. The WEAP model is used to simulate the amount of water that enters the system at the upstream in Mohembo and the amount that leaves at the downstream channels in Etsatsa. Since the study area is a closed system, the volume of water that enters the system is measured against water discharge that leaves the system at the downstream channel at Etsatsa. The model uses monthly time series data between January and December 2015 and therefore, the daily water discharge data recorded by ORI was used to compute mean monthly variables that can be input into the model. The main activities that influence water discharge in the study area include irrigation, domestic water use, watering of livestock and wildlife, evaporation and groundwater inflow and outflow.

To simulate water discharge, the WEAP model requires that all water demand sites and activities be input into the model. For this study, the number of water rights permits allocated was used to calculate the amount of daily water abstractions along the river channel. In Botswana, the issuance of water rights is governed by the Water Act which allows every water right holder to withdraw an amount of 22 750 litres of water per day for the purposes stipulated in the application form (WaterAct, 1968). Additionally, the act allows all individuals who reside near surface water bodies to use the same volume of water for personal use even without official water rights permits. Due to lack of real-time daily water abstraction rates, the figure 22 750 litres of water per day per water right permit was multiplied by the total number of water rights that have been issued in the area to estimate daily abstractions to establish agricultural water demand in the area.

$$(22\,750L/day) * 38 \text{ permits} = \text{Agricultural water demand}$$

For domestic water demand, the total number of people for each location in the study area was multiplied by the recommended daily water use rate of each person. In Botswana, the recommended daily water usage is 40L per person per day (SB, 2015) but this limit is only applicable in areas where there is an acute shortage of water. USGS recommends daily water use per person to be between 302 and 378L/day. For the study area, the 378L/day was used to calculate the daily use rate per person. This is because the Okavango River provides an endless supply of surface water to the local communities. Moreover, there are no restrictions to domestic water use from the river since the points of water withdrawals are not gauged and at the same time, they are not monitored. As a result, the people are at liberty to withdraw as much water as they wish to meet their daily demands. The calculations were done due to lack of real-time domestic water demand in the study area. The statistics office conducts the Botswana Housing and Population census after every 10 years. The last census was conducted in 2011 and consequently, population statistics data for 2011 was used as a baseline to simulate the population in 2015 using the 2.1% growth rate.

Table 4. 2: Population projections *(SB, 2015)*.

Name of location	**2011 population**	**Population increase**
Mohembo	2538	(2538*2.1%/)year*4years
Shakawe	7420	(7420*2.1%/)year*4years
Sepopa	2824	(2824*2.1%/)year*4years
Etsatsa	912	(912*2.1%/)year*4years
Seronga	3716	(3716*2.1%/)year*4years

4.2.4 Rainfall

Since WEAP uses both the monthly and yearly time series data, the measured daily rainfall amounts recorded in the study area were used to compute mean monthly rainfall between January and December in 2015 in the study area. The mean monthly rainfall for Shakawe was used to represent the upper section of the study area where the catchment is recharged with surface water.

4.3 Limitations to the study

The main limitations to this study was access to data that is needed to run the WEAP model. Since Botswana is a developing country with limited updated data and online resources, access to reliable and real-time data remains a challenge. Online sources are not frequently updated immediately after data acquisition from the field. This is particularly the case with government official websites that collect water data across the country. As a result, data acquisition is only through an exchange of emails with the officers who have access to updated databases. The challenge to this is that, in many cases, when one lodges a request for data, the response is that the officer responsible for the required data is not in office, either on leave or at the field. This causes delays in data acquisition and consequently the overall timely delivery of the research project. The other challenge is with data gaps. Most of the data that is readily available has some gaps, and as a result, it becomes irrelevant for models like WEAP that requires consistency in data input for maximum results. For this study, the intention was to cover a small manageable area between Mohembo and Sepopa, but due to lack of adequate data variables, the study area had to be extended up to Etsatsa where all the variables needed to run the model were available. The study was intended to model 5 basic water quality parameters in EC, pH, temperature, turbidity and DO but due to limitations with data availability and the model capabilities, the investigation was narrowed down to model EC, pH and temperature.

5.0 RESULTS

This section is an outline of the results obtained from the measured variables used in the study. The results of the measured values are compared with those obtained in the WEAP to note any differences between the methods. Since the study focuses on water quality, the results of water quality alongside water discharge are discussed in full because the volume of water in the study has direct impacts on water quality.

5.1 Water quality

This section is a description of the results obtained from the simulated results from the model and the measured variables for turbidity, EC, pH and temperature. Botswana does not have water quality standards for environmental water. However, the country has adopted the South African Water Guidelines for Aquatic Ecosystems of 1996. Table 5.1 below is a summary of the comparison between the South African and Australian and New Zealand guidelines are used for fresh water ecosystems.

Table 5. 1: Comparison of South African and Australian and New Zealand environmental water quality guidelines *(DWAF, 1996; ANZECC, 2000).*

Parameter	DWAF (1996)	ANZECC (2000)
Temperature	Must not vary by 10%	Must not change by 80%
pH	4-9	6.5-8.0
EC	Not applicable	Not applicable

5.1.1 Temperature

In general, the surface water temperatures of the panhandle are almost below 30℃ for the entire year of the study. The results of temperature indicate that December was the hottest month with the highest temperature reading of 36.6℃ in Etsatsa followed by 28.7ºC recorded at Mohembo in April with the lowest summer temperature of 26.8℃ recorded in Cresent Island in February.

Figure 9 below shows that the lowest temperature of 15.8 °C was also recorded in Cresent Island just after the winter season in August. As expected, a graph of the monthly temperature readings shows two distinct temperature variations between the winter months with the lowest temperatures and the summer months with higher temperature readings. The transition from summer to winter temperatures between April and June is quite visible with temperatures dropping steadily until they are constant between June and August. During spring time when the temperatures start to be warm, a steady increase is observed between August and October until they reach peak values in summer between November and March.

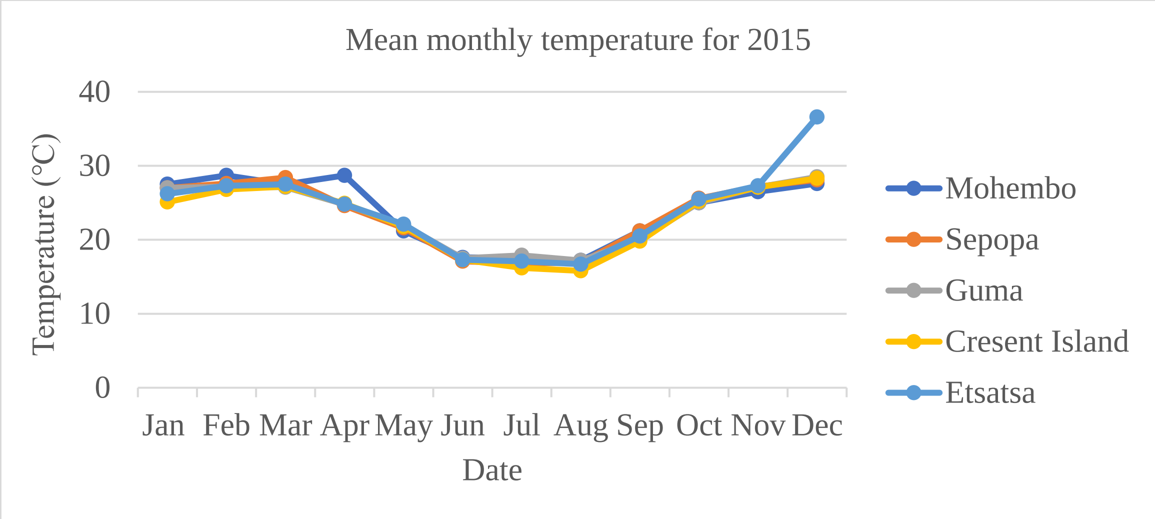

Figure 9: Measured mean monthly temperature for the panhandle for 2015

Figure 10 is a comparison between the measured upstream and gauge temperatures and the results obtained from the model. The results indicate that the simulated water discharge show a slight variation from those obtained from the measured results between January and March. The difference between the modelled and the measured results is pronounced in April where the head-flow at Mohembo was 28.70 °C, the measured gauge at Etsatsa was 24.80 °C while the simulated temperature stood at 27.42 °C. The lowest and the highest temperature readings with a low of 16.70 °C and a high of 36.60 °C were recorded in Etsatsa against the modelled temperature of 28.80 °C. The results of the modelled and the measured temperatures follow a similar trend across the seasons. In general, the difference in temperature across months is less 2 °C except during seasonal changes between the summer and winter months.

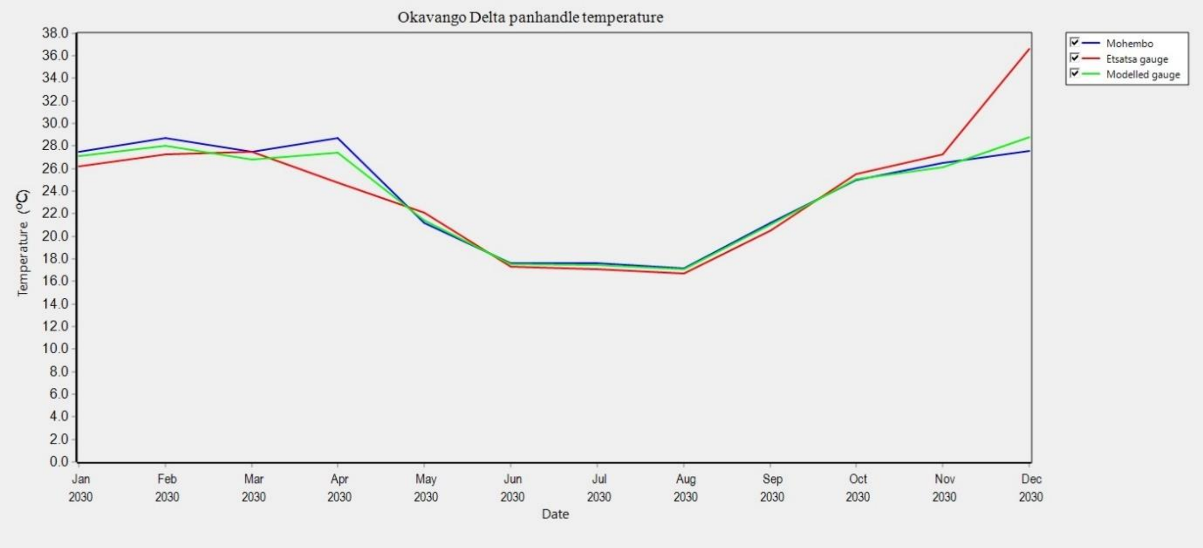

Figure 10: Comparison between measured and modelled water temperature

5.1.2 pH

The results of the measured pH, shown in figure 11 below, showed a low of 5.7 and a high of 7.2 recorded in Mohembo in April and November respectively during the study period. Cresent Island recorded the lowest pH of 5.9 and 5.8 at the beginning of the year when the river had high discharge. For most of the months during the study, there was a slight variation in pH between 6.0 and 6.8.

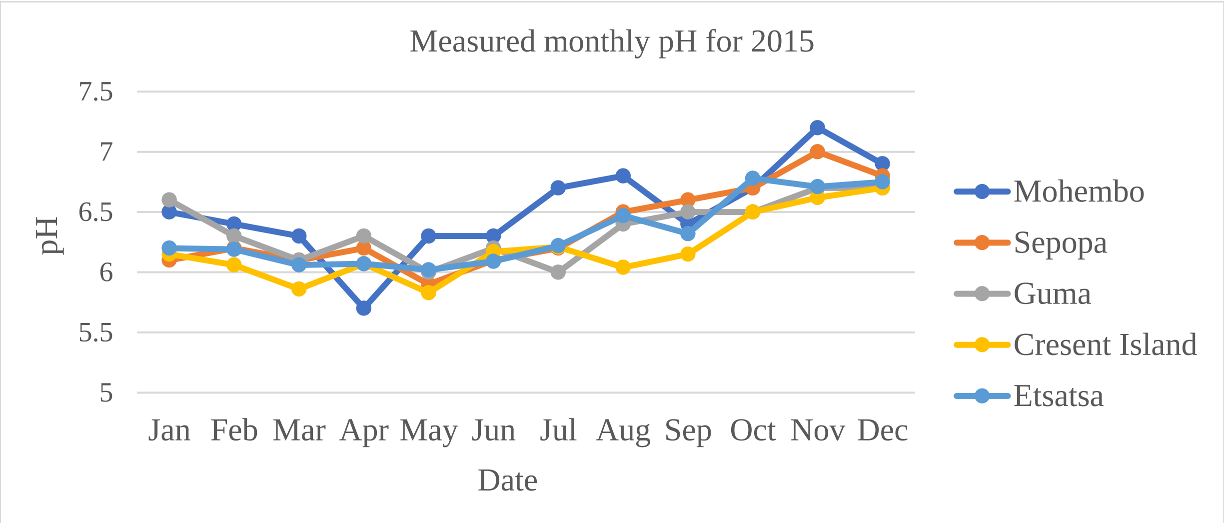

Figure 11: Mean monthly pH for the panhandle for 2015

Figure 12 below is an illustration of the difference between of the results obtained from the measured pH in Mohembo and Etsatsa, and the values obtained from the model at the gauge in Etsatsa. The lowest measured pH of 5.63 was recorded in Mohembo in April while the lowest pH obtained from the model was 5.77 during the same month. Although the results obtained from the model are lower than those obtained in Mohembo, an increase in the modelled pH is observed in November with a value of 6.98.

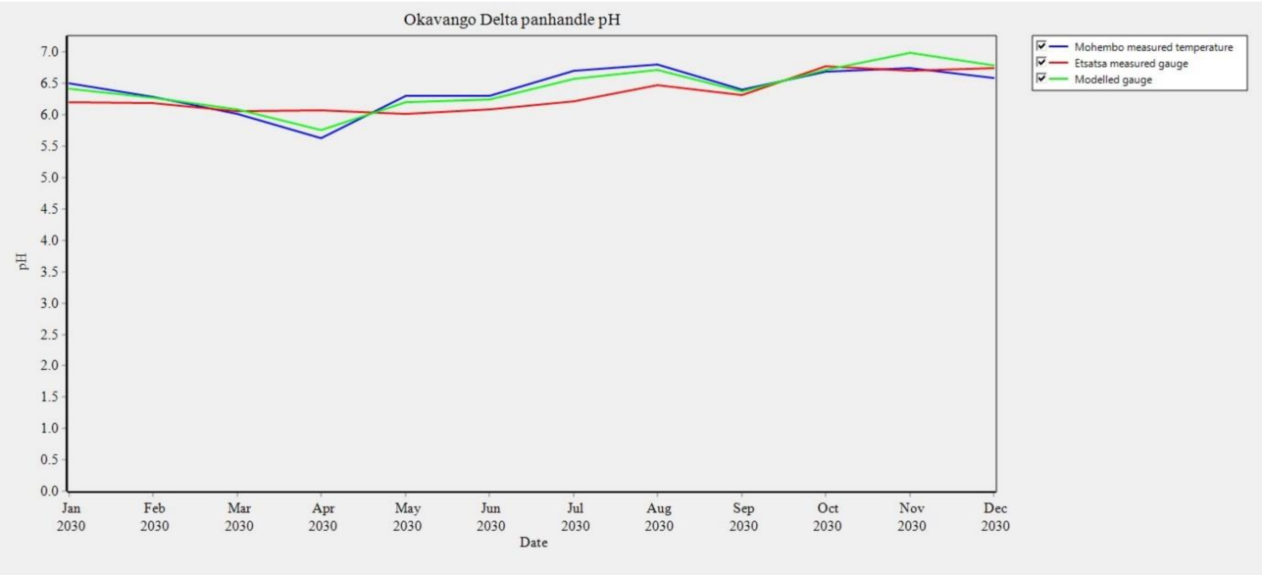

Figure 12: Comparison between measured and modelled pH

5.1.3 EC

The results of the graph of the measured EC and those obtained from the simulated plot follow the same trend. Figure 13 below shows the results of the measured EC at the demand sites in the Okavango catchment area. Figure 14 is a summary of the results of the combined simulated EC, the measured EC at Mohembo and Etsatsa.

Results of the measured EC in figure 13 show that the highest value of 89.6 µS/cm was recorded at Cresent Island in January in 2015. From figure 14, the highest measured conductivity was 67.90 µS/cm in Etsatsa while the simulated result was 45.69 µS/cm during the same period. For Mohembo, even during the highest water discharge at the beginning of 2015, conductivity ranged between 27.3 µS/cm and 39.6 µS/cm. During the winter months between April and August, conductivity measurements for all the sampling sites were relatively the same and started increasing in September when the temperatures were getting warmer. The same trend was observed from the graph of the modelled results.

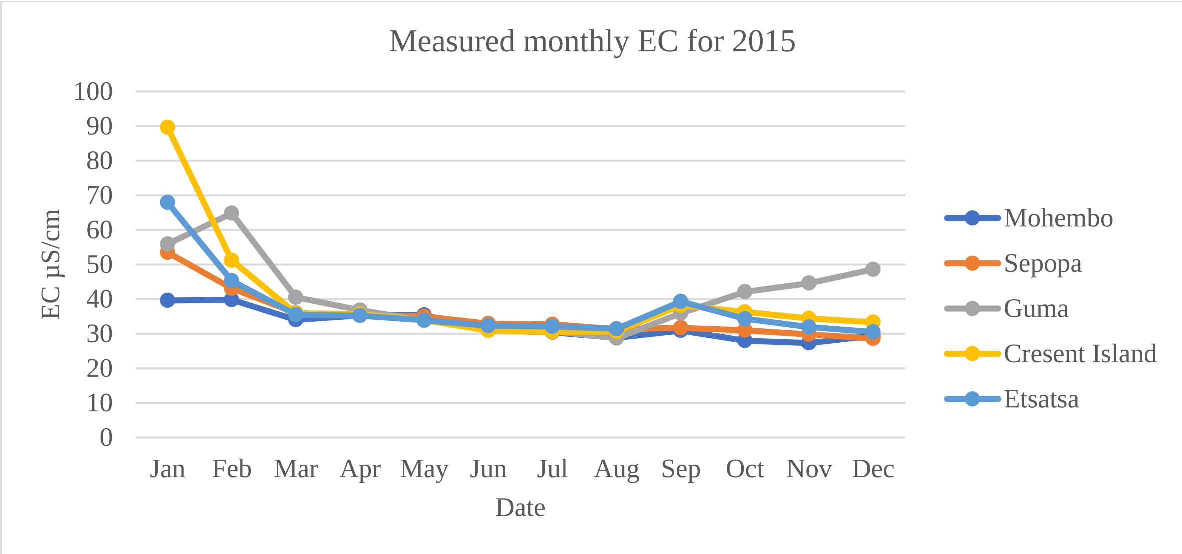

Figure 13: Mean monthly EC for the panhandle for 2015

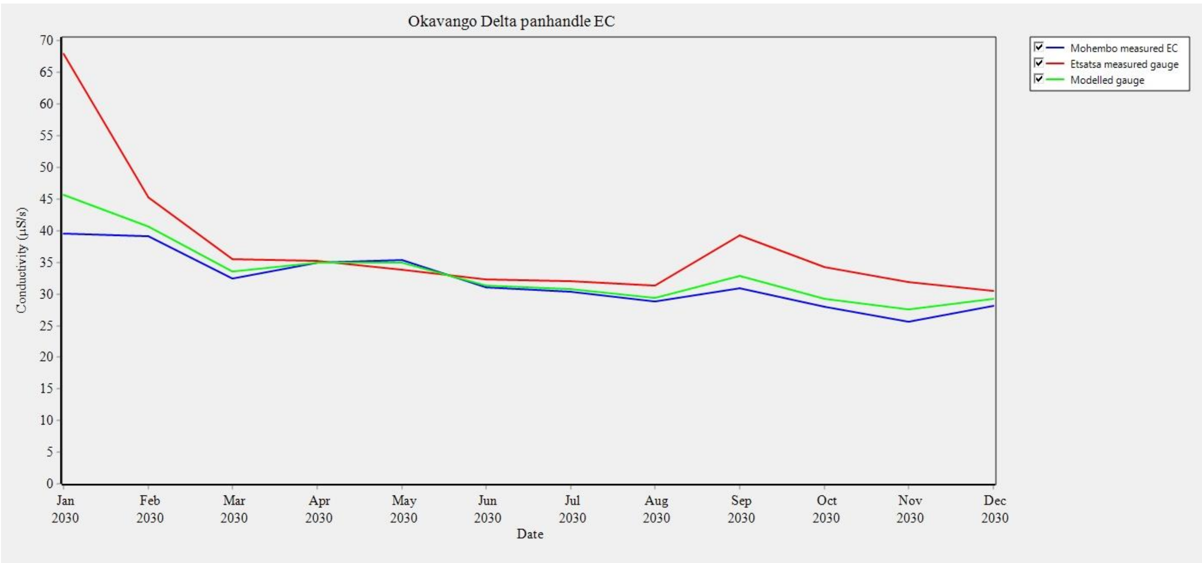

Figure 14: Comparison between measured and modelled EC.

5.2 Water discharge

Figure 15 below shows the scenarios created to represent all activities related to water discharge in the WEAP model. The boundary of the study area is shown in black. The main channel, the Okavango River, is represented by the blue line that runs across the area and the small tributaries are also shown. Demand sites are shown by the red dots while the green and red lines depict water that leaves the system and water that flows back into the system after it has been used at the demand sites. The water entering the system was measured in Mohembo and measured again at a gauge in Etsatsa as shown by a bold blue dot. Groundwater is also part of the water balance in the system and it is included in a green square.

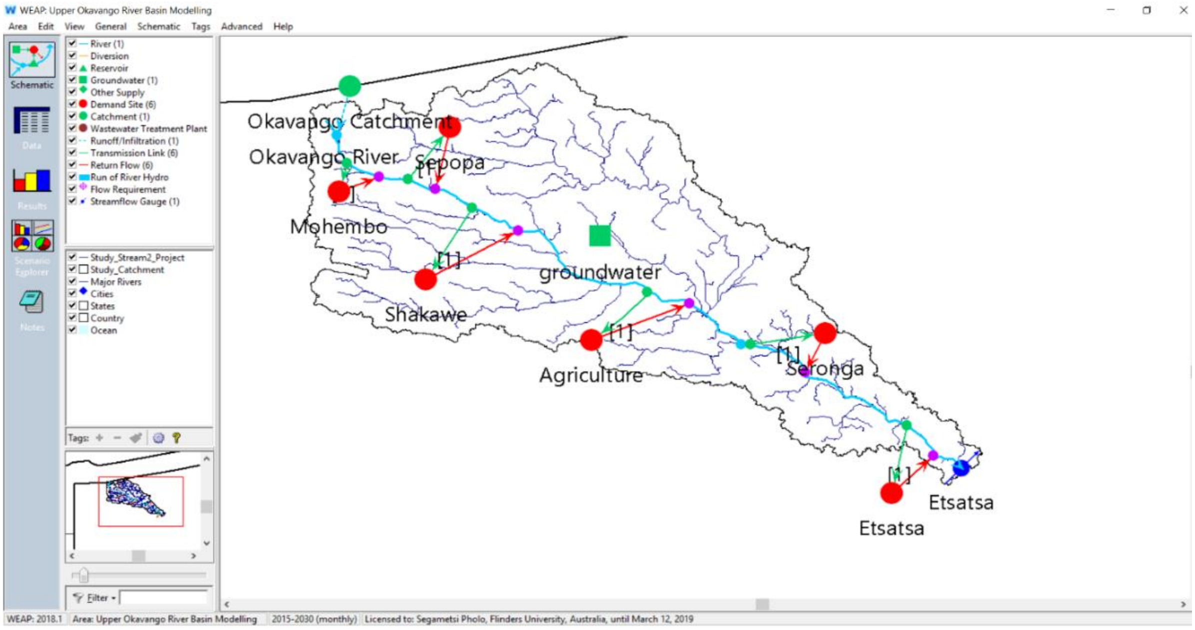

Figure 15: Okavango Delta panhandle WEAP interface.

A plot of the measured and simulated water discharge in Okavango Delta panhandle, in figure 16, shows high discharge rates during the rainy season between February and April. The highest inflow was 689.92 m^3/s for April in Mohembo while during the same month, a much lower outflow of 182.43 m^3/s was recorded at Etsatsa. For the first half of the study period, between January and June, the difference in monthly volume of inflow water at Mohembo and the outflow at Etsatsa is significant. The gap in the difference between water that enters the system and water that leaves at Etsatsa narrows in June and throughout to December, showing a steady decline in water discharge at the upstream and downstream gauge. Although the results of the simulated water discharge are higher than the measured outflow, they follow the same trend of those of the measured water discharge at the gauge in Etsatsa.

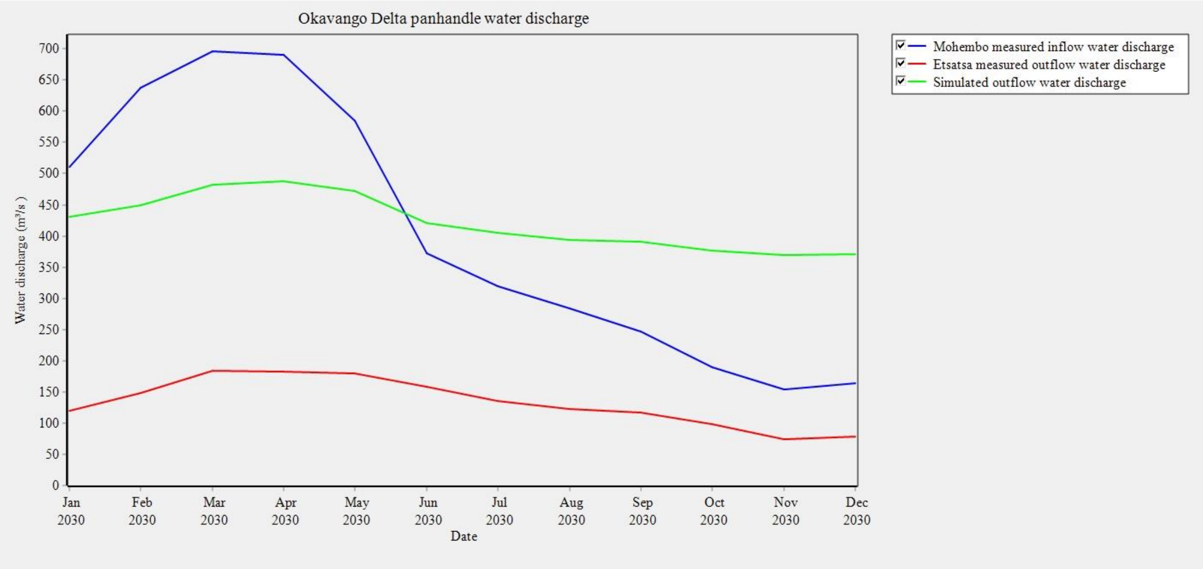

Figure 16: Results of measured inflow, outflow and simulated outflow.

5.3 Rainfall

The results of measured rainfall, shown in figure 17 below, indicate that the total precipitation for the study area was 361 mm in 2015. It was wet at the beginning of the year between January and April. April was the wettest month with a maximum precipitation of 74.4 mm and the second wet month was January with a maximum record of 40.2 mm. During the winter months of May to August, it was relatively dry with only 0.4 mm of rain recorded in August.

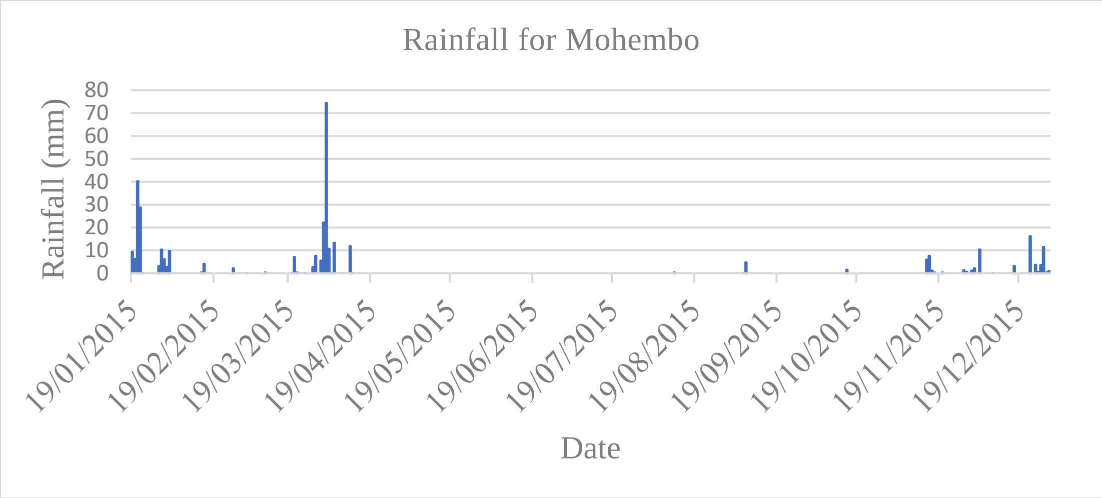

Figure 17: Mean monthly rainfall for Mohembo for 2015.

6.0 DISCUSSION

6.1 Water quality

Surface water temperatures are influenced by air temperatures. For the study area, the difference between summer and winter temperatures is the main cause of temperature fluctuations in the system. The highest temperature recorded in 2015 was 36.6℃ during the summer month of December at Etsatsa and the highest temperature obtained from the model was 28.80 ℃. During the hot summer months, the surface water temperature of the study area ranged between 24 ℃ and 28 ℃. The measured temperature ranges during the winter season are between 20 ℃ and 21 ℃. Changes in water temperature across months for both the measured and modelled temperature are minimal except during the transition across seasons. However, the temperature difference between November and December was 8.7 ℃. The modelled water temperature is lower than the measured head-flow temperature but higher than temperature at the outflow gauge.

Water quality standards for temperature requires that water temperature for surface water ecosystems must not vary by 10% by 2℃ of the normal temperature of a system (DWAF, 1996). The monthly average water temperature in the Okavango panhandle falls within the required limits except for the 36.6 ℃ recorded in Etsatsa. The observed difference between maximum and minimum temperatures could be a result of the time of day during sampling, the density of vegetation cover at sampling points and the depth at which the water sample was collected. For domestic water use, temperature is not an important determinant, but elevated temperatures on surface waters deplete oxygen and may be harmful to aquatic ecosystems (West, et al., 2015). Temperature controls the rate of chemical reactions in water. At high temperatures, ionic pollutants contained in surface water bodies dissolve rapidly and ultimately increases the build-up of pollutants on surface waters.

The results of pH indicate that the water in the Okavango River is slightly acidic to neutral with values ranging between 5.83 and 7.2 over the entire study area. (Mmualefe & Torto, 2011) reports that water sampled between Mohembo and Lake Ngami during the floods from 2005 to 2009 had pH values between 6.7 and 9.0. Mmualefe states that pH 9.0 was recorded at a spot that was used as a watering hole for livestock, and as a result, ammonia from cow-dung increased the pH. In a study conducted by (Hart, 1997) between January and February of 1986 at the panhandle, pH ranged between 5.70 and 9.20, and these values were slightly outside the pH range of 6.09 and 7.38 obtained by (West, et al., 2015) at the same study site between 2006 and 2009. Hart also associates the abnormal pH values with the presence of animal droppings as the sites were used as watering holes for livestock in the area. A report prepared for the OKACOM indicates that, generally, pH in Okavango catchment varies between 5.9 and 7.6 and in some areas, there is little variation of pH between 6.9 and 7.0 (Warmeant, 1997). The variability in pH is associated with the accumulation of CO_2 that is produced when organic matter decomposes.

Most freshwater ecosystems have pH in the range of 6.5 and 8.0 (ANZECC, 2000). However, according to ANZECC, high pH must not be associated with human induced pollutants as there are some naturally acidic waters such as those found in Australia. Based on the results of previous research, (Hart, 1997; Mmualefe & Torto, 2011; West, et al., 2015), it is worthy to note that even across seasons, the pH of the panhandle remained unchanged throughout the duration of the study. The pH of the measured and the simulated values satisfy the (ANZECC, 2000) and (DWAF, 1996) water quality standards for freshwater ecosystems. It is an indication that no pollutants have been introduced and as a result, the water is safe to use for all purposes of domestic, agriculture and for livestock watering. However, as already indicated, there are some areas within the delta that have proved to have high pH ranges indicating signs of water pollution.

EC is influenced by the dissolution of mineral particles in rocks, soils as well as the decomposition of organic matter in the water. The ionic particles of natural water bodies are influenced by the physical and chemical properties of the geological formation within which the water flows (DWAF, 1996). DWAF narrates that rainwater has EC less than 1 µS/s, sandy soils have less than 30 µS/s while in areas with high evaporation rates, EC can be as high as

1100 µS/s. According to (West, et al., 2015), the low conductivity values in the Okavango Delta are influenced by the alluvium sandy soils that filter out most of the solutes as the water flows through the system. For this study, the low EC levels are a result of low concentrations of solutes brought about by lack of weathering. The results of EC obtained by (Masamba & Mazvimavi, 2008) indicate that lowest EC of 23 µS/s was recorded in Mohembo while the highest EC of 384 µS/s was obtained at Lake Ngami.

the highest reading of 89.6 µs/s for EC was recorded in Cresent Island in January while the lowest reading of 27.3 µs/s was recorded at Mohembo in November. A plot of EC shows that high values were recorded when the inflows were high and gradually decreased with a decrease in the volume of discharge for the entire panhandle.

6.2 Water discharge

There are various sources of surface water that include surface runoff, rainfall, excess soil moisture that drains into the water and water table discharge. The quality and the amount of water that flows on watersheds is influenced by climatic and geological conditions of an area. River water discharge is an important component in the functioning of biological and physical processes in freshwater bodies. It affects geomorphology, salinity and turbidity which in turn influence the distribution and functioning of aquatic organisms (Wolski, et al., 2014). The amount of rainfall is not important in enclosed water bodies such as lakes reservoirs where water was collected and stored over a long time, but in streams and river channels where water is in constant and continuous motion, the total volume of water is influenced by the prevailing climatic conditions (Gray, 2008). Gray asserts that a small reduction in the average rainfall of a catchment may reduce the annual water discharge by half.

For the Okavango River panhandle, the high volumes obtained for the measured and the simulated water discharge is associated with the wet months between January and March. The mean annual inflow of water into the Okavango River is 348m^3/s with maximum flow levels during the wet season between March and April (Ellery, et al., 2003). Research indicates that the average annual discharge in the catchment is highly variable ranging between 520 m^3/s and 190 m^3/s over the last 60 years (Gumbricht, et al., 2004). Between 2014 and 2016, Botswana experienced low rainfall levels that led to drought conditions and as a result, there were some water supply failures especially in the capital city, Gaborone (Nkemelang, et al., 2018). This phenomenon is reflected in the low rainfall amounts summarised in figure 17 above which ultimately impacted water discharge rates especially at the downstream channels. The high volumes of water discharge obtained in this study between March and April are a result of the rainfall events that occurred during this period. This is the case because, according to (McCarthy & Ellery, 1998), water discharge at Mohembo reaches peak in April. This reflects that local summer rains have an impact on the overall water flow in catchment systems. Similarly, (Wolski & Murray-Hudson, 2006) and (Masamba & Mazvimavi, 2008) report that, in the Okavango catchment, precipitation occurs between November and March and the floods peak at the upstream in April and the maximum floods are recorded between June and September. Wolski and Murray-Hudson explain that the delay of the floods is caused by the distance the head-waters travel as well as the speed of the water.

The notable difference between the simulated and the measured water discharge could be attributed to several factors. The low gradient of the study results in the slow movement of water from the upstream to the downstream. Some of the water is lost through groundwater recharge. It is estimated that about 99% of the total water in the Okavango catchment is lost through evapo-transpiration at a rate of 1500 mm/year (Gondwe & Masamba, 2016) and this accounts to the low water discharge downstream. The consequence of high evaporation rate is that, during evapo-transpiration, solutes are left behind, and this impacts water quality.

Before splitting into numerous channels, the Okavango River divides into 3 main river tributaries namely Khwai, Maunachira and Boro with the Boro channel spreading much of the water across the delta as compared to the other channels (Gondwe & Masamba, 2016). During the study, low volumes of water discharge were recorded at Etsatsa. Due to uncertainties with the data used, water discharge at the gauge might have been measured after the main river channel had split into tributaries and thus the low values. The Okavango catchment is very permeable with an active exchange of water between channels, floodplains and groundwater, and consequently, some channels are classified as gaining while some are losing streams (Gumbricht, et al., 2004). The high-water discharge rate observed in the simulated results could be explained in terms of the channel being a gaining stream as described by Gumbricht et al. It is also an indication that that water outflow responds to local rainfall and the historical wet conditions of the area. Channels loose or gain water due to the spilling of water as it flows from the main river into the floodplains and some of the water may flow back to the same channel and thereby causing fluctuations in flood levels (McCarthy, 2005). McCarthy explains that further research is needed to establish the thresholds at which water spills from the channels as well as from the floodplains.

In addition to local precipitation, the flood waters of the Angolan highlands feed the system between February and May and gradual decreases in volume occur in summer between November and March (McCarthy, et al., 2003). McCarthy et al. reveal that due to the complexity of the delta, the annual variation in water recharge is high and the extent and dynamics of flooding patterns is still not understood. During periods of low flows, flooding is confined to the middle and the lower panhandle.

7.0 CONCLUSION AND RECOMMENDATIONS

7.1 Conclusion

This paper aimed to investigate how climate change and human-related activities will impact water quality of the Okavango Delta in the future. The WEAP model was used to simulate future water quality of the system at the upstream of the delta, popularly known as the panhandle, between Mohembo and Etsatsa covering 122 kilometres. The study area covers an area of 3460 square kilometres including the settlements of Seronga, Sepopa and Guma. Due to data availability, the year 2015 was used as the current accounts year within which all scenarios in water quality data, upstream and downstream discharge, rainfall, latitude, air temperature, humidity and cloudiness fraction were built with respect to what the model requires. 2030 was set as the target year to explore the possible changes that may occur to the water quality of the system in the future.

The major insights emerging from this investigation is that, although the measured and the simulated water quality results for EC, pH and temperature of the Okavango River fall within the water quality standards stipulated in (DWAF, 1996) and (ANZECC, 2000), there are possibilities of future water pollution. Currently, the overall impression of surface water quality of the Okavango panhandle in all the sampled sites is generally of acceptable quality for domestic consumption and aquatic systems water quality standards. Considering the planned expansion of the irrigation schemes and hydropower generation in Angola, and the construction of a water transfer pipeline in Namibia, the overall amount of water that flows in the Okavango River as well as in the delta will decline and thereby impacting water quality. Additionally, since the area is a famous tourist attraction site, it present great opportunities for future expansion of the tourism industry, increasing human population and demand for space and water resources, the overall ecological integrity of the Okavango catchment area could be disrupted. The tested water quality parameters in EC, pH and temperature are not sufficient to draw valid conclusions of what will happen to water quality in the future.

7.2 Recommendations

Following the results obtained from the study, it is recommended that;

i. more research can be conducted to include other water quality parameters, outside pH EC and temperature, that the current study did not cover. However, when conducting water quality modelling using WEAP, one must be mindful of the limitations of the model. WEAP does not model DO without BOD. For this study, DO was one of the parameters to be tested, but since there was no data available for BOD, DO could not be modelled. DO is an important parameter in determining the health of surface water ecosystems.

ii. For water discharge and demand, it is important to collect real-time water data on the ground than to make assumptions based on primary data provided. For example, daily water abstractions, assumptions cannot be made based on the maximum allowable abstraction rate, but on the exact amount of water withdrawn from the system and used. This involves putting up gauges at the abstraction sites to record real-time abstraction rates and this could be a challenge. This exercise could even be difficult in areas where there are illegal water abstractions that are not accounted for.

iii. Before attempting to conduct modelling using WEAP, it is vital to collect all the data the model requires in order to obtain the best results and ultimately draw valid conclusions. This study was intended to model 5 water quality parameters, but due to limited data and the limitations of the model, the study was narrowed down to 3 water quality parameters.

iv. Since the Okavango Delta covers a large surface area, it has a variety of habitats that make it complex. As a result, it is a difficult ecosystem to conserve. Proper water management and conservation, especially at the upstream where there plans to divert the water in Angola and Namibia. If proper water management structures are put in place at the upstream, the results will reflect at the downstream channels.

v. Data collection and availability about the Okavango River catchment remains a challenge. It is therefore recommended that all relevant stakeholders that conduct water data collection in the systems be consistent with data collection and make it available through online resources. Information on water resources planning and management is of utmost importance for water planning and management.

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