The Impact of Dam Construction on Downstream Water Resources: A case of Nandoni Dam in Luvuvhu quaternary catchment A91F, North-Eastern South Africa.

By

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A dissertation submitted to the Department of Earth Sciences Faculty of Science, Engineering and Agriculture for the fulfilment of a Master's degree of Earth Sciences in Hydrology and Water Resources

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Declaration

I, Phathutshedzo Mathule hereby declares that this dissertation submitted for the fulfilment of a master's degree in Earth Sciences in Hydrology and Water Resources at the University of Venda, the Department of Earth Sciences Faculty of Science, Faculty of Science Engineering and Agriculture by me, has not been previously submitted for a degree at this or any other University, and that it is my own work in concept and design. All materials used are duly acknowledged and referenced in the text and a compilation of them can be found in the list of references.

Signature: ______________________ Date: 21 August 2023

Abstract

Globally, there is increasing concern over the increased damming of rivers, as this has led to a change in the hydrological regime and transformation of river runoff. There are varying impacts of dams on river flow regimes depending on how these dams are operated. Damming of rivers has altered the hydrologic cycle globally, causing severe consequences for streams' ecological and morphological equilibrium. Reservoir use and its impact on flow regimes have not yet been linked in a recognizable way. This study assessed Nandoni Dam water resources in relation to inflow and outflow, and the amount of streamflow required to maintain the ecological integrity. The inflows and outflows in dam were determined using the traditional water balance approach. Streamflow data collected at Mhinga station A9H012 downstream of Nandoni Dam before dam construction was used to calculate environmental flows using the IHA/RVA methodologies. Inflows trends over the study period were found to be on a downward trend. Peaks in computed inflow occur during periods of heavy rainfall as excepted for rainfall-runoff relationships. Abstraction of water from the Nandoni Dam for domestic purposes (i.e., to water treatment plants) increases over the study period despite increases or decreases in dam water storage. The downstream flow of the dam is impacted both positively and negatively, despite quantitative suggestions regarding streamflow required to maintain ecological integrity. A range of environmental flow requirements was presented in this study downstream of the Nandoni dam. Values for selected Environmental Flow Components (EFCs) parameters are presented as percentiles between 10% and 90%. Different durations of analysis show significant variations in minimum and maximum flows. High pulse numbers, as well as the rate at which they rise and fall, have changed significantly. Hydrologic regime downstream was disturbed, and streamflow variations were directly affected by the construction of the dam. It is crucial to build a detailed water budget model that considers climatic, hydrological, and stakeholder interests to optimize dam operation rules. Reservoir operations must be developed with the participation of riparian communities, engineers, hydrologists, physical geographers and climatologists and general environmentalists to be socially, economically, and environmentally sustainable.

Keywords: climate change, ecological integrity, hydrologic alteration, inflows, Nandoni Dam, water balance.

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Dedication

This dissertation is dedicated to my father, Kanakana Albert Mathule, and my big brother, Rolivhuwa Mathule. They have been a constant source of support and encouragement throughout my life's challenges. This work is also dedicated to my younger brothers Vhutshilo Mathule, Mulalo Mathule and Rabelani Mathule. In addition, my uncle Nditsheni Mathule whom I am truly grateful to have in my life. Lastly, to my wonderful and deeply missed mother, Avhashoni Daphne Ndou, you will always be in my heart as you loved me unconditionally and taught me to work hard on everything I aspire to do.

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List of Abbreviations

EFR:	Environmental Flow Requirement
MDGs:	Millennium Development Goals
EF:	Environmental Flow
EFC:	Environmental Flow Components
IHA:	Indicators of Hydrologic Alteration
RVA:	Range of Variability Approach
SEI:	Stockholm Environment Institute
WEAP:	Water Evaluation and Planning system
SWAT:	Soil Water Assessment Tool
DST:	Decision Support Tool
CA:	Correlation Analysis
RA:	Regression Analysis
ITCZ:	Intertropical Convergence Zone
SDGs:	Sustainable Development Goals
NDP:	National Development Plan

CHAPTER 1: INTRODUCTION

1.1. Background

Globally, there is increasing concern about increased river damming, which has resulted in a change in the hydrological regime and the modification of river runoff (Gierszewski et al., 2020). According to a 1990 internal World Bank analysis of hydroelectric dam projects, 58% were planned and completed without any consideration of downstream impacts, even when these impacts might be projected to create major coastal erosion, pollution, and other problems (Pottinger, 1996). In-stream dams alter river baseflows and flooding regimes, affecting river water quality, pollution dilution, and habitat availability, and have resulted in the fragmentation of more than half of the world's main river systems (Mantel et al., 2017). In South Africa, 84% of 112'major rivers' (the main channel of a river that connects water management regions) have been identified as critically endangered or vulnerable due to human intervention (Mantel et al., 2017). Studies on the Pongolo River floodplain in South Africa have revealed a decline in forest species variety following damming, and forests along Kenya's Tana River appear to be slowly dying off due to a reduction in large floods caused by a succession of dams (Pottinger, 1996). According to Mantel et al. (2010), the cumulative effect of a large number of small dams is affecting the quality and quantity of water in South African rivers, and these consequences must be carefully incorporated into the environmental water monitoring procedure.

The study area is set on the Luvuvhu River in quaternary catchment A91F. The Luvuvhu River Catchment is in the Luvuvhu/Letaba Water Management Area of South Africa's Limpopo Province. The Luvuvhu River flows for around 200 kilometers across a variety of landscapes before joining the Limpopo River near Pafuri in the Kruger National Park (Odiyo et al., 2015). Dams in the LRC, according to Griscom (2007), have exerted a significantly greater impact upon dry season flows than changes in land cover and are expected to continue to do so in the future. The amount of water that is stored, how high the water level fluctuates, how much silt is caught and released, and downstream flow patterns are all determined by dam operation modes. Large dams impact downstream flows and change the physiography of catchment areas all throughout the world (Schmutz and Moog, 2018). Streamflow variability has increased within the Luvuvhu River Catchment over an 86-year period, indicating that anthropogenic activities and reservoir construction may be influencing river flow (Ramulifho et al., 2019).

The Luvuvhu River is dammed to form the Albasini Dam, which is located upstream of the Nandoni Dam. Albasini Dam meets a portion of the irrigation needs of big commercial farms in the catchment, whereas Nandoni Dam mostly meets domestic water supply needs. It also promotes recreational and fishing activities (Odiyo et al., 2020). The Luvuvhu River Catchment is one of South Africa's regions experiencing fast land cover and land use change. The catchment has been subjected to significant land use change over the past decades as a result of increased population growth and associated developments in Vhembe District, causing accelerated environmental degradation and negatively impacting the hydrology and water availability in the area (Kundu et al., 2015). Water availability for irrigated agriculture, flow availability for dam water supplies, or water harvesting, and storage are all likely to change as catchment water flows change (Odiyo et al., 2020).

1.2. Problem statement

The inflow into Nandoni Dam is ungauged. The Nandoni Dam receives inflows from Luvuvhu River (water releases from Albasini dam) and its tributaries of Mambedi, Latonyanda and Mvudi (Makhera et al., 2011). The flow contributions from tributaries to Luvuvhu River are important for ecosystem sustenance, meeting downstream domestic and agricultural water demand and ecological water requirements particularly in Kruger National Park (Odiyo et al., 2012). According to Masupha and Moeletsi (2017) since the 1980's, the Luvuvhu River Catchment had been subjected to arrange of mild to extreme droughts. It has been estimated that if Nandoni Dam is not managed to maintain ecological flows, the river will dry five times more than before the dam was constructed (Griscom, 2007). The variability of streamflow has increased within the Luvuvhu River Catchment (Ramulifho et al., 2019).

1.3. Motivation

Studies that focus on Environmental Flow Requirements (EFR) in the Luvuvhu River are limited and it is still unknown how the Nandoni Dam is affecting the downstream water users. River restoration and water resources management could benefit greatly from investigating and assessing downstream impacts of dams (Li et al., 2012). As a result of damming a river ecosystem, natural resources, habitat quality, ecosystem integrity, and environmental sustainability can be lost (WCD, 2000). Due to rapidly changing land use and land cover in the Luvuvhu River Catchment (Kundu et al., 2015), it is also crucial to estimate impacts of change in its water yield and water balance for the sustainable management of this water resource (Adeogun et al., 2014) to ensure water security and environmental sustainability. An integrated approach is required to manage Nandoni Dam in the Luvuvhu River Government Water Scheme, supplying water for domestic, industrial, irrigation, and to maintain ecosystem health (Maré et al., 2007). Due to potential of Nandoni Dam impacting the streamflow regimes and downstream water users in the LRC, it is crucial that such a study is conducted.

1.4. Objectives

The main objective of this study is to assess Nandoni Dam water resource pertaining to its inflow and outflow and evaluate the dam construction impacts on downstream water users. The specific objectives are to.

- Assess Nandoni Dam water resources in relation to inflow and outflow.
- Determining the amount of streamflow required to maintain the ecological integrity.
- Assessing Nandoni Dam impacts on streamflow trends between current and historic flow conditions downstream.

1.5. Research questions

- How much water flows into and out of Nandoni Dam?
- How much water is required to meet environmental flow requirement downstream of the dam?
- Does the Nandoni Dam affect the trends of streamflow downstream when compared to historical flow conditions?

CHAPTER 2: LITERATURE REVIEW

2.1. Chapter overview

The goal of this chapter is to review the literature on water resources, downstream dam effects on water flow requirements at dams, and other topics relevant to the study. Water consumption and water resources are also discussed in relation to the impact of a variety of factors. A literature review is also conducted on water availability and distribution in South Africa. Furthermore, dams' effects on water supplies, flow requirements, and the environment were discussed.

2.2. Introduction

Climate change and changing land-use patterns are driving global change, putting pressure on natural water resources worldwide (Perry, 2015). Water quality and catchment water protection are currently top priorities for policy makers, as well as sustainable water management policies (Tena et al., 2019). Water from surface sources is an essential resource in semi-arid regions (Tulbure et al., 2016). In order to secure future water supplies, reservoir dynamic models should be developed for a river basin of a large size, considering environmental change and an increase in water demand (Güntner et al., 2004). Runoff generation and water consumption need to be considered when evaluating hydrological dynamics under environmental change (Güntner et al., 2004). There is typically a need to cover a large area when evaluating a river basin, since any impact on the river basin will affect downstream areas (Barbier, 2003). To ensure optimal water management, it is necessary to analyse and measure the hydrologic processes occurring within the area of interest. By relating runoff and reservoir storage to hydrologic processes within a watershed, flood risk can be determined, or water availability can be anticipated (Vining and Vecchia, 2007). Flow rate and catchment balance are key factors in managing water resources at the watershed level. Managing water resources efficiently requires understanding how water flows through watersheds and basins (Adeogun et al., 2014).

2.3. Agenda 21 of the Earth Summit in Rio 1992, and the successor reports on Millennium Development Goals, followed by Sustainable Development Goals.

Since 1992, local governments have been working towards implementing Local Agenda 21, an agreement made at the Earth Summit in Rio to promote sustainable development. Local authorities have a crucial role in educating and motivating the public, as well as responding to their needs, in order to achieve sustainable development (Carter and Darlow, 1997). The actual implementation of Local Agenda 21 practices does not align with the ideal model. There is limited progress in terms of participation and many processes lack long-term planning and monitoring. This disconnect between intentions and reality can be attributed to limited resources and decision-making power of local governments, a hierarchical political-administrative system, and the top-down mindset of local representatives. Despite these challenges, Local Agenda 21 processes have had a lasting impact on how we approach and carry out sustainable development (Alvesson and Sveningsson, 2015).

Sustainable development is a concept that considers the environmental, economic, and socio-cultural needs in a way that is renewable and viable in the long term. Although the idea of sustainable development is widely accepted, its actual implementation is lacking. At the United Nations Conference on Environment and Development, a plan called Agenda 21 was proposed to make sustainable development more practical. This plan included actions at various levels, including international, national, regional, and local. At the local level, this plan was referred to as Local Agenda 21 and was given a significant role due to the close proximity of local authorities to citizens and businesses, their understanding of local needs, and their influence on local actors (Barrutia et al., 2015). The World Summit on Sustainable Development in 2002 was supposed to address global poverty and environmental protection and provide specific targets and timelines for implementing Agenda 21. However, the summit did not meet these goals. Negotiations were slow and often focused on minor details, and instead of making significant progress, the summit ended up being more about damage control (Von Frantzius, 2004).

The Sustainable Development Goals (SDGs) improve upon the Millennium Development Goals (MDGs) by addressing more comprehensive challenges and emphasizing the need for global economic reforms. Unlike the MDGs, the SDGs reject the idea that simplicity and quantification are the best approach to setting global goals. However, the successful implementation of the SDGs will require ongoing advocacy to ensure that authorities are held accountable for achieving the targets (Fukuda-Parr, 2016). The Millennium Development Goals (MDGs) were an effective way for the world to come together and address important social issues such as poverty, hunger, disease, education, gender inequality, and environmental problems. By establishing specific goals and measurable targets, the MDGs helped to raise global awareness, hold governments accountable, improve data collection, gather public feedback, and create pressure for action. They were seen as a way to evaluate progress in the fight against poverty over a 15-year period (2000 – 2015) (Sachs, 2012).

The United Nations adopted the Sustainable Development Goals (SDGs) in 2015 as a successor to the Millennium Development Goals. The SDGs encompass a wide range of objectives, including energy, climate, water, food, health, poverty, and innovation. This is a significant improvement from the MDGs, which did not address these issues comprehensively. The seventh SDG focuses on ensuring access to affordable, reliable, sustainable, and modern energy for all. This goal is supported by three specific targets. By 2030, the goal is to make sure everyone can access energy that is affordable, reliable, and up-to-date. Additionally, there should be a significant increase in the use of renewable energy sources worldwide, and the rate at which energy efficiency improves should be doubled (McCollum et al., 2018).

Mthembu and Nhamo (2021) discussed how South Africa has been adopting and implementing the United Nations' Sustainable Development Goals (SDGs). The study found that South Africa has made progress in aligning its initiatives with the SDGs, particularly through its National Development Plan (NDP) Vision 2030. However, there are still some challenges, such as uncertainty about funding for the SDGs. Overall, South Africa has taken steps to domesticate the SDGs, but there is still work to be done (Lince-Deroche et al., 2016). The "barometer for inclusive sustainable development in South Africa" is one way of summarizing national SDG status. Using 20 critical indicators of environmental stress and social deprivation, the barometer downscales global social and planetary boundaries. Compared to the national average, provinces need different approaches to dealing with environmental stress (Cole et al., 2014). However, there are some areas where environmental stress is decreasing, including marine harvesting. In terms of social deprivation, historically disadvantaged provinces show a greater degree of deprivation overall, with high levels of unemployment, income and safety. Despite general decreases in deprivation, there are notable exceptions, including food security in six provinces. The regional barometers and trend plots provide comparisons of environmental and social indicators for all South African provinces over time, which is unique (Cole et al., 2017).

2.4. Water resources availability in South Africa

Almost 260 million people in Sub-Saharan Africa suffer from undernutrition, while 600 million in Africa lack access to clean water (Faramarzi et al., 2013). Various factors contribute to the scarcity and difficulty of accessing and using water. Among these elements are variable weather, uneven distribution of water resources, unexpected rainfall patterns, and human factors like population growth and conflict over shared water resources (Yang et al., 2013). Water resources in developing countries could be impacted significantly by climate change. Dams and reservoirs have been built throughout the North African region in order to ensure the steady flow of water in the face of significant interannual precipitation changes (Tramblay et al., 2018). Water resources management and domestic water provision remain formidable challenges for many countries, especially in Africa. It is no exception for South Africa, despite its relatively high economic development relative to its neighbours (Dungumaro, 2007).

South Africa is one of the driest nations in the world as a result of its semi-arid climate. Unless the nation manages its current reserves and use patterns well, it will experience severe water shortages (De Wet, 2010). South Africa, which has 450 mm of annual rainfall, falls short of the global average of 860 mm (Botai et al., 2018). It is almost exclusively arid or semi-arid in the interior and western parts of the country, with the exception of a tiny area along the south-eastern coast. There are parts of the country that receive less than 500mm of rainfall per year, while there are parts of the country which receive less than 200mm (Mukheibir, 2007).

Compared to other rivers in South Africa (Inkomati, Pongola, Limpopo, Orange), the Zambezi River is the longest and most navigable. With a combined annual flow of only 49,000 m3/a, the Zambezis contain more than twice as much water (Thopil and Pouris, 2016). South African rivers are commonly dry throughout most of the year due to low stream flows. In view of this physical characteristic, only a small proportion of stream flow is usable (Mukheibir and Sparks, 2003). According to Hanson and Basson (2003), Approximately 49 200 million m^3 of surface water are available annually in South Africa, with the amount being highly variable in the drier regions, which requires large reservoirs for relatively low yields. It is estimated that 50% of water runoff in South Africa comes from strategic water source areas, despite only covering 8% of the land. It is estimated that these regions contribute to the economy and population of South Africa by at least 51% and 64%, respectively (Nel et al., 2017). The growing population and expansion of the economy in South Africa are putting a strain on freshwater resources (Oberholster and Ashton, 2008).

In order to store more than two thirds of the average rainfall in the country, the government-built dams. There are more than 500 dams registered in the country based on the 2016 dam database (Mwendera and Atyosi, 2018). Physical water scarcity is predicted to severely impact South Africa by 2030. In order to avoid a future water crisis, conventional schemes involving impounding rivers need to be reduced (Fisher-Jeffes, 2017). Several parts of South Africa depend heavily on groundwater for their freshwater, so protecting and allocating it has become a key issue (Knüppe, 2011). Due to the country's hard rock geology, only 20% of its major aquifer systems are exploitable at large scales (Thopil and Pouris, 2016). Several parts of the country depend heavily on groundwater to sustain their livelihoods (Abiye and Bhattacharya, 2019). Ebrahim and Villholth (2016) report that groundwater has become an important water resource in South Africa for multiple purposes. Aside from drinking, irrigation, and numerous industrial processes, it is frequently used in its natural state because of its good quality (Edokpayi et al., 2018).

South African government officials have identified rainwater harvesting as a sustainable alternative source of water for households (Strauss et al., 2016). Agricultural and domestic activities can benefit from rainwater harvesting systems that collect, concentrate, and store runoff (de Kwaadsteniet et al., 2013). A changing climate makes rainwater harvesting a viable option for supplementing surface and groundwater supplies (Singh et al., 2017). Its affordability and ease of operation and maintenance make rainwater harvesting (RWH) superior to other sources of water supply (Ndiritu et al., 2014).

2.5. Water demand and supply in South Africa

In South Africa, the water crisis is being exacerbated by a decreasing water supply and declining water quality (du Plessis, 2017b). Water supply within the country is under pressure from increasing demand (Jacobs-Mata et al., 2018). Over 51 million people live in South Africa, and 60% of them live in urban areas. Around 77% of the South African population depends on surface water resources due to the uneven distribution of water resources. More than 60% of Africans lack improved sanitation facilities and 40% lack improved water supply (Molekoa et al., 2021). Approximately 70% of South Africans' drinking water is surface water, originating from, streams, rivers, springs, lakes and ponds (George et al., 2010).

Water resources in South Africa are already at their limit after 97% of the supply has been allocated. 60 percent of the water available for use is allocated to agriculture, 27 percent to domestic use, 3 percent to industry, 3 percent to mining, and 2 percent to power. Other smaller consumers make up the remainder (Ahjum et al., 2018). The consumption of water by South Africans per month exceeds 6 kilolitres (Jacobs-Mata et al., 2018). Many large urban areas are predicted to face water shortages, which will require interventions (Du Plessis, 2017b). In order for a country to develop socio-economically, it must have access to water for food security, industrial production, ecosystem maintenance, and industrial production. South African suburban families consume approximately 300 liters of water per day, according to Jacobs-Mata et al., 2018.

2.6. Dams/reservoirs as a source of water supply

The development of water resources worldwide has evolved in various ways and directions throughout history. For a long time, humans have been trying to find ways to manage freshwater resources in order to reduce their dependence on unpredictable river flows and rainfall (Gleick, 2000). To ensure a consistent water supply for human activities, it is necessary to build dams and reservoirs to store water during rainy seasons and use it during droughts. Dams are barriers that collect and raise the water level, while reservoirs are artificial bodies of water created in river valleys for water storage (dos Anjos Luís and Cabral, 2021). There are several factors that engineers consider when categorizing dams, including their size, purpose, and age. Dams come in different sizes and the size of a dam can have significant environmental impacts (Hansen et al., 2021). However, the criteria used to classify dam size by government agencies and organizations do not accurately reflect this variation and are not consistently applied. For example, the US Army Corps of Engineers considers dams to be large if they pose a high risk to human life, are taller than 7.6 meters with a storage capacity of over 18,500 cubic meters or are taller than about 1.8 meters with a storage capacity exceeding 61,700 cubic meters. Other organizations have different criteria, such as classifying dams as large if they are taller than 15 meters or have a reservoir capacity greater than 3 x 106 cubic meters (Poff and Hart, 2002).

Civilization built dams for flood control, irrigation, storage and during the development of civilization. In addition to generating hydropower, dams are used as recreational facilities, waste disposal sites, and for generating water for mills (Okyereh et al., 2019). Many countries with seasonal rainfall regimes benefit from the installation of small dams to increase water reliability for agricultural production (Hughes and Mantel, 2010). A dam can ensure a dependable supply of water by storing freshwater during seasons and years of abundance (Niasse, 2005). As a result of these dams, industries, municipalities, and farms gain increased access to water, flood control is improved, and hydropower is produced. As a result of these dams, industries, municipalities, and farms gain increased access to water, flood control is improved, and hydropower is produced (Li et al., 2012a).

There are over 45,000 large dams in more than 140 countries, with the majority being in China, the United States, India, Spain, and Japan (Tannahill et al., 2014). During times of water stress, South Africa relies on storage reservoirs for water. Boardman and Foster (2011) report that over 98% of the country's water resources have already been allocated to the use of their citizens. Until after Apartheid, South Africa rarely constructed dams within or near homelands (Mettetal, 2019). There are about 0.33 million people who receive a significant portion of their livelihoods from surface water in the Mogalakwena River catchment area, where agricultural livelihoods, industrial operations, and everyday use are highly dependent on surface water. (Molekoa et al., 2022). 16 km southeast of Thohoyandou lies the Nandoni Dam of the Luvuvhu River South African Government Water Scheme. Pumping stations, bulk water distribution pipelines, and two water treatment plants make up the system. In addition to supplying water for domestic purposes, the scheme is also designed to supply irrigation water and water for forestry (Fouche et al., 2013). South Africa's Eastern Cape province, at the mouth of the Tsitsa River, two dams are being built as part of the Mzimvubu Water Project (MWP). (Ntabelanga and Laleni dams). Rural, underdeveloped, and poor regions of this region will benefit significantly from this investment (Bester et al., 2019).

2.7. Factors affecting downstream water uses.

The availability of water is fundamental to the survival of life, societies, and livelihoods. Both managers and users face extraordinary challenges as water resource availability changes (Okyereh et al., 2019). It is essential to understand the current challenges and to develop innovative approaches to manage water resources effectively (Goonetilleke and Vithanage, 2017). Some of the difficulties cited by Connor (2015) include socioeconomic inequalities and the lack of policies to address them effectively, chronic poverty, and discrimination and inequalities in access to water and sanitation (Despite the fact that water services play a significant role in human and economic development, they remain low on the policy priority list)). Increasing air pollution and climate change increase the challenges associated with environmental degradation, particularly water resources. (Okyereh et al., 2019). The movement of terrestrial water is influenced by climate as well as human intervention, including the operation of dams and withdrawal of water. The water cycle will be impacted by climate change, which will affect how much water is available and how much water is demanded (Haddeland et al., 2014; Oberholster and Ashton, 2008).

2.7.1. Climate change

In the past century, increased greenhouse gas emissions have greatly impacted global and regional hydrological cycles (Hagemann et al., 2013). Temperature and precipitation fluctuations have increased as a result of climate change. It is predicted that these changes will both persist and accelerate in the future (Misra, 2014). When more stress is applied to a shrub or woodland, evapotranspiration increases, water is used more efficiently, and precipitation is intercepted more frequently. Surface water balance will be affected by this, along with evapotranspiration, runoff, and groundwater flows (Garca-Ruiz et al., 2011). According to most climate models, temperatures will rise, and precipitation will fall by the end of the 21st century (Garca-Ruiz et al., 2011).

The quality, availability, and accessibility of water resources in Africa are under threat due to climate change (Ziervogel et al., 2010). It is becoming increasingly evident that climate change is adversely affecting nearly every aspect of human life in southern Africa. This includes agricultural productivity, energy consumption, flood control, water supply to municipal and industrial facilities, as well as wildlife management and conservation. Throughout the region, rainfall patterns vary greatly, as well as variations in rainfall over time and space (Kusangaya et al., 2014). As a result of climate change, most climate models predict a 20% decrease in precipitation for southern Africa by the 2080s. These changes are predicted to result in a decrease in water availability and crop yields (Conway et al., 2015).

The South African government is one of the most concerned nations about climate change. Extreme rainfall occurrences have increased, and global warming has increased by 1.5°C over the past fifty years Ziervogel et al. (2014). climate change may create an increase in variability in the availability and demand of water resources in South Africa, according to Cullis et al. (2011). These dangers exist throughout the Orange River Basin in southern Africa because to agrochemical runoff, population growth, farming pressure, and extreme weather. Climate change, according to Sullivan (2011), is a factor in these risks because it is leading to higher temperatures and shifting water availability.

2.7.2. Land use

Population and economic activity are growing in the Limpopo region (Cullis et al., 2011). Afforestation, irrigation, and domestic use of water to supply the LRC large population, as well as the construction of large dams in the catchment, negatively affect the flow of the Luvuvhu River, especially in Kruger National Park (Maré et al., 2007). In addition to dams constructed to store water, humans also withdraw water for industrial, agricultural, or domestic use. (Haddeland et al., 2014) The region is growing in population as a result of migration from outside South Africa and as a result of agriculture and mining (Todes et al., 2010). A recent United Nations report predicts that nearly 6 billion people will lack access to clean water by 2050. In response to dramatic population growth and economic growth, water demand is on the rise, resources are being depleted, and pollution is increasing (Boretti and Rosa, 2019a).

2.8. Impact of dam on downstream water uses.

Riparian communities are at risk of losing many environmental and social benefits as a result of dam construction. Water competition and the livelihoods that depend on them can be adversely affected by altered natural flow regimes downstream (Okyereh et al., 2019). There are varying impacts of dams on river flow regimes depending on how they are operated. Studying the impacts of dams on downstream ecosystems has gained worldwide attention in recent years (Li et al., 2012a). As a result of damming, the hydrologic cycle has been altered globally, causing severe consequences for streams' ecological and morphological equilibrium. Reservoir use and its impact on flow regimes have not yet been linked in a recognizable way.

The increase in water supply, on the other hand, promotes regional heterogeneity and streamflow variability (Ferrazzi and Botter, 2019).

Water and other resources that depend on dams are often negatively impacted by their presence. Multiplication of dams results in more withdrawals and altered flow regimes due to fragmentation of river courses caused by dam construction (Niasse, 2005). Climate change, unpredictability, and increased water withdrawal have all led to a decrease in water availability in West Africa. The growth of huge dam projects has increased tensions and conflict risks due to the interdependence of water supplies, which is at a high level (Niasse, 2005). Several characteristics of the Yangtze River's flow regime have changed as a result of human activity like dam construction. Different water users' water allocations and instream biological water needs may not be guaranteed at certain times of the year, particularly during reservoir storage phases, as a result of dam-induced changes in Yangtze River flow regimes (Li et al., 2012a).

2.9. Environmental impacts of the dam

Because they provide food, water, and other ecosystem services, rivers play a crucial part in determining the physical and ecological landscapes of the planet (Beck et al., 2012). Dams, artificial lakes, and large reservoirs on rivers are built to meet a large portion of a society's water demand (Manouchehri and Mahmoodian, 2002), which may cause significant changes to ecosystems. A growing number of people are concerned that dam projects will result in irreversible environmental changes (Manatunge et al., 2008). During the construction phase and after the completion of construction, dams cause many negative impacts on the environment and society, but their most severe impacts last for thousands of years during the operational phase (Alla and Liu, 2021). A dam can negatively affect the environment upstream, downstream, and in a reservoir (Beck et al., 2012). It, however, has adverse effects on, aquatic ecology, air quality, vegetation, wildlife, land, and water quality (Alla and Liu, 2021).

2.9.1. Impacts on Water Quality

There are many factors affecting water quality from dams, including their size, where they are located in the river system, their altitude and latitude, and how long they are in operation (Wang et al., 2014). Agricultural activities on floodplains are hampered owing to limited nutrient-rich sediments in the reservoir, which limits its storage capacity and at the same time limits sediment flow downstream (Manatunge et al., 2008). As a result of the reservoir's large amount of nutrients, algae can grow freely. There is a possibility that this will lead to eutrophication (Wang et al., 2012).

Water quality has been investigated in the sub-catchments of the Vaal Dam and Wilge River as part of the Lesotho Highlands Water Project. Water quality in the upper Vaal River reaches has improved due to this management, and there have been no adverse effects on the Vaal Dam. Despite this, the greater flow of water into the system could harm the environment of the river due to the soil erosion caused by increased water flow (Wright, 2008). It was determined that the Steelpoort River still has the same water quality as before the construction of the De Hoop Dam and bulk water transfer pipeline, which was based on an assessment of the impacts of both the dam and bulk water transfer pipeline just downstream of the dam. However, sediment loads added during construction deteriorated the water quality in Steelpoort River (Magala, 2015).

2.9.2. Impacts on Aquatic Ecology

In addition to altering natural flow regimes, dams adversely affect aquatic biodiversity in several ways, including fragmenting habitat, reducing habitat quality and complexity, and nutrient cycling, disrupting erosion, sediment transport and channel scouring (Beatty et al., 2017). There are certain migratory patterns that aquatic species follows in rivers throughout their life cycle. During different stages of their lives, such as spawning, juvenilehood, or sexual maturity, species move between different reaches of a river.Many species may be driven to extinction because of dams blocking their migratory paths and reducing their populations (Wang, 2012). As a result of reservoir formation, water temperature, salt distribution, and oxygen distribution may change vertically. Consequently, various species may emerge, and the original environment may be replaced (Dwivedi et al., 2010). A dam's construction may alter sediment charge, flows, temperatures, water quality, food availability or other water physicochemical parameters affecting planskton (Wu et al., 2019).

Heath and Plater (2010) Identified sediment composition within two floodplain pans of the Pongolo River floodplain, KwaZulu-Natal. The hydrological regimes of Bumbe and Sokhunti pans differ due to their connection to the main Pongolo channel. According to the results, the sediment composition and variability of the two pans are similar in their lower parts, but in Bumbe pan, fine-grained mineral supply and nutrient influx are increased while in Sokhunti pan, nutrient status is enhanced resulting in increased biogenic productivity. As a result of a change in hydrology, flood frequencies have reduced, and baseline flows are more regular resulting in a reduction in average flow velocity.

2.9.3. Impacts on Land Use

Land use patterns may be impacted by reservoir inundation. Locals may be required to shift upward so that new cropland can be cleared where forest originally covered the region. Furthermore, this change in land usage may worsen soil erosion, endangering biodiversity (Wang, 2012). Large dam developments have a negative impact on agricultural production on various levels. The most direct and substantial effect that dams have on agriculture is flooding of farms (Wang, 2012). Millions of people have been uprooted or relocated due to dam building throughout the world, which has caused the ruin of innumerable archaeological and cultural sites, the loss of more than a million dwellings, and substantial ecological impacts (Dwivedi et al., 2010).

Following the construction of the Pongolapoort Dam on the Phongolo River in KwaZulu-Natal in 1973, it drastically changed the hydrological response of the downstream floodplain. (2015) (Dube et al.). The socioeconomic importance of wetlands and floodplains has been impacted by the shifting flooding regime. Based on the rhetoric of economic opportunity and poverty relief, it was investigated if the Nandoni dam would produce economic opportunities, reduce poverty, and whether its development would develop rural areas. The Nandoni Dam benefits the wealthy, powerful, and influential at the expense of the local community, with long-lasting negative effects on their lives and livelihoods (Sinthumule, 2021).

(Kibret et al., 2021) four river basins in sub-Saharan Africa, the effects of minor and large dams were examined (i.e., Omo-Turkana, Limpopo, Zambezi and Volta). Findings indicate that dams' influence on malaria is far bigger than previously believed. Future disease control efforts should be heavily focused on small and large dams because they are malaria hotspots. On the Mngeni River near Durban, in the province of KwaZulu-Natal, this study looked at how the relocation affected the quality of life for more than 1300 rural households with community ("tribal") tenure, settlement options, and barriers to effective adaptation. The dam generally had a detrimental impact on the displaced households' quality of life. Even though people may have access to amenities like electricity and water pipes, the lack of sufficient homes and land overwhelm these advantages. There is an increase in monetary-based livelihoods due to an inaccessibility to common property resources. In addition to internal constraints, external factors also limit adaptability. People are moving to locations with bad economic conditions, a lack of environmental resources, and an unfavourable political climate (Ninela, 2002).

2.9.4. Impact on Vegetation/Terrestrial livings

As a result of damming, plants and other biota are impacted, which decreases bird populations and diversity (Wu et al., 2019). When reservoirs are built, terrestrial plants are most affected by flooding. However, animals emigrate far away from reservoirs as habitats are destroyed, food habitats disappear, and activity spaces are diminished. In addition to regulating the local climate, the reservoir fills with water and has a variety of vegetation types surrounding it. Waterfowl habitats can also be created by irrigation development due to its wet climate (Wang et al., 2012). A dam's impact on downstream river ecosystems was assessed in Limpopo Province, South Africa. An assessment of five dams was conducted (Damani, Albasini, Mambedi, Vondo and Nandoni) (Mokgoebo et al., 2018) incorporating aerial photography, orthophotos, and fieldwork. It was observed that riparian vegetation decreased at Mambedi and Vondo dams, indicating that they were more fragile and less resilient (Mokgoebo et al., 2018).

2.10. Assessment of water resources in relation to inflow and outflow

The water balance is a basic principle in hydrology that is used to predict streamflow, soil moisture, and groundwater availability (Al-Sudani, 2020). The balance of water in a catchment area is mainly influenced by the overall climate conditions, with local factors playing a role as well (Han et al., 2022, Makhtoumi et al., 2020). It is represented by an equation that considers water inputs, outputs, and storage in a watershed. Inputs can be rainfall, snowmelt, or imported water. Outputs include evaporation, transpiration, and sublimation, as well as streamflow and water diversions. Water storage can be in the form of snow or ice, surface water bodies, or underground (Kampf et al., 2020). The water budget equation explains how water moves between the land, ocean, and atmosphere. If we can accurately calculate the water budget, it means we can confidently study the changes in the water cycle and its components over time and space (Lehmann et al., 2022).

Various hydrological models have been created with differences in their approach and methods for calculating water balance components. These models also vary in complexity and their suitability for different areas and time periods. The interconnected nature of the hydrological cycle necessitates complex mathematical techniques and the use of hydrometeorological and geophysical data (Ivezic et al., 2017). The several models available for assessing the water balance, including the WBalMo Model, SWAT, SEI's WEAP, and CaWAT. These models are used to manage water resources, determine hydrologic components, and plan for water allocation. Among these models, WEAP is widely used globally for accounting water balance on a monthly basis and can be applied to various scales of water management (Phue and Chuenchooklin, 2020).

The WEAP model was used to evaluate and examine the management of water resources in western Algeria's watersheds. The WEAP program provides planners with a strong foundation to make recommendations for future water resource management by highlighting actionable hotspots (Hamlat et al., 2013). WEAP was used to assess the water resource management plans in Binhai New Area (BHNA). Several suggestions were made as a result of these findings to help decision-makers organize water management to satisfy future demands in the BHNA region (Li et al., 2015). The WEAP model was tested in the Steelpoort sub-basin of the Olifants River in South Africa. The model may simulate and assess a range of water allocation scenarios, but most significantly, user behavior scenarios, according to study by Lévite et al. (2003a). WEAP was utilized to evaluate, analyse, and project prospective future circumstances as well as the current balance and contribution of treated wastewater to the Nablus and Tulkarm watersheds. The WEAP program provides a solid framework for planners to use when making suggestions for managing water resources (Yaqob et al., 2015).

The hydrologic cycle in the SWAT model utilizes the water balance equation, which includes the unsaturated zone and shallow aquifer as a single unit above the impermeable layer. water balance equation is a crucial equation used in SWAT to forecast hydrology in a watershed (Ghoraba, 2015). The water balance equation is a useful tool for understanding and studying the water cycle in a river catchment. It has been used in various studies to explain changes in hydro-climate, validate model estimates, and estimate components of the water cycle (Lehmann et al., 2022). The advantage of this method is that it can help calculate unknown components of the water balance equation (Maswanganye et al., 2022).

A study by Maswanganye et al., 2022, was conducted in pools located along the Touws River in the Karoo region of South Africa. It examines water storage changes in pools along non-perennial rivers in the semi-arid Karoo environment. To determine how water fluxes impact pool dynamics, the study uses the water balance equation. By using water balance equations and meteorological data, Al-Sudani (2020) estimated Iraq's water surplus and natural groundwater recharge. In a study conducted in Southern Burkina Faso over two years, a small reservoir was monitored. Reservoir fluxes were estimated using a simple approach based on the mass conservation equation (Fowe et al., 2015). Water levels in Lake Victoria, which spans Uganda, Kenya, Tanzania, Rwanda and Burundi, are determined by the water balance of precipitation, evaporation, inflow from tributaries and outflow from the lake, which is controlled by two hydropower dams (Vanderkelen et al., 2018). This surface water balance approach has the benefit of not needing in-depth groundwater modelling or evaluation and does not rely on data or assumptions about lateral groundwater flows (Ahmad et al., 2020).

2.11. Environmental flow requirements

Due to the growing demand for water in communities, humans have built several water structures over the past few decades. In recent years, reservoirs, especially multiple reservoirs, have become increasingly popular because of their effects on river flow regimes and ecosystems (Zhou et al., 2020). Globally, governments are reducing these impacts through environmental flows requirements (Weber et al., 2017). Freshwater ecosystems, human livelihoods, and human well-being are supported by environmental flows in quantities, quality, and timing (Partel, 2019). According to Hughes and Hannart (2003), international recognition is growing for the importance of retaining some elements of a river's natural flow regime for sustainable development. The conservation of river systems with high biodiversity profiles is a global priority. Water supply, nutrient cycling, and disturbance regulation are all benefits of functioning river systems to society (Watson et al., 2019).

The water availability and ecosystem resilience have been severely strained in a number of perennial river systems in South Africa due to excessive abstractions (Gokool et al., 2019). Different catchments of the South African Lowveld have faced water shortages over the past century (Pollard and Du Toit, 2011). The recently enacted Water Law of South Africa emphasizes that low flows are crucial to aquatic and riparian ecosystems. In order to protect aquatic and riparian ecosystems, meet rural community water demands, and fulfill international obligations where rivers cross borders, an 'ecological reserve' must be maintained at all times (Dye and Croke, 2003). Flow regimes of rivers include low flows as part of a seasonal phenomenon (Smakhtin, 2001).

Environmental flow requirements must be considered when managing water resources in South Africa. Our method simulates natural flow conditions using near-real-time rainfall observations and operating rules. To ensure that downstream environmental flow objectives are met, the operating rules define curtailments in water use supply and reservoir releases (Hughes and Mallory, 2008). The characteristics of river flow must therefore be evaluated before and after a river's flow regime is altered (Ali et al., 2019). As a result of dams and other infrastructure, water flow regimes are altered in magnitude and pattern as a result of hydrological alteration (AH) (Ali et al., 2019).

The practice and science of environmental flow assessment (EFA) should guide water managers or regulators in choosing the best approach for their context (Opperman et al., 2018). A holistic approach to hydrological flow, habitat simulation, hydraulic flow, and rating flow methodologies are currently the four major environmental flow methodologies (Partel, 2019). The relative simplicity and the ease of application of hydrological methods across the globe make them widely used across the globe (Damiani, 2018). The Montana Method, the Range of Variability Approach, etc., are several common classification methods (Hao et al., 2016). River width, depth, and discharge are used to determine a hydraulic rating method (Damiani et al., 2018). This classification is based on the Wetted Perimeter Method (Hao et al., 2016). The use of habitat simulation methods is used in addition to hydrological and hydraulic approaches for quantifying potential suitable habitats. Instream Flow Incremental Methodology represents this classification best (Hao et al., 2016).

Water resources management relies heavily on hydrology, so hydrological methods are frequently used to estimate EF. Many places provide time series of river flow data, from which indices can be calculated (Jain, 2012). Water flow data from a daily or monthly basis is analysed as part of an integrated hydrologic desktop approach, along with the basic principles of river biophysical processes, which are linked to riverine resources through flow regimes (Opperman et al., 2018). EFR estimates for the remaining categories call for in-depth research at a specific location, which, depending on the methodology, can take weeks or even years. When a specific project is being reviewed at a location along a river, these methodologies are more appropriate (Mazvimavi et al., 2007). A thorough desktop hydrological analysis can be facilitated using the Indicators of Hydrologic Alteration (IHA) (Ali et al., 2019). Since its introduction by experts in the field of ecological hydrology in the 1990s, the IHA/RVA technique has been successfully used in many basins throughout the world (Lin et al., 2016). The most efficient way to evaluate hydrological alteration is to use IHA/RVA, which evaluates hydrological alteration thoroughly and extensively based on 33 indicators in five groups (Richter et al., 1996).

2.12. Assessing Dam impacts on streamflow trends between current and historic flow conditions downstream.

Changes in the flow and availability of water along a river can have negative impacts on both the environment and those who rely on the river downstream (Zhang et al., 2019). The way dams are operated, and rivers are modified has led to changes in the riparian vegetation dynamics in many river floodplain systems (Benjankar et al., 2012). Managing rivers by building dams can change the way water flows, impacting the environment (Zimmerman et al., 2010). These effects include disrupting ecological systems, reducing sediment delivery, changing water temperature, and interfering with the life cycles of aquatic species (Grill et al., 2015). Dams are a significant factor in changing river systems, as they impact the ecology of the water and surrounding areas by altering the flow of water downstream in terms of quality, quantity, and timing (Aguiar et al., 2016).

It is important to study changes in river flow to understand the impact of dams on aquatic and riparian species. Changes in the frequency, magnitude, and predictability of flow fluctuations caused by dams have negative effects on the survival, reproductive success, and abundance of these species (Zimmerman et al., 2010). The relationship between a river and its floodplain is crucial for many environmental processes, but human activities have disrupted this connection. Recent research suggests that we need to consider the natural processes involved in order to maintain a healthy ecosystem (Stone et al., 2017). In order to achieve sustainable dam development globally, there is a need for new methods and approaches to better predict the impact of future dam construction on biodiversity, ecosystem functioning, and river geomorphology (Grill et al., 2015).

A review by Mianabadi et al. (2021) identifies and examines three major categories of harm, namely health, environmental, and economic harm. The exploitation of the Kamal Khan dam, which is shared between Iran and Afghanistan, is being studied as a case. To do this, a model that combines the Soil and Water Assessment Tool (SWAT), Indicators of Hydrologic Alteration (IHA), dust storm events (DST), and crop production is being used to simulate the effects of the dam under both past and future conditions. Marak et al. (2020) propose a methodological framework for generating natural streamflow from postimpact data used in the Umiam Watershed when prior impact data are unavailable. For simulating streamflow in the presence of a reservoir as well as water transfer out of a watershed, the Soil and Water Assessment Tool (SWAT) model is used. Changes in streamflow were analyzed using the Indicators of Hydrologic Alteration (IHA) method.

The impact of the "Włocławek" dam on the flow of the Vistula River was assessed using the IHA and RVA methods. The study found that the operation of the hydroelectric power plant significantly alters the frequency and duration of low and high-flow pulses, as well as the rate and frequency of flow changes (Gierszewski et al., 2020). The Mekong River basin's hydrologic patterns were analysed by measuring 33 IHA parameters to determine the effects of reservoir operations and climate change scenarios. Mean values of each IHA parameter were calculated for pre- and post-impact periods for every downstream dam. The pre-impact flow data, which represents the natural flow regime, were obtained from SWAT simulation runs using historical climate data from 1986-2005. The post-impact flow data were obtained by simulating reservoir operations and climate change scenarios using HydROR for the period 2051-2070 (Shrestha et al., 2020).

Singh et al. (2022) attempt to assess the impacts of climate change on the discharge regime of the Godavari River based on multidimensional flow characteristics. 32 indicators of hydrologic alteration (IHAs) and flow duration curves (FDCs) were used to assess how climate change is impacting river flow regimes. A monsoon-dominated mesoscale river basin in India was investigated for the alteration of its hydrology caused by dam construction and for the potential effects on its hydrology caused by expected climate changes. The natural flow of a river was analyzed using 15 years of data before a dam was built. A hydrological model called Soil and Water Assessment Tool (SWAT) was used to simulate future river flow based on climate models for the near future. The Indicators of Hydrologic Alteration (IHA) method was used to measure changes in the river's flow characteristics before and after the dam's construction (Mittal et al., 2014).

A study conducted by Kim et al. (2016) looked at the impact of climate change and a new water resource project on future runoff in the region. A rainfall-runoff model was created for the Geum River, which recently underwent large-scale construction. Climate change scenarios were generated using the HadGEM3-RA RCM model, and the SWAT model was used to construct daily runoff series. The variability of runoff during two future periods was compared to a reference period using the IHA program. The study conducted by El Jeitany et al. in 2023 examines how climate change impacts river ecosystems in the Upper Arno River basin. They used a combination of methods to analyze the changes in streamflow and its effects on water ecosystem services. Twenty hydrological models were used, specifically the Soil and Water Assessment Tool (SWAT), along with different climate models and emission scenarios. The researchers analyzed the streamflow data using the IHA method.

IHA has been used to study the effects of dam construction on environmental flows. For example, Yang (2016) used IHA to examine the impact of dam construction on the Trinity and Brazos rivers. Similarly, Zuo and Liang (2015) studied how the construction of a dam on the Shaying River in China would affect its environmental flows (Mianabadi et al., 2021). (Taylor, 2001) found that the IHA methodology was applied by (Jewitt, 1999) for the evaluation of its applicability to South African conditions. Streamflow gauging station C9H008 at Schoolplaats downstream of the Vaalharts Dam, streamflow gauging station X2HOI0 on the Noordkaap River in the Northern Province, and IFR Site 2 on the Mkomazi River, which compares naturalised streamflow’s generated at the IFR site with those generated by Rughes et al., are the three sites where case studies were conducted by (Jewitt, 1999) when there was sufficient

(1997). The three case studies showed that there were significant variations in streamflow in South African rivers. Because of this, (Jewitt, 1999) thought the non-parametric analysis (based on percentile data) option of the IRA technique was more appropriate for South African contexts than parametric analysis (based on Gaussian statistics such as the mean). Moreover, (Jewitt, 1999) pointed out that other criteria, like the Julian dates of annual severe occurrences, were not well suited to semi-arid conditions even if this will rely on the amount and timing of rain throughout the year (Taylor, 2001).

The SWAT model is a hydrological model that can simulate how water processes are affected by different climate conditions and human actions using various types of data. It has been commonly used in studies to evaluate the impact of dam and sluice operations on the hydrological regime and ecological flow by incorporating the IHA (Luo et al., 2023). SWAT does not simulate environmental flows directly. To overcome this limitation, researchers have connected it with the hydrologic alteration model (IHA) in several studies (Mianabadi et al., 2021). The SWAT model was used to simulate runoff in the Luvuvhu River watershed in South Africa. In this architecture, QSWAT served as the interface between QGIS and SWAT. With the exception of the validation results, the SWAT model's calibration generated results that were acceptable. In the Luvuvhu River basin, the model is more appropriate for evaluating general water resources than hydrological extreme analysis (Thavhana et al., 2018). The Olifants Basin in South Africa was investigated using the SWAT model. The model's calibration, validation, and uncertainty analysis were the main areas of focus. The SWAT model can be used to recreate the hydrology of the Olifants Basin, making it a Decision Support Tool (DST) for water managers and other decision-making organizations. This DST may have an impact on policy priorities for managing watershed processes, particularly water resources (Gyamfi et al., 2016).

2.13. Water resources assessment techniques

Computer technology has changed water resource management and hydrologic systems (Jayakrishnan et al., 2005). Finding the most important components is the focus of water sciences more and more. Many water assessment models have been developed as a result of the mentioned issues (Abdollahi et al., 2018). Water resources studies and hydrologic modelling have been supported by several computer-based hydrologic models (Jayakrishnan et al., 2005).

2.13.1. IHA and /RVA Models

The IHA allows for quick analysis of daily hydrologic records and was initially created to characterize natural flow conditions and evaluate changes to flow regimes brought on by humans (Mathews and Richter, 2007). We can use comparative statistical analysis to compare before-and-after changes using the IHA variables (Ali et al., 2019). Hydrologic recordings of daily flow measurements are used to construct 67 ecologically significant flow statistics (Richter et al., 1996). Two categories are used by the IHA to analyze changes: first, a hydrological perspective with 33 parameters. 34 environmental indices are also included in the environmental parameters (Kim et al., 2011), which are shown in Tables A1 and A2 of the appendices, respectively. The 33 hydrologic parameters that make up the IHA are divided into five groups: the magnitude and duration of annual extreme water conditions, the magnitude of monthly water conditions, the frequency and duration of high and low pulses, rate and frequency of water condition changes and the timing of annual extreme water conditions (Cheng et al., 2018).

Users can evaluate inter-annual variability and trends for selected time periods or for the full period by evaluating each of the 33 components for each year of data (Mathews and Richter, 2007). Users can either do a trend analysis of more gradual changes in hydrologic conditions, such as those brought on by the conversion of a landscape from forest to agricultural usage, or they can conduct an impact study utilizing data from before and after an impact, such as the construction of a dam. It is simpler to assess changes in hydrologic parameters over time thanks to the tabular summaries and graphical output of IHA software (Mathews and Richter, 2007). Several environmental flow components, such as RVA and Environmental Flow Components (EFC), have developed as a result of the IHA (Ma et al., 2014). The Range of Variability Approach was created by Richarder et al. (1997) based on the intrinsic variability of a river's flow (RVA). The IHA software now includes the RVA. Based on the IHA, the RVA adds hydrological variability and river ecological integrity. This tool assists river managers in setting early flow management goals prior to the production of definitive, long-term ecological research findings Taylor et al (2003). To effectively assess RVA's ability to capture natural variability, 20 years of daily hydrological data are needed (Linnansaari et al., 2012).

Daily flow records obtained over a time period representing the natural flow regime can be used to determine target values for each of the 33 parameters of the IHA (Richter et al., 1997). Using quartiles, recommend three target ranges: lower targets are below the first quartile, middle targets are 25-75th quartiles, and upper targets are above 75th quartiles (Richter et al., 1998). Data points fall into both low and high target ranges for half of the data points. If the flow is relatively unaltered, the altered flow regime should result in about the same number of data points as the natural flow regime. In natural, pre-development flow regimes, the targeted flow range is not reached every year. Management objectives are to achieve it as frequently as possible. The goal range for RVAs in the 25th and 75th percentiles should be reached by only 50% of RVAs. Hydrological alteration can be measured by determining whether the RVA target range has not been reached (Richter et al., 1998).

2.13.2. SWAT (Soil Water Assessment Tool)

The Soil and Water Assessment Tool (SWAT) is a model that assesses soil water using physical-based methods at a river basin or watershed scale. It operates on a daily time step and uses a command structure to route runoff and chemicals through the watershed (Adnan et al., 2019). SWAT is a model created by the United States Department of Agriculture that uses GIS technology to estimate how land management practices affect water flow, sediment movement, and contaminant transport in large and intricate watersheds (Dhami et al., 2018, Akoko et al., 2021). SWAT is a model that uses hydrological response units (HRUs) to represent the different characteristics of land use, soil types, and slope within a watershed. It divides the watershed into subbasins based on the size of the tributaries, and then further divides these subbasins into smaller units called HRUs for more detailed modelling (Himanshu et al., 2017).

The main benefit of SWAT is its ability to simulate large watersheds without needing a lot of monitoring data. It can also predict how hydrological factors will change under different management practices and environmental conditions. To run simulations, SWAT requires data on elevation, land use, soil, and climate for the study area. These inputs are used to analyse surface runoff and groundwater recharge. SWAT divides the simulation into two phases: the land phase, which controls the amount of water and pollutants in each sub-basin, and the routing phase, which considers how water and pollutants move through the channel network (Nasiri et al., 2020).

A water balance equation (1) is used in SWAT to model the land phase of the hydrologic cycle:

$$SW_t = SW_0 + \sum_{i=1}^{t} \left[R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw}\right] \tag{1}$$

where, SW_t is the final soil water content (mm); SW_0 is the initial water content (mm).; t is the time (days); R_{day} is the amount of precipitation on day i (mm); Q_{surf} is the amount of surface runoff on day i (mm); E_a is the amount of evapotranspiration on day i (mm); w_{seep} is the amount of water entering the vadose zone from the soil profile on day i (mm); : Q_{gw} is the amount of return flow on day i (mm) (Nasiri et al., 2020). Surface runoff occurs when precipitation exceeds infiltration, and the precipitation does not get intercepted, infiltrated, or evaporated (Ayivi and Jha, 2018).

2.13.3. WEAP (Water Evaluation and Planning system)

A model called WEAP was created by the Stockholm Environment Institute (SEI). The water balance accounting principle calls for using a monthly basis. When a system is represented, a variety of sources of supply and withdrawals are considered, along with water demands and ecosystem requirements (Lévite et al., 2003a). These sources and withdrawals include things like rivers, groundwater, and reservoirs. A sizable database must be entered for each component of the network in order for the WEAP model to function. Because they may be quickly modified, data structures and levels of detail can serve as a reflection of the restrictions imposed when data is scarce (Hamlat et al., 2013). In a WEAP model, linkages that transport water from the resource node to the demand site connect water resources and demand sites. An essential part of the WEAP network is the water return flows from demand regions to wastewater treatment plants (WWTPs) (Li et al., 2015). The physical hydrology of the region and water management infrastructure are seamlessly integrated by the WEAP model to determine how to allocate the available water resources to suit a variety of water needs (Mounir et al., 2011).

The components of the water demand-supply system and their spatial relationships are provided for the catchment under consideration in order to simulate water allocation. A system's reservoirs, water sources, water demands, withdrawals, transmission, and wastewater treatment facilities are all displayed. Surface water, groundwater, desalination, and water reuse are some of these sources (Mounir et al., 2011). Under various assumptions and management practices, WEAP forecasts demand and supply structures. Which supports decision-making and planning, enables the design of resource allocation strategies to meet future demands (Höllermann et al., 2010). Due to its simplicity of use and user-friendly interface, this model is especially beneficial for stakeholder conversations on water resource management. It can be helpful in increasing public comprehension and awareness of significant issues (Lévite et al., 2003b). The WEAP model is also made to adapt to changing user requirements, such as better knowledge, a change in policy, planning specifications, or regional restrictions and conditions (Lévite et al., 2003a). WEAP is one of the most widely used tools for worldwide integrated water resource management (IWRM) (Tena et al., 2019). Several countries have utilized the WEAP model to investigate and simulate various water systems, including Massachusetts, California, Southern Africa, Georgia, North Africa, and many in Asia (Li et al., 2015).

2.13.4. Water balance equation

The water balance can be calculated for any part of the hydrological cycle, regardless of its size or shape, in order to determine an unknown aspect of the water balance. It is a way of keeping track of all-important factors in a basin or reservoir over a specific time period (BENIN, 2016). The hydrologic balance for water bodies involves controlling the amount of stored water and inflows from the surrounding area. It is calculated using a simple mass balance equation, where the sum of all outflows is subtracted from the sum of inflows to determine the change in the stored volume over a specific time period (Kahil et al., 2016). The equation used to calculate the water balance of a system can be expressed as the basin continuity equation (2):

$$\text{Input} - \text{output} = \text{change in storage} \qquad (2)$$

The daily runoff of the reservoir can be calculated by using information about the volume of inflow and outflow, spillway capacity, precipitation, evaporation, seepage, reservoir area, and other related factors. This information can be obtained from daily measurements of the reservoir levels, an elevation-area-capacity table, a spillway capacity table, and records of outflows such as irrigation release, seepage loss, and transfers to other reservoirs (Jaiswal et al., 2020). Figure 2.1 summarizes the components of water balance in a reservoir (The arrows indicate the input and output):

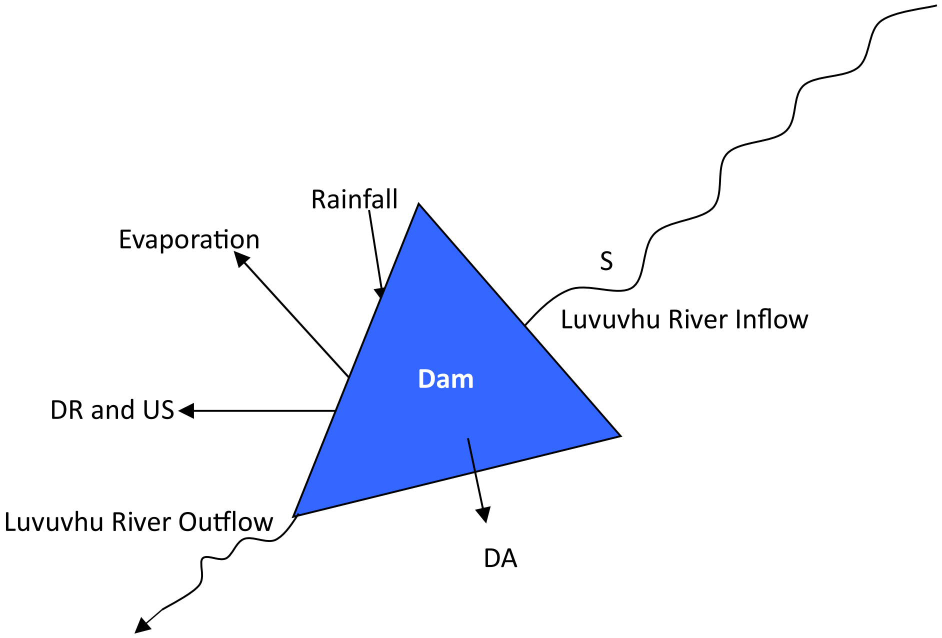


Figure 2.1: A conceptual diagram for Dam water balance.

The classical method of water balance calculation considers precipitation as the input and factors such as runoff, evaporation, and infiltration as the output. Its goal is to provide the most accurate estimation of these components using a simple formula and the least amount of input data. The water balance equation can be written as follows (Al-Sudani, 2020).

The inflow to a reservoir is important for determining its optimal operation policy. However, in many cases, the inflow is not directly measured. Instead, the reservoir level is measured at regular time intervals (Turner et al., 2021). The working table for the reservoir on a particular day provides information on the reservoir level, releases, spillage, evaporation loss, and rainfall inputs. To analyze the reservoir's operation, it is necessary to know the amount of water entering the reservoir within a specific time interval (Edalat and Stephen, 2019). This can be estimated using the water balance equation and the elevation-area-capacity table for the reservoir. The net inflow to a reservoir is usually calculated based on the outflows, losses, rainfall, and changes in storage. Reservoir storage is estimated using data on the reservoir level and the elevation-storage curve. Ideally, inflows to a reservoir should be positive or at least zero, but sometimes the calculations result in negative inflow estimates, which can be due to various reasons (Fowe et al., 2015).

- The estimation of reservoir volume can be affected greatly by small errors (of the order of mm) in the measurement and recording of reservoir level data. Further, strong winds may result in incorrect measurements of reservoir levels at dam sites if they blow over the surface of the reservoir
- A lack of elevation-area-capacity curves after sedimentation has led to a wrong calculation of reservoir capacity at particular elevations.
- Negative inflows can occur if there is an error in the observations or data entry of variables such as storage capacities, releases, losses/gains, and spill from a reservoir.

The water balance model of a reservoir explains how water levels change in response to different inflow and outflow situations. It assumes that groundwater has little impact on the reservoir over a long time period, so its contribution is considered negligible compared to other inflows and outflows (Maswanganye et al., 2022).

2.14. Trend analysis

For rivers to be protected and developed efficiently, socioeconomic development needs to be quantified in terms of water quantity and quality (Luo et al., 2019). The post-bias correction method mixed with a hydrological model was proposed to estimate how dam construction impacts hydrological indicators (Lu et al., 2018). Since correlations and regressions are relatively simple theories, they are often used to assess the significance of the relationship between two factors (Gan et al., 2014).

2.14.1. Correlation analysis

The correlation between two variables serves as a gauge for their linear relationship. It is used by academics to explain the strength and direction of correlations between two typically continuous variables, according to O'Brien and Scott (2012). There are many applications for correlation tests, including exploratory data analysis, data engineering, structural modelling, and other applications (Makowski et al., 2020). The correlation coefficient, which ranges from -1 (signifying a perfect negative correlation) to +1, indicates the "unitless" relationship between two variables (indicating a perfect positive correlation). Hence, neither variable is used to predict nor determine the outcome (Crawford, 2006).

It is useful to conduct correlation analyses when researchers are attempting to establish if there is an association between two variables (O'Brien and Scott, 2012). It is the correlation between systems that underlies their interaction in systems research. A strong correlation between two systems increases the likelihood of them interacting with each other (Luo et al., 2019). Statistics often use correlation analysis in many fields. In correlation analysis, two numerical variables are compared to determine their degree of correlation. Considering the study objective when estimating the sample size for correlation analysis is important (Bujang and Baharum, 2016). In data analysis and methodological research, associations between variables are often of interest. To measure monotone relationships, the Pearson's, Spearman's, and Kendall's correlation coefficients are frequently used, with the latter two typically being advised for data that are not normally distributed (Chok, 2010). The Pearson correlation method is the most popular correlation methodology. Essentially, it is the covariance between the two variables divided by the sum of their standard deviations (Makowski et al., 2020).

Linear regression is the process by which an independent variable determines the value of a dependent variable. It involves predicting one or more independent variables based on a dependent variable (Kumari and Yadav, 2018). Analysis of regression is a statistical technique used for building models based on two or more variables. In linear regression, two variables are assumed to change proportionally when one changes (Bazdaric et al., 2021). As a result of regression analysis, the value of dependent variable 'y' is calculated based on the range of independent variable values 'x' (Maulud and Abdulazeez, 2020). Based on the mathematical equation $y = mx + c$ (Kumari and Yadav, 2018)

Historical trends in global floods and streamflows were determined using a linear regression. As a result, streamflow and flood timing impact the management of water resources and the environment. From 1950 to 2016, changes in monthly, seasonal, and annual rainfall series in

Bihar, India, were analyzed using non-parametric Mann-Kendall and parametric linear regression tests. During the majority of the year, rainfall is projected to decline in the study area, except for May (Zakwan and Ara, 2019). An investigation of the rainfall trend (mm/year) in 13 districts of Uttarakhand State, located in the Central Himalayan region of India, was conducted using Theil-Slope Sen's (TSS) and Simple Linear Regression (SLR). There are both negative and positive tendencies in the rainfall time series of Uttarakhand's 13 districts (Malik and Kumar, 2020). Mann-Kendall, Sen's slope estimator, and linear regression were used to examine changes in annual and seasonal rainfall in the Udumalpet region of Tamil Nadu. Both the Mann-Kendall test and Sen's slope estimator showed little difference between the parametric (linear regression) and nonparametric techniques. Mann-Kendall Z statistics of yearly and seasonal rainfall and Sen's slope estimator of yearly and seasonal rainfall showed a trend based on a linear regression analysis (Thenmozhi and Kottiswaran, 2016). Four well-known models for forecasting short-term streamflow were evaluated in the Heihe River basin in North China and the Pearl River basin in South China, and each model was integrated with the wavelet transform. An ANN, an autoregressive model, a regression model, an autoregressive moving average, and a regressive moving average are all models that can be used to develop each model (Sun et al., 2019).

2.15. Measures of model performance

Model performance is divided into four categories, each with a corresponding set of quantitative thresholds: very good, good, fair, and poor (Da Silva Lelis et al., 2020). Performance evaluation criteria (PECs) and performance measures (PMs) are necessary for the calibration and validation of hydrologic and water quality models (Moriasi et al., 2015).

2.15.1. Model calibration

In calibration, input parameter values are adjusted along with boundary conditions to ensure that the simulated and observed results are as close as possible (Moriasi et al., 2015). Calibration consists of adjusting parameters to ensure that model solutions best fit observations (Hamlat et al., 2013). Nowadays, it is normal practice to study the natural hydrological laws and answer practice questions using distributed hydrological models. However, its usefulness is constrained by the definition of the model parameters (Li et al., 2012b). Due to the numerous parameters that must be simultaneously estimated, manual calibration is time-consuming and challenging. As an alternative to manual calibration, automatic calibration could provide users with an independent and time-saving method for estimating model parameters (Perin et al., 2020).

The IHA software allows users to change the settings of the algorithm by resetting the calibration parameters. In Version 7.1, there are more options for calibrating the algorithm. The default calibration now uses a single fixed threshold to separate high flows from low flows. To effectively use the EFC outputs, it is important to calibrate the parameters used in the EFC calculation algorithm. The best way to calibrate the algorithm is to view the graph of daily flow data with EFC type coding, adjust the EFC parameters in the Analysis Properties window, and save the changes. The IHA will then automatically rerun the Analysis and display the results on the daily EFC graph. The graph can be evaluated to determine if the IHA is accurately distinguishing between high and low flows, achieving the desired return interval for floods, and other desired flow characteristics. The calibration parameters can also be displayed on the graph.

The calibration of the Environmental Flow Components (EFC) algorithm involves two steps. In the first step, the algorithm is adjusted to correctly split the hydrograph into low flows and high flows. Only the parts of the hydrograph influenced by surface flow should be classified as high flows. This can be done by adjusting the high flow threshold parameter in the non-Advanced Calibration method, or by adjusting up to four parameters in the Advanced Calibration method. The Advanced Calibration method provides more flexibility in calibration but is more complex. It is recommended to experiment with adjusting these parameters to understand how they control high flow events. The classification of high flows can vary depending on the calibration method used. Multiple peaks can be classified as one long event if they are above the high flow threshold, but individual peaks will be classified as separate events if the classification is governed by rate thresholds. If it is desired to treat all high flow events as separate events, the high flow threshold can be increased to a large value. The choice of calibration method depends on the ecological needs of the study. If the focus is on flow above a certain threshold, relying on the high flow threshold is recommended. If individual flow peaks are ecologically significant, treating them as separate events may be better.

Step 2 involves calibrating the separation of high flows and low flows in the hydrograph. This calibration is done by determining the desired number of high flow classes and extreme low flows, and adjusting the minimum peak flows for small floods, large floods, and extreme low flows. The bottom two boxes in the Environmental Flow Components tab of the Analysis Properties window contain parameters. It would be helpful to have data on the flow rate that causes floods, as well as the flow rates necessary for specific ecological functions, in order to calibrate the return interval thresholds and the EFC algorithm. This calibration could be based on floods that promote cottonwood recruitment, fish spawning, or other functions. Similar considerations can be used to calibrate extreme low flows.

2.15.2. Model validation

A model is validated when it reproduces field observations or predicts future conditions with little adjustment (Moriasi et al., 2015). Model calibration takes place when the simulated and observed outcomes nearly coincide (Khalil et al., 2018). Model validation, which is a continuation of the calibration process, is necessary for every model application. It guarantees that all factors and circumstances that may have an impact on model outcomes are considered and makes it possible to forecast future behavior (Fonseca et al., 2014). A hydrological model is evaluated by analysing observed and simulated variables. In most cases, simulated and measured flows are compared (Waseem et al., 2017). Various approaches have been employed, ranging from statistical and numerical comparisons to expert assessments of similarity between observed and estimated variables (Willmott et al., 2015). Hydrological models are automated and calibrated using performance criteria to minimize misfits between observations and simulations (Wöhling et al., 2013). Methods and metrics can be used to assess the performance of hydrological models (Steyerberg et al., 2010). Model performance has been evaluated widely using correlation-based methods, However, peak flows are sensitive to these measures, while low flows are not. It is possible for Nash-Sutcliffe to produce better agreement despite these limitations by improving its efficiency and coefficient of determination (Waseem et al., 2017).

2.15.3. Coefficient of determination and Nash-Sutcliffe efficiency

A coefficient of determination, whose value ranges from 0 to 1, is a measurement of how much variance is explained by observable data (Waseem et al., 2017). As R2 approaches 1, its goodness of fit improves. In general, a result larger than 0.5 is regarded as acceptable (Yaykiran et al., 2019). Although its shortcomings have been publicly publicized, Nash-Sutcliffe efficiency is still commonly employed. When normalized by the variance of the actual discharge, an observer's discharge deviates from his projected discharge in order to remove bias. The range is specifically 1 to -, with 1 being perfect (Waseem et al., 2017). The approach performs well when NSE values range from 0.0 to 1.0. Values below this make it impossible to use the model since the simulated value will be lower than the mean observed value (Yaykiran et al., 2019).

2.16. Chapter summary

To effectively manage water resources, it is important to consider the creation of runoff and the amount of water being used. Studying hydrologic processes in a specific area can help predict flood risks and determine water availability by analyzing runoff and reservoir storage. Managing water resources at the watershed level involves understanding the rate of water flow and the balance of water collected. A thorough understanding of how water moves through watersheds and basins is crucial for efficient water resource management. Agenda 21 was proposed at a United Nations conference to promote sustainable development. At the local level, this plan was known as Local Agenda 21 and was considered important due to the influence of local authorities on citizens and businesses. The Sustainable Development Goals (SDGs) improve upon the Millennium Development Goals (MDGs) by addressing more comprehensive challenges and emphasizing the need for global economic reforms. However, ongoing advocacy is necessary to ensure that authorities are accountable for achieving the SDGs.

The management of water resources has varied over time. Constructing dams and reservoirs is essential for ensuring a consistent water supply for human activities. Dams have been built for different reasons, including flood control, irrigation, storage, and hydropower generation. They are also used for recreational activities, waste management, and providing water to mills. South Africa has a dry climate and is at risk of experiencing water shortages unless it manages its water reserves effectively. To address this, the government has built over 500 dams to store rainfall. However, if steps are not taken to reduce the reliance on traditional river impoundment methods, the country could face severe water scarcity by 2030.

Building dams can cause long-lasting damage to the environment, affecting aquatic life, air and water quality, vegetation, wildlife, and land. The water balance, which is influenced by climate and local factors, is important in predicting streamflow, soil moisture, and groundwater availability. Different models can be used to calculate water balance components. Assessing environmental flow is crucial for water managers and regulators, and the Indicators of Hydrologic Alteration is a widely used tool for this. Introduced in the 1990s, this technique evaluates hydrological alteration using 33 indicators in five groups, providing an efficient way to assess water flow.

CHAPTER 3: MATERIALS AND METHODS

3.1. Chapter overview

This chapter describes the study area which is Nandoni Dam in the LRC and its characteristics. The different datasets required to achieve the objective of study are also described. Also discussed are the sources and methods of collecting the data, as well as the lengths of the hydro-meteorological variables. A detailed outline of the methods used to accomplish the study's objectives concludes the chapter.

3.2. Study area

The study area lies between Nandoni Dam downstream of Thohoyandou, with coordinates 22°59′20″S and 30°36′27″E, and Kruger National Park about 58.84 km downstream. Nandoni Dam is situated in quaternary catchment A91F on the Luvuvhu River (Figure 3.1 and 3.2). The Luvuvhu River Catchment (LRC) is one of the South African places where floods have caused significant damage and severe harm to fauna and vegetation. It is located in the Limpopo Province of South Africa, in the Luvuvhu/Letaba Water Management Area. In this catchment area, 5941 km² are subdivided into 14 quaternary catchments (Masupha and Moeletsi, 2017). The catchment area of Nandoni Dam covers 169 233 hectares. Luvuvhu flows along the southern edge of the Soutpansberg mountain range before meeting the Limpopo River, which eventually reaches the Indian Ocean near the border with South Africa, Zimbabwe, and Mozambique in Kruger National Park.

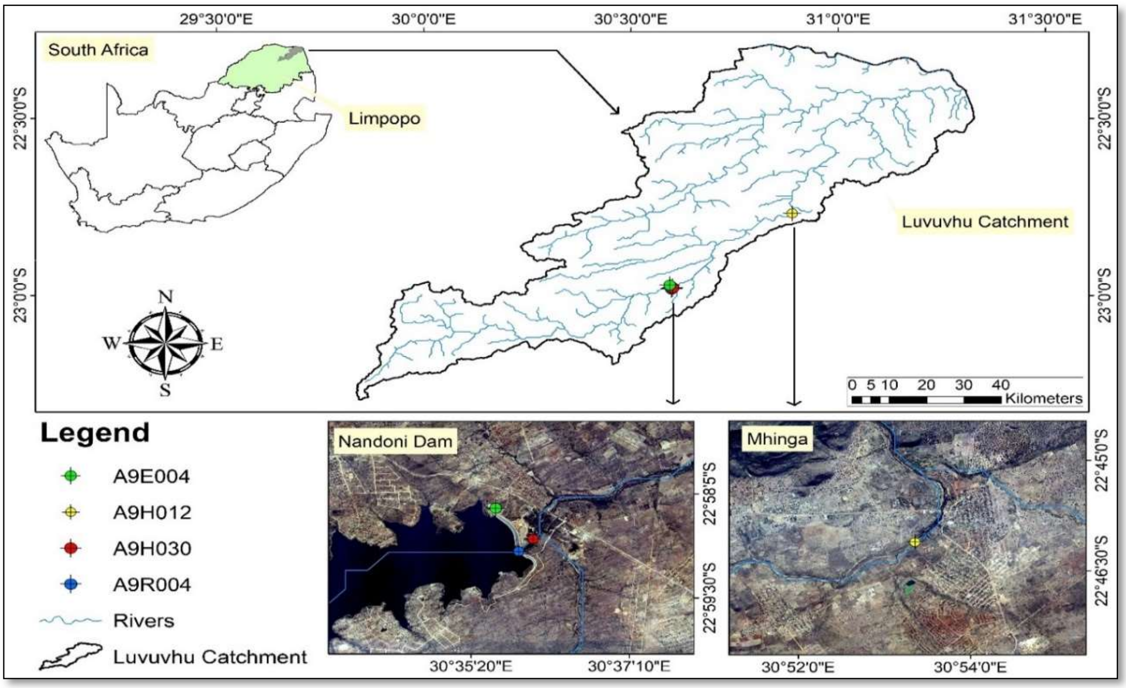


Figure 3.1: Nandoni Dam in the Luvuvhu River Catchment, Vhembe district in Limpopo South Africa.

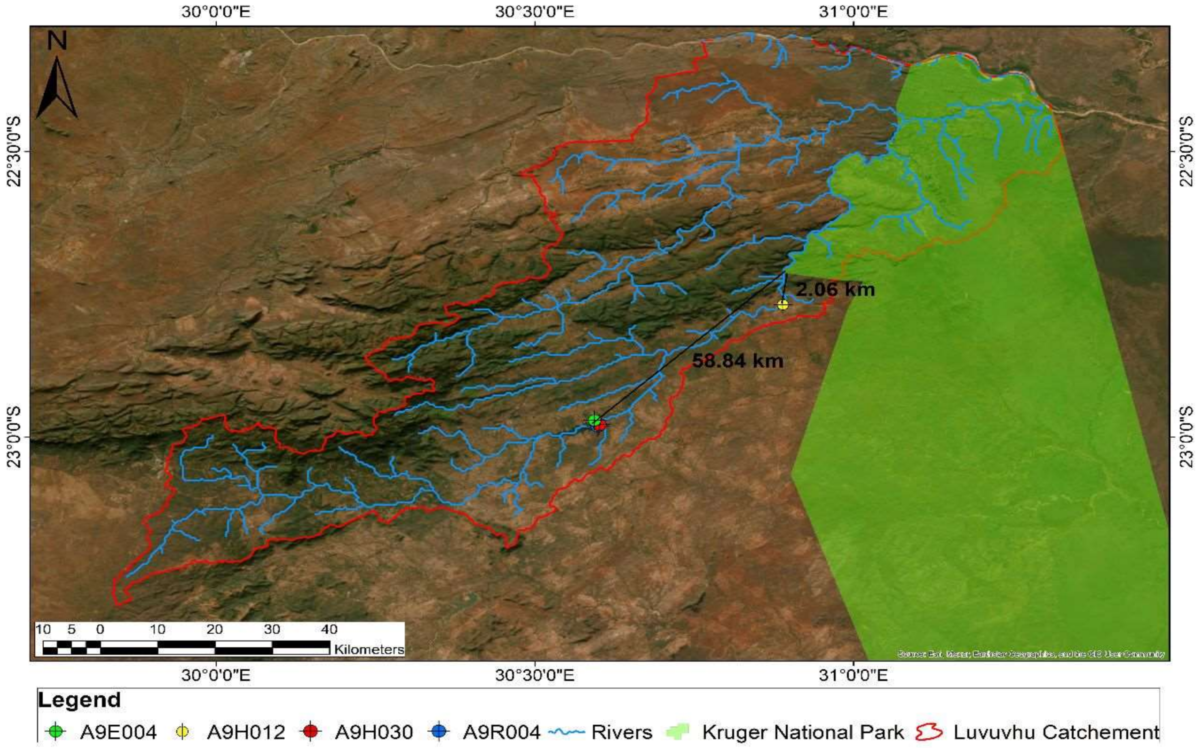


Figure 3.2 The downstream area of Nandoni dam includes Mhinga station (A9H012) and Kruger National Park.

The Luvuvhu River serves a number of purposes, including domestic and agricultural water needs, as well as ecological water needs for Kruger National Park. Odiyo et al. (2012) estimated the flows that Latonyanda River contribute to Luvuvhu River downstream of Albasini Dam. The Nandoni Dam has been chosen for this study in order to evaluate the impact it has on the Luvuvhu River downstream. The Department of Water Affairs and Forestry (DWAF) constructed the Nandoni dam in the Luvuvhu River to supply raw water supplies for 1.3 million people in the Vhembe and portions of Mopani districts, Limpopo province, as well as controlled releases downstream to supply water for wildlife in Kruger National Park (Gumbo et al., 2016). The dam has a 1446 km catchment area and is made up of concrete and earth fill (Nthunya et al., 2019). The dam has a storage capacity of 166,200,000 m^3 (Sinthumule, 2021).

The study area's climate is characterized by warm, humid summers and cold, dry winters (Masupha and Moeletsi, 2018). Winter temperatures range from 9°C to 17°C, while summer temperatures range from 22°C to 37°C (Kom et al., 2020). Between October and April, the area receives 95% of its rain, and geography has a significant impact on the climate (Nemaxwi et al., 2019). According to Odiyo et al. (2015), the distribution of precipitation is highly varied, with the top portions of the catchment receiving the majority of precipitation and the lower reaches around the Kruger National Park receiving the least. The annual average rainfall ranges from 750 mm in dry years to 1500 mm in wet years (Louw, 2017). For quaternary catchment A91F, the mean annual precipitation, mean annual evaporation, and mean annual runoff are 676 mm, 1647 mm, and 136 mm, respectively (Village and Town, 2017).

Floods have occurred in the basin over the years as a result of high rainfall related with the ITCZ (Singo et al., 2012). Extreme occurrences in the watershed, according to Mathivha et al. (2021), have an impact on groundwater resources, with a declining trend in groundwater levels, streamflow, and rainfall over the study area. Several catastrophic floods and droughts have been observed in the LRC, with significant negative impacts on agriculture and rural people (Mathivha et al., 2021). According to Odiyo et al. (2015), the distribution of precipitation is highly varied, with the upper regions of the catchment receiving the most amount of precipitation and the lower reaches around the Kruger National Park receiving the least.

The dam is flanked by the Nandoni Game Park Resort and a Golf Estate, both of which provide a variety of activities and services for the surrounding people (Bassey et al., 2012). Several waterfront villages near the Nandoni dam are typical examples of emerging rural communities with poor service delivery, a high unemployment rate, and poverty. The Nandoni dam provides these villages with access to water for domestic needs such as bathing, washing, drinking, and cooking. Many unemployed men in the area now make a living by catching fish and selling them to local communities (Gumbo et al., 2016). Along the Nandoni dam and Levuvhu riverbanks, soil is frequently mined for construction purposes as well as for the profitable brick-making sector (Musakwa et al., 2020).

3.3. Data requirements, sources, and collection

Daily rainfall, evaporation station A9E004 and Downstream flow releases station A9H030 were selected because are within Nandoni dam area (Figure 3.1). Dam water level, Downstream flow releases, Uncontrolled spills and Domestic abstractions data were measured directly from the dam stations, together with daily rainfall and evaporation data were used for assessing Nandoni Dam water resources in relation to inflow and outflow. The streamflow gauging station A9H012 at Mhinga is the most downstream point on the Luvuvhu River where flow observations are taken. With the Kruger National Park (KNP) downstream of this flow gauging station, any attempt to estimate flows into the park would have to be based on the flows measured at this gauging station (Kagoda et al., 2010). The streamflow data from gauge station A9H012 was used for determining the amount of streamflow required to maintain the ecological integrity and assessing Nandoni Dam impacts on streamflow trends between current and historic flow conditions downstream. Table 1 below summarizes all data gathered for this study which were requested and obtained via email from their respective departments or organisations.

Table 1: Datasets requirements description and sources.

Data	Description	Gauge station	Duration	Sources
Climatic data	Rainfall	A9E004	2009 – 2021	Department of water and Sanitation
	Evaporation	A9E004	2009 – 2021	
Hydrological data	Streamflow	A9H012	1987 – 2021	Department of water and Sanitation
	Dam water level	A9R004	2007 – 2021	
	Downstream flow releases	A9H030	2007 – 2021	
	Uncontrolled spills	A9R0041	2006 – 2021	
	Domestic abstractions		2017 – 2021	Lepelle Northern Water

Preliminary data scanning and cleaning found that there was missing data for different years for different selected variables. About 23% of rainfall data from 2017 to 2020, 30% of evaporation data from 2017 to 2020, 11% of downstream release data from 2017 to 2020 and 1.92% of streamflow data from 2017 to 2020 were missing. There were no missing data of Dam Water level from 2017 to 2020 and Spill way data from 2017 to 2020. Domestic abstractions by the treatment plant were obtained from the Lephelle Northern Water and this was available from 2017 to 2020 with no missing data. In this study, the closest station to station A9E004 is station A9E003. However, station A9E003 does not have reliable data (Odiyo et al., 2020). Therefore, missing data in the study were filled in using the average monthly data and, when applicable, the average between consecutive days of station A9E004. The same principle was also implemented at station A9H030 since dams have varying discharge rates. In the case of missing data in station A9H012, the IHA software automatically implemented an interpolation method to fill in the gaps.

3.4. Determination of trends and variability of hydroclimatic variables in the study area

To demonstrate long-term changes and variability, the mean, standard deviation, and skewness of each station were computed using Microsoft Excel's Data Analysis tool. The standard deviation is a statistical parameter that has been widely used to examine rainfall and/or streamflow variability (Odiyo et al., 2015). The mean, standard deviation, and skewness uses the mathematical Equation, (3); (4); and (5), respectively.

$$\bar{x} = \frac{\Sigma x}{n} \tag{3}$$

$$\sigma = \sqrt{\frac{\sum(x-\bar{x})^2}{n-1}} \quad (4)$$

$$\bar{u}_3 = \frac{\sum_i^N (x_i-\bar{x})^3}{(n-1)\times\sigma^3} \quad (5)$$

where: $\bar{x}$= The mean value of the data set, x_i=Value of the i^th^ point in the data set, n=The number of data points in the data set, σ= standard deviation and $\bar{u}_3$ = skewness

Over the study period, using Microsoft Excel's Data Analysis tool, regression analysis was conducted to determine trends in daily mean rainfall, streamflow and volume of dam storage. This method fits a regression line to time series data, and the slope shows whether or not the trend is strong. The null hypothesis states that the line's slope is zero. A number of trend analysis studies have used linear regression (Odiyo et al., 2015). The linear regression analysis uses the mathematical Equation (6), i.e.,

$$y = mx + c \quad (6)$$

Linear regression analysis uses Y' as the outcome variable (dependent variable), c as an intercept, and m as the slope (regression coefficient) of X (Bazdaric et al., 2021). When Y increases as x increases, "m" is positive. The value of "m" becomes negative as x rises and Y falls. If Y did not alter with x, one would anticipate that "m" would be 0. In addition, the higher the magnitude of "m", the steeper the change in Y with the change in x (Aggarwal and Ranganathan, 2017).

3.5. Assess Nandoni Dam water resources in relation to inflow and outflow.

In order to balance the difference between inflow and outflow, the mass conservation principle is used, or the storage equation (Goel et al., 2018). The components of the water balance considered in this study were shown in Figure 2.1. Based on the availability and length of the data period, the study selected a five-year study period (2017–2021) to accommodate the amount of water abstracted from the dam to the water treatment plant. Equations (7) and (8) were used to evaluate the dam's water resources based on inflows and outflows.

$$\text{Inflow} - \text{Outflow} = \pm\,\Delta\text{storage} \quad (7)$$

$$\text{S} = \pm\Delta\text{Storage} - \text{R} + \text{E} + \text{DA} + \text{DR} + \text{US} \quad (8)$$

where: Rainfall (R), Streamflow (S), Evaporation (E), Domestic abstractions (DA), Downstream flow releases (DR) and Uncontrolled spills (US). Data from Nandoni dam storage, rainfall, evaporation, uncontrolled spillway releases, and downstream flow releases were imported into Excel Spreadsheets, while domestic water abstractions were manually entered into Excel Spreadsheets to compute Nandoni Dam's inflows.

3.6. Determining the streamflow required to support the ecological integrity downstream of the Nandoni Dam

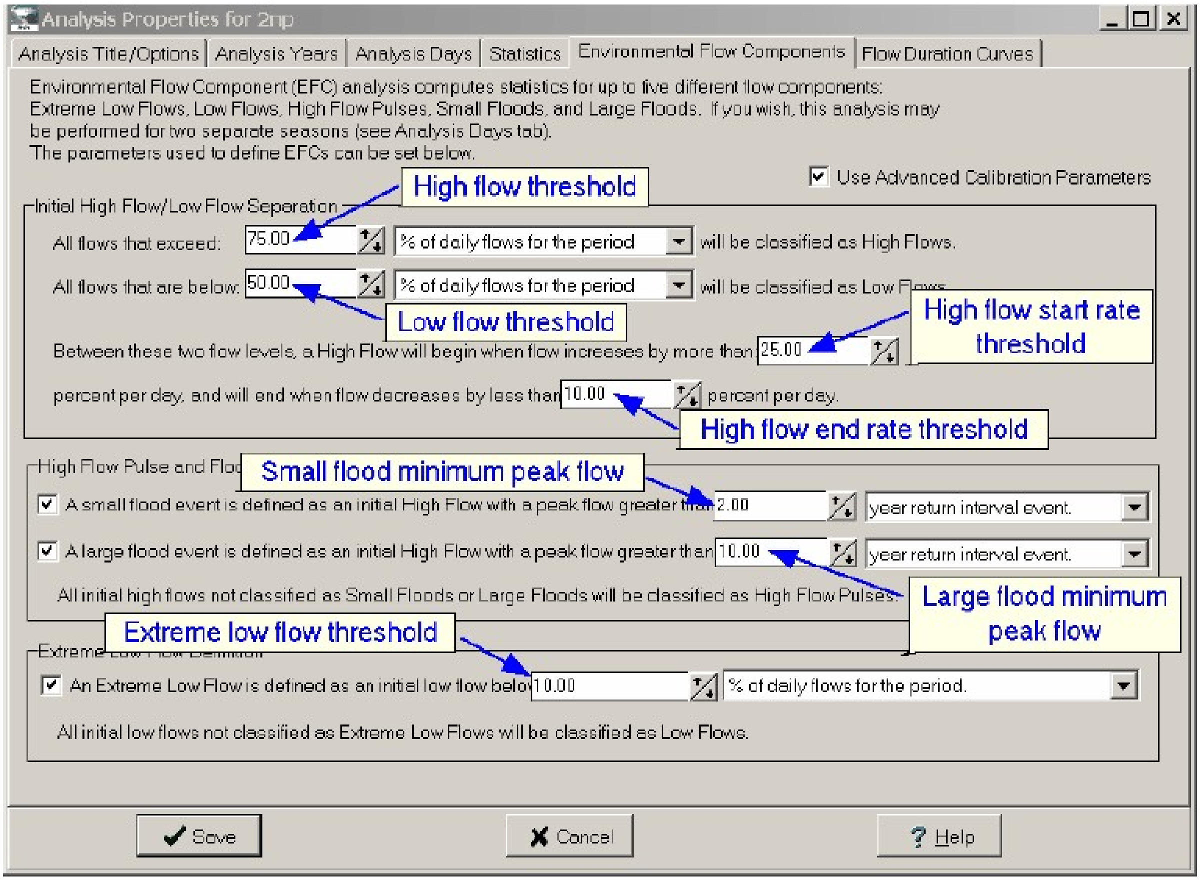
Indicators of Hydrologic Alteration (IHA) are 67 parameters that are grouped into two groups for determining hydrological alterations and environmental flow requirements. There are 34 parameters that indicate natural environmental flow types and the ecological integrity components of those flows (e.g., duration, magnitude, timing, frequency, and rate of change) (Richter et al., 1996, Richter et al., 1997, Richter et al., 1998). This study determined environmental flow components on the Luvuvhu River downstream of Nandoni Dam using only these Environmental Flow Components (EFC) parameters. Determination of ecological integrity was conducted using IHA software (Version 7.1) provided by The Nature Conservancy (TNC). Within the software, there are threshold values that identify natural flow and are characteristic of each EF component. This software requires data on natural streamflow's on a daily basis. The data from 1988 before the dam was constructed to 1998 was used as natural streamflow. For the EFC calculations in Luvuvhu River downstream of Nandoni Dam, threshold values presented in Table 2 were used.

Table 2: Percent of changes in the flood free season lengths of target sites in the Luvuvhu River downstream of Nandoni Dam (adapted from, Özcan, 2021).

EFC name	Threshold defined to the software
Extreme low flows	10% of daily flows for the period
Low flows	50% of daily flows for the period
High flow pulses	75% of daily flows for the period
Small floods	2-year return interval value
Large floods	10-year return interval value

As shown in Table 2, an extreme low flow event is defined as a low flow peaking below 10% of the average daily flow for the period (i.e., minimum) and ending when the next flow peak exceeds this threshold value. In contrast, a low flow event is characterized by flow values below 50% of the period's daily flows. A low flow should be above a threshold value for extreme low flows. High flow pulse events occur when daily flows exceed 75% but peak below the threshold for small floods. Initiation of a high flow occurs at a rate of 25% per day, and it ends at a rate of 10% per day. An event is defined by the initial high flow exceeding its threshold, which for small floods is a 2-year return flow and for large floods is a 10-year return flow (Conservancy, 2009, Ozcan, 2021).

The data were prepared in a format that suits the IHA software model input data requirements. The process involved in set up for calibration and validation of streamflow are illustrated below based on IHA Version 7.1. The default calibration in this study has been used (Figure 3.3).



Environmental Flow Component (EFC) analysis computes statistics for up to five different flow components: Extreme Low Flows, Low Flows, High Flow Pulses, Small Floods, and Large Floods. If you wish, this analysis may be performed for two separate seasons (see Analysis Days tab). The parameters used to define EFCs can be set below.

☑ Use Advanced Calibration Parameters

Initial High Flow/Low Flow Separation

All flows that exceed: 75.00 % of daily flows for the period will be classified as High Flows.

All flows that are below: 50.00 % of daily flows for the period will be classified as Low F

Between these two flow levels, a High Flow will begin when flow increases by more than 25.00 percent per day, and will end when flow decreases by less than 10.00 percent per day.

High Flow Pulse and Flo

☑ A small flood event is defined as an initial High Flow with a peak flow greater than 2.00 year return interval event.

☑ A large flood event is defined as an initial High Flow with a peak flow greater than 10.00 year return interval event.

All initial high flows not classified as Small Floods or Large Floods will be classified as High Flow Pulses.

Extreme

☑ An Extreme Low Flow is defined as an initial low flow belov 10.00 % of daily flows for the period.

All initial low flows not classified as Extreme Low Flows will be classified as Low Flows.

High flow threshold

Low flow threshold

High flow start rate threshold

High flow end rate threshold

Small flood minimum peak flow

Large flood minimum peak flow

Extreme low flow threshold

Figure 3.3: The Environmental Flow Components tab

3.7. Assessing changes in streamflow trends between current and historic flow conditions downstream of Nandoni Dam

The IHA was used to assess hydrologic changes associated with dam construction. Mhinga A9H012 station downstream of the Nandoni Dam on the Luvuvhu River was used to achieve this. Pre-impact (i.e., the period before construction of the dam) and post-impact (i.e., the period after construction of the dam), were taken into consideration when conducting the analysis. Pre-impact was considered 1988-1998, while post-impact was considered 2005-2021. Analyses were not conducted during the period 1998–2005, which corresponded to the actual construction of the dam. Non-parametric analysis was used as suggested in the IHA manual (Conservancy, 2009). A middle Range of Variability Approach (RVA) zone upper and lower boundary is defined by the 25th percentile and 75th percentile of each IHA parameter. Low and high RVA zones are automatically defined. The occurrence frequencies within each RVA range were calculated based on the determination of these two boundaries. In order to determine the number of occurrences of these flow events during altered conditions, the same calculations were performed. Using these natural and altered frequency information, we calculated the hydrologic alteration degrees within each RVA zone. As a result of Equation (9), the hydrologic alterations were calculated as follows:

$$\mathrm{HA} = \frac{\mathrm{Obeserverd} - \mathrm{Expected}}{\mathrm{Expected}} \tag{9}$$

Hydrologic alteration percentage (HA) represents the hydrologic alteration percentage, expected is how many years annual statistics fall within RVA limits before impact, and observed is how many years they fall within RVA limits after impact. When the observed frequency of post-impact annual values that fall within the RVA target range equals the expected frequency, HA equals zero. A positive deviation value implies that the annual parameter values occur more frequently than expected; a negative value suggests that the annual values occur less frequently than expected. Richter et al. (1998) developed a simple three-class grading approach for individual IHA, with degrees of HA defined by minimal or no alteration (0%-33% as indicated by L), moderate alteration (34%-67% as indicated by M), and high alteration (68%-100% as indicated by H) (Richter et al., 1996, Richter et al., 1997, Richter et al., 1998).

CHAPTER 4: RESULTS AND DISCUSSION

4.1. Chapter overview

This chapter presents the findings of the study and further discuss the impacts of Nandoni Dam construction on downstream water resources. These impacts are presented through assessing Nandoni Dam water resources in relation to inflow and outflow. In addition, this include determining the amount of streamflow required to maintain ecological integrity and evaluating Nandoni Dam impacts on streamflow trends between current and historic flow conditions downstream.

4.2. Hydrometeorological data analysis

4.2.1. Rainfall

Average daily rainfall in station A9E004 at Nandoni Dam was 1.8 mm, with maximum and minimum of 182.1 mm and 0.1 mm, respectively, as it can be seen in Figure 4.1 the daily rainfall varies throughout the study period. The standard deviation of 7.05 shows that there is high rainfall variability over time in the study area. The skewness of 9.94 shows that rainfall series have right-skewed distributions with sharp peaks near the mean. It can also be seen that the slope of the trend line is positive which indicate that the value of rainfall is slightly increasing with time, with equation of $y = 1\mathrm{E}-04x - 2.3196$, although there are small changes between time and amount of rainfall.

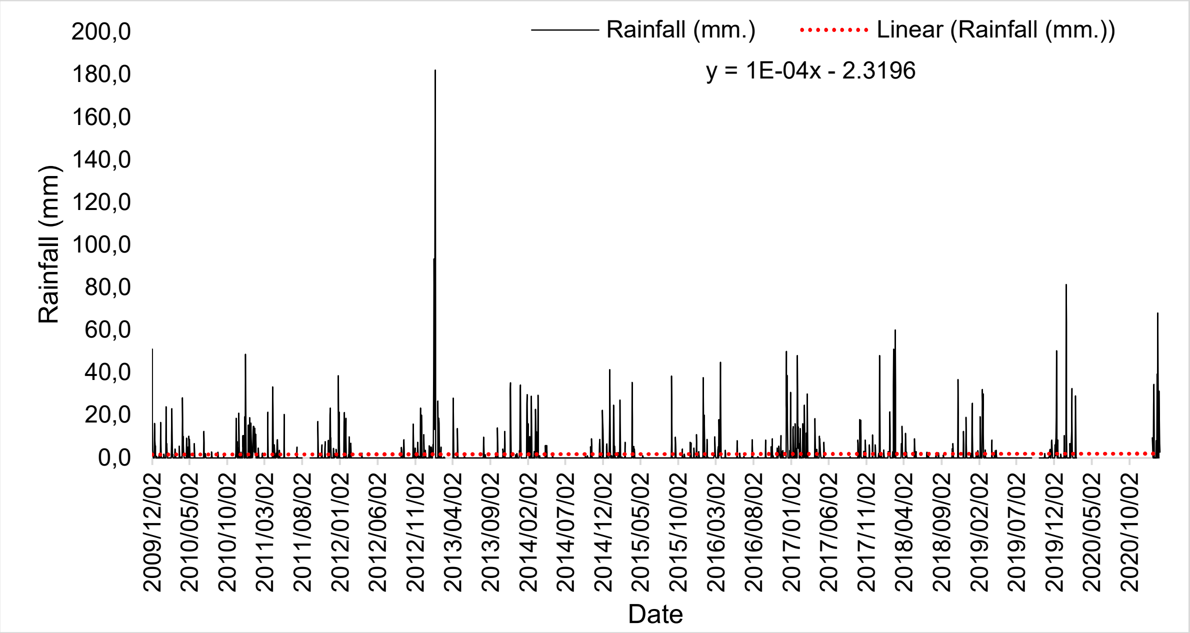


Figure 4.1: Daily average rainfall Time Series for station A9E004 at Nandoni Dam (2009 – 2021).

The average monthly and annual observed rainfall are shown in Figures 4.2(a) and 5(b). Figure 4.2a showed that most rainfall is received in the summer months compared to winter months in the Nandoni Dam sub-catchment. Nandoni Dam experiences hot, humid summers and cool, dry winters as has been reported by Masupha and Moeletsi (2018). The month of January experienced the highest rainfall average of 5.58 mm and June having the lowest daily rainfall average of 0.08 mm. For annual rainfall as shown in Figure 4.2(b), excluding the year 2021, 2020 recorded the highest annual rainfall of 5.05 mm and the year 2012 recorded the lowest annual rainfall of 0.77 mm. The highest rainfall in 2020 occurred after two consecutive droughts that harmed water supplies in the LRC (i.e., 2014/15 and 2015/16), whereas the lowest rainfall occurred in 2012 due to a drought (Odiyo et al., 2020).

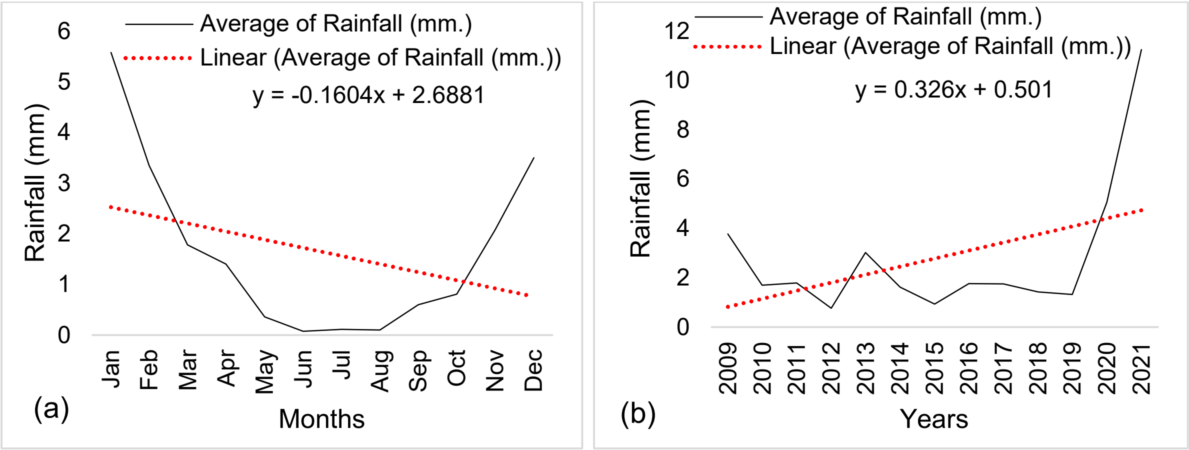


Figure 4.2: (a) A9E004- Monthly average Rainfall (2009 – 2021), (b) A9E004- Annual average Rainfall (2009 – 2021).

According to Odiyo et al. (2020), rainfall trends in the LRC are affected by the rise in extreme events. Historically, the wettest period has been the 1999/2000 rainfall season, which was characterized by the landfall of tropical cyclone Eline in February 2000, which caused major devastation in the northern region of South Africa (Odiyo et al., 2020). This occurred during the construction period of the Nandoni Dam, therefore, did not have impact on the dam water storage. In February 2012, tropical cyclone Dando caused flooding in the lower Luvuvhu River Catchment. As a result of a tropical continental low in 2013, heavy rainfall was experienced, and tropical cyclone Dineo was just north of the Limpopo River. As of March 2019, tropical cyclone Idai was the strongest in the Southern Hemisphere since records were kept. The years 2014/15 and 2015/16 were two of the most severe drought seasons in the catchment's history (Odiyo et al., 2020)

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4.2.2. Streamflow

The average daily streamflow at station A9H012 in Luvuvhu River downstream of the Nandoni Dam was 6.252 m³/s. An 86-year study suggests anthropogenic activities and reservoir development may be affecting river flow in the Luvuvhu River Catchment (Ramulifho et al., 2019). As shown in Figure 4.3, daily streamflow varies throughout the study period with a standard deviation of 17.47. Skewness of 10.18 shows that streamflow series have right-skewed distributions with sharp peaks near the mean. Furthermore, the slope of the trend showed slightly decrease of streamflow over the period of the study, with the equation $y = 6E - 05x + 4.00535$. Matsika and Kruger stations are more likely than Mhinga station to cross the zero-flow intercept in the near future (around 2030) as their streamflow data indicate declining trends (Ramulifho et al., 2019).

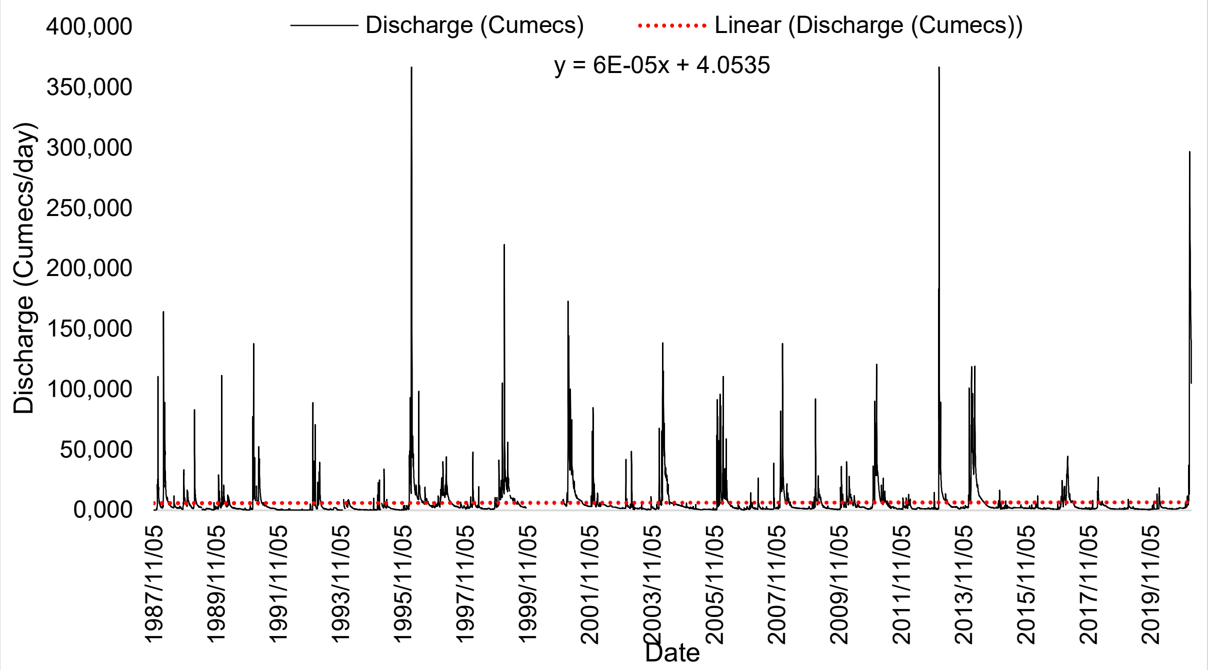

Figure 4.3: A9H012 - Daily average streamflow time series (1987 – 2021).

Figures 4.4(a) and 7(b) shows streamflow variation on a monthly and annual scale, respectively. For Figure 4.4a, summer months register the highest streamflow's, whereas winter months record the lowest, and this is a similar behaviour to that showed by the rainfall time series over the study period. February recorded the highest average streamflow of 20.7 m³/s and June recording the lowest at 1.44 m³/s. On an annual basis (Figure 4.4b), average annual streamflow was 6.25 m³/s. About 1.21 m³/s was recorded as the lowest annual streamflow in 1996, while the highest annual streamflow of 18.77 m³/s in 2019. The high annual streamflow in 2019 resulted from tropical cyclone Idai which was the strongest tropical cyclone ever recorded in the Southern Hemisphere (Odiyo et al., 2020). For the year 2000 at

Mhinga station, the station has the highest missing data and this is as a result of the heavy downpour caused by tropical cyclone Eline's when it made landfall in 1999/2000.

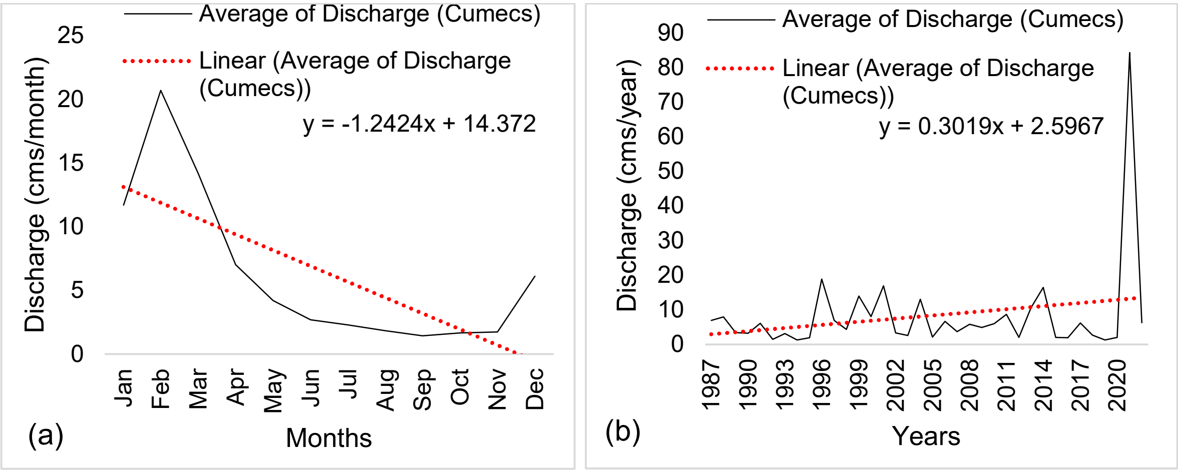

Figure 4.4: (a) A9H012- Monthly Average Streamflow (1987 – 2021), (b) A9H012- Annual average Streamflow (1987 – 2021).

4.2.3. Temperature

Average maximum daily temperature in station AF91 (07236646) at Thohoyandou AWS was 27.16 ºC, with maximum and minimum of 43.2 ºC and 9 ºC, respectively, as it can be seen in Figure 4.5 that daily temperature varies throughout the study period. The skewness of -1.32, shows that evaporation series have left-skewed distributions with low peaks near the mean with standard deviation of 5.67 which shows that there is minimal evaporation variability. The slope of the linear trend showed slightly increase of temperature over the period of the study with the equation y = -5E-05x – 29.202.

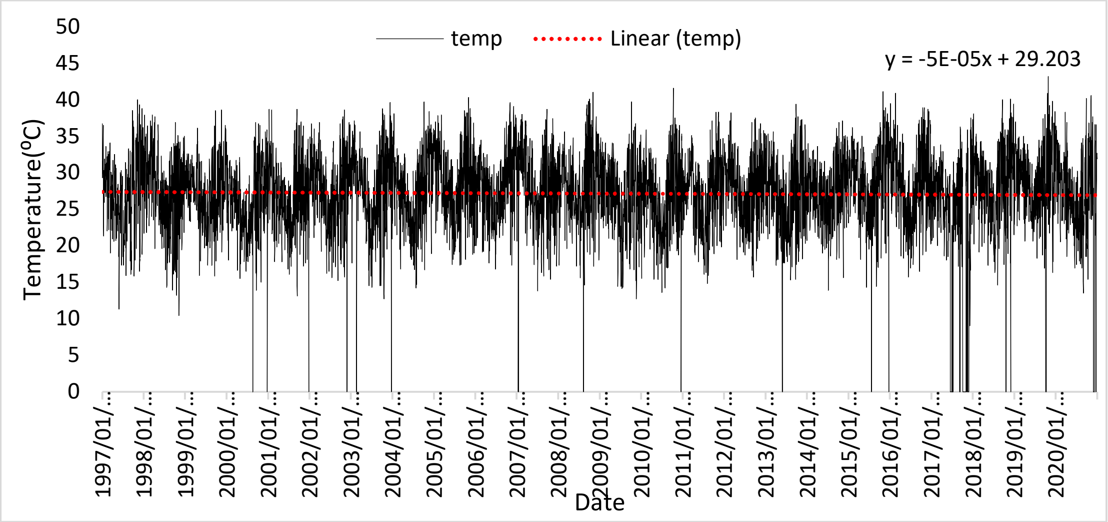

Figure 4.5: AF91 (07236646)- Daily average maximum temperature time series (1987 – 2021).

The average monthly observed maximum temperature in Figure 4.6a showed that high temperature is received in the summer months compared to winter months. The month of January and February experienced the highest maximum average temperature of 29.46 ºC and July having the lowest maximum average temperature of 23.23 ºC. Figure 4.6b shows the maximum average annual temperature variation over the study period., the year 2005 recorded the highest annual maximum average temperature of 28.46 ºC and the year 2017 recorded the lowest annual maximum average temperature of 21.47 ºC (with a lot of missing data), followed by the year 2000 with annual maximum average temperature of 25.87 ºC.

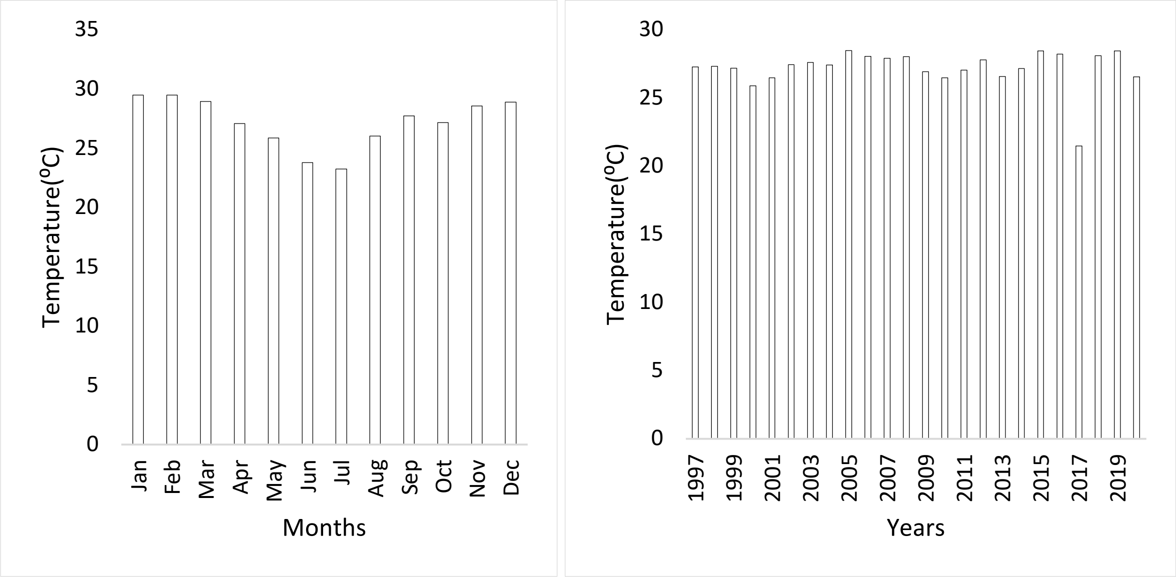

Figure 4.6: (a) AF91 (07236646) - Monthly average maximum temperature (1997 – 2020), (b) AF91 (07236646) - Annual average maximum temperature (1997 – 2020).

4.2.4. Evaporation

Figure 4.7 shows the variation of daily evaporation rates in the study area over the study period. The average daily evaporation for the Nandoni Dam sub-catchment was found to be 4.4 mm, with maximum and minimum of 14.5 mm. The skewness of 0.82 shows that evaporation series have right-skewed distributions with low peaks near the mean with standard deviation of 2.11 which shows that there is minimal evaporation variability around Nandoni Dam. A study by Kundu et al. (2015) report that the evaporation rates in the Luvuvhu Catchment are highly variable during the summer (October to March) and gradually decline during the winter (April to September). Furthermore, the slope of the linear trend showed a slightly increase of evaporation over the period of the study with the equation $y = 0.0002x - 3.9321$.

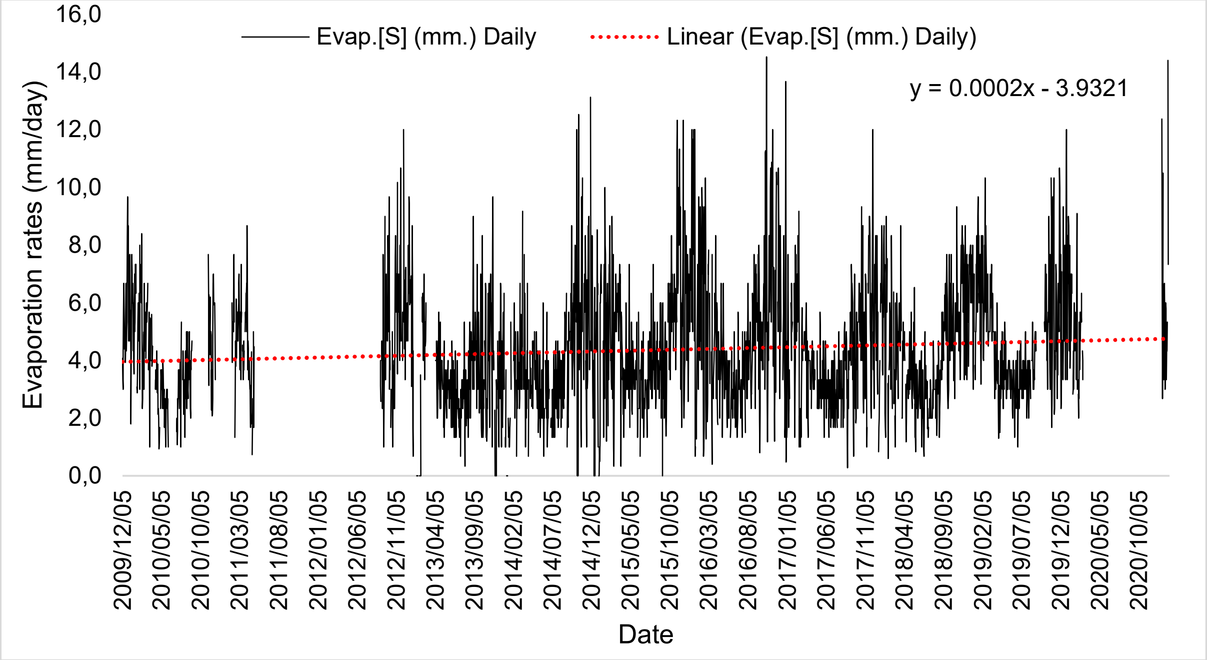

Figure 4.7: A9E004- Daily average evaporation time series (2009–2021).

Figures 4.8 (a) and 11(b) shows the variation of monthly and annual evaporation over the study period, respectively. The summer months have the highest evaporation compared to winter months, with November having the highest average evaporation of 5.85 mm and June having the lowest average evaporation of 2.82 mm. On an annual basis, the year 2009 had the highest annual evaporation of 5.72 mm with an average annual evaporation of 4. 38 mm. The lowest annual evaporation was recorded in 2013, with an average of 3.48 mm. A high evaporation rate significantly reduces effective rainfall and runoff in the catchment (Singo, 2018). Due to its impact on water resources, evaporation is an important factor in the study.

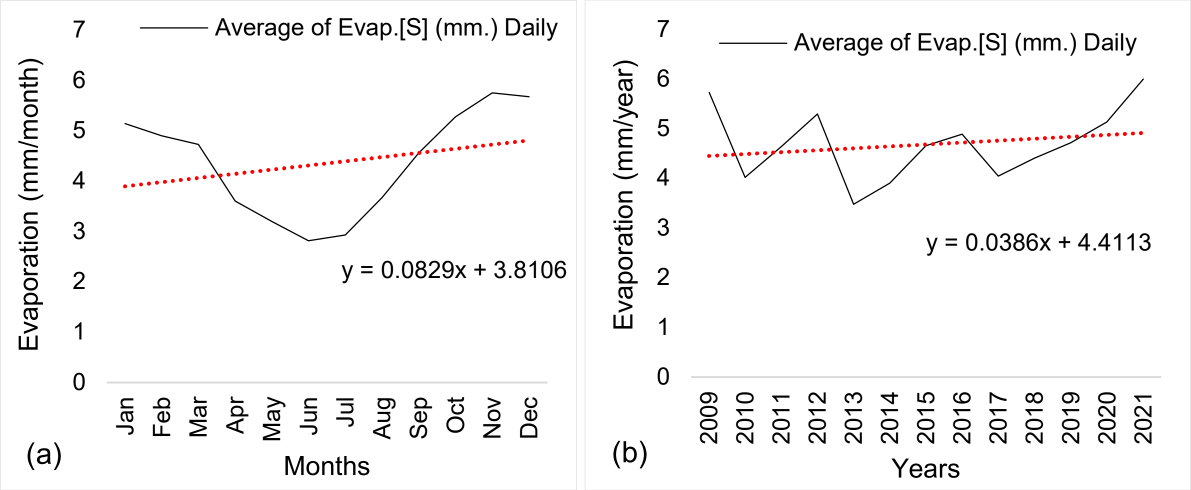

Figure 4.8: (a) A9E004- Monthly average of evaporation (2009– 2021), (b) A9E004- Annual average of evaporation (2009– 2021).

4.3 Analysis of Nandoni Dam water resources

4.3.1. Dam water storage

Figure 4.9 shows how the average daily dam storage varies throughout the study period. The average daily dam storage was 157 845.84 M.L, with the maximum and minimum values being 192 463.369 M.L and 76 724.044 M.L, respectively over the study period. Based on the skewness of -2.59, dam storage series have left-skewed distributions with low peaks near the mean with standard deviation of 18 030.52, which shows that there is high storage volume variability within Nandoni Dam. The slope of the trend line decreases with $y = -2.328x + 164046$, which indicate that the dam storage is decreasing over the period of the study.

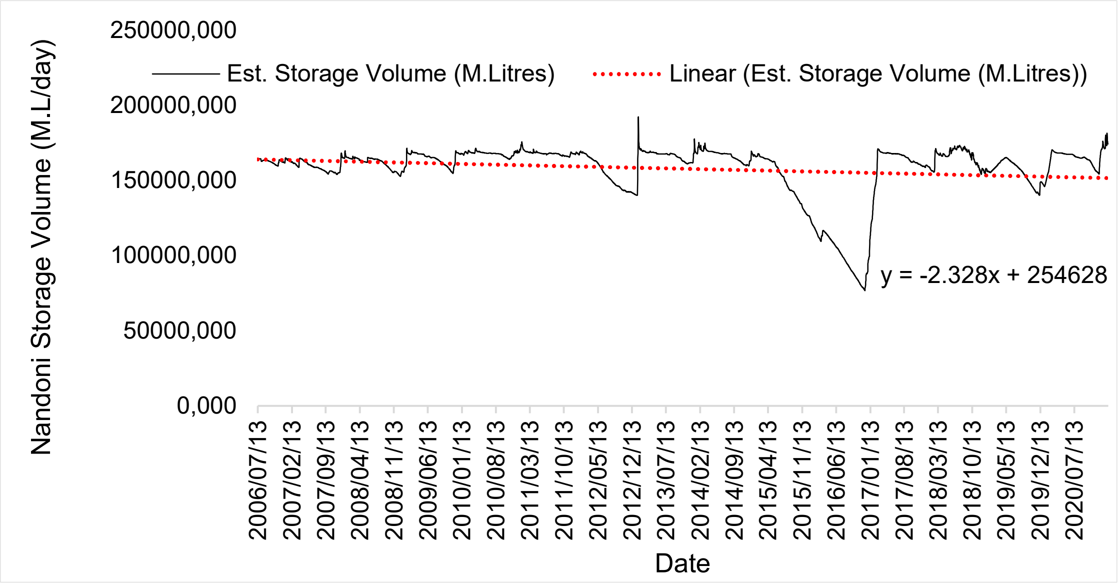

Figure 4.9: A9R004 – Nandoni Dam daily average water level time series 2007 – 2021.

Figures 4.10(a) and (b) shows the monthly and annual Nandoni Dam water storage for the study period, respectively. As can be seen from Figure 4.10(a), the dam storage level decreased from March to December, with March having the highest level of 162 919.38 M.L and November having the lowest level of 150 584.66 M.L. The rainy season begins in the third week of October and ends in the first week of April in the catchment area with high rainfall (Tshililo, 2017). The slope of the trend line decreases with $y = -952.87x + 164168$, which shows that the dam storage volume is decreasing over the period (months) of the study. On an annual basis, Figure 4.10(b) shows the amount of dam storage water level of different years with an average annual water storage of 157 845.84 M.L. The year 2011 had the highest annual storage water of 168 178.98 M.L and the lowest annual storage water level was recorded in 2016, with an average of 101096.24 M.L. This means that the amount of water stored in dams is influenced by the amount of rainfall received. In 2011/2012, heavy rainfall caused by tropical cyclone Dando led to an increase in dam storage in the Luvuvhu River

Catchment. However, the catchment experienced two extremely dry seasons in 2014/15 and 2015/16, resulting in severe drought conditions (Odiyo et al., 2020). The slope of the linear trend line decreases with y = -338.52x + 161797, which shows that dam storage is decreasing over the period (years) of the study.

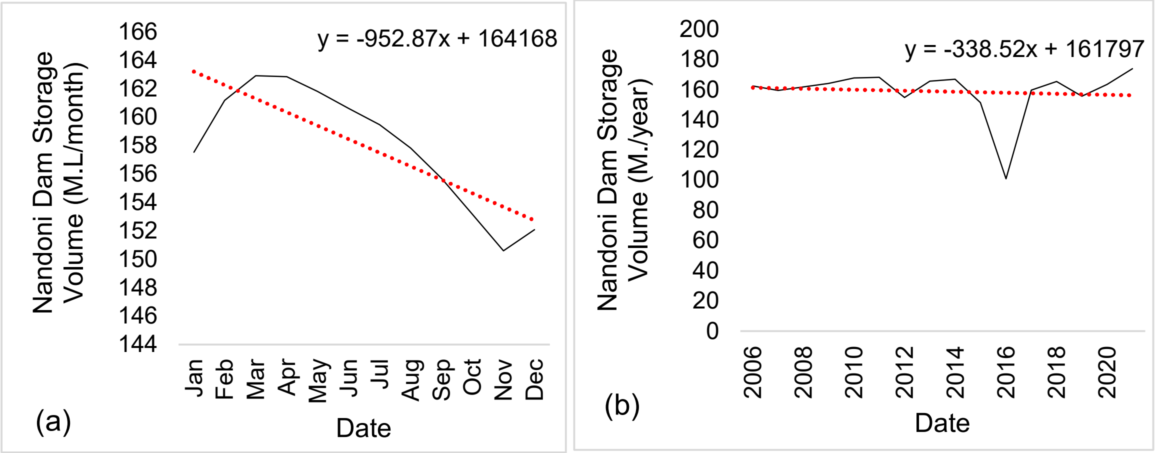

Figure 4.10: (a) A9R004 – Monthly average of Nandoni Dam water level (2007 – 2021), (b) A9R004 – Annual average of Nandoni Dam water level (2007 – 2021).

4.3.2. Uncontrolled spillway

As shown in Figure 4.11, the daily spillway varies throughout the study period. Average daily spillway was found to be 4.02 m³/s and the maximum at 588.23 m³/s. The skewness of 20.91 shows that uncontrolled spillway series have right-skewed distributions with sharp peaks near the mean and standard deviation of 14.92 indicate that the is high uncontrolled spillway variability. The slope of the linear trend line increases with $y = 0.0007x + 1.9493$, which shows that there is slightly increase of uncontrolled spillway over the period of the study.

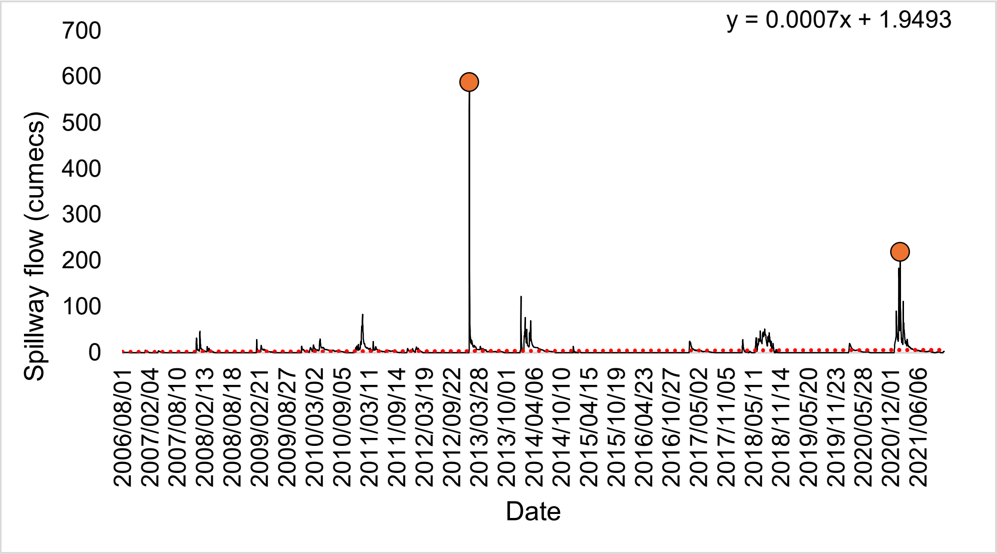

Figure 4.11: A9R0041– Nandoni Dam daily average uncontrolled spill (2006 – 2021).

Figures 4.12 (a) and (b) shows the annual and monthly dam water spill, respectively. From Figure 4.12(a), the amount of spillway flow varies every year, with an average annual spillway flow of 4.02 m³/s. About 9.7 m³/s of uncontrolled spills was recorded as the highest annual spillway flow in 2018. In 2016 and 2019, no spillway flow was recorded. In Figure 4.12(b), it can be observed that summer months recorded the highest amount of spillway from the dam compared to winter months, with January having the highest discharge value of 12.26 m³/s and October having the lowest discharge of 0.14 m³/s.

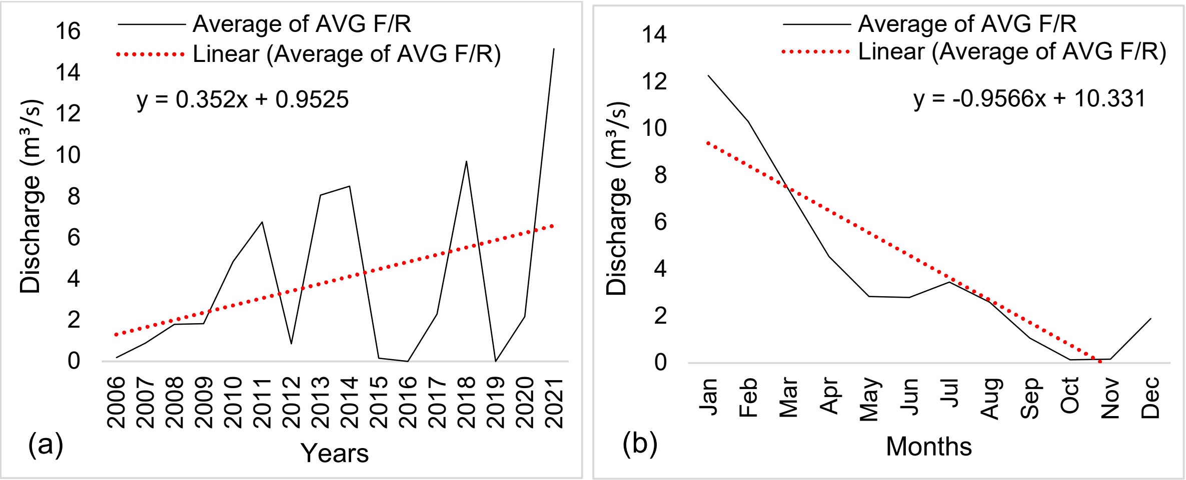

Figure 4.12: (a) A9R0041– Annual average of Nandoni Dam uncontrolled spillway (2006 – 2021), (b) A9R0041– Monthly average of Nandoni Dam uncontrolled spillway (2006 – 2021).

4.3.3. Domestic water abstraction

Figure 4.13 illustrates how daily water abstraction varies throughout the study period. The average daily domestic water abstraction from the dam was 48 298.65 m³/s, with maximum and minimum values of 72 700 m³/s and 0 m³/s, respectively. The skewness of -1.304 water abstraction series have left-skewed distributions with low peaks near the mean with standard deviation of 72 44.51 which shows there is high variability. Equation of $y = 8.377x - 336056$ shows that the slope of the trend line increases, indicating that the amount of domestic water abstraction is increasing over the period of the study.

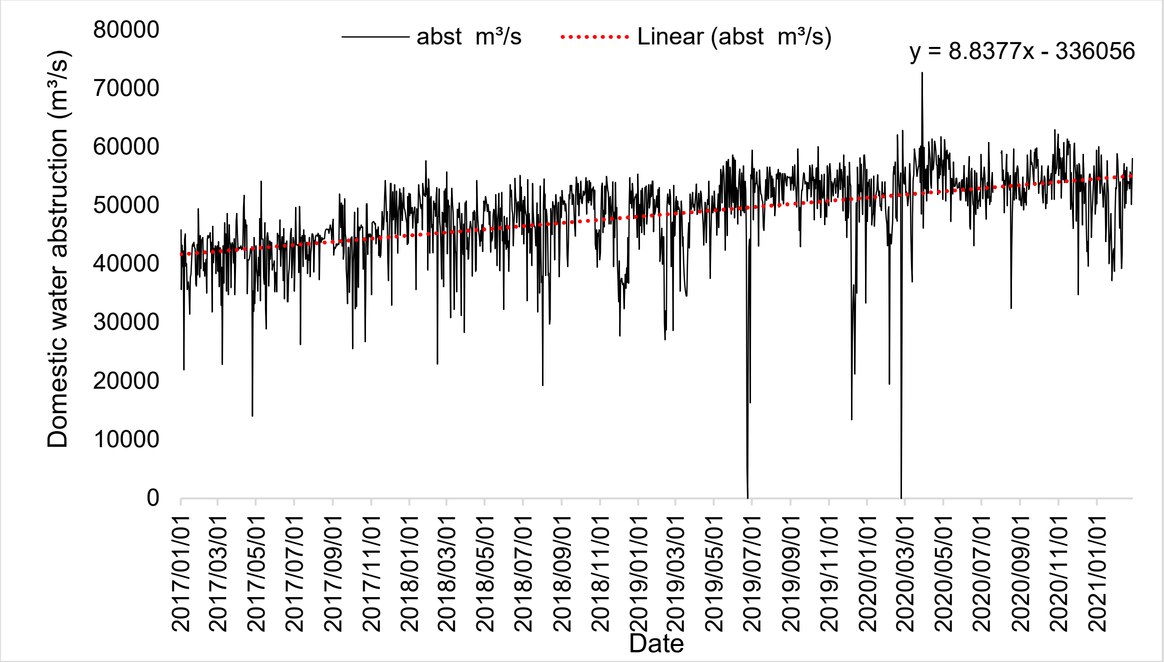

Figure 4.13: Nandoni Dam daily domestic water abstraction time series (2017 – 2021).

4.3.4. Dam outlet flow analysis

In 2018, 160 daily values were missing. The average daily outflow from the dam was 3.876 m³/s, with maximum and minimum values of 57.07 m³/s and 0.179 m³/s, respectively. As shown in Figure 4.14, the average daily outflow varies throughout the study period. The skewness 4.17 of dam outlet flow series have right-skewed distributions with peaks near the mean with standard deviation of 8.3. The slope of the linear trend line increases with $y = 0.0008x - 28.904$, which shows that the amount of dam outlet flow is slightly increasing over the period of the study.

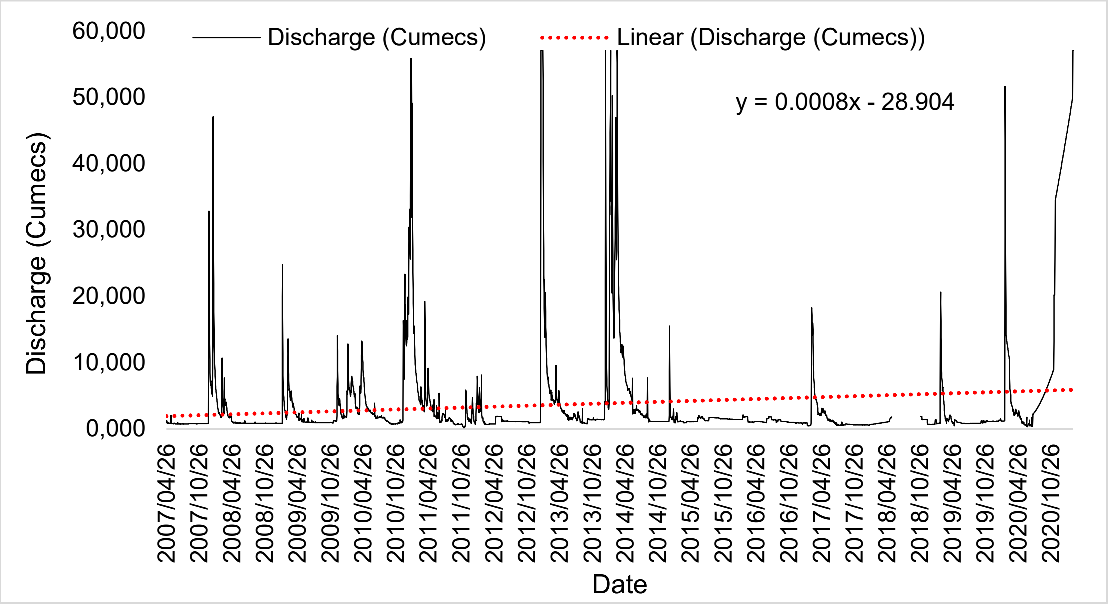

Figure 4.14: A9H030 - Nandoni Dam outflow Time Series (2007 – 2021).

Figures 4.15 (a) and (b) shows the annual and monthly dam outflow time series, respectively. From Figure 4.15(a), the amount of Nandoni Dam outflow varies every year, with an average annual of 3.23 m³/s. About 8.44 m³/s was recorded as the highest annual average outflow in 2020. The lowest average annual outflow was recorded in 2018, with an average of 0.97 m³/s. As the study area receives high rainfall in summer (Masupha and Moeletsi, 2018), in Figure 4.15(b), it can be observed that summer months recorded the highest amount of outflow from the dam compared to winter months, with January having the highest discharge value of 10.27 m³/s and September having the lowest discharge of 1.32 m³/s. This may be influenced by high temperature and rates of evaporation over the summer months.

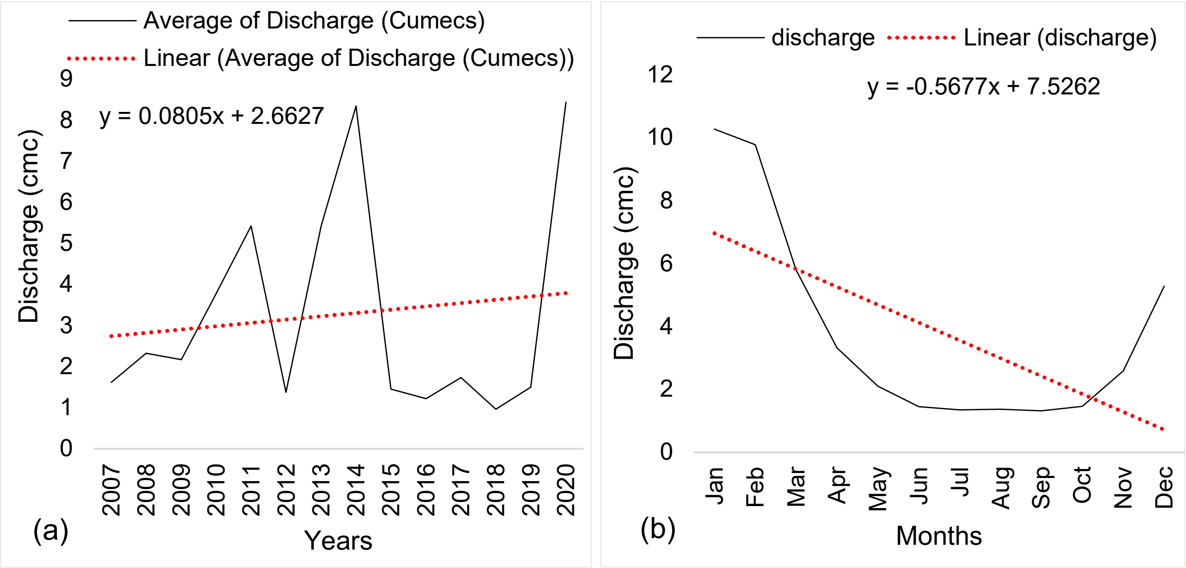

Figure 4.15: (a) A9H030 - Annual average of - Nandoni Dam outflow (2007 – 2021), (b) A9H030– Monthly average of Nandoni Dam water outflow (2007 – 2021).

Evaporation is high during summer months due to high temperatures. Furthermore, when there is high rainfall in late summer, dam storage peaks. Early summer is characterized by high evaporation and low dam storage. The Luvuvhu Catchment experiences highly variable evaporation during the summer (October to March) and a gradual decline during the winter (April to September) (Kundu et al., 2015). In the catchment, the rainy season begins in the third week of October and ends in the first week of April the following year (Tshililo, 2017). The catchment is characterised by high evaporation rate significantly reduces effective rainfall and runoff (Singo, 2018). In South Africa, rainfall distribution is skewed due to high solar radiation and high evaporation rates, resulting in low water availability (Olivier et al., 2020).

Figures 4.16 (a) and (b) shows the outflow vs storage and abstractions vs storage for Nandoni Dam, respectively. It can be seen in Figure 4.16(a) that there was a constant outflow for the most part except when the dam storage increases and reaches its peak, that's when the outflow increases rapidly. In March 2017, for instance, the dam's storage increased from 97683.72 M/L in January to 170299.86 M/L, and the outflow increased rapidly from 0.55M/L in February to 18.03 M/L in March. The dam's storage rises from 155130.30 M/L in February to 164598.78 M/L in May 2019, and the outflow spiked in February 2019 to reach 18.82. Dam storage reached 169 338.41 M/L in March 2020, and the outflow reached 51.66. In February 2021, dam storage reached 181 519.02 M/L, and the outflow reached 47.2 m^3/s. It appears that the outflow of the dam is being controlled in response to dam storage peaks. It can be seen in Figure 4.16(b) that despite increases or decreases in dam storage, the amount of water abstracted from the dam to water treatment plant is increasing over time.

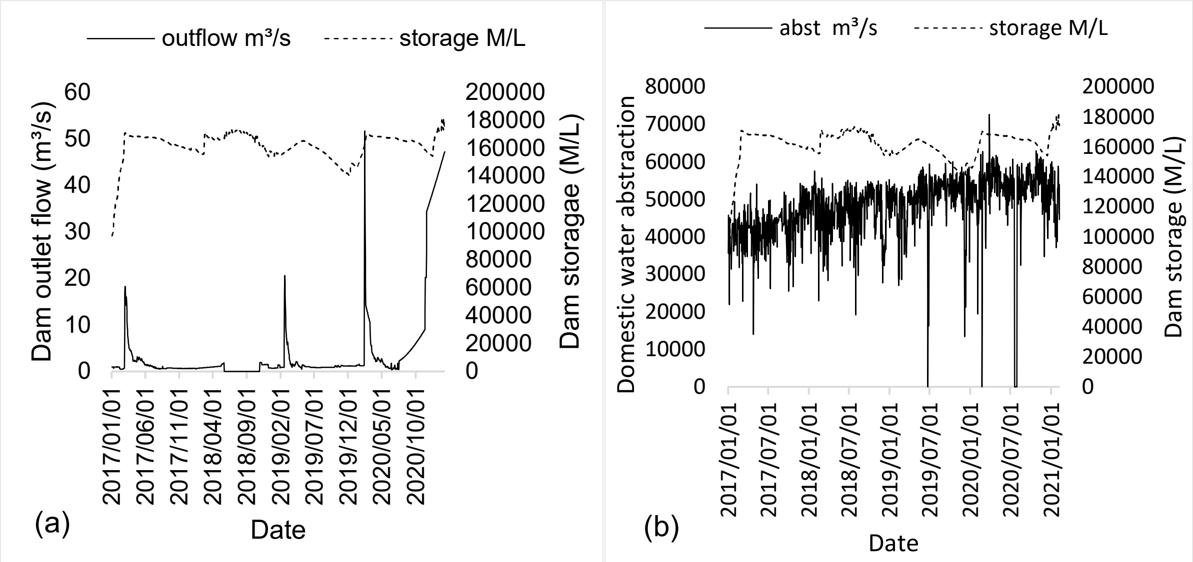

Figure 4.16: (a) Daily average dam outlet flow against daily average dam storage, (b) Daily domestic water abstracted to water treatment against dam storage.

4.3.5. Inflow data analysis

Inflow into the Nandoni Dam was computed and is presented in Figure 4.17. The average daily inflow was found to be 0.099 m^3, with the maximum and minimum values being 6.15 m^3 and -3.546 m^3, respectively. The skewness of 4.00 computed inflow series has right-skewed distributions with low peaks near the mean with standard deviation of 0.596 which shows there is low variability of computed inflow. Equation $y = -0.0001x + 5.769$, shows that the slope of the trendline decreases, indicating that the computed inflow is slightly decreasing over the period of the study.

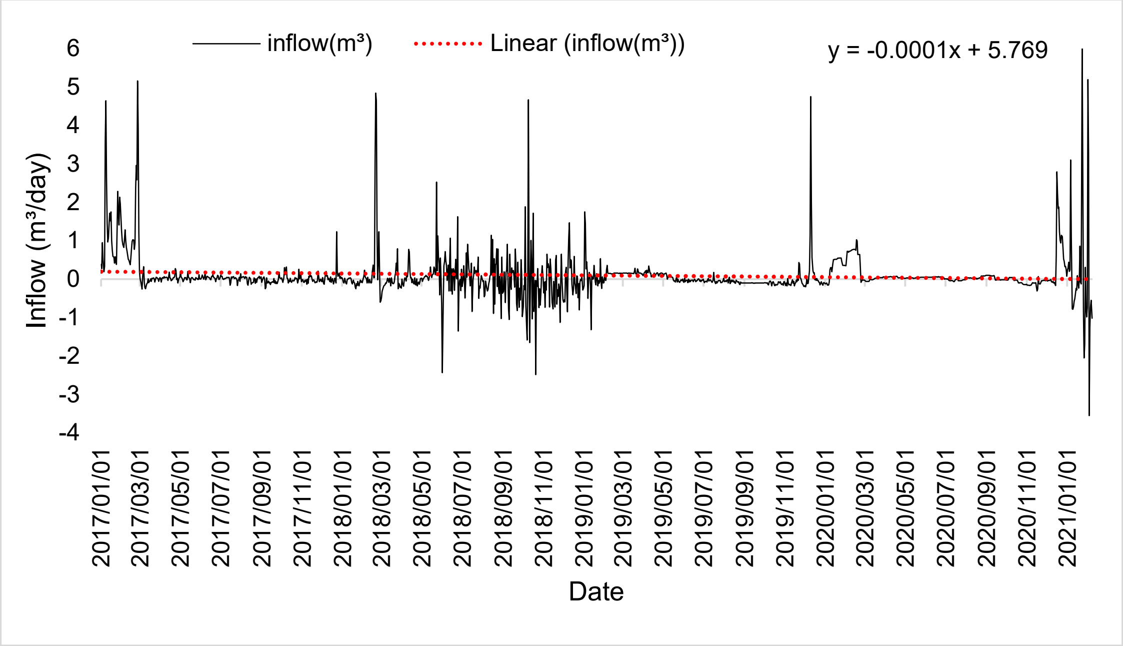

Figure 4.17: Estimated daily average inflow of Nandoni dam (2017-2021).

Figures 4.18 (a) and (b) shows the average annual and monthly inflow time series to the dam, respectively. Figure 4.18(a), the amount of computed inflow varies every year, with an average annual inflow of 0.099m³. The highest annual inflow in 2017 was 0.215m³ and the lowest annual inflow in 2019 was -0.030. The skewness of 0.078 computed inflow series has right-skewed distributions with low peaks near the mean with standard deviation of 0.429 which shows there is low variability of computed inflow. The equation $y = -0.0072x + 0.1276$ shows that the slope of the trend line decreases, indicating that the computed inflow is slightly decreasing over the period of the study. The skewness of 1.816 computed inflow series has right-skewed distributions with low peaks near the mean with standard deviation of 0.2 which shows there is low variability of computed inflow. The equation $y = -0.032x + 0.3022$ shows that the slope of the trend line decreases, indicating that the computed inflow is slightly decreasing over the period (days) of the study (Figure 4.18b).

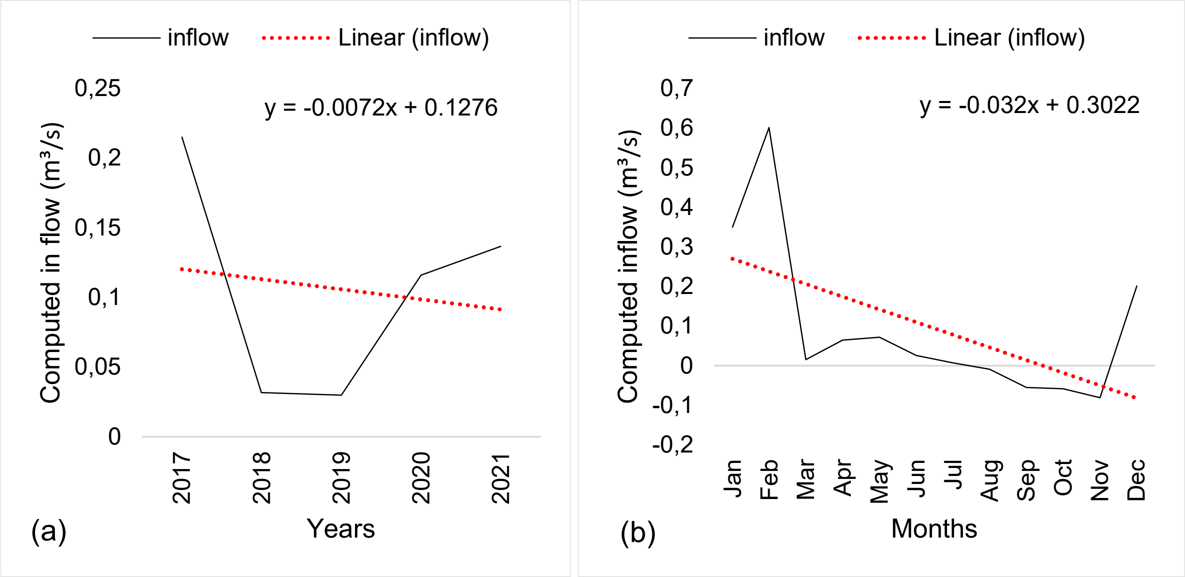

Figure 4.18: (a) Estimated annual average inflow for Nandoni Dam and (b) monthly average of Nandoni Dam.

Negative values were observed in the inflows to a reservoir, which is not ideal as they should ideally be positive or zero. This could be due to errors in measuring and recording reservoir level data, as even small errors can greatly affect volume estimation. Additionally, incorrect measurements may occur if strong winds blow over the reservoir's surface. Furthermore, without elevation-area-capacity curves after sedimentation, the calculation of reservoir capacity at specific elevations may be incorrect.

Figures 4.19 (a) and (b) shows the relationship between storage vs inflow and rain inflow for the study area, respectively. When inflows peak, dam storage increases and peaks during those periods, as shown in Figure 4.19a, and vice versa. The operationalization of the reservoir is closely related to the behavior of inflows, according to a study done at the reservoir of the Queimado Hydroelectric Power Plant in the Preto River Basin within the So Francisco River Basin (Generoso et al., 2022). The coefficient of correlation between dam storage change and computed inflow is 0.99, which indicates that the two have a strong positive relationship. The computed inflow peaks during periods of high rainfall, as illustrated in Figure 4.19(b), and vice versa. The correlation between the two variables is 0.27, indicating that there is only a weak positive relationship between them.

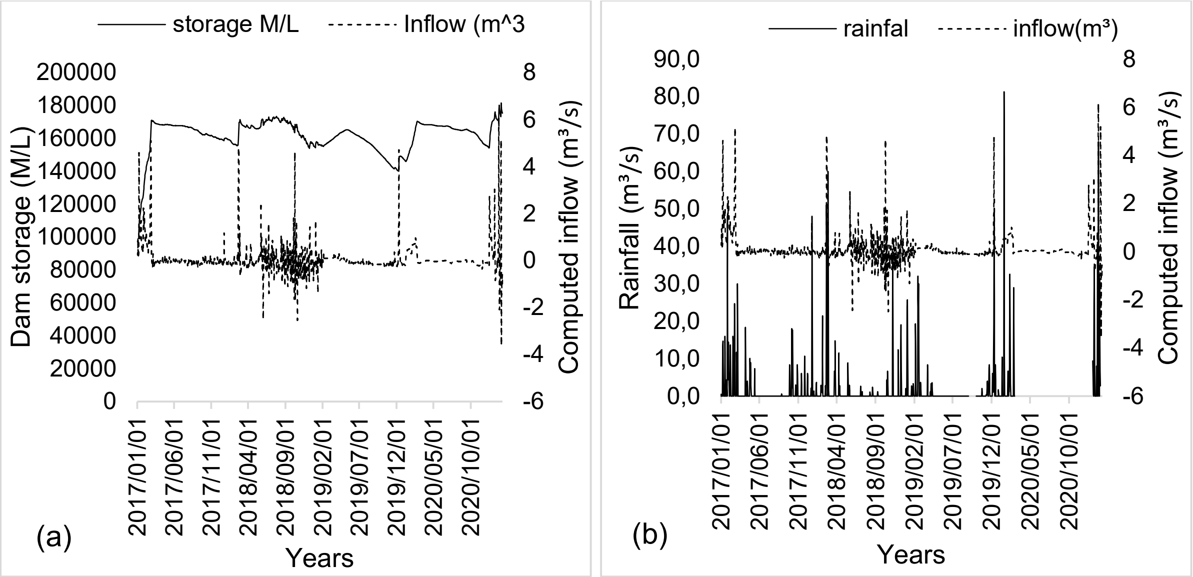

Figure 4.19: (a) Daily average dam storage water against computed inflow, (b) Daily average rainfall against computed inflow.

4.3.6. Dam water resources

The indicators of water level in Nandoni Dam storage are shown in Figure 4.20. It can be observed that maximum and high are above 100% and below 120%, where minimum water level is above 40% and below 70% of the dam storage. Moderately high-water level is between 97% and 100%, normal is between 94 and 100%, low is between 70% and 96 %, and very low is below 96% and 70% depending on the months of a year.

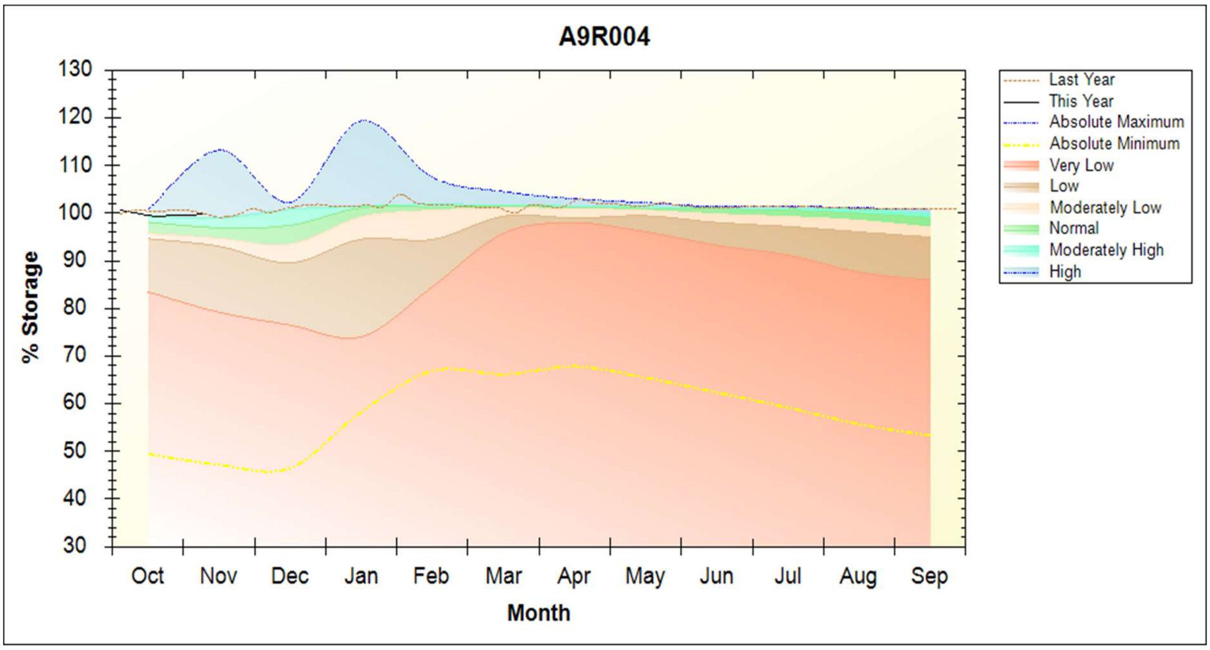

Figure 4.20: Variation of the Nandoni Dam storage (Source; DWS, 2022).

As it is illustrated in Figure 4.21, it was observed that the recorded highest daily dam storage was 109% in February 2021 which fall under high water level, and the lowest daily dam storage was 58.42% in 2017 January which falls under very low dam storage. Dam storage in 2017 increased rapidly from 58.42% in January to 102.03% in March which is within high dam storage. From March peak it started to decrease and reached 93.83% in 2018 February which is within low dam storage and rapidly increased to 101.46% in March which is within high dam storage. In July 2018 it reached maximum storage with 103.7% and decreased to 92.62% in December 2018 which is within low water level storage. From December 2018 it increases and reach 99.15% in May 2019 which is within normal range of water level storage and after it decreases and reached 84.49% in 2019 December which is within low water level storage. From December 2019 it increased to 102.02% in March which is within high water level storage then decreased to 92.75% in December 2020 which is within low water level and increased to 109.27 in February 2021.

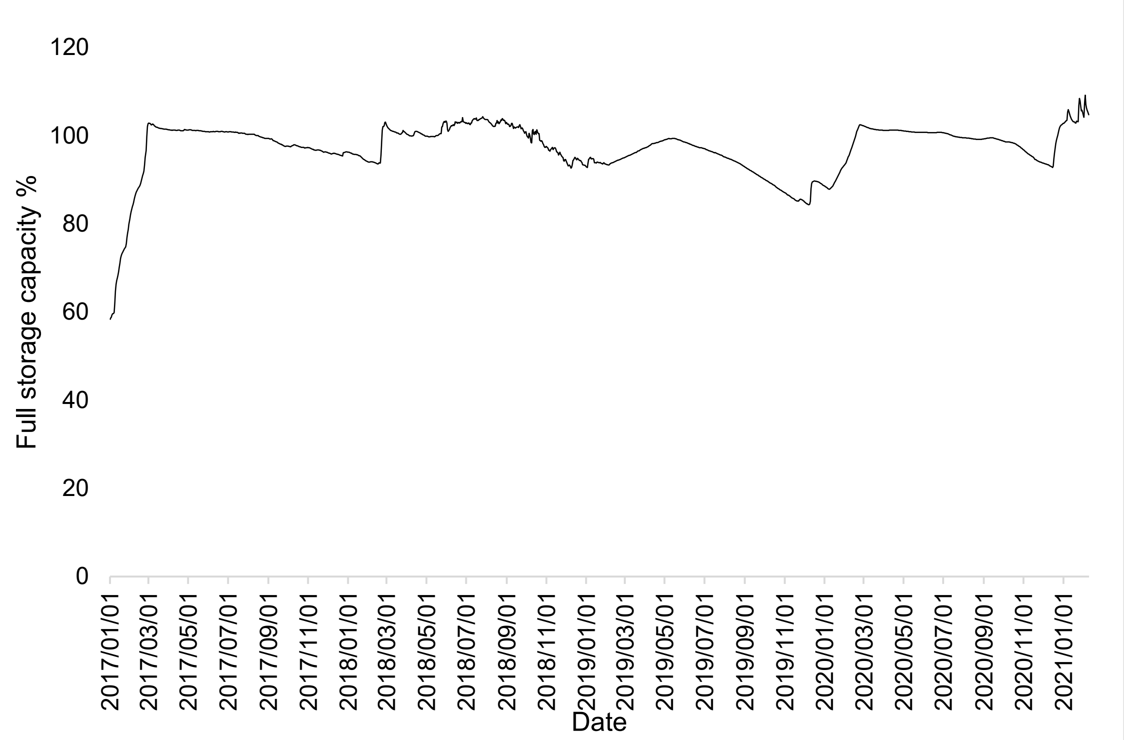

Figure 4.21: Daily percentage of Nandoni Dam water level.

Rainfall and streamflow variability affect the amount and distribution of water available (Odiyo et al., 2015). A change in precipitation amounts tends to affect runoff volume, while a change in air temperatures tends to affect runoff timing. Seasonal water supplies and regional water resources are adversely impacted by the change in streamflow regime. By operating reservoirs appropriately, the burden of sustainable water resources can be mitigated, and adverse impacts caused by climate change and variations are mitigated (Li et al., 2010). It is common to experience extremely dry and wet conditions in the Luvuvhu River Catchment (Mazibuko et al., 2021). Luvuvhu River Catchment rainfall and streamflow variability have increased over 86 years (Odiyo et al., 2015). The catchment experiences high variations in rainfall and evaporation (Onyari and Ilunga, 2013). Evaporation is highest during the rainfall season (about 60%), while evaporation is lowest during the dry season (DWA, 2003). In areas with high evaporation, effective rainfall is reduced, runoff is reduced, soil is infiltrated, ground water recharge is impeded, and sediment concentrations in water bodies increase. (Singo et al., 2016). There has been a rise in extreme events in the Luvuvhu River catchment, which has affected rainfall trends. Since then, several landfalls have occurred in this catchment (Odiyo et al., 2020).

It was already evident in 2009 that Cape Town's water supplies needed to be boosted, but officials dismissed the recommendations (Muller, 2018). Some industries and agricultural activities were not drawing their full allocation during the –ainy years (2013 & 2014). During the three years (2015 - 2017), where the city experienced severe drought, the city experienced day zero, (Muller, 2018). In the Luvuvhu catchment, where Nandoni dam is located, there is plenty of water, though the catchment is likely to face water shortages soon (Nare et al., 2013). According to Odiyo et al., 2020, most stations along the Luvuvhu River indicated that temperatures and rainfall would increase and decrease, respectively, over the short-term and long-term. It is estimated that by the year 2076, temperatures will have increased by more than 2°C (Odiyo et al., 2020). According to Odiyo et al., 2020, annual cumulative inflows into Albasini and Nandoni Dams in the near future will increase linearly while those in the far future will decrease (Odiyo et al., 2020). Odiyo et al., 2020 found that cumulative inflows vary from year to year, which will affect water resource availability and allocation. To meet the increasing demands of Thohoyandou and Louis Trichardt's industrial and urban areas, Nandoni Dam was built (Nare et al., 2013). As home water usage rises and there is a need to augment the Giyani regional and Matoks bulk water delivery schemes, the Nandoni Dam system is predicted to have severe water supply shortages in the future (Odiyo et al., 2020, Rikhotso, 2020). As the Nandoni Dam augments Albasini Dam, Louis Trichardt originally received transferred water from Albasini Dam. As part of the Sinthumule Kutama Bulk Water Augmentation Project and the Makhado West Regional Bulk Water Supply (Lombaard et al., 2015). In addition to water availability, the study area will also be impacted by water consumption increases downstream and the reduced capacity of the dams due to sedimentation and evaporation losses (Odiyo et al., 2020).

4.4. Streamflow required to maintain the ecological integrity

The IHA calculated parameters for five ecologically relevant EFCs: large flood, small floods, high flow pulse, low flow pulse and extreme low flows. According to the EFCs of the IHA, the 34 environmental flow parameters were calculated using the daily natural time series downstream of Nandoni Dam in the Luvuvhu River at station A9H012 (Mhinga). Values for selected parameters are presented as percentiles between 10% and 90%. Each parameter is analysed based on the environmental flow suggestions shown in Table 3, for more details Table A2 in the appendices provides a summary of these EFCs Parameters and their Ecosystem Influences. These are potential effects that flow alteration by dams have to negatively impact the environment by disturbing biological life in streams. For extreme low flows, lowest flow that can be observed is between 0.001 and 0.05. Duration of the highest event can be between 1 and 15 days for once as it is presented in Table 3. The possible timings of the occurrence can be between 282 and 82 Julian date. The frequency of occurring in a year ≤ 8.8. For high flow pulses, highest flow that was observed ranged between 3.75 – 22.5. Duration of the highest event can be between 3.5 and 28.8 days for once. The possible timings of the occurrence can be between 330.5 and 167.1 Julian date. The frequency of occurring in a year 0.6 ≥ and ≤ 10.4. For the small floods, the highest flow that can be observed ranged between 83.09 – 137.8. Duration of the highest event can be between 12 and 62 days for once. The possible timings of the occurrence can be between 349 and 56 Julian date. The frequency of occurring in a year ≤ 1.8. For the large flood peak, the IHA software only showed the 50% percentile of the highest flow, duration of the highest event and possible timing of the occurrence. Which are 366.7, 233 days for once and 43 Julian date. The frequency of occurring in a year ≤ 0.8. It is important to emphasize that these environmental flow suggestions are based on natural requirements. Dam operational or management-related issues either have no or little effect.

Table 3: The Environmental Flow Components (EFCs) Values as cumulative percentiles ranging from 10% to 90%.

	10%	**25%**	**50%**	**75%**	**90%**
EFC Monthly Low Flows					
October Low Flow	0.1432	0.1548	0.4605	1.205	2.856
November Low Flow	0.0874	0.12	0.3625	1.672	3.419
December Low Flow	0.1952	0.5191	1.32	2.773	4.233
January Low Flow	0.157	0.7195	1.921	3.01	3.431
February Low Flow	0.231	1.251	1.537	3.668	4.462
March Low Flow	0.251	2.245	2.954	4.425	4.436
April Low Flow	0.073	1.164	2.346	3.272	4.462
May Low Flow	0.599	0.9175	2.025	3.911	4.446
June Low Flow	0.16	0.3843	0.991	1.825	4.141
July Low Flow	0.289	0.6845	1.068	2.55	4.215
August Low Flow	0.2741	0.3755	1.077	1.583	2.24
September Low Flow	0.1564	0.3661	1.012	1.721	3.62
Extreme low Flows					
Extreme low peak	0.001	0.001	0.0075	0.0295	0.05
Extreme low duration	1	3.25	8	13.25	15
Extreme low timing	282	302.4	324	342.5	82
Extreme low frequency	0	0	1	3	8.8
High flow					
High flow peak	3.762	4.772	5.908	13.44	22.5
High flow duration	3.2	5.75	7	19.5	28.8
High flow timing	330.5	349.3	5	30.75	167.1
High flow frequency	0.6	3	5	7	10.4
Small Flood					
Small Flood peak	83.09	85.9	111.4	137.6	137.8
Small Flood duration	12	15.5	39	55.75	63
Small Flood timing	349	362	19	41.25	56
Small Flood frequency	0	0	0	1	1.8
Large flood					
Large flood peak	-	-	366.7	-	-
Large flood duration	-	-	233	-	-
Large flood timing	-	-	43	-	-
Large flood frequency	0	0	0	0	0.8

Figure 4.22 show the daily natural flow hydrograph for the Mhinga station downstream of the Nandoni Dam, the Figure 25 further shows the different EFC representations. To maintain riverine integrity, it is essential to maintain these five types of flow events. By default, high flows are set to >75%, low flows to 50%, extreme low flows to 10%, two-year return flows for small floods and 10-year return flows for large floods (Kannan et al., 2018).

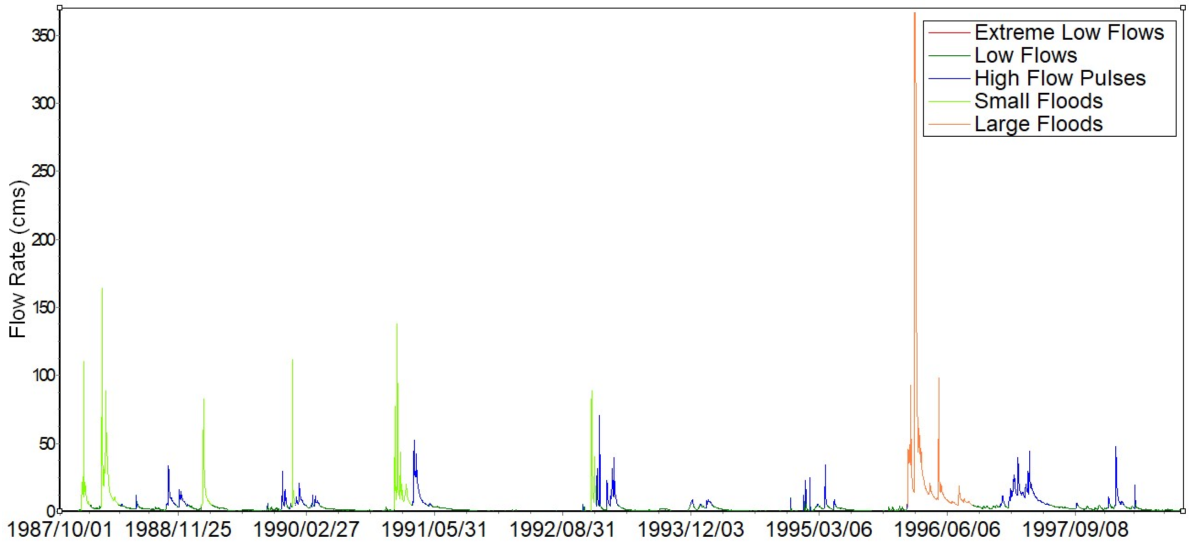

Figure 4.22: Daily natural hydrographs of the Luvuvhu River downstream of Nandoni Dam at Mhinga station A9H012 with EFC representations.

Ecologists have classified river hydrographs into five EFCs based on a recurrent set of ecologically important hydrographic patterns in order to preserve the integrity of riverine ecosystems. It is crucial to maintain enough flows during high flow periods, floods, and extremely low flow situations in addition to maintaining adequate flows during low flow times (Mathews and Richter, 2007). Moreover, environmental flow recommendations, flow-ecology models, flow restoration and protection programs, monitoring and research programs are developed using the output of IHA software, particularly the EFCs and their intra- and inter-annual characteristics (Mathews and Richter, 2007).

These thresholds were used to gauge the amount of water in the Luanginga basin, a section of the upper Zambezi River, and the results served as the foundation for future multi-criteria decision analyses (MCDA). Hydrological indicators and MCDA were combined to produce a methodology that is adaptable to both application platforms and subject matter (Butchart-Kuhlmann et al., 2018). To assess current flow conditions and estimate environmental flow of the Turag River in Bangladesh, range of variability approach (RVA), flow duration curve (FDC) and mean annual flow (MAF) methods were applied. (Rahman et al., 2013), and IHA software was utilized to calculate environmental flow. Environmental flow requirements for Sakarya watershed in Turkey were defined in terms of 34 Environmental Flow Components (EFCs) parameters (Özcan, 2021). A natural river restoration perspective should be used when selecting these environmental flow components. If these values are implemented, the Luvuvhu River downstream of Nandoni Dam would return to its near-natural state similar to its condition before the dam was built.

4.5. Changes in streamflow between current and historic flow conditions downstream of Nandoni Dam

Figure 4.23 depicts a summary of hydrologic indicators below the Nandoni dam, with Table 4 showing the RVA Scorecard, Pre, and post impact downstream of the dam. Prior to and after dam construction, the impacts of the dam on middle RVA categories flow were analyzed for comparison. Tables A1 and A2 in appendices provide the summary of IHA parameters and EFC parameters, along with the ecosystem influences they have on the ecosystems.

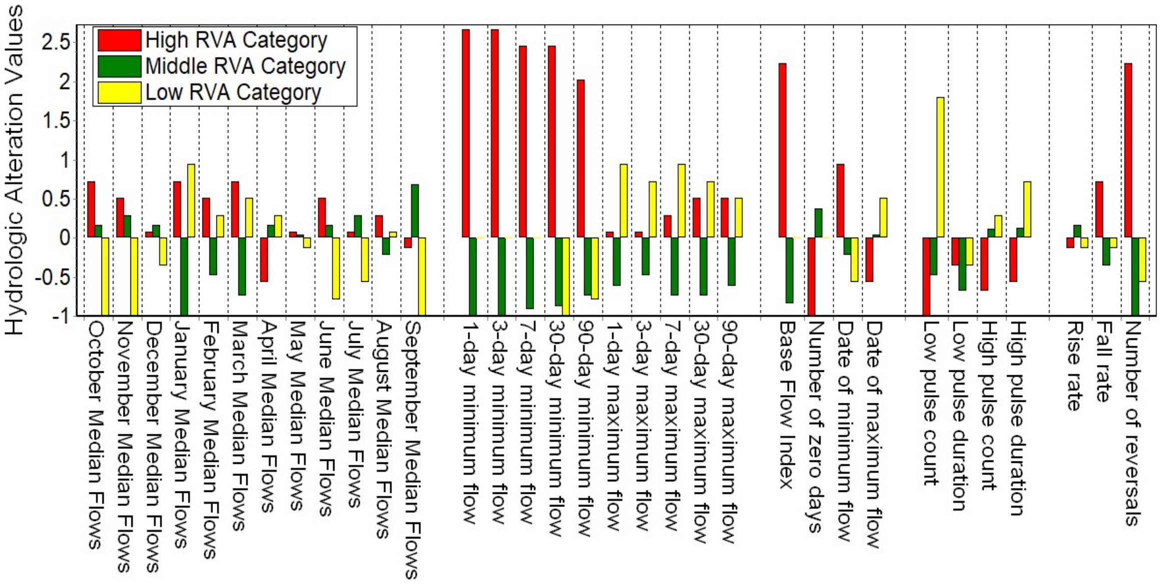

Figure 4.23: RVA categorisation of hydrologic indicators downstream of Nandoni Dam.

Table 4: IHA Non-Parametric RVA Scorecard, Pre, and post impact downstream of Nandoni Dam

	Pre-impact period: 1988-1998				**Post-impact period: 2005-2021**			
	Medians	**Coeff. of Dispersion**	**Minimum**	**Maximum**	**Medians**	**Coeff. of Dispersion**	**Minimum**	**Maximum**
Parameter Group #1								
October	0.386	5.516	0	4.526	1.153	0.9219	0.272	3.427
November	0.22	7.827	0.0175	5.422	1.177	0.5994	0.396	2.785
December	3.41	1.207	0.089	7.58	2.174	1.99	0.878	16.46
January	3.836	0.811	0.028	12.12	3.38	3.392	0.92	35.87
February	7.118	1.353	0.013	55.8	7.178	1.825	1.344	165.2
March	5.688	2.014	0.119	25.36	7.297	1.512	0.98	104.9
April	2.995	2.415	0	12.45	4.941	1.208	0.771	104.9
May	2.029	1.848	0	13.06	2.403	1.642	0.46	104.9
June	1.463	2.014	0	7.205	2.002	0.8563	0.361	104.9
July	1.068	2.048	0	6.525	1.549	0.8312	0.61	104.9
August	1.214	1.143	0.02	6.937	1.368	0.8465	0.61	104.9
September	0.6897	2.469	0	3.805	1.114	0.6667	0.534	104.9
Parameter Group #2								
1-day minimum	0.001	180	0	1.724	0.628	0.7811	0.106	1.507
3-day minimum	0.003667	51.27	0	1.771	0.6817	0.7435	0.11	1.527
7-day minimum	0.007714	30.7	0	1.88	0.733	0.7124	0.1151	1.593
30-day minimum	0.0983	5.303	0	2.127	0.8705	0.6619	0.3189	1.868
90-day minimum	0.7072	0.928	0.008489	2.9	1.351	0.5803	0.4922	2.146
1-day maximum	83.09	1.249	1.222	366.7	39.99	2.624	5.995	366.7
3-day maximum	48.62	1.231	1.127	366.6	33.32	2.932	4.674	297
7-day maximum	27.86	1.173	1.003	322.8	22.39	3.342	3.754	259.8
30-day maximum	15.76	1.137	0.6197	118.3	14.28	2.985	3.179	170
90-day maximum	8.863	1.552	0.3755	55.78	10.37	2.225	2.165	126.6
Number of zero days	0	0	0	160	0	0	0	0
Base flow index	0.003918	14.12	0	0.2574	0.1563	1.529	0.02032	0.5859
Parameter Group #3								
Date of minimum	275	0.1093	25	322	312	0.1475	14	363
Date of maximum	43	0.2158	9	349	35	0.1175	11	366
Parameter Group #4								
Low pulse count	4	1.75	0	8	0	0	0	4
Low pulse duration	9.25	1.568	3	29.5	7	1.929	1	23.5
High pulse count	5	0.6	0	10	3	0.8333	1	8
High pulse duration	7.5	4.083	3	117	8	1.469	1	207
The low pulse threshold is			0.47					
The high pulse threshold is			4.56					
Parameter Group #5								
Rise rate	0.081	1.235	0.034	0.315	0.054	1.032	0.032	0.2475
Fall rate	-0.111	-0.8784	-0.2765	-0.0265	-0.102	-0.8186	-0.2275	-0.033
Number of reversals	88	0.375	52	128	120	0.2375	49	162

4.5.1. The magnitude of monthly water flow rates (parameters in group 1 IHA)

Except for December and January, the monthly median flow has increased from pre-impact to post-impact, as shown in Figure 4.24. November has the lowest median flow of 0.22 m³/s and February has the highest median flow of 7.12 m³/s during the pre-impact period, whereas October has the lowest median flow of 1.15 m³/s. March has the highest median flow of 7.3 m³/s during the post impact period as can be seen in Table 4. With the exception of August, January, February, and March, the monthly flow alteration in the middle RVA category has increased throughout the post-impact period. The highest alteration with increasing and decreasing value was shown for September by 68.24% and January by 100%, respectively. Table 5 shows additional supporting results of the RVA Scorecard, Assessment of Hydrologic Alteration. Figure 4.24 further shows that, summer flow is higher than winter flow before and after the dam was constructed. This is results from the fact that summer months receives high rainfalls than winter months which impact streamflow in the catchment (Nemaxwi et al., 2019). It should be noted that the flow is higher after the dam was built, this is explained by dam releases, which support low river flows in times of drought and hydrological deficit.

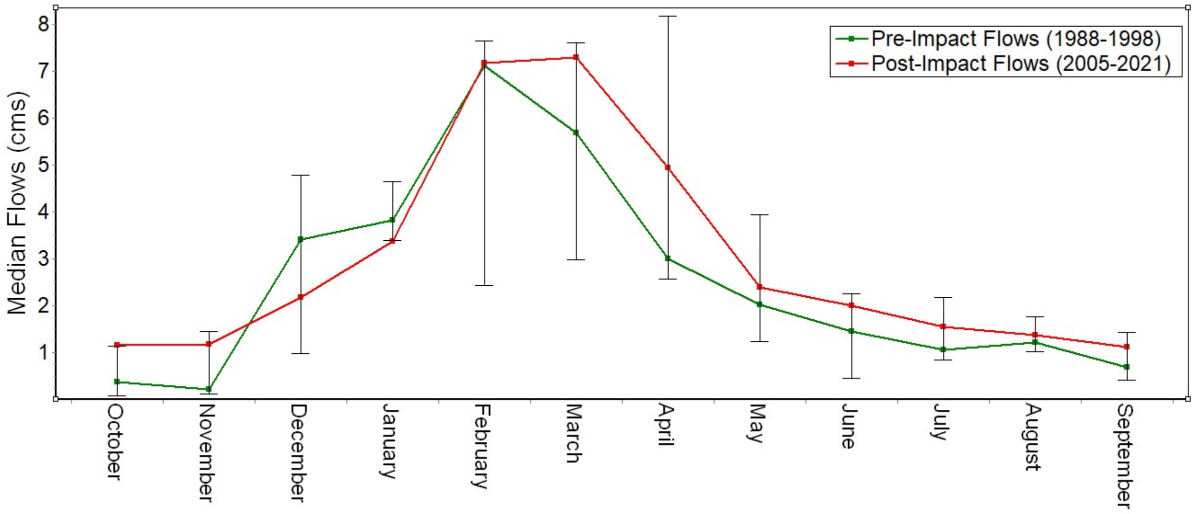

Figure 4.24: The pre- and post-impact on monthly flows downstream of Nandoni Dam.

Table 5: IHA Non-Parametric RVA Scorecard, Assessment of Hydrologic Alteration.

	Middle RVA Category			High RVA Category			Low RVA Category		
	Expected	**Observed**	**Alter.**	**Expected**	**Observed**	**Alter.**	**Expected**	**Observed**	**Alter.**
Parameter Group #1									
October	7.727	9	0.1647	4.636	8	0.7255	4.636	0	-1
November	7.727	10	0.2941	4.636	7	0.5098	4.636	0	-1
December	7.727	9	0.1647	4.636	5	0.07843	4.636	3	-0.3529
January	7.727	0	-1	4.636	8	0.7255	4.636	9	0.9412
February	7.727	4	-0.4824	4.636	7	0.5098	4.636	6	0.2941
March	7.727	2	-0.7412	4.636	8	0.7255	4.636	7	0.5098
April	7.727	9	0.1647	4.636	2	-0.5686	4.636	6	0.2941
May	7.727	8	0.03529	4.636	5	0.07843	4.636	4	-0.1373
June	7.727	9	0.1647	4.636	7	0.5098	4.636	1	-0.7843
July	7.727	10	0.2941	4.636	5	0.07843	4.636	2	-0.5686
August	7.727	6	-0.2235	4.636	6	0.2941	4.636	5	0.07843
September	7.727	13	0.6824	4.636	4	-0.1373	4.636	0	-1
Parameter Group #2									
1-day minimum	12.36	0	-1	4.636	17	2.667	0	0	
3-day minimum	12.36	0	-1	4.636	17	2.667	0	0	
7-day minimum	12.36	1	-0.9191	4.636	16	2.451	0	0	
30-day minimum	7.727	1	-0.8706	4.636	16	2.451	4.636	0	-1
90-day minimum	7.727	2	-0.7412	4.636	14	2.02	4.636	1	-0.7843
1-day maximum	7.727	3	-0.6118	4.636	5	0.07843	4.636	9	0.9412
3-day maximum	7.727	4	-0.4824	4.636	5	0.07843	4.636	8	0.7255
7-day maximum	7.727	2	-0.7412	4.636	6	0.2941	4.636	9	0.9412
30-day maximum	7.727	2	-0.7412	4.636	7	0.5098	4.636	8	0.7255
90-day maximum	7.727	3	-0.6118	4.636	7	0.5098	4.636	7	0.5098
Number of zero days	12.36	17	0.375	4.636	0	-1	0	0	
Base flow index	12.36	2	-0.8382	4.636	15	2.235	0	0	
Parameter Group #3									
Date of minimum	7.727	6	-0.2235	4.636	9	0.9412	4.636	2	-0.5686
Date of maximum	7.727	8	0.03529	4.636	2	-0.5686	4.636	7	0.5098
Parameter Group #4									
Low pulse count	7.727	4	-0.4824	4.636	0	-1	4.636	13	1.804
Low pulse duration	6.182	2	-0.6765	3.091	2	-0.3529	3.091	2	-0.3529
High pulse count	10.82	12	0.1092	3.091	1	-0.6765	3.091	4	0.2941
High pulse duration	6.182	7	0.1324	4.636	2	-0.5686	4.636	8	0.7255
Parameter Group #5									
Rise rate	7.727	9	0.1647	4.636	4	-0.1373	4.636	4	-0.1373
Fall rate	7.727	5	-0.3529	4.636	8	0.7255	4.636	4	-0.1373
Number of reversals	7.727	0	-1	4.636	15	2.235	4.636	2	-0.5686

Figure 4.25 depicts the hydrological regime changes for the month of October, with targets for the 75th percentile and 25th percentile RVA (other months are presented in the appendices). Nonetheless, it should be observed that flow has a positive and less variable flow pattern in the post impact period. In addition, the 25th, median, and 75th percentiles of flow are also seen to be altered. Figure 4.25 for October, for instance, shows that while the 75th percentile has somewhat fallen from the pre-impact to the post-impact period, the 25th percentile and median have increased. It can be also observed that in the post-impact period, monthly flow variability was decreased altering the natural structure of stream flow in the system. The results of long-term pattern in monthly median streamflow downstream of Nandoni Dam can be contrasted with that for streams below dams in other areas. The results indicate the positive and negative effects of streamflow downstream of dams over multiple stations in different months, with the 25th median and 75th percentiles of flow being observed to be altered in most studies. One main factor contributing to the decrease in river flows is the reservoir's retention (Sojka et al., 2016). Yet, water release from the reservoir is what is responsible for the increased river flow (Suwal, 2019). This conclusion suggests that the dam is also utilized to manage floods or other extreme events.

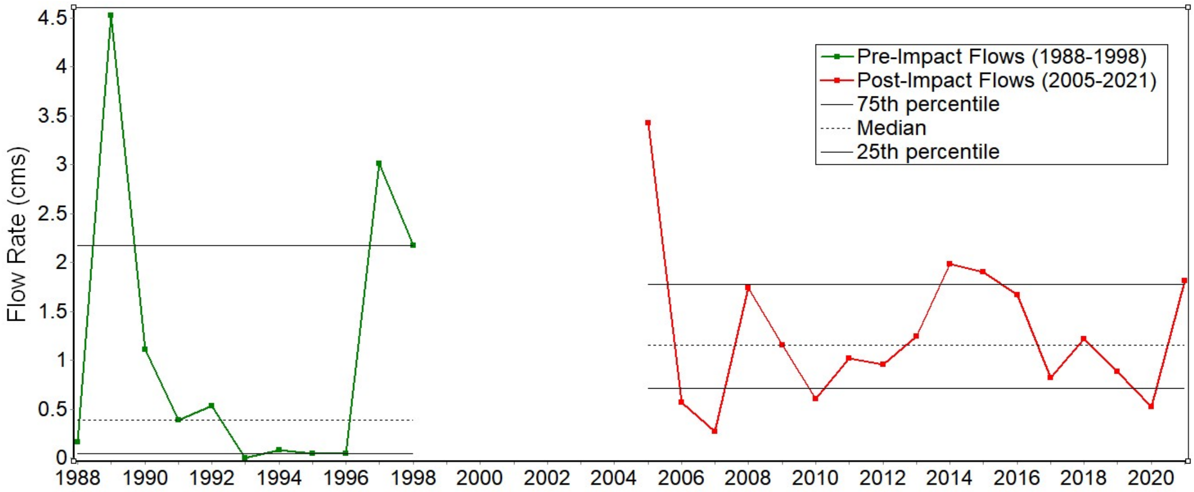

Figure 4.25: Example of changes in the hydrological regime, with 75th percentile and 25th percentile RVA targets downstream of Nandoni dam in the month of October.

For example, regardless of different of wet and dry months in different study areas. The pattern in the Nkomazi River in KwaZulu-Natal; Shaying River in China and Yangtze River of China, at Cuntan and Miaohe Station shows a decreasing trend of the median monthly flow throughout the post-impact period compared with that in the pre-impact period except in 3 to 4 months where it increases (Taylor et al., 2003; Ali et al., 2019; Qiting and Shikui, 2016; Zuo and Liang, 2015), which shows opposite trend with the results of downstream flow of Nandoni

Dam. Another example is the pattern in Mountain Creek at Grand Prairie station below Joe Pool Lake in the Trinity River Basin in Texas, and in Observations on the operation of Diama and Manatali Dams on Lake Guiers, Senegal which showed an increasing trend throughout the post-impact period except in few months where a deviation were observed decreasing (Sheet, 2003; Djiby et al., 2017). This therefore the same trend with those of this study. In flood control operations on water reservoirs, high magnitude flooding is virtually eliminated, which has an obvious impact on hydrological processes (Zhang et al., 2014). Faye (2018) reported that the monthly median flows of the Bafing River in Senegal were positively affected by flood rolling actions and low flow support during the wet natural period and negatively affected by high water periods because of Manantali Dam management. Floods allow fish and other mobile organisms to access additional habitats in floodplains and flooded wetlands, including secondary channels, backwaters, sloughs, or shallow flooded areas. These areas are usually inaccessible but contain substantial food resources. Because low flow levels vary from season to season, they determine how much aquatic habitat is available throughout the year for aquatic communities. (Conservancy, 2009).

4.5.2. Extreme Conditions

Figure 4.26 shows the variation of 90-days minimum flows pre- and post-impact. The medians flow of annual 1-, 3-, 7-, 30-, 90-day minimum increases from pre-impact to post-impact period in the study area. They increased from 0.001; 0.004; 0.0077; 0.0983 and 0.7072 to 0.628; 0.6817; 0.733; 0.8705 and 1.351, respectively, as presented in Table 4 above. It can be seen from Figure 4.26 of 90-day minimum as an example, that medians, 25th and 75th percentiles increased from pre-impact to post-impact period. The extremes flow coefficient of dispersion decreases from pre-impact (ranging from 0.928 – 180) to post-impact period (ranges from 0.5803 to 0.7811). Moreover, Figure 4.26 shows that there is less variation in the data. The hydrologic modification was estimated using the middle RVA border and is shown in Table 5 above. As indicated in Figure 4.23 the maximum alteration was at the 1-, 3-, 7-, and 90-day minimum by 100%, 100%, 91.91%, 87.06%, and 74.12%, respectively, with frequency values decreasing from the pre-impact to the post-impact period. Figure 4.26 further demonstrates that following the construction of the dam, the frequency of lowest values declines, suggesting that more water is released downstream than before the dam was built.

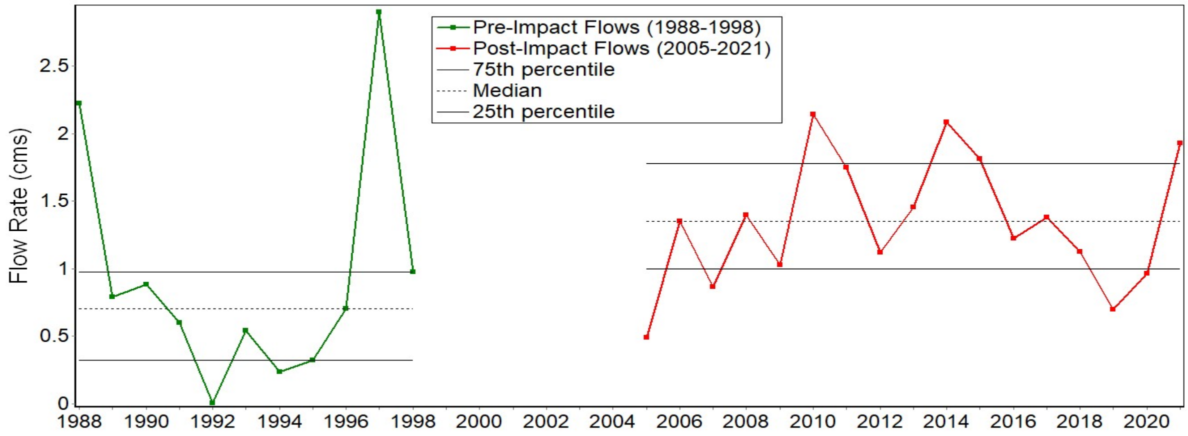

Figure 4.26: Variation of 90-days minimum flows pre- and post-impact.

The medians of annual 1-, 3-, 7-, 30-day maximum decreases from 83.09; 48.62; 27.86 and 15.76 in the pre-impact to 39.99; 33.32; 22.39 and 14.28 in the post-impact, respectively (see Table 4 above). The 90-day maximum increases from 8.863 in the pre-impact to 10.37 in the post impact period as it is shown in Figure 4.27 (which illustrate 90-days maximum). In the middle RVA category the 1-, 3-, 7-, 30-, 90-day maximum alteration flow throughout the post-impact period decreases. The highest alteration value was shown for 7-, 30-day maximum by 74.12%, as shown in Table 5 above. Large reservoir reserves are operated with increased minimum flows and decreased maximum flows. The maximum flow of big reservoirs can be significantly reduced to prevent flooding (Graf, 2006). To avoid floods, large reservoirs must release water to downstream users as well, resulting in a higher minimum flow during dry seasons (Van Vliet and Zwolsman, 2008).

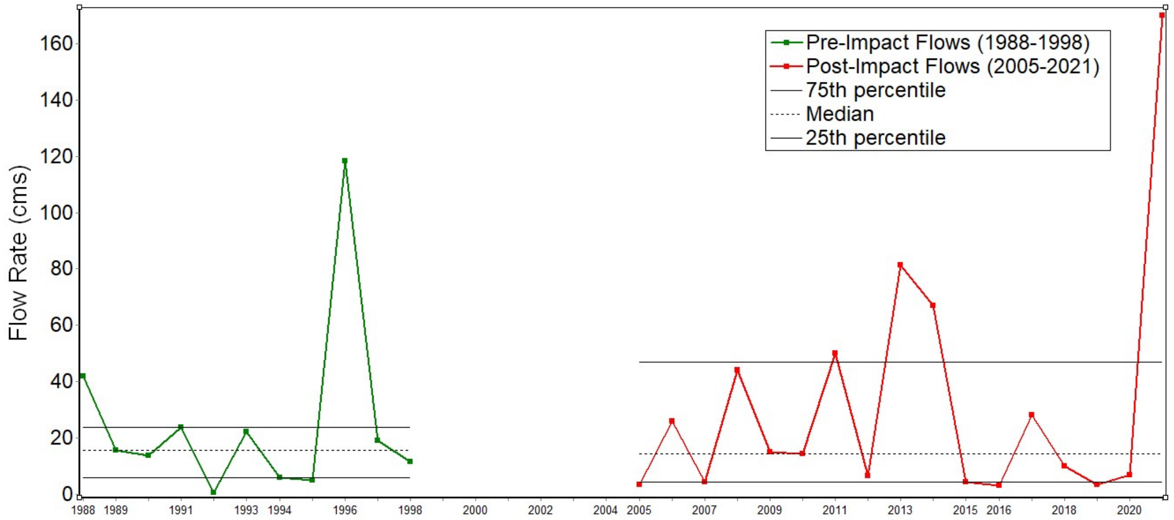

Figure 4.27: Variation of 90-days maximum flows pre- and post-impact.

4.5.3. Timing of annual extreme water conditions

Figure 4.28 demonstrates that during the post-impact period, the median Julian dates of each annual 1-day minimum shift backwards from 275 to 312 days. The median Julian dates of each annual 1-day maximum advance from the 43rd to the 35th day following impact, as shown in Figure B1 in the appendices. The coefficient of dispersion for the date of lowest rises to 0.1475 in the post-impact period from 0.1093 in the pre-impact period, whereas that for the date of maximum falls to 0.1175 from 0.2158 in the pre-impact period. While the maximum value of the date of minimum declines from 349 in the pre-impact period to 11, the minimum value of the date of minimum drops from 25 in the pre-impact period to 14 in the post-impact period.

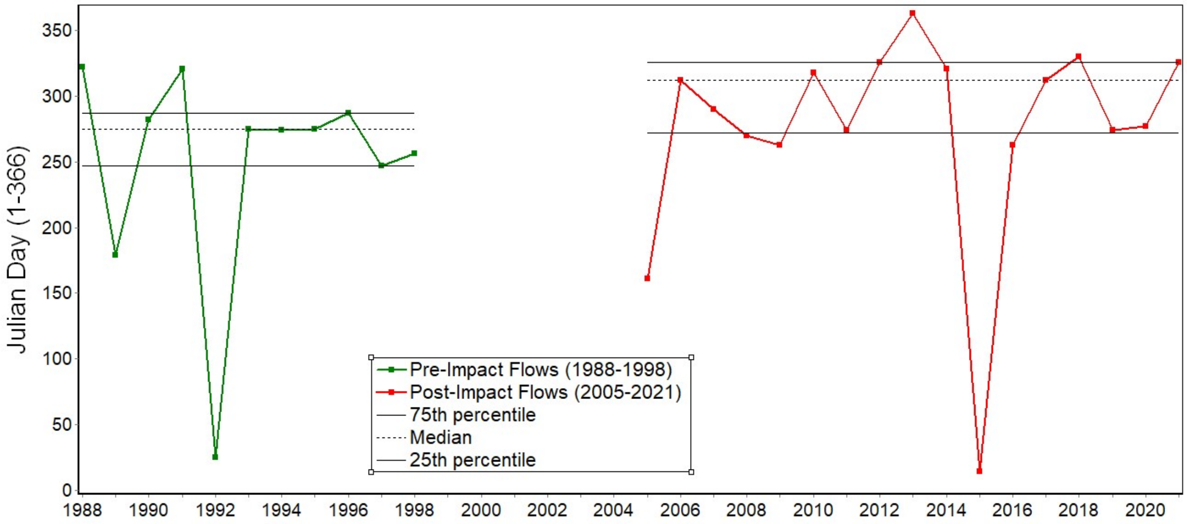

Figure 4.28: The median Julian dates of each annual 1-day minimum.

The timing of yearly extreme water conditions is discussed in this study, and two parameters are included (1-day annual minimum water condition and 1-day annual maximum water condition). Both variables offer vital information about environmental changes or water stress in aquatic habitats (Ali et al., 2019). The findings align with those of other studies. An illustration is the Julian date of the annual 1-day minimum over Cuntan Station in Yangtze River, China, which fell by 17% in the years following the event. Julian dates of each annual 1-day maximum similarly revealed that the days are 247 for pre-impact and 206 for post-impact. It is clear that these alterations are a result of dam operation. The lowered 1-day maximums at Miaohe were 229 before the hit and 206 after, similar to Cuntan. Unlike the maximum, the minimum grew by 14 percent (Ali et al., 2019). For both Zhoukou and Fuyang stations, the median Julian dates of each annual 1-day minimum in Shaying River, China advanced in the aftermath of the impact. In Fuyang station, in the pre-impact period, the median Julian date of each annual

1-day maximum moved backward to the 213th day, while in the post-impact period, it moved backward to the 207th day (Qiting and Shikui, 2016).

4.5.4. Frequency and duration of high and low pulses

The median, coefficient of dispersion and maximum value of low pulse count decreased from 4; 1.75 and 8, respectively, in the pre-impact period to 0; 0; and 4 respectively in the post-impact period (Table 4 above). If the low pulse count is decreased or increased, it impacts the availability of floodplain habitats for aquatic organisms, soil moisture and anaerobic stress for plants (Graf, 2006). Having fewer low pulses allows more plant and animal species to thrive, including species that are not adapted to low-flow environments (Rolls et al., 2012). The maintenance of a low pulse count in aquatic systems is therefore beneficial (Lu et al., 2018). The minimum value of low pulse count which is 0 remain the same in the pre-impact and post-impact period. Figure 4.29 illustrates the results, which are also presented in Table 4 above. The median, minimum and maximum value of low pulse duration decreased from 9.25; 3 and 29.5 respectively in the pre-impact to 7; 1 and 23.5, respectively, in the post-impact period. The coefficient of dispersion of low pulse duration increased from 1.568 in the pre-impact to 1.929 in the post-impact period (Figure B5 and Table 4 above).

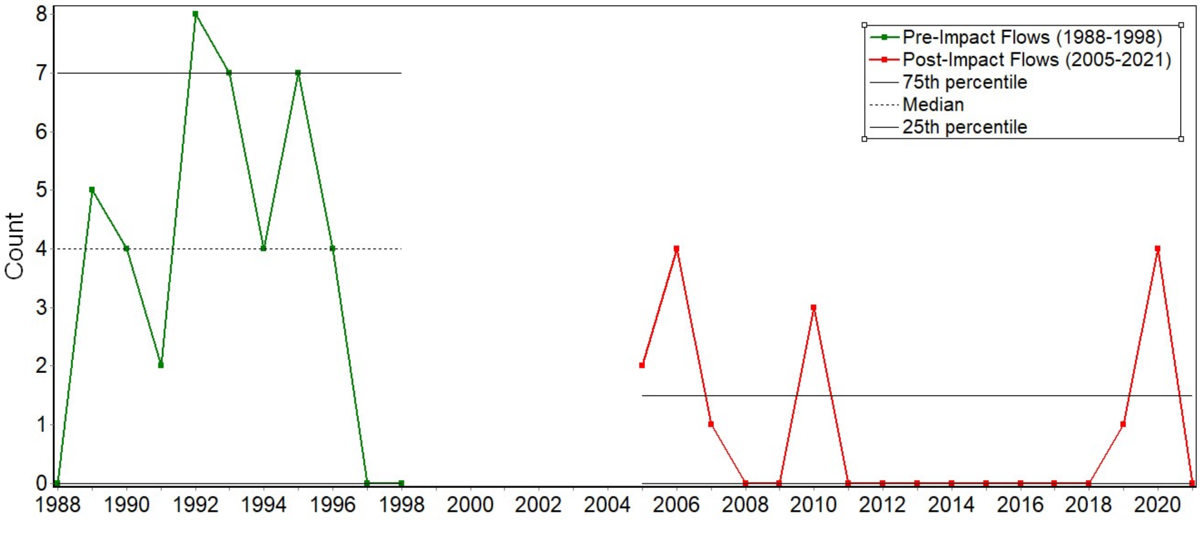

Figure 4.29: The pre- and post-impact on Low pulse count.

The median and maximum value of high pulse count decreased from 5 and 10, respectively, in the pre-impact period to 3 and 8, respectively, in the post-impact period. As the high pulse counts decreased, floodplains and river systems became less connected, resulting in a decline in biodiversity (Lu et al., 2018). The coefficient of dispersion and minimum value of high pulse count increased from 0.6 and 0, respectively in the pre-impact period to 0.83 and 1, respectively, in the post-impact period. It is also expected that the increase in pulse duration may reduce habitat heterogeneity, resulting in a decline in biodiversity as a consequence (Lu et al., 2018). Figure 4.30 illustrates the results, which are also presented in Table 4 above. The median, coefficient of dispersion and minimum value of high pulse duration decreased from 7.5; 4.083 and 3, respectively, in the pre-impact period to 8; 1.469 and 1 respectively in the post-impact period. The maximum value of high pulse duration increased from 117 in the pre-impact to 207 in the post-impact period (Appendix Figure B7 and Table 4 above). Hydrological connectivity may be maintained in an equilibrium when the duration and number of high pulses are increased and decreased, which may have a beneficial effect on maintaining organic matter and nutrient exchanges between rivers and floodplains (Lu et al., 2018).

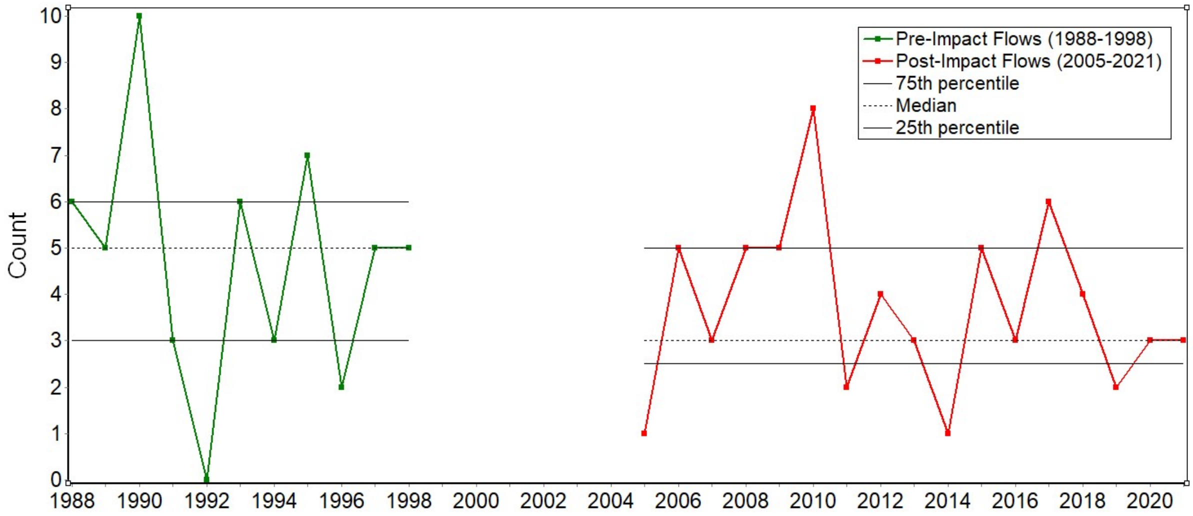

Figure 4.30: The pre- and post-impact on High pulse count.

There is a low pulse threshold value of 0.47 and a high pulse threshold value of 4.56 in the middle RVA category. From pre-impact to post-impact, the frequency value of low pulse count and low pulse duration decreased by 48.24% and 67.65 percent respectively. From pre-impact to post-impact, the frequency value of high pulse count and high pulse duration increased by 10.92% and 13.24%, respectively (see Table 5 above). The greater median pulse counts at Zhoukou and Fuyang stations in Shaying River, China during the post-impact era compared to the pre-impact period may be the result of insufficient pre-impact period records. The medians of low and high pulse durations in Fuyang station are lower after impact than they were before, showing that the sluices mostly affect the hydrology of low and high pulse durations (Qiting and Shikui, 2016). Low pulse counts and extended pulse durations were shown to be decreased along the Yangtze River in China, according to research. In the low pulse count, a 20% reduction is seen, but a 40% reduction is seen in the high pulse count. The durations of low and high pulses are found to be longer at Cuntan, though. With the low pulse duration, the rise was 162%, while for the high pulse duration, it was 133%. Low pulse count increased while low pulse length and high pulse count fell in Yangtze River, China's

Miaohe Station. No change was predicted compared to the high pulse duration (Ali et al., 2019). Taylor et al. (2003) observed that existing land use increased the frequency of low pulses in the Mkomazi River located in KwaZulu-Natal, South Africa. Low pulses are occurring more frequently, but because of present land usage, their duration is less varied. The change in low pulse counts and their durations causes a shift in the hydrograph's rise and fall rates, despite the fact that the current land use has little impact on high pulse counts and their durations. As a result, every annual hydrograph reversal happens above the top RVA target, which indicates an increase in intra- and inter-annual environmental volatility (Taylor et al., 2003).

4.5.5. Rate and Frequency of Flow Changes

The median, coefficient of dispersion, minimum and maximum value of rise rate decreased from 0.081; 1.235; 0.03 and 0.315, respectively in the post-impact to 0.054; 1.032; 0.032 and 0.2475, respectively, in post-impact period as shown in Figure 4.31. The median, coefficient of dispersion and minimum value of fall rate slightly decreased from 0.111; 0.8784 and 0.2765, respectively, in the pre-impact to 0.102; 0.8186 and 0.2275, respectively, in the post-impact period with decreasing value over time. The maximum value of fall rate slightly increased from 0.0265 in the pre-impact to 0.033 in the post-impact period with decreasing in frequency value over time. The median and maximum value of number of reversals increased from 88 and 128, respectively, in the pre-impact to 120 and 162, respectively, in the post-impact period. The coefficient of dispersion and minimum value of number of reversals decreased from 0.375 and 52, respectively, in the pre-impact to 0.2375 and 49 in the post-impact period.

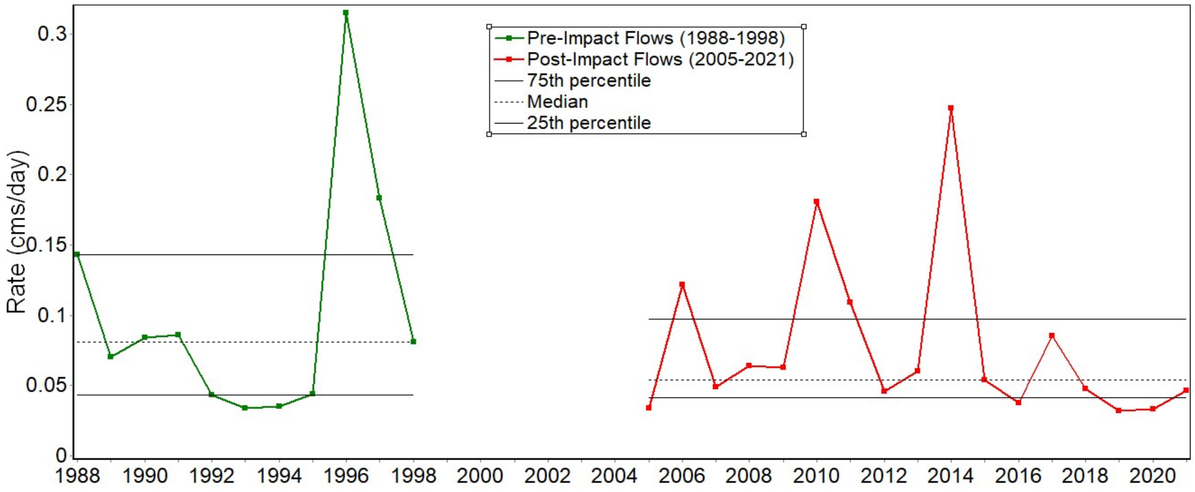

Figure 4.31: The pre- and post-impact on Rise rate.

With an increase in value frequency from pre-impact to post-impact, the rise rate alteration in the middle RVA category is 16.47%, whereas the fall rate and number of reversals alteration are 35.29% and 100% respectively with a decrease in frequency value between pre-impact and post-impact periods (as shown in Table 5 above). Similar results have also been reported in other studies. According to observations at Cuntan Station, rising and falling rates in China have declined significantly. There was a decrease in reverses between the pre-impact and post-impact periods. The rise and fall rates at Miaohe Station also showed comparable results, with a decrease in the rise rate and an increase in the fall rate, respectively. Cuntan, however, experienced a decrease in reversals while Miaohe experienced an increase. The medians of rise, fall, and reversals at Zhoukou and Fuyang stations in Shaying River, China, were higher than in the earlier period, and their coefficients of dispersion of rise rate were higher (Ali et al., 2019).

4.6. Chapter summary

This chapter presented the analysis of Nandoni Dam water resources in relation to inflow and outflow. It also presented the analysis of required streamflow to maintain ecological integrity and analysis of impacts of Nandoni Dam on the down streamflow trends before and after the dam constructions. Some of factors (such hydrometeorological variables) which affect Nandoni Dam water resources were analysed using Linear regression analysis. It was found that rainfall, temperature, evaporation, uncontrolled spillway, and amount of domestic water abstraction were increasing over the period of the study, where elsewhere streamflow, dam storage, and computed inflow were decreasing over the period of the study. The required streamflow to maintain ecological integrity was analysed based on the output of IHA software, which include five relevant ecological parameters know as EFCs (large flood, small floods, high flow pulse, low flow pulse and extreme low flows). Values of this parameters were presented as cumulative percentiles ranging from 10% to 90%. The dam impacts were analysed using IHA parameters. The results indicate that there were both positive and negative impacts of the dam on down streamflow among the IHA parameters.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

The study focused on the impact of the Nandoni Dam in South Africa on downstream water resources. It examined the inflow and outflow of the dam, assessed the amount of streamflow needed to maintain ecological balance, and compared current streamflow trends to historical conditions. The estimated dam inflow revealed a weak downward trend for the Nandoni Dam, while it was also evident that when inflows peak, dam storage increases. The outflow is constant for the most part over the study period considered, except when the dam storage increases and reaches its peak, at which point the outflow increases rapidly. The water resources of Nandoni Dam are significantly influenced by climate factors. The amount of water stored in Nandoni dam is impacted by changes in precipitation and air temperatures. With an increase in temperature, Nandoni Dam faces significant changes in rainfall and evaporation. Dry and wet weather are frequent in the study area, where severe events are also becoming more frequent. This makes the amount of water stored and discharged from the dam more unpredictable. It has been observed that despite increases or decreases in dam storage, the amount of water abstracted from the dam for domestic use is increasing over time.

It was proposed that the ecological integrity of the dam be upheld by maintaining streamflow downstream. The necessary streamflow for maintaining ecological integrity was examined using the data from IHA software, which assess five ecological parameters known as EFCs (including large flood, small floods, high flow pulse, low flow pulse, and extreme low flows). The values of these parameters were presented as cumulative percentiles ranging from 10% to 90%. If these suggestions are embraced by environmental authorities, there may be certain benefits in terms of improving hydrologic conditions downstream of Nandoni Dam in the Luvuvhu River.

Furthermore, Mhinga station A9H012 successfully assessed the influence of Nandoni dams on the downstream flow of the Luvuvhu River between 1988 and 2021. Flow patterns on the river have been significantly impacted by the construction of dams. As a result of assessing the flow separately for each month, both positive and negative impacts were found on the dam's downstream flow. Monthly alteration flows for the middle RVA category, except for August, January, February, and March, indicate an increase from the pre-impact period. September witnessed the highest increase, while January experienced the highest decrease. According to the results of extremes, the dam reduced minimum flow frequencies on days 1-, 3-, 7-, 30-, and 90-days, as well as maximum flow frequencies on days 7-, 30-days. At low pulse counts and low pulse durations, there is a decrease, while at high pulse counts and high pulse durations, there is an increase. It was found that the rise rate increased, whereas the fall rate and number of reversals decreased. Accordingly, we can use the results of this study to monitor and develop adaptation measures aimed at mitigating the dam's negative downstream impacts.

5.2 Recommendations

Based on the finds of this study pertaining to the influence of dam construction on the Luvuvhu River downstream water users, this study makes the following recommendations for future studies and practice.

- An in-depth study is required to determine how dams are affecting ecosystems services including an investigation into how aquatic living organisms in the catchment are adjusting to the impacts of dams in the catchment area.
- The IHA software provides EFC calculations that can be used by ecologists, water managers, and other stakeholders to determine how much flow alteration is acceptable in the downstream of the dam.
- Efforts must be made to assess major water abstraction from Nandoni Dam including the regulating and monitoring water users to ensure proper water management and conservation of water resources.
- It is essential to take rainfall variability into account when planning future developments in terms of water allocations for different water users around the dam. Therefore, water resources managers need to take this into consideration.
- To promote sustainable development, all stakeholders in the catchment should participate in a stakeholder participation processes in establishment in significant infrastructures such as dams. This will aid in cooperation amongst stakeholders during the project operation.

REFERENCES

ABDOLLAHI, K., BAZARGAN, A. & MCKAY, G. 2018. Water Balance Models in Environmental Modeling. Handbook of Environmental Materials Management; Springer: Berlin, Germany.

ABEBE, W. B., TILAHUN, S. A., MOGES, M. M., WONDIE, A., DERSEH, M. G., NIGATU, T. A., MHIRET, D. A., STEENHUIS, T. S., CAMP, M. V. & WALRAEVENS, K. 2020. Hydrological foundation as a basis for a holistic environmental flow assessment of tropical highland rivers in ethiopia. Water, 12, 547.

ABIYE, T. A. & BHATTACHARYA, P. 2019. Arsenic concentration in groundwater: Archetypal study from South Africa. Groundwater for Sustainable Development, 9, 100246.

ADEOGUN, A. G., SULE, B. F., SALAMI, A. W. & DARAMOLA, M. O. 2014. Validation of SWAT model for prediction of water yield and water balance: case study of upstream catchment of Jebba dam in Nigeria. International Journal of Mathematical, Computational, Physical and Computer Engineering, 8, 264-270.

ADNAN, M., KANG, S., ZHANG, G., SAIFULLAH, M., ANJUM, M. N. & ALI, A. F. 2019. Simulation and analysis of the water balance of the Nam Co Lake using SWAT model. Water, 11, 1383.

AGARWAL, S., PATIL, J. P., GOYAL, V. & SINGH, A. 2019. Assessment of water supply–demand using water evaluation and planning (WEAP) model for Ur River watershed, Madhya Pradesh, India. Journal of The Institution of Engineers (India): Series A, 100, 21-32.

AGGARWAL, R. & RANGANATHAN, P. 2017. Common pitfalls in statistical analysis: Linear regression analysis. Perspectives in clinical research, 8, 100.

AGUIAR, F. C., MARTINS, M. J., SILVA, P. C. & FERNANDES, M. R. 2016. Riverscapes downstream of hydropower dams: Effects of altered flows and historical land-use change. Landscape and Urban Planning, 153, 83-98.

AHJUM, F., MERVEN, B., CULLIS, J., GOLDSTEIN, G., DELAQUIL, P. & STONE, A. 2018. Development of a national water-energy system model with emphasis on the power sector for south africa. Environmental Progress & Sustainable Energy, 37, 132-147.

AHMAD, M., STEWART, J., PEÑA-ARANCIBIA, J. & KIRBY, J. 2020. Sindh water outlook: Impacts of climate change, dam sedimentation and urban water supply on irrigated agriculture. Sustainable Development Investment Portfolio (SDIP) project. CSIRO, Australia.

AHMED, T. F., SHAH, S. U. S., KHAN, M. A., AFZAL, M. A. & SHEIKH, A. A. 2020. Rainwater harvesting scenarios and its prospective in Pakistan. Meteorology Hydrology and Water Management. Research and Operational Applications, 8.

AHN, K.-H. & MERWADE, V. 2014. Quantifying the relative impact of climate and human activities on streamflow. Journal of Hydrology, 515, 257-266.

AKOKO, G., LE, T. H., GOMI, T. & KATO, T. 2021. A review of SWAT model application in Africa. Water, 13, 1313.

ALI, R., KURIQI, A., ABUBAKER, S. & KISI, O. 2019. Hydrologic alteration at the upper and middle part of the Yangtze River, China: towards sustainable water resource management under increasing water exploitation. Sustainability, 11, 5176.

ALLA, Y. M. K. & LIU, L. 2021. Impacts of Dams on the Environment: A Review. International Journal of Environment, Agriculture and Biotechnology, 6.

AL-SUDANI, H. I. Z. 2020. Derivation mathematical equations to estimate water surplus and groundwater recharge in Iraq. Applied Water Science, 10, 1-11.

ALVESSON, M. & SVENINGSSON, S. 2015. Changing organizational culture: Cultural change work in progress, Routledge.

AMADOR, A., SÁNCHEZ-JUNY, M., POMARES, J., DOLZ, J. & ABADÍA R IBÁÑEZ-DE-ALDECOA, F. 2018. Feasibility study of stepped spillways in RCC dams controlled by a Tainter gate. RCC Dams-Roller Compacted Concrete Dams. Routledge.

ANAND, J., GOSAIN, A. K. & KHOSA, R. 2018. Prediction of land use changes based on Land Change Modeler and attribution of changes in the water balance of Ganga basin to land use change using the SWAT model. Science of the total environment, 644, 503-519.

AWOTWI, A., YEBOAH, F. & KUMI, M. 2015. Assessing the impact of land cover changes on water balance components of W hite V olta B asin in W est A frica. Water and Environment Journal, 29, 259-267.

AYIVI, F. & JHA, M. K. 2018. Estimation of water balance and water yield in the Reedy Fork-Buffalo Creek Watershed in North Carolina using SWAT. International Soil and Water Conservation Research, 6, 203-213.

BAGGIO, G., QADIR, M. & SMAKHTIN, V. 2021. Freshwater availability status across countries for human and ecosystem needs. Science of The Total Environment, 792, 148230.

BARBIER, E. B. 2003. Upstream dams and downstream water allocation: The case of the Hadejia-Jama'are floodplain, northern Nigeria. Water Resources Research, 39.

BARRUTIA, J. M., ECHEBARRIA, C., PAREDES, M. R., HARTMANN, P. & APAOLAZA, V. 2015. From Rio to Rio+ 20: twenty years of participatory, long term oriented and monitored local planning? Journal of Cleaner Production, 106, 594-607.

BASSEY, A., THOBEJANE, T. & ATU, E. 2012. Gender mainstreaming as a strategy for poverty reduction in small-scale community fisheries: a case study of Nandoni Dam, Limpopo Province, South Africa. OIDA International Journal of Sustainable Development, 4, 127-142.

BAZDARIC, K., SVERKO, D., SALARIC, I., MARTINOVIC, A. & LUCIJANIC, M. 2021. The ABC of linear regression analysis: What every author and editor should know. European Science Editing, 47, e63780.

BEATTY, S., ALLEN, M., LYMBERY, A., JORDAAN, M. S., MORGAN, D., IMPSON, D., MARR, S., EBNER, B. & WEYL, O. L. 2017. Rethinking refuges: Implications of climate change for dam busting. Biological Conservation, 209, 188-195.

BECK, M. W., CLAASSEN, A. H. & HUNDT, P. J. 2012. Environmental and livelihood impacts of dams: common lessons across development gradients that challenge sustainability. International journal of river basin management, 10, 73-92.

BENIN, C. 2016. RESPONSES OF HYDRO-CLIMATOLOGICAL INDICES TO CLIMATIC VARIABILITY AND CHANGE IN THE SOKOTO-RIMA RIVER BASIN, NORTH-WESTERN NIGERIA.

BENJANKAR, R., JORDE, K., YAGER, E. M., EGGER, G., GOODWIN, P. & GLENN, N. F. 2012. The impact of river modification and dam operation on floodplain vegetation succession trends in the Kootenai River, USA. Ecological Engineering, 46, 88-97.

BESTER, R., BLIGNAUT, J. N. & CROOKES, D. J. 2019. The impact of human behaviour and restoration on the economic lifespan of the proposed Ntabelanga and Laleni dams, South Africa: A system dynamics approach. Water Resources and Economics, 26, 100126.

BOARDMAN, J. & FOSTER, I. D. 2011. The potential significance of the breaching of small farm dams in the Sneeuberg region, South Africa. Journal of Soils and Sediments, 11, 1456-1465.

BORETTI, A. & ROSA, L. 2019a. Reassessing the projections of the world water development report. NPJ Clean Water, 2, 1-6.

BORETTI, A. & ROSA, L. 2019b. Reassessing the projections of the world water development report. NPJ Clean Water, 2, 15.

BOTAI, C. M., BOTAI, J. O. & ADEOLA, A. M. 2018. Spatial distribution of temporal precipitation contrasts in South Africa. South African Journal of Science, 114, 70-78.

BOURAOUI, F., BENABDALLAH, S., JRAD, A. & BIDOGLIO, G. 2005. Application of the SWAT model on the Medjerda river basin (Tunisia). Physics and Chemistry of the Earth, Parts A/B/C, 30, 497-507.

BROUZIYNE, Y., DE GIROLAMO, A. M., ABOUBDILLAH, A., BENAABIDATE, L., BOUCHAOU, L. & CHEHBOUNI, A. 2021. Modeling alterations in flow regimes under changing climate in a Mediterranean watershed: An analysis of ecologically-relevant hydrological indicators. Ecological Informatics, 61, 101219.

BUJANG, M. A. & BAHARUM, N. 2016. Sample size guideline for correlation analysis. World, 3.

BUTCHART-KUHLMANN, D., KRALISCH, S., FLEISCHER, M., MEINHARDT, M. & BRENNING, A. 2018. Multicriteria decision analysis framework for hydrological decision support using environmental flow components. Ecological Indicators, 93, 470-480.

CARTER, N. & DARLOW, A. 1997. Local Agenda 21 and developers: are we better equipped to build a consensus in the 1990s? Planning Practice & Research, 12, 45-58.

CHENG, J., XU, L., WANG, X., JIANG, J. & YOU, H. 2018. Assessment of hydrologic alteration induced by the Three Gorges Dam in Dongting Lake, China. River Research and Applications, 34, 686-696.

CHOK, N. S. 2010. Pearson's versus Spearman's and Kendall's correlation coefficients for continuous data. University of Pittsburgh.

COLE, M. J., BAILEY, R. M. & NEW, M. G. 2014. Tracking sustainable development with a national barometer for South Africa using a downscaled “safe and just space” framework. Proceedings of the National Academy of Sciences, 111, E4399-E4408.

COLE, M. J., BAILEY, R. M. & NEW, M. G. 2017. Spatial variability in sustainable development trajectories in South Africa: provincial level safe and just operating spaces. Sustainability science, 12, 829-848.

CONNOR, R. 2015. The United Nations world water development report 2015: water for a sustainable world, UNESCO publishing.

CONSERVANCY, N. 2009. IHA software version 7.1 user’s manual. The Nature Conservancy, Virginia, United States.

CONWAY, D., VAN GARDEREN, E. A., DERYNG, D., DORLING, S., KRUEGER, T., LANDMAN, W., LANKFORD, B., LEBEK, K., OSBORN, T. & RINGLER, C. 2015. Climate and southern Africa's water–energy–food nexus. Nature Climate Change, 5, 837-846.

CRAWFORD, S. L. 2006. Correlation and regression. Circulation, 114, 2083-2088.

CULLIS, J., STRZEPEK, K., TADROSS, M., SAMI, K., HAVENGA, B., GILDENHUYS, B. & SMITH, J. 2011. Incorporating climate change into water resources planning for the town of Polokwane, South Africa. Climatic change, 108, 437-456.

DA SILVA LELIS, L. C., NASCIMENTO, J. G., DUARTE, S. N., PACHECO, A. B., BOSQUILIA, R. W. D. & WOLFF, W. 2020. Assessment of hydrological regionalization methodologies for the upper Jaguari River basin. Journal of South American Earth Sciences, 97, 102402.

DAMIANI, M., NÚÑEZ, M., ROUX, P., LOISEAU, E. & ROSENBAUM, R. K. 2018. Addressing water needs of freshwater ecosystems in life cycle impact assessment of water consumption: state of the art and applicability of ecohydrological approaches to ecosystem quality characterization. The International Journal of Life Cycle Assessment, 23, 2071-2088.

DE KWAADSTENIET, M., DOBROWSKY, P. H., VAN DEVENTER, A., KHAN, W. & CLOETE, T. E. 2013. Domestic Rainwater Harvesting: Microbial and Chemical Water Quality and Point-of-Use Treatment Systems. Water, Air, & Soil Pollution, 224, 1629.

DE WET, H. 2010. The Environmental Handbook: a guide to green business in South Africa. Trialogue: Cape Town, South Africa.

DHAMI, B., HIMANSHU, S. K., PANDEY, A. & GAUTAM, A. K. 2018. Evaluation of the SWAT model for water balance study of a mountainous snowfed river basin of Nepal. Environmental Earth Sciences, 77, 1-20.

DJIBY, S., DIEKKRUGER, B., GAYE, A. & GAYE, A. T. 2017. Assessment of Hydrologic Alteration within Ecosystem in a Sahalian Shallow Lake: Lake Guiers, Senegal. Editors, 200.

DOS ANJOS LUÍS, A. & CABRAL, P. 2021. Small dams/reservoirs site location analysis in a semi-arid region of Mozambique. International Soil and Water Conservation Research, 9, 381-393.

DOS SANTOS, V., LAURENT, F., ABE, C. & MESSNER, F. 2018. Hydrologic response to land use change in a large basin in eastern Amazon. Water, 10, 429.

DU PLESSIS, A. 2017a. South Africa’s water availability and use. Freshwater Challenges of South Africa and its Upper Vaal River. Springer.

DU PLESSIS, A. 2017b. Water Scarcity and Other Significant Challenges for South Africa. Freshwater Challenges of South Africa and its Upper Vaal River. Springer.

DUBE, T., WEPENER, V., VAN VUREN, J., SMIT, N. & BRENDONCK, L. 2015. The case for environmental flow determination for the Phongolo River, South Africa. African Journal of Aquatic Science, 40, 269-276.

DUNGUMARO, E. W. 2007. Socioeconomic differentials and availability of domestic water in South Africa. Physics and Chemistry of the Earth, Parts A/B/C, 32, 1141-1147.

DWIVEDI, V., GUPTA, S. & PANDEY, S. A study of environmental impact due to construction and operation of dam. National Conference on Eco friendly Manufacturing for Sustainable Development, 2010. 1-6.

DYE, P. J. & CROKE, B. F. 2003. Evaluation of streamflow predictions by the IHACRES rainfall-runoff model in two South African catchments. Environmental Modelling & Software, 18, 705-712.

EBRAHIM, G. Y. & VILLHOLTH, K. G. 2016. Estimating shallow groundwater availability in small catchments using streamflow recession and instream flow requirements of rivers in South Africa. Journal of Hydrology, 541, 754-765.

EDALAT, M. M. & STEPHEN, H. 2019. Socio-economic drought assessment in Lake Mead, USA, based on a multivariate standardized water-scarcity index. Hydrological Sciences Journal, 64, 555-569.

EDOKPAYI, J. N., ENITAN, A. M., MUTILENI, N. & ODIYO, J. O. 2018. Evaluation of water quality and human risk assessment due to heavy metals in groundwater around Muledane area of Vhembe District, Limpopo Province, South Africa. Chemistry Central Journal, 12, 2.

EL JEITANY, J., PACETTI, T. & CAPORALI, E. 2023. Evaluating climate change effects on hydrological functionality and water-related ecosystem services. Ecohydrology, e2557.

ENQVIST, J. P. & ZIERVOGEL, G. 2019. Water governance and justice in Cape Town: An overview. Wiley Interdisciplinary Reviews: Water, 6, e1354.

FADIL, A., RHINANE, H., KAOUKAYA, A., KHARCHAF, Y. & BACHIR, O. A. 2011. Hydrologic modeling of the Bouregreg watershed (Morocco) using GIS and SWAT model. Journal of Geographic Information System, 3, 279.

FAO, F. 2018. The future of food and agriculture: alternative pathways to 2050. Food and Agriculture Organization of the United Nations Rome.

FARAMARZI, M., ABBASPOUR, K. C., VAGHEFI, S. A., FARZANEH, M. R., ZEHNDER, A. J., SRINIVASAN, R. & YANG, H. 2013. Modeling impacts of climate change on freshwater availability in Africa. Journal of Hydrology, 480, 85-101.

FAYE, C. 2018. Characterization of the effects of manantali dam on the hydrological regime of the Senegal river by the IHA/RVA method.

FERRAZZI, M. & BOTTER, G. 2019. Contrasting signatures of distinct human water uses in regulated flow regimes. Environmental Research Communications, 1, 071003.

FISHER-JEFFES, L. 2017. The viability of domestic rainwater harvesting in the residential areas of the Liesbeek River Catchment, Cape Town. Water SA, 43, 81-90.

FONSECA, A., AMES, D. P., YANG, P., BOTELHO, C., BOAVENTURA, R. & VILAR, V. 2014. Watershed model parameter estimation and uncertainty in data-limited environments. Environmental Modelling & Software, 51, 84-93.

FOUCHE, P., VLOK, W., ROOS, J., LUUS-POWELL, W. & JOOSTE, A. 2013. Establishing the fishery potential of Lake Nandoni in the Luvuvhu River, Limpopo Province. Water Research Commission, 1-135.

FOWE, T., KARAMBIRI, H., PATUREL, J.-E., POUSSIN, J.-C. & CECCHI, P. 2015. Water balance of small reservoirs in the Volta basin: A case study of Boura reservoir in Burkina Faso. Agricultural Water Management, 152, 99-109.

FRECKLETON, D. R., JOHNSON, M. C., LESLIE BOYD, M. & MORTENSEN, D. G. 2011. Stop logs for emergency spillway gate dewatering. Journal of Hydraulic Engineering, 137, 644-650.

FUKUDA-PARR, S. 2016. From the Millennium Development Goals to the Sustainable Development Goals: shifts in purpose, concept, and politics of global goal setting for development. Gender & Development, 24, 43-52.

GAN, Y., DUAN, Q., GONG, W., TONG, C., SUN, Y., CHU, W., YE, A., MIAO, C. & DI, Z. 2014. A comprehensive evaluation of various sensitivity analysis methods: A case study with a hydrological model. Environmental Modelling & Software, 51, 269-285.

GARCÍA-RUIZ, J. M., LÓPEZ-MORENO, J. I., VICENTE-SERRANO, S. M., LASANTA–MARTÍNEZ, T. & BEGUERÍA, S. 2011. Mediterranean water resources in a global change scenario. Earth-Science Reviews, 105, 121-139.

GENEROSO, T. N., DA SILVA, D. D., RODRIGUES, L. N., AMORIM, R. S. S. & DE ALMEIDA, L. T. 2022. Analysis of flow behavior as influenced by reservoir with flow regularization. Water Resources Management, 36, 4721-4737.

GEORGE, M. O., EPHRAHIM, S. S. & ONYEKA, I. N. 2010. Impacts of mining on water resources in South Africa: A review. Scientific Research and Essays, 5, 3351-3357.

GHORABA, S. M. 2015. Hydrological modeling of the Simly Dam watershed (Pakistan) using GIS and SWAT model. Alexandria Engineering Journal, 54, 583-594.

GIERSZEWSKI, P. J., HABEL, M., SZMAŃDA, J. & LUC, M. 2020. Evaluating effects of dam operation on flow regimes and riverbed adaptation to those changes. Science of the Total Environment, 710, 136202.

GLEICK, P. H. 2000. A look at twenty-first century water resources development. Water international, 25, 127-138.

GOEL, M., JAIN, S. K., RANI, D. & CHALISGAONKAR, D. 2018. Methodology to deal with computed negative inflows in Indian reservoirs.

GOKOOL, S., RIDDELL, E., NEL, J., RAUBENHEIMER, R., STRYDOM, T., SWEMMER, A. & CHETTY, K. 2019. Quantifying the contribution of riparian total evaporation to streamflow transmission losses: Preliminary investigations along the Groot Letaba River. Physics and Chemistry of the Earth, Parts A/B/C, 114, 102805.

GOOCH, G. 2010. What are the central issues of the livelihoods and biodiversity interface in our case areas?

GOONETILLEKE, A. & VITHANAGE, M. 2017. Water resources management: Innovation and challenges in a changing world. MDPI.

GRAF, W. L. 2006. Downstream hydrologic and geomorphic effects of large dams on American rivers. Geomorphology, 79, 336-360.

GRILL, G., LEHNER, B., LUMSDON, A. E., MACDONALD, G. K., ZARFL, C. & LIERMANN, C. R. 2015. An index-based framework for assessing patterns and trends in river fragmentation and flow regulation by global dams at multiple scales. Environmental Research Letters, 10, 015001.

GRISCOM, H. 2007. The drying of the Luvuvhu River, South Africa: Distinguishing the roles of dams and land cover change. University of Wyoming.

GUERRA, J., SCHMIDT, L. & LOURENÇO, L. B. 2019. From Local Agenda 21 to a localized Agenda 2030–the Portuguese and Brazilian cases in perspective. Community Development, 50, 352-367.

GUMBO, J. R., DZAGA, R. A. & NETHENGWE, N. S. 2016. Impact on water quality of Nandoni water reservoir downstream of municipal sewage plants in Vhembe District, South Africa. Sustainability, 8, 597.

GÜNTNER, A., KROL, M. S., ARAÚJO, J. C. D. & BRONSTERT, A. 2004. Simple water balance modelling of surface reservoir systems in a large data-scarce semiarid region/Modélisation simple du bilan hydrologique de systèmes de réservoirs de surface dans une grande région semi-aride pauvre en données. Hydrological sciences journal, 49.

GYAMFI, C., NDAMBUKI, J. M. & SALIM, R. W. 2016. Application of SWAT model to the Olifants Basin: calibration, validation, and uncertainty analysis. Journal of Water Resource and Protection, 8, 397.

HADDELAND, I., HEINKE, J., BIEMANS, H., EISNER, S., FLÖRKE, M., HANASAKI, N., KONZMANN, M., LUDWIG, F., MASAKI, Y. & SCHEWE, J. 2014. Global water resources affected by human interventions and climate change. Proceedings of the National Academy of Sciences, 111, 3251-3256.

HAGEMANN, S., CHEN, C., CLARK, D. B., FOLWELL, S., GOSLING, S. N., HADDELAND, I., HANASAKI, N., HEINKE, J., LUDWIG, F. & VOSS, F. 2013. Climate change impact on available water resources obtained using multiple global climate and hydrology models. Earth System Dynamics, 4, 129-144.

HAGHIGHI, A. T., MARTTILA, H. & KLØVE, B. 2014. Development of a new index to assess river regime impacts after dam construction. Global and Planetary Change, 122, 186-196.

HAMLAT, A., ERRIH, M. & GUIDOUM, A. 2013. Simulation of water resources management scenarios in western Algeria watersheds using WEAP model. Arabian Journal of Geosciences, 6, 2225-2236.

HAN, J., YANG, Y., RODERICK, M. L., MCVICAR, T. R., YANG, D., ZHANG, S. & BECK, H. E. 2020. Assessing the steady-state assumption in water balance calculation across global catchments. Water Resources Research, 56, e2020WR027392.

HANSEN, C., MUSA, M., SASTHAV, C. & DENEALE, S. 2021. Hydropower development potential at non-powered dams: Data needs and research gaps. Renewable and Sustainable Energy Reviews, 145, 111058.

HAO, C., HE, L., NIU, C. & JIA, Y. A review of environmental flow assessment: methodologies and application in the Qianhe River. IOP Conference Series: Earth and Environmental Science, 2016. IOP Publishing, 012067.

HEATH, S. & PLATER, A. 2010. Records of pan (floodplain wetland) sedimentation as an approach for post-hoc investigation of the hydrological impacts of dam impoundment: The Pongolo river, KwaZulu-Natal. Water Research, 44, 4226-4240.

HELLBERG, S. 2020. Scarcity as a means of governing: Challenging neoliberal hydromentality in the context of the South African drought. Environment and Planning E: Nature and Space, 3, 186-206.

HIMANSHU, S. K., PANDEY, A. & SHRESTHA, P. 2017. Application of SWAT in an Indian river basin for modeling runoff, sediment and water balance. Environmental Earth Sciences, 76, 1-18.

HÖLLERMANN, B., GIERTZ, S. & DIEKKRÜGER, B. 2010. Benin 2025—Balancing future water availability and demand using the WEAP 'Water Evaluation and Planning'System. Water resources management, 24, 3591-3613.

HU, W.-W., WANG, G.-X., DENG, W. & LI, S.-N. 2008. The influence of dams on ecohydrological conditions in the Huaihe River basin, China. Ecological engineering, 33, 233-241.

HUGHES, D. & MALLORY, S. 2008. Including environmental flow requirements as part of real-time water resource management. River Research and Applications, 24, 852-861.

HUGHES, D. & MANTEL, S. 2010. Estimating the uncertainty in simulating the impacts of small farm dams on streamflow regimes in South Africa. Hydrological Sciences Journal–Journal des Sciences Hydrologiques, 55, 578-592.

HUGHES, D. A. & HANNART, P. 2003. A desktop model used to provide an initial estimate of the ecological instream flow requirements of rivers in South Africa. Journal of Hydrology, 270, 167-181.

HUGHES, D. A. & MANTEL, S. K. 2010. Estimating the uncertainty in simulating the impacts of small farm dams on streamflow regimes in South Africa. Hydrological Sciences Journal–Journal des Sciences Hydrologiques, 55, 578-592.

IVEZIC, V., BEKIC, D. & ZUGAJ, R. 2017. A review of procedures for water balance modelling. 25.

JABER, A. Z. 2018. WEAP MODELING F MANAGEMENT SUPPLY IN SHATT AL. International Journal of Civil Engineering, 9.

JACOBS-MATA, I. M., DE WET, B., BANOO, I., MEISSNER, R., DE LANGE, W. J. & STRYDOM, W. F. 2018. Understanding residential water-use behaviour in urban South Africa. Alive2green.

JAIN, S. K. 2012. Assessment of environmental flow requirements. Hydrological processes, 26, 3472-3476.

JAISWAL, R. K., YADAV, R. N., LOHANI, A. K., TIWARI, H. L. & YADAV, S. 2020. Water balance modeling of Tandula (India) reservoir catchment using SWAT. Arabian Journal of Geosciences, 13, 1-13.

JAYAKRISHNAN, R., SRINIVASAN, R., SANTHI, C. & ARNOLD, J. 2005. Advances in the application of the SWAT model for water resources management. Hydrological Processes: An International Journal, 19, 749-762.

JEWITT, G. P. W., HAWKINS, G. THIEL, C 1999. Indicators of hydrologic alteration for South African rivers. Proceedings of the 9th South African National Hydrology Symposium.

JIANG, L., BAN, X., WANG, X. & CAI, X. 2014. Assessment of hydrologic alterations caused by the Three Gorges Dam in the middle and lower reaches of Yangtze River, China. Water, 6, 1419-1434.

KAGODA, P. A., NDIRITU, J., NTULI, C. & MWAKA, B. 2010. Application of radial basis function neural networks to short-term streamflow forecasting. Physics and Chemistry of the Earth, Parts A/B/C, 35, 571-581.

KAHIL, M. T., WARD, F. A., ALBIAC, J., EGGLESTON, J. & SANZ, D. 2016. Hydro-economic modeling with aquifer–river interactions to guide sustainable basin management. Journal of Hydrology, 539, 510-524.

KAMPF, S. K., BURGES, S. J., HAMMOND, J. C., BHASKAR, A., COVINO, T. P., EURICH, A., HARRISON, H., LEFSKY, M., MARTIN, C. & MCGRATH, D. 2020. The case for an open water balance: Re-envisioning network design and data analysis for a complex, uncertain world. Water Resources Research, 56, e2019WR026699.

KANNAN, N., ANANDHI, A. & JEONG, J. 2018. Estimation of stream health using flow-based indices. Hydrology, 5, 20.

KHALIL, A., RITTIMA, A. & PHANKAMOLSIL, Y. 2018. The projected changes in water status of the Mae Klong Basin, Thailand, using WEAP model. Paddy and Water Environment, 16, 439-455.

KIBRET, S., MCCARTNEY, M., LAUTZE, J., NHAMO, L. & YAN, G. 2021. The impact of large and small dams on malaria transmission in four basins in Africa. Scientific reports, 11, 1-12.

KIESEL, J., GERICKE, A., RATHJENS, H., WETZIG, A., KAKOUEI, K., JAEHNIG, S. C. & FOHRER, N. 2019. Climate change impacts on ecologically relevant hydrological indicators in three catchments in three European ecoregions. Ecological engineering, 127, 404-416.

KIM, B. S., KIM, B. K. & KWON, H. H. 2011. Assessment of the impact of climate change on the flow regime of the Han River basin using indicators of hydrologic alteration. Hydrological Processes, 25, 691-704.

KIM, S., NOH, H., JUNG, J., JUN, H. & KIM, H. S. 2016. Assessment of the impacts of global climate change and regional water projects on streamflow characteristics in the Geum River Basin in Korea. Water, 8, 91.

KISHIWA, P., NOBERT, J., KONGO, V. & NDOMBA, P. 2018. Assessment of impacts of climate change on surface water availability using coupled SWAT and WEAP models: case of upper Pangani River Basin, Tanzania. Proceedings of the International Association of Hydrological Sciences, 378, 23-27.

KNÜPPE, K. 2011. The challenges facing sustainable and adaptive groundwater management in South Africa. Water SA, 37.

KOM, Z., NETHENGWE, N., MPANDELI, N. & CHIKOORE, H. 2020. Determinants of small-scale farmers’ choice and adaptive strategies in response to climatic shocks in Vhembe District, South Africa. GeoJournal, 1-24.

KUMARI, K. & YADAV, S. 2018. Linear regression analysis study. Journal of the practice of Cardiovascular Sciences, 4, 33.

KUNDU, P., MATHIVHA, F. & NKUNA, T. 2015. The Use of GIS and Remote Sensing Techniques to Evaluate the Impact of Land Use and Land Cover Change on the Hydrology of Luvuvhu River Catchment in Limpopo Province: Report to the Water Research Commission, Water Research Commission.

KUNDU, P., MATHIVHA, F. & NKUNA, T. 2015. The Use of GIS and Remote Sensing Techniques to Evaluate the Impact of Land Use and Land Cover Change on the Hydrology of

Luvuvhu River Catchment in Limpopo Province: Report to the Water Research Commission, Water Research Commission Pretoria, South Africa.

KUSANGAYA, S., WARBURTON, M. L., VAN GARDEREN, E. A. & JEWITT, G. P. 2014. Impacts of climate change on water resources in southern Africa: A review. Physics and Chemistry of the Earth, Parts a/b/c, 67, 47-54.

LEHMANN, F., VISHWAKARMA, B. D. & BAMBER, J. 2022. How well are we able to close the water budget at the global scale?

LEHNER, B., LIERMANN, C. R., REVENGA, C., VÖRÖSMARTY, C., FEKETE, B., CROUZET, P., DÖLL, P., ENDEJAN, M., FRENKEN, K. & MAGOME, J. 2011. High-resolution mapping of the world's reservoirs and dams for sustainable river-flow management. Frontiers in Ecology and the Environment, 9, 494-502.

LEMKE, W. 2016. The role of sport in achieving the sustainable development goals. UN chronicle, 53, 6-9.

LEONE, M., GENTILE, F., PORTO, A. L., RICCI, G. F. & DE GIROLAMO, A. M. 2023. Setting an ecological flow regime in a Mediterranean basin with limited data availability: The Locone River case study (SE Italy). Ecohydrology & Hydrobiology.

LÉVITE, H., SALLY, H. & COUR, J. 2003a. Testing water demand management scenarios in a water-stressed basin in South Africa: application of the WEAP model. Physics and Chemistry of the Earth, Parts A/B/C, 28, 779-786.

LÉVITE, H., SALLY, H. & COUR, J. Water demand management scenarios in a water-stressed basin in South Africa. Proc. 3rd WARFSA/WaterNet Symp, 2003b. 15-17.

LI, D., LONG, D., ZHAO, J., LU, H. & HONG, Y. 2017. Observed changes in flow regimes in the Mekong River basin. Journal of Hydrology, 551, 217-232.

LI, L., XU, H., CHEN, X. & SIMONOVIC, S. 2010. Streamflow forecast and reservoir operation performance assessment under climate change. Water resources management, 24, 83-104.

LI, Q., YU, M., ZHAO, J., CAI, T., LU, G., XIE, W. & BAI, X. 2012a. Impact of the Three Gorges reservoir operation on downstream ecological water requirements. Hydrology Research, 43, 48-53.

LI, X. H., ZHANG, Q., SHAO, M. & LI, Y. L. A comparison of parameter estimation for distributed hydrological modelling using automatic and manual methods. Advanced Materials Research, 2012b. Trans Tech Publ, 2372-2375.

LI, X., ZHAO, Y., SHI, C., SHA, J., WANG, Z.-L. & WANG, Y. 2015. Application of Water Evaluation and Planning (WEAP) model for water resources management strategy estimation in coastal Binhai New Area, China. Ocean & Coastal Management, 106, 97-109.

LIN, K., LIN, Y., LIU, P., HE, Y. & TU, X. 2016. Considering the order and symmetry to improve the traditional RVA for evaluation of hydrologic alteration of river systems. Water Resources Management, 30, 5501-5516.

LINCE-DEROCHE, N., PLEANER, M., MORRONI, C., MULLICK, S., FIRNHABER, C., HARRIES, J., SINANOVIC, E., MULONGO, M. & HOLELE, P. 2016. Achieving universal access to sexual and reproductive health services: the potential and pitfalls for contraceptive services in South Africa. South African Health Review, 2016, 95-108.

LINNANSAARI, T., MONK, W., BAIRD, D. & CURRY, R. 2012. Review of approaches and methods to assess Environmental Flows across Canada and internationally. DFO Can. Sci. Advis. Sec. Res. Doc, 39, 74.

LOMBAARD, J., PIETERSE, H., ROSSOUW, J. & NDITWANI, T. 2015. Project Name: Limpopo Water Management Area North Reconciliation Strategy.

LORENZO-LACRUZ, J., VICENTE-SERRANO, S. M., LÓPEZ-MORENO, J. I., BEGUERÍA, S., GARCÍA-RUIZ, J. M. & CUADRAT, J. M. 2010. The impact of droughts and water management on various hydrological systems in the headwaters of the Tagus River (central Spain). Journal of Hydrology, 386, 13-26.

LOUW, D. 2017. Horticutural development plan for the Thulamela local municipality.

LU, W., LEI, H., YANG, D., TANG, L. & MIAO, Q. 2018. Quantifying the impacts of small dam construction on hydrological alterations in the Jiulong River basin of Southeast China. Journal of hydrology, 567, 382-392.

LUO, Z., ZHANG, S., LIU, H., WANG, L., WANG, S. & WANG, L. 2023. Assessment of multiple dam-and sluice-induced alterations in hydrologic regime and ecological flow. Journal of Hydrology, 617, 128960.

LUO, Z., ZUO, Q., SHAO, Q. & DING, X. 2019. The impact of socioeconomic system on the river system in a heavily disturbed basin. Science of The Total Environment, 660, 851-864.

MA, Z., WANG, Z., XIA, T., GIPPEL, C. & SPEED, R. 2014. Hydrograph-Based Hydrologic Alteration Assessment and Its Application to the Yellow River. Journal of Environmental Informatics, 23.

MAGALA, M. 2015. Aquatic Health Assessment of the Steelpoort River System, Limpopo, South Africa, University of Johannesburg (South Africa).

MAKHERA, M., GUMBO, J. & CHIGAYO, K. 2011. Monitoring of microcystin-LR in Luvuvhu River catchment: Implications for human health. African Journal of Biotechnology, 10, 405-412.

MAKHTOUMI, Y., LI, S., IBEANUSI, V. & CHEN, G. 2020. Evaluating water balance variables under land use and climate projections in the upper Choctawhatchee River Watershed, in Southeast US. Water, 12, 2205.

MAKOWSKI, D., BEN-SHACHAR, M. S., PATIL, I. & LÜDECKE, D. 2020. Methods and algorithms for correlation analysis in R. Journal of Open-Source Software, 5, 2306.

MALANO, H. M. & VAN HOFWEGEN, P. 2018. Management of irrigation and drainage systems, CRC Press.

MALIK, A. & KUMAR, A. 2020. Spatio-temporal trend analysis of rainfall using parametric and non-parametric tests: case study in Uttarakhand, India. Theoretical and Applied Climatology, 140, 183-207.

MANATUNGE, J., NAKAYAMA, M. & PRIYADARSHANA, T. 2008. Environmental and social impacts of reservoirs: issues and mitigation. Oceans and aquatic ecosystems, 1, 212-255.

MANAVHELA, P. & SPENCER, J. 2012. Assessment of the potential for sustainable community tourism development: a study at the Nandoni Dam in Limpopo Province, South Africa: recreation and tourism. African Journal for Physical Health Education, Recreation and Dance, 18, 535-551.

MANOUCHEHRI, G. & MAHMOODIAN, S. 2002. Environmental impacts of dams constructed in Iran. International Journal of Water Resources Development, 18, 179-182.

MANTEL, S. K., HUGHES, D. A. & MULLER, N. W. 2010. Ecological impacts of small dams on South African rivers Part 1: Drivers of change–water quantity and quality. Water Sa, 36, 351-360.

MANTEL, S. K., RIVERS-MOORE, N. & RAMULIFHO, P. 2017. Small dams need consideration in riverscape conservation assessments. Aquatic Conservation: Marine and Freshwater Ecosystems, 27, 748-754.

MARAK, J. D. K., SARMA, A. K. & BHATTACHARJYA, R. K. 2020. Assessing the impacts of interbasin water transfer reservoir on streamflow. Journal of Hydrologic Engineering, 25, 05020034.

MARÉ, H., MWAKA, B. & SINHA, P. 2007. Development of simplified drought operating rules. URL: http://www. miya-water. com/data-and-research/articles-by-miyas-experts/water-resource-management (Accessed 1 April 2012).

MARTEN, R. 2019. How states exerted power to create the millennium development goals and how this shaped the global health agenda: lessons for the sustainable development goals and the future of global health. Global public health, 14, 584-599.

MASUPHA, T. E. & MOELETSI, M. E. 2017. Use of standardized precipitation evapotranspiration index to investigate drought relative to maize, in the Luvuvhu River catchment area, South Africa. Physics and Chemistry of the Earth, Parts A/B/C, 102, 1-9.

MASUPHA, T. E. & MOELETSI, M. E. 2018. Analysis of potential future droughts limiting maize production, in the Luvuvhu River catchment area, South Africa. Physics and Chemistry of the Earth, Parts A/B/C, 105, 44-51.

MASWANGANYE, S. E., DUBE, T., JOVANOVIC, N., KAPANGAZIWIRI, E. & MAZVIMAVI, D. 2022. Using the water balance approach to understand pool dynamics along non-perennial rivers in the semi-arid areas of South Africa. Journal of Hydrology: Regional Studies, 44, 101244.

MATHEWS, R. & RICHTER, B. D. 2007. Application of the Indicators of hydrologic alteration software in environmental flow setting 1. JAWRA Journal of the American Water Resources Association, 43, 1400-1413.

MATHIVHA, F., NKOSI, M. & MUTOTI, M. 2021. Evaluating the relationship between hydrological extremes and groundwater in Luvuvhu River Catchment, South Africa. Journal of Hydrology: Regional Studies, 37, 100897.

MAULUD, D. & ABDULAZEEZ, A. M. 2020. A review on linear regression comprehensive in machine learning. Journal of Applied Science and Technology Trends, 1, 140-147.

MAZIBUKO, S., MUKWADA, G. & MOELETSI, M. 2021. Assessing the frequency of drought/flood severity in the Luvuvhu River catchment, Limpopo Province, South Africa. Water SA, 47, 172-184.

MAZVIMAVI, D., MADAMOMBE, E. & MAKURIRA, H. 2007. Assessment of environmental flow requirements for river basin planning in Zimbabwe. Physics and Chemistry of the Earth, Parts A/B/C, 32, 995-1006.

MBONIMPA, E. G., GAUTAM, S., LAI, L., KUMAR, S., BONTA, J., WANG, X. & RAFIQUE, R. 2015. Combined PEST and Trial–Error approach to improve APEX calibration. Computers and Electronics in Agriculture, 114, 296-303.

MCCOLLUM, D. L., ECHEVERRI, L. G., BUSCH, S., PACHAURI, S., PARKINSON, S., ROGELJ, J., KREY, V., MINX, J. C., NILSSON, M. & STEVANCE, A.-S. 2018. Connecting the sustainable development goals by their energy inter-linkages. Environmental Research Letters, 13, 033006.

MCDANIEL, R. D. & O'DONNELL, F. C. 2019. Assessment of hydrologic alteration metrics for detecting urbanization impacts. Water, 11, 1017.

MEKONNEN, M. M. & HOEKSTRA, A. Y. 2016. Four billion people facing severe water scarcity. Science advances, 2, e1500323.

METTETAL, E. 2019. Irrigation dams, water, and infant mortality: Evidence from South Africa. Journal of Development Economics, 138, 17-40.

MIANABADI, H., ALIOGHLI, S. & MORID, S. 2021. Quantitative evaluation of 'No-harm'rule in international transboundary water law in the Helmand River basin. Journal of Hydrology, 599, 126368.

MISRA, A. K. 2014. Climate change and challenges of water and food security. International Journal of Sustainable Built Environment, 3, 153-165.

MITTAL, N., MISHRA, A., SINGH, R., BHAVE, A. G. & VAN DER VALK, M. 2014. Flow regime alteration due to anthropogenic and climatic changes in the Kangsabati River, India. Ecohydrology & Hydrobiology, 14, 182-191.

MOKGOEBO, J. M., KABANDA, T. A. & GUMBO, J. R. 2018. Assessment of the Riparian Vegetation Changes Downstream of Selected Dams in Vhembe District, Limpopo Province on Based on Historical Aerial Photography. Environ. Risks, 65-84.

MOLEKOA, M. D., AVTAR, R., KUMAR, P., THU MINH, H. V., DASGUPTA, R., JOHNSON, B. A., SAHU, N., VERMA, R. L. & YUNUS, A. P. 2021. Spatio-temporal analysis of surface water quality in Mokopane area, Limpopo, South Africa. Water, 13, 220.

MOLEKOA, M. D., KUMAR, P., CHOUDHARY, B. K., YUNUS, A. P., KHARRAZI, A., KHEDHER, K. M., AL SHAIB, M., SINGH, B. P., MINH, H. V. T. & KURNIAWAN, T. A. 2022. Spatio-temporal variations in the water quality of the Doorndraai Dam, South Africa: An assessment of sustainable water resource management. Current Research in Environmental Sustainability, 4, 100187.

MORAMARCO, T., BARBETTA, S., PANDOLFO, C., TARPANELLI, A., BERNI, N. & MORBIDELLI, R. 2014. Spillway collapse of the Montedoglio Dam on the Tiber River, Central Italy: Data collection and event analysis. Journal of Hydrologic Engineering, 19, 1264-1270.

MORIASI, D. N., GITAU, M. W., PAI, N. & DAGGUPATI, P. 2015. Hydrologic and water quality models: Performance measures and evaluation criteria. Transactions of the ASABE, 58, 1763-1785.

MOUNIR, Z. M., MA, C. M. & AMADOU, I. 2011. Application of water evaluation and planning (WEAP): A model to assess future water demands in the Niger River (in Niger Republic). Modern Applied Science, 5, 38.

MTHEMBU, D. E. & NHAMO, G. 2021. Domestication of the UN Sustainable Development Goals in South Africa. South African Journal of International Affairs, 28, 1-28.

MUDELSEE, M. 2010. Climate time series analysis. Atmospheric and, 397.

MUKHEIBIR, P. & SPARKS, D. 2003. Water resource management and climate change in South Africa: Visions, driving factors and sustainable development indicators. Report for Phase I of the Sustainable Development and Climate Change project. Energy and Development Research Centre (EDRC), University of Cape Town.

MUKHEIBIR, P. 2007. The impact of climate change on small municipal water resource management. The case of Bredasdorp, South Africa.

MULLER, M. 2018. Cape Town’s drought: don’t blame climate change. Nature Publishing Group.

MULUNGU, D. M. & MUNISHI, S. E. 2007. Simiyu River catchment parameterization using SWAT model. Physics and Chemistry of the Earth, Parts A/B/C, 32, 1032-1039.

MWENDERA, E. & ATYOSI, Y. 2018. A Review of Water Storage for Socio-Economic Development in South Africa. Journal of Water Resource and Protection, 10, 266.

NARE, L., ODIYO, J., FRANCIS, J. & POTGIETER, N. 2011. Framework for effective community participation in water quality management in Luvuvhu Catchment of South Africa. Physics and Chemistry of the Earth, Parts A/B/C, 36, 1063-1070.

NARE, L., ODIYO, J., RAVULULU, F. & POTGIETER, N. 2013. Evaluation of community knowledge, attitudes, practices, and perceptions relating to water quality and safety in Luvuvhu catchment of South Africa. Journal of Environmental Science and Water Resources, 2, 67-74.

NASIRI, S., ANSARI, H. & ZIAEI, A. N. 2020. Simulation of water balance equation components using SWAT model in Samalqan Watershed (Iran). Arabian Journal of Geosciences, 13, 1-15.

NDIRITU, J., MCCARTHY, S. & TSHIRANGWANA, N. 2014. Probabilistic assessment of the rainwater harvesting potential of schools in South Africa. Proceedings of the International Association of Hydrological Sciences, 364, 435-440.

NEL, J. L., LE MAITRE, D. C., ROUX, D. J., COLVIN, C., SMITH, J. S., SMITH-ADAO, L. B., MAHERRY, A. & SITAS, N. 2017. Strategic water source areas for urban water security: Making the connection between protecting ecosystems and benefiting from their services. Ecosystem Services, 28, 251-259.

NEMAXWI, P., ODIYO, J. & MAKUNGO, R. 2019. Estimation of groundwater recharge response from rainfall events in a semi-arid fractured aquifer: Case study of quaternary catchment A91H, Limpopo Province, South Africa. Cogent Engineering, 6, 1635815.

NETSHIPALE, L. L. 2016. Water services delivery in Mukondeni Village in Limpopo Province, South Africa.

NIASSE, M. 2005. Climate-induced water conflict risks in West Africa: recognizing and coping with increasing climate impacts on shared watercourses. Human Security and Climate Change. PRIO, CICERO and GECHS, Asker, Norway, 21-23.

NINELA, P. G. 2002. Environmental justice and the long-term impacts of large dam projects: a case study of communities displaced by the Inanda dam, Durban.

NTHUNYA, L. N., KHUMALO, N. P., VERLIEFDE, A. R., MAMBA, B. B. & MHLANGA, S. D. 2019. Quantitative analysis of phenols and PAHs in the Nandoni Dam in Limpopo Province, South Africa: A preliminary study for dam water quality management. Physics and Chemistry of the Earth, Parts A/B/C, 112, 228-236.

NYAM, Y., KOTIR, J., JORDAAN, A., OGUNDEJI, A. & TURTON, A. 2020. Drivers of change in sustainable water management and agricultural development in South Africa: a participatory approach. Sustainable Water Resources Management, 6, 1-20.

O'BRIEN, D. & SCOTT, P. S. 2012. Correlation and regression. Approaches to quantitative research: A guide for dissertation students, 106-124.

OBERHOLSTER, P. J. & ASHTON, P. J. 2008. State of the nation report: An overview of the status of water quality and eutrophication in South African rivers and reservoirs. Parliamentary Grant Deliverable. Pretoria: Council for Scientific and Industrial Research (CSIR), 2006.

ODIYO, J. O., MAKUNGO, R. & NKUNA, T. R. 2015. Long-term changes and variability in rainfall and streamflow in Luvuvhu River Catchment, South Africa. South African Journal of Science, 111, 1-9.

ODIYO, J. O., MAKUNGO, R. & NKUNA, T. R. 2015. Long-term changes and variability in rainfall and streamflow in Luvuvhu River Catchment, South Africa. South African Journal of Science, 111, 1-9.

ODIYO, J., MAKUNGO, R., NKUNA, T. & CHIKOORE, H. 2020. Hydrological Modelling of Climate Change Impacts for Development of Adaptation Strategies: The Case of Luvuvhu River Catchment, Limpopo, South Africa. Water Research Commission, Pretoria, South Africa.

ODIYO, J., PHANGISA, J. & MAKUNGO, R. 2012. Rainfall–runoff modelling for estimating Latonyanda River flow contributions to Luvuvhu River downstream of Albasini Dam. Physics and Chemistry of the Earth, Parts A/B/C, 50, 5-13.

OKYEREH, S. A., OFOSU, E. A. & KABOBAH, A. T. 2019. Modelling the impact of Bui dam operations on downstream competing water uses. Water-Energy Nexus, 2, 1-9.

OLIVIER, C., ENGELBRECHT, C., BOPAPE, M.-J. & BOTAI, J. 2020. Status of Climate in South Africa and predictions for the 2020-2021 summer season.

ONYARI, E. K. & ILUNGA, F. 2013. Application of MLP neural network and M5P model tree in predicting streamflow: A case study of Luvuvhu catchment, South Africa. International Journal of Innovation, Management and Technology, 4, 11.

OPPERMAN, J. J., KENDY, E., THARME, R. E., WARNER, A. T., BARRIOS, E. & RICHTER, B. D. 2018. A three-level framework for assessing and implementing environmental flows. Frontiers in Environmental Science, 6, 76.

ÖZCAN, C. 2021. Assessment of the Hydrological Alterations and Environmental Flows in Sakarya Watershed, Turkey. Middle East Technical University.

PARTEL, B. 2019. ASSESSMENT OF ENVIRONMENTAL FLOWS REQUIREMENTS OF

PÉREZ-SÁNCHEZ, J., SENENT-APARICIO, J., MARTÍNEZ SANTA-MARÍA, C. & LÓPEZ-BALLESTEROS, A. 2020. Assessment of ecological and hydro-geomorphological alterations under climate change using SWAT and IAHRIS in the Eo River in Northern Spain. Water, 12, 1745.

PERIN, R., TRIGATTI, M., NICOLINI, M., CAMPOLO, M. & GOI, D. 2020. Automated calibration of the EPA-SWMM model for a small suburban catchment using PEST: a case study. Environmental monitoring and assessment, 192, 1-17.

PERRY, K. A. 2015. Application of the SWAT hydrological model in a small, mountainous catchment in South Africa. University of Pretoria.

PETES, L. E., BROWN, A. J. & KNIGHT, C. R. 2012. Impacts of upstream drought and water withdrawals on the health and survival of downstream estuarine oyster populations. Ecology and Evolution, 2, 1712-1724.

PHUE, H. & CHUENCHOOKLIN, S. Existing Water Balance in the Bago River Basin, Myanmar. IOP Conference Series: Earth and Environmental Science, 2020. IOP Publishing, 012003.

PINIEWSKI, M. 2016. Natural streamflow simulation for two largest river basins in Poland: a baseline for identification of flow alterations. Proceedings of the International Association of Hydrological Sciences, 373, 101-107.

POFF, N. L. & HART, D. D. 2002. How dams vary and why it matters for the emerging science of dam removal: an ecological classification of dams is needed to characterize how the tremendous variation in the size, operational mode, age, and number of dams in a river basin influences the potential for restoring regulated rivers via dam removal. BioScience, 52, 659-668.

POLLARD, S. & DU TOIT, D. 2011. Towards adaptive integrated water resources management in southern Africa: The role of self-organisation and multi-scale feedbacks for learning and responsiveness in the Letaba and Crocodile catchments. Water resources management, 25, 4019-4035.

POTTINGER, L. 1996. Environmental Impacts of Large Dams: African Examples. International Rivers, 1.

PRESTON, I. R. 2015. Water supply development decision-making in South Africa. Rhodes University Grahamstown.

PSOMAS, A., PANAGOPOULOS, Y., KONSTA, D. & MIMIKOU, M. 2016. Assessment of impacts of climate change on surface water availability using coupled SWAT and WEAP models: case of upper Pangani River Basin, Tanzania. Procedia engineering, 162, 269-276.

QICAI, L. 2011. Influence of dams on river ecosystem and its countermeasures. Journal of Water Resource and Protection, 2011.

QITING, Z. & SHIKUI, L. 2016. Assessment of Hydrologic Alterations Associated with Water Projects in Shaying River, China. International Journal of Simulation--Systems, Science & Technology, 17.

RAHMAN, M. A. T., MOLY, S. H. & SAADAT, A. 2013. Environmental flow requirement and comparative study of the Turag River, Bangladesh. International Journal of Scientific Research in Environmental Sciences, 1, 291.

RAMULIFHO, P., NDOU, E., THIFHULUFHELWI, R. & DALU, T. 2019. Challenges to implementing an environmental flow regime in the Luvuvhu River Catchment, South Africa. International Journal of Environmental Research and Public Health, 16, 3694.

RAMULIFHO, P., NDOU, E., THIFHULUFHELWI, R. & DALU, T. 2019. Challenges to implementing an environmental flow regime in the Luvuvhu River Catchment, South Africa. International Journal of Environmental Research and Public Health, 16, 3694.

RENSHAW, C. A. 2012. The effect of environmental aspects on the biological communities of the Olifants and Luvuvhu Rivers in the Kruger National Park, University of Johannesburg (South Africa).

RICHTER, B. D., BAUMGARTNER, J. V., BRAUN, D. P. & POWELL, J. 1998. A spatial assessment of hydrologic alteration within a river network. Regulated Rivers: Research & Management: An International Journal Devoted to River Research and Management, 14, 329-340.

RICHTER, B. D., BAUMGARTNER, J. V., POWELL, J. & BRAUN, D. P. 1996. A method for assessing hydrologic alteration within ecosystems. Conservation biology, 10, 1163-1174.

RICHTER, B. D., POSTEL, S., REVENGA, C., SCUDDER, T., LEHNER, B., CHURCHILL, A. & CHOW, M. 2010. Lost in development's shadow: The downstream human consequences of dams. Water alternatives, 3, 14.

RICHTER, B., BAUMGARTNER, J., WIGINGTON, R. & BRAUN, D. 1997. How much water does a river need? Freshwater biology, 37, 231-249.

RIKHOTSO, N. M. 2020. Rural Water Governance in the Mopani District Municipality, University of Johannesburg (South Africa).

ROLLS, R. J., LEIGH, C. & SHELDON, F. 2012. Mechanistic effects of low-flow hydrology on riverine ecosystems: ecological principles and consequences of alteration. Freshwater Science, 31, 1163-1186.

SACHS, J. D. 2012. From millennium development goals to sustainable development goals. The lancet, 379, 2206-2211.

SARAIVA OKELLO, A., MASIH, I., UHLENBROOK, S., JEWITT, G., VAN DER ZAAG, P. & RIDDELL, E. 2015. Drivers of spatial and temporal variability of streamflow in the Incomati River basin. Hydrology and Earth System Sciences, 19, 657-673.

SCHAAKE, J. & LIU, C. Development, and application of simple water balance models to understand the relationship between climate and water resources. New Directions for Surface Water Modeling Proceedings of the Baltimore Symposium, 1989.

SCHMUTZ, S. & MOOG, O. 2018. Dams: ecological impacts and management. Riverine ecosystem management. Springer, Cham.

SCHMUTZ, S. & MOOG, O. 2018. Dams: ecological impacts and management. Riverine Ecosystem Management. Springer, Cham.

SCHUOL, J. & ABBASPOUR, K. 2007. Using monthly weather statistics to generate daily data in a SWAT model application to West Africa. Ecological modelling, 201, 301-311.

SEIF-ENNASR, M., ZAABOUL, R., HIRICH, A., CAROLETTI, G. N., BOUCHAOU, L., EL MORJANI, Z. E. A., BERAAOUZ, E. H., MCDONNELL, R. A. & CHOUKR-ALLAH, R. 2016. Climate change and adaptive water management measures in Chtouka Aït Baha region (Morocco). Science of the Total Environment, 573, 862-875.

SELLAM, V. & POOVAMMAL, E. 2016. Prediction of crop yield using regression analysis. Indian Journal of Science and Technology, 9, 1-5.

SHAND, M. & BASSON, M. South African water resources, availability, demands and strategic issues. Proceedings of a joint RSA-Australian workshop on water resources management, 2003. 29-41.

SHEET, U. F. 2003. Applying Indicators of Hydrologic Alteration to Texas Streams—Overview of Methods with Examples from the Trinity River Basin.

SHRESTHA, J. P., PAHLOW, M. & COCHRANE, T. A. 2020. Development of a SWAT hydropower operation routine and its application to assessing hydrological alterations in the Mekong. Water, 12, 2193.

SINGH, L. K., JHA, M. K. & CHOWDARY, V. 2017. Multi-criteria analysis and GIS modeling for identifying prospective water harvesting and artificial recharge sites for sustainable water supply. Journal of Cleaner Production, 142, 1436-1456.

SINGH, R. K., JAIN, M. K. & GUPTA, V. 2022. Impact of climate change on runoff regime of the Godavari River in India. Sustainable Water Resources Management, 8, 69.

SINGO, L. R. 2018. Application of GIS and Remote Sensing techniques to evaluate the impact of land cover and land use changes on the hydrology and water resources of Luvuvhu River Catchment in Limpopo Province, South Africa.

SINGO, L., KUNDU, P. & MATHIVHA, F. 2016. Spatial variation of reference evapotranspiration and its influence on the hydrology of Luvuvhu River Catchment.

SINGO, L., KUNDU, P. & ODIYO, J. 2016. Impact of land use change on surface runoff and stream discharges in Luvuvhu River Catchment.

SINGO, L., KUNDU, P., ODIYO, J., MATHIVHA, F. & NKUNA, T. 2012. Flood frequency analysis of annual maximum stream flows for Luvuvhu river catchment, Limpopo province, South Africa.

SINTHUMULE, N. I. 2021. Window of Economic Opportunity or Door of Exclusion? Nandoni Dam and Its Local Communities. Sustainability, 13, 2502.

SMAKHTIN, V. U. 2001. Low flow hydrology: a review. Journal of hydrology, 240, 147-186.

SOJKA, M., JASKUŁA, J., WICHER-DYSARZ, J. & DYSARZ, T. 2016. Assessment of dam construction impact on hydrological regime changes in lowland river–A case of study: the Stare Miasto reservoir located on the Powa River. Journal of Water and Land Development, 119--125.

STEFANIDIS, K., PANAGOPOULOS, Y., PSOMAS, A. & MIMIKOU, M. 2016. Assessment of the natural flow regime in a Mediterranean river impacted from irrigated agriculture. Science of the Total Environment, 573, 1492-1502.

STEYERBERG, E. W., VICKERS, A. J., COOK, N. R., GERDS, T., GONEN, M., OBUCHOWSKI, N., PENCINA, M. J. & KATTAN, M. W. 2010. Assessing the performance of prediction models: a framework for some traditional and novel measures. Epidemiology (Cambridge, Mass.), 21, 128.

STONE, M. C., BYRNE, C. F. & MORRISON, R. R. 2017. Evaluating the impacts of hydrologic and geomorphic alterations on floodplain connectivity. Ecohydrology, 10, e1833.

STRAUSS, A., DOBROWSKY, P. H., NDLOVU, T., REYNEKE, B. & KHAN, W. 2016. Comparative analysis of solar pasteurization versus solar disinfection for the treatment of harvested rainwater. BMC microbiology, 16, 1-16.

SULLIVAN, C. A. 2011. Quantifying water vulnerability: a multi-dimensional approach. Stochastic Environmental Research and Risk Assessment, 25, 627-640.

SUN, Y., NIU, J. & SIVAKUMAR, B. 2019. A comparative study of models for short-term streamflow forecasting with emphasis on wavelet-based approach. Stochastic Environmental Research and Risk Assessment, 33, 1875-1891.

SUWAL, N. 2019. Research on Optimal Operation of Cascade Hydropower Stations Considering Ecological Flows. Hohai University Nanjing, China.

TANNAHILL, K., MILLS, P. & BOOTH, C. A. 2014. Impacts and issues of dams and reservoirs. Water Resources in the Built Environment: Management Issues and Solutions, 45-60.

TAYLOR, V. 2001. Hydrological modelling applications for water resources management in the Mkomazi Catchment.

TAYLOR, V., SCHULZE, R. & JEWITT, G. 2003. Application of the indicators of hydrological alteration method to the Mkomazi River, KwaZulu-Natal, South Africa. African Journal of Aquatic Science, 28, 1-11.

TENA, T. M., MWAANGA, P. & NGUVULU, A. 2019. Hydrological Modelling and Water Resources Assessment of Chongwe River Catchment using WEAP Model. Water, 11, 839.

THAVHANA, M., SAVAGE, M. & MOELETSI, M. 2018. SWAT model uncertainty analysis, calibration, and validation for runoff simulation in the Luvuvhu River catchment, South Africa. Physics and Chemistry of the Earth, Parts A/B/C, 105, 115-124.

THAVHANA, M., SAVAGE, M. & MOELETSI, M. 2018. SWAT model uncertainty analysis, calibration and validation for runoff simulation in the Luvuvhu River catchment, South Africa. Physics and Chemistry of the Earth, Parts A/B/C, 105, 115-124.

THENMOZHI, M. & KOTTISWARAN, S. 2016. Analysis of rainfall trend using Mann-Kendall test and the Sen’s slope estimator in Udumalpet of Tirupur district in Tamil Nadu. International journal of agricultural science and research, 6, 131-138.

THOPIL, G. A. & POURIS, A. 2016. A 20-year forecast of water usage in electricity generation for South Africa amidst water scarce conditions. Renewable and Sustainable Energy Reviews, 62, 1106-1121.

TODES, A., KOK, P., WENTZEL, M., VAN ZYL, J. & CROSS, C. Contemporary south African urbanization dynamics. Urban forum, 2010. Springer, 331-348.

TRAMBLAY, Y., JARLAN, L., HANICH, L. & SOMOT, S. 2018. Future scenarios of surface water resources availability in North African dams. Water resources management, 32, 1291-1306.

TSHILILO, F. P. 2017. Rainy season characteristics with reference to maize production for the Luvuvhu river catchment, Limpopo Province, South Africa.

TULBURE, M. G., BROICH, M., STEHMAN, S. V. & KOMMAREDDY, A. 2016. Surface water extent dynamics from three decades of seasonally continuous Landsat time series at subcontinental scale in a semi-arid region. Remote Sensing of Environment, 178, 142-157.

TURNER, S. W., STEYAERT, J. C., CONDON, L. & VOISIN, N. 2021. Water storage and release policies for all large reservoirs of conterminous United States. Journal of Hydrology, 603, 126843.

UNGUREANU, N., VLĂDUȚ, V. & VOICU, G. 2020. Water scarcity and wastewater reuse in crop irrigation. Sustainability, 12, 9055.

VAN VLIET, M. & ZWOLSMAN, J. 2008. Impact of summer droughts on the water quality of the Meuse River. *Journal of Hydrology,* 353**,** 1-17.

VANDERKELEN, I., VAN LIPZIG, N. P. & THIERY, W. 2018. Modelling the water balance of Lake Victoria (East Africa)<? xmltex\break?>–Part 1: Observational analysis. Hydrology and Earth System Sciences, 22, 5509-5525.

VILLAGE, P. A. T. & TOWN, N. V. 2017. FLOOD LINE ASSESSMENT STUDY FLOOD LINES ASSESSMENT FOR THE PROPOSED POWER LINE DEVELOPMENT AT THE MAMPHULI-DZWERANI EXT A SUBSTATION AT MAMPHULI VILLAGE AND AN APPROXIMATELY 6KM LOOP IN LOOP OUT BERSFORT OF 2X132KV POWER LINE FROM AN EXISTING 132KV.

VINING, K. C. & VECCHIA, A. V. 2007. Water-balance simulations of runoff and reservoir storage for the Upper Helmand watershed and Kajakai Reservoir, Central Afghanistan, US Department of the Interior, US Geological Survey.

VISHWAMITRI RIVER USING HYDROLOGICAL METHODS. Indian Water Resour. Soc., 39.

VON FRANTZIUS, I. 2004. World Summit on Sustainable Development Johannesburg 2002: A critical analysis and assessment of the outcomes. Environmental Politics, 13, 467-473.

WANG, P. 2012. Social impact analysis of large dams: a case study of cascading dams on the upper-mekong river, China.

WANG, P., DONG, S. & LASSOIE, J. 2014. The large dam dilemma: an exploration of the impacts of hydro projects on people and the environment in China, Springer.

WANG, Q., DU, Y., SU, Y. & CHEN, K. 2012. Environmental impact post-assessment of dam and reservoir projects: a review. Procedia Environmental Sciences, 13, 1439-1443.

WANG, Q., LI, S. & LI, R. 2019. Evaluating water resource sustainability in Beijing, China: Combining PSR model and matter-element extension method. Journal of Cleaner Production, 206, 171-179.

WANG, X., XIAO, X., QIN, Y., DONG, J., WU, J. & LI, B. 2022. Improved maps of surface water bodies, large dams, reservoirs, and lakes in China. Earth System Science Data, 14, 3757-3771.

WANG, Y., WANG, D., LEWIS, Q. W., WU, J. & HUANG, F. 2017. A framework to assess the cumulative impacts of dams on hydrological regime: A case study of the Yangtze River. Hydrological Processes, 31, 3045-3055.

WASEEM, M., MANI, N., ANDIEGO, G. & USMAN, M. 2017. A review of criteria of fit for hydrological models. Int. Res. J. Eng. Technol, 4, 1765-72.

WASKO, C., NATHAN, R. & PEEL, M. C. 2020. Trends in global flood and streamflow timing based on local water year. Water Resources Research, 56, e2020WR027233.

WATSON, A., MILLER, J., FINK, M., KRALISCH, S., FLEISCHER, M. & DE CLERCQ, W. 2019. Distributive rainfall–runoff modelling to understand runoff-to-baseflow proportioning and its impact on the determination of reserve requirements of the Verlorenvlei estuarine lake, west coast, South Africa.

WCD 2000. Dams and development: A new framework for decision-making: The report of the world commission on dams, Earthscan.

WEBER, M., RINKE, K., HIPSEY, M. R. & BOEHRER, B. 2017. Optimizing withdrawal from drinking water reservoirs to reduce downstream temperature pollution and reservoir hypoxia. Journal of Environmental Management, 197, 96-105.

WILLMOTT, C. J., ROBESON, S. M., MATSUURA, K. & FICKLIN, D. L. 2015. Assessment of three dimensionless measures of model performance. Environmental Modelling & Software, 73, 167-174.

WÖHLING, T., SAMANIEGO, L. & KUMAR, R. 2013. Evaluating multiple performance criteria to calibrate the distributed hydrological model of the upper Neckar catchment. Environmental earth sciences, 69, 453-468.

WRIGHT, J. S. 2008. The impact of Katse dam water on water quality in the Ash, Liebenbergsvlei and Wilge rivers and the Vaal dam, University of Johannesburg (South Africa).

WU, H., CHEN, J., XU, J., ZENG, G., SANG, L., LIU, Q., YIN, Z., DAI, J., YIN, D., LIANG, J. & YE, S. 2019. Effects of dam construction on biodiversity: A review. Journal of Cleaner Production, 221, 480-489.

XUE, L., ZHANG, H., YANG, C., ZHANG, L. & SUN, C. 2017. Quantitative assessment of hydrological alteration caused by irrigation projects in the Tarim River basin, China. Scientific Reports, 7, 4291.

YANG, H., FARAMARZI, M. & ABBASPOUR, K. Assessing freshwater availability in Africa under the current and future climate with focus on drought and water scarcity. Proceedings of the 20th International Congress on Modeling and Simulation, Adelaide, Australia, 2013. 1-6.

YANG, Z., YAN, Y. & LIU, Q. 2012. Assessment of the flow regime alterations in the Lower Yellow River, China. Ecological Informatics, 10, 56-64.

YAQOB, E., AL-SA'ED, R., SORIAL, G. & SUIDAN, M. 2015. Simulation of transboundary wastewater resource management scenarios in the Wadi Zomer watershed, using a WEAP model.

YASARER, L. M., TAYLOR, J. M., RIGBY, J. R. & LOCKE, M. A. 2020. Trends in land use, irrigation, and streamflow alteration in the Mississippi River Alluvial Plain. Frontiers in Environmental Science, 8, 66.

YAYKIRAN, S., CUCELOGLU, G. & EKDAL, A. 2019. Estimation of water budget components of the Sakarya River Basin by using the WEAP-PGM model. Water, 11, 271.

YUAN, Y., ZHANG, C., ZENG, G., LIANG, J., GUO, S., HUANG, L., WU, H. & HUA, S. 2016. Quantitative assessment of the contribution of climate variability and human activity to streamflow alteration in Dongting Lake, China. Hydrological Processes, 30, 1929-1939.

ZAKWAN, M. & ARA, Z. 2019. Statistical analysis of rainfall in Bihar. Sustainable Water Resources Management, 5, 1781-1789.

ZHANG, Q., XIAO, M., LIU, C.-L. & SINGH, V. P. 2014. Reservoir-induced hydrological alterations and environmental flow variation in the East River, the Pearl River basin, China. Stochastic environmental research and risk assessment, 28, 2119-2131.

ZHANG, X., YANG, H., ZHANG, W., FENICIA, F., PENG, H. & XU, G. 2022. Hydrologic impacts of cascading reservoirs in the middle and lower Hanjiang River basin under climate variability and land use change. Journal of Hydrology: Regional Studies, 44, 101253.

ZHANG, Y., ZHENG, H., HERRON, N., LIU, X., WANG, Z., CHIEW, F. H. & PARAJKA, J. 2019. A framework estimating cumulative impact of damming on downstream water availability. Journal of Hydrology, 575, 612-627.

ZHOU, X., HUANG, X., ZHAO, H. & MA, K. 2020. Development of a revised method for indicators of hydrologic alteration for analyzing the cumulative impacts of cascading reservoirs on flow regime. Hydrology and Earth System Sciences, 24, 4091-4107.

ZIERVOGEL, G., JOHNSTON, P., MATTHEW, M. & MUKHEIBIR, P. 2010. Using climate information for supporting climate change adaptation in water resource management in South Africa. Climatic Change, 103, 537-554.

ZIERVOGEL, G., NEW, M., ARCHER VAN GARDEREN, E., MIDGLEY, G., TAYLOR, A., HAMANN, R., STUART-HILL, S., MYERS, J. & WARBURTON, M. 2014. Climate change impacts and adaptation in South Africa. Wiley Interdisciplinary Reviews: Climate Change, 5, 605-620.

ZIMMERMAN, J. K., LETCHER, B. H., NISLOW, K. H., LUTZ, K. A. & MAGILLIGAN, F. J. 2010. Determining the effects of dams on subdaily variation in river flows at a whole-basin scale. River research and applications, 26, 1246-1260.

ZULFAN, J. & GINTING, B. Investigation of spillway rating curve via theoretical formula, laboratory experiment, and 3D numerical modeling: A case study of the Riam Kiwa Dam, Indonesia. IOP Conference Series: Earth and Environmental Science, 2021. IOP Publishing, 012030.

ZUO, Q. & LIANG, S. 2015. Effects of dams on river flow regime based on IHA/RVA. Proceedings of the International Association of Hydrological Sciences, 368, 275-280.

APPENDICES

Appendices A: Tables

Table A1: Summary of IHA Parameters and their Ecosystem Influences

IHA Parameter Group	Hydrologic Parameters	Ecosystem Influences
1. Magnitude of monthly water conditions	Mean or median value for each calendar month *Subtotal 12 parameters*	• Aquatic organisms have access to adequate habitat • Plants' ability to access soil moisture • Terrestrial animals have access to water • Fur-bearing mammals have access to food and cover • The reliability of terrestrial animal water supplies • The ability of predators to access nesting sites. • The amount of oxygen in the water column and the amount of photosynthesis in the water column are affected
2. Magnitude and duration of annual extreme water conditions	Annual minima, 1-day mean Annual minima, 3-day means Annual minima, 7-day means Annual minima, 30-day means Annual minima, 90-day means. Annual maxima, 1-day mean Annual maxima, 3-day means Annual maxima, 7-day means Annual maxima, 30-day means Annual maxima, 90-day means Number of zero-flow days Base flow index: 7-day minimum flow/mean flow for year. *Subtotal 12 parameters*	• An organism's ability to compete, grow rudely, and adapt to stress • The creation of colonization sites for plants • The influence of abiotic and biotic factors on the structure of aquatic ecosystems • Characterizing the morphology of river channels and the physical characteristics of habitats • Plant stress caused by soil moisture • An animal's dehydration • Stress in plants caused by anaerobic conditions • Rivers and floodplains exchange nutrient volume • Stressful conditions in aquatic environments, such as low oxygen levels and concentrated chemicals • A description of the plant communities in lakes, ponds, and floodplains • Aeration of spawning beds in channel sediments during high flows for waste disposal
3. Timing of annual extreme water conditions	Julian date of each annual 1-day maximum Julian date of each annual 1-day minimum Subtotal 2 parameters	• Adaptability to organisms' life cycles • Organisms' ability to predict and avoid stress • For reproduction or to avoid predators, access to special habitats is essential. • Migration cues for spawning • Mechanisms of life history adaptation and behavioural evolution
4. Frequency and duration of high and low pulses	Number of low pulses within each water year Mean or median duration of low pulses (days) Number of high pulses within each water year Mean or median duration of high pulses (days) Subtotal 4 parameters	• Stress caused by soil moisture on plants: frequency and magnitude • Plant anaerobic stress frequency and duration • The availability of aquatic habitats in floodplains • The exchange of nutrients and organic matter between rivers and floodplains • Mineral availability in the soil • Providing access to feeding, resting, and breeding sites for waterbirds. • Contributes to the transport of bed loads, sediment textures in channels, and the duration of substrate disturbance (high pulses).
5. Rate and frequency of water condition changes	Rise rates: Mean or median of all positive differences between consecutive daily values Fall rates: Mean or median of all negative differences between consecutive daily values Number of hydrologic reversals Subtotal 3 parameters. Grand total 33 parameters	• Plant stress due to drought (falling levels) • Biological entrapment on islands and floodplains (rising levels) • Reduced mobility at streamedges (varial zones) caused by desiccation

Table A2: Summary of Environmental Flow Component (EFC) Parameters and their Ecosystem Influences

EFC Type	Hydrologic Parameters	Ecosystem Influences
1. Monthly low flows	Mean or median values of low flows during each calendar month *Subtotal 12 parameters*	• Ensure that aquatic organisms have an adequate habitat. • Make sure the water temperature, dissolved oxygen, and chemical composition are appropriate. • Ensure soil moisture for plants in floodplains by maintaining the water table levels. • Ensure terrestrial animals have access to drinking water. • Maintain a suspended environment for fish and amphibian eggs. • Make it possible for fish to move to areas where they can feed and spawn. • Provide support for hyporheic organisms (living in saturated sediments)
2. Extreme low flows	Frequency of extreme low flows during each water year or season Mean or median values of extreme low flow event: • Duration (days) • Peak flow (minimum flow during event) • Timing (Julian date of peak flow) *Subtotal 4 parameters*	• Incorporate specific floodplain plants into the enrolment process • Ensure that aquatic and riparian communities are free from invasive, introduced species. • Predators benefit from concentrating prey in limited areas
3. High flow pulses	Frequency of high flow pulses during each water year or season Mean or median values of high flow pulse event: • Duration (days) • Peak flow (maximum flow during event) • Timing (Julian date of peak flow) • Rise and fall rates. Subtotal 6 parameters	• Including pools, riffles, and other physical characteristics of the river channel. • Identify the substrate sizes (sand, gravel, cobbles) in streambeds • Maintain riparian vegetation at a distance from the channel to prevent encroachment. • Ensure normal water quality after prolonged low flows by flushing waste products and pollutants from the system • Keep gravels aerated in spawning grounds to prevent silting • Ensure the estuary is salinity-appropriate
4. Small floods	Frequency of small floods during each water year or season Mean or median values of small flood event: • Duration (days) • Peak flow (maximum flow during event) • Timing (Julian date of peak flow) • Rise and fall rates. Subtotal 6 parameters	Floods of all sizes are covered by this rule: • Provide fish with cues for migration and spawning. • Trigger new phase in life cycle (such as insects) • Provide spawning grounds for fish in the floodplain, as well as nursery areas for juvenile fish • Enable fish and waterfowl to feed on new food sources • Recharge the water table in floodplains • The diversity of floodplain forests can be maintained by prolonged inundation (e.g., different plant species tolerate prolonged flooding differently). • Ensure that floodplain plants are distributed and abundant • Fill floodplains with nutrients
5. Large floods	Frequency of large floods during each water year or season Mean or median values of large flood event: • Duration (days) • Peak flow (maximum flow during event) • Timing (Julian date of peak flow) • Rise and fall rates. Subtotal 6 parameters. Grand total 34 parameters	• The following applies to both small and large floods: • Ensure that aquatic and riparian communities are maintained in balance • Recruit colonizing plants by creating sites for recruitment • Floodplain habitats are shaped by physical habitats • Make sure spawning areas are covered with gravel and cobbles • Put organic material (food) and woody debris (habitat structures) into the channel. • Ensure that aquatic and riparian communities are free from invasive, introduced species. • Distribute riparian plant seeds and fruits. • Develop secondary channels and oxbow lakes by driving lateral river channel movement • Maintain a prolonged moisture level in the soil for plant seedlings

Appendices B: Figures

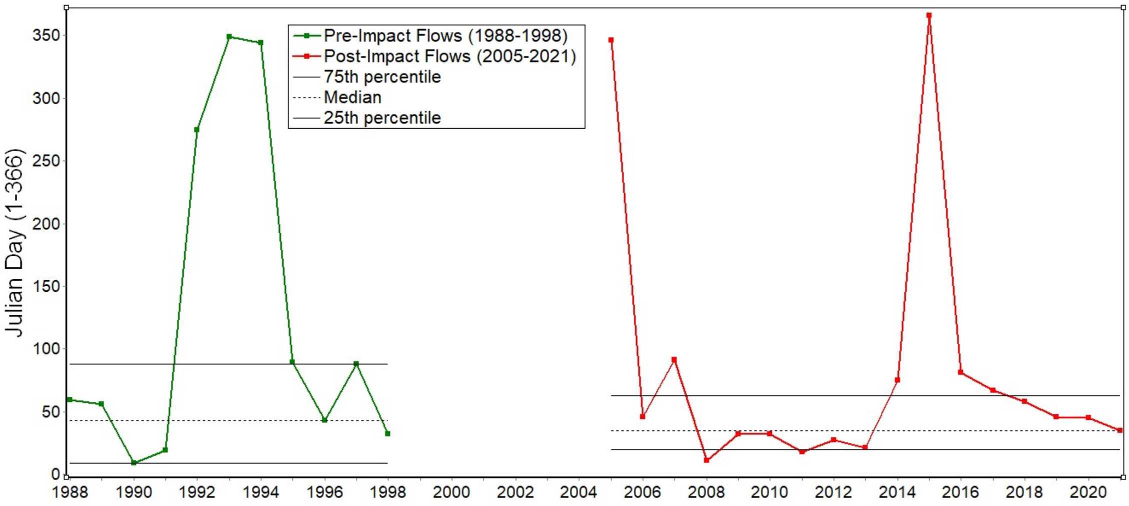

Figure B1: The pre- and post-impact on 1-day maximum date

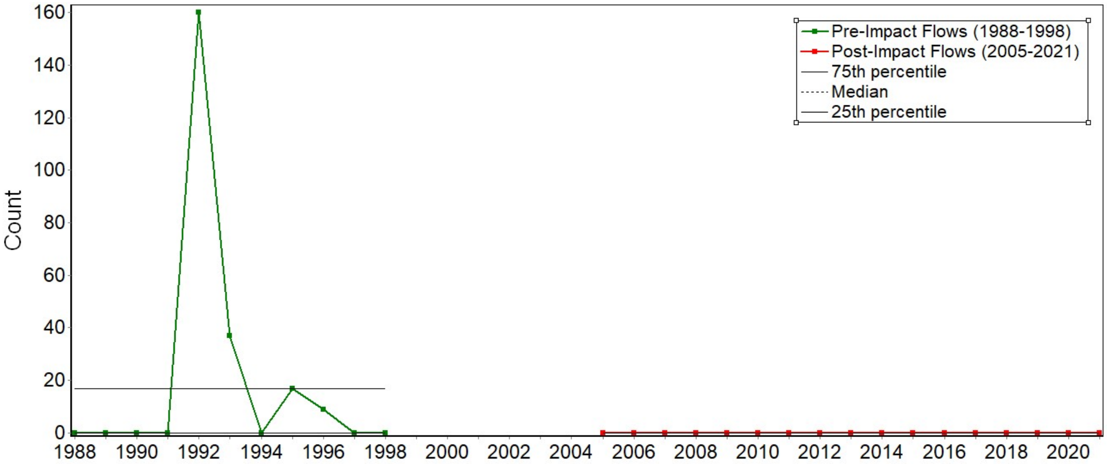

Figure B2: The pre- and post-impact on zero days

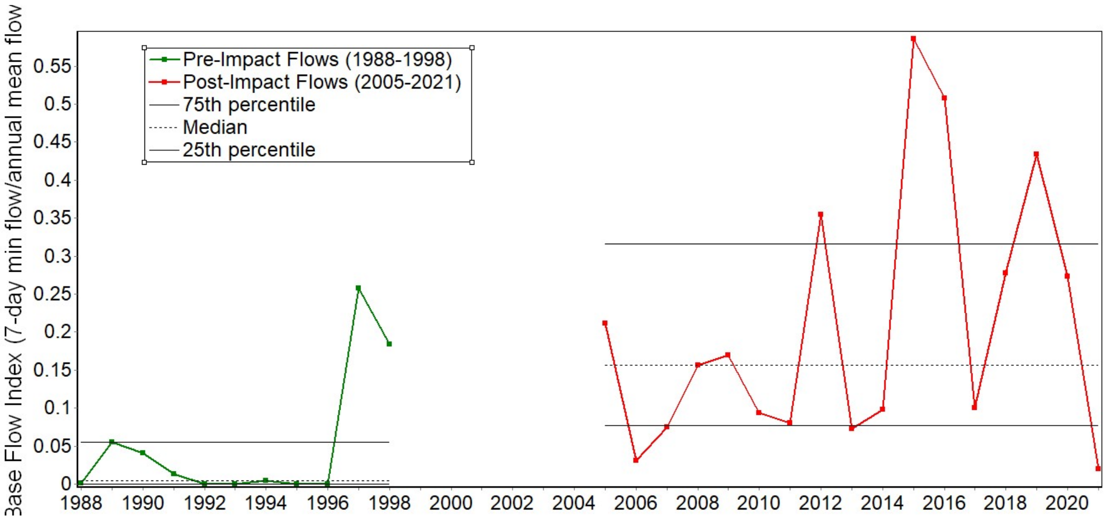

Figure B3: The pre- and post-impact on baseflow

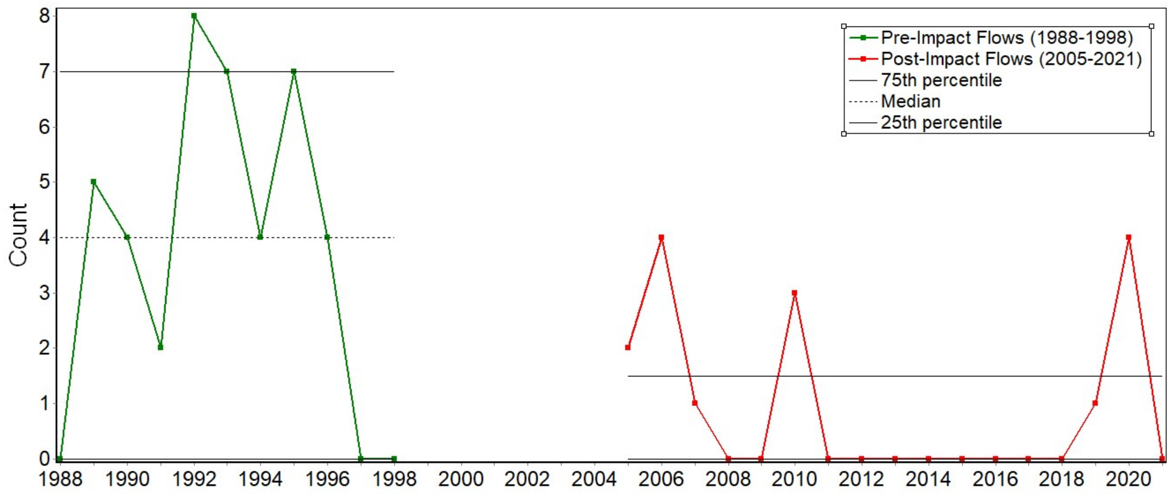

Figure B4: The pre- and post-impact on Low pulse count

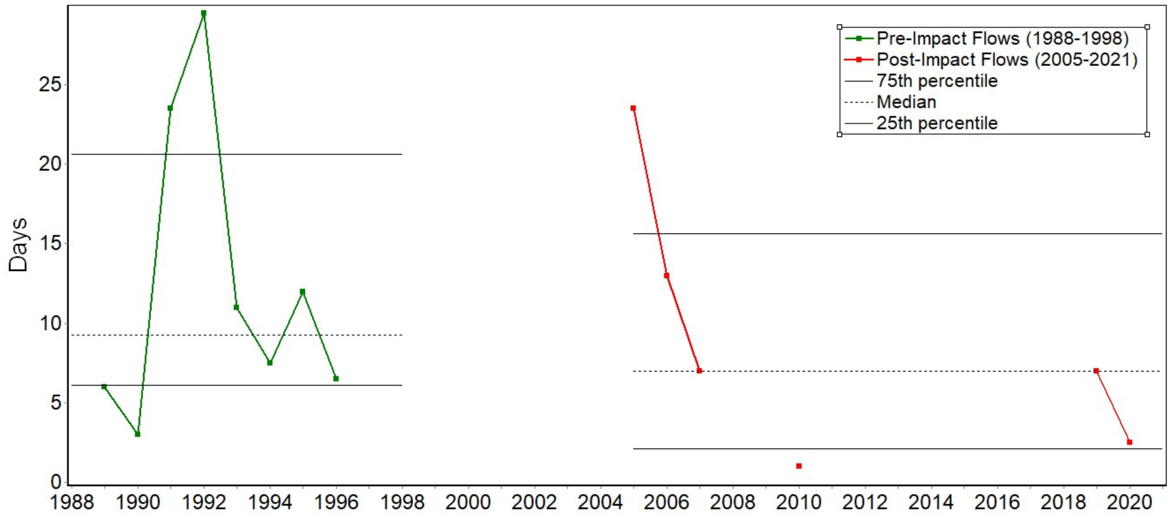

Figure B5: The pre- and post-impact on Low pulse duration

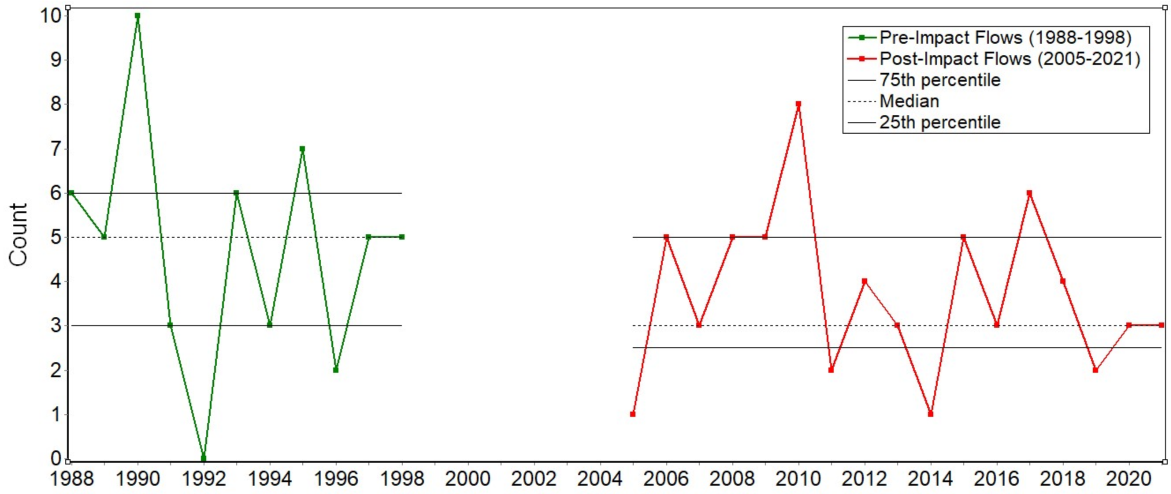

Figure B6: The pre- and post-impact on High pulse count

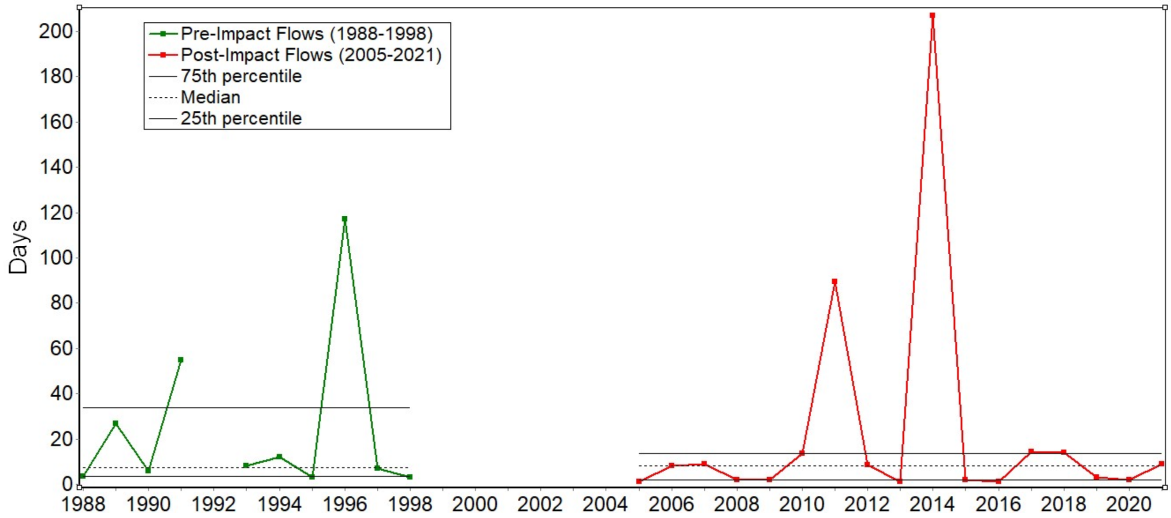

Figure B7: The pre- and post-impact on High pulse duration

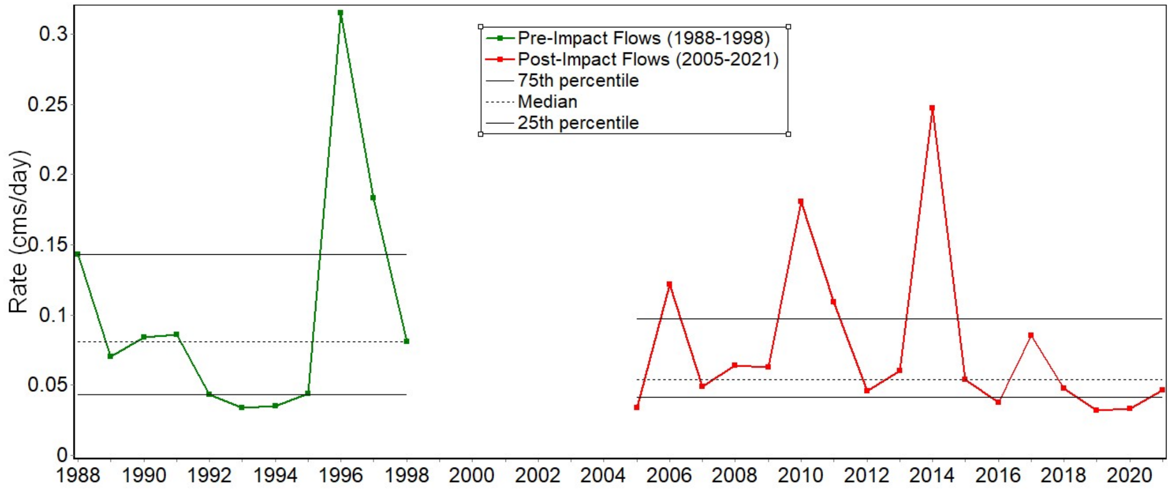

Figure B8: The pre- and post-impact on Rise rate

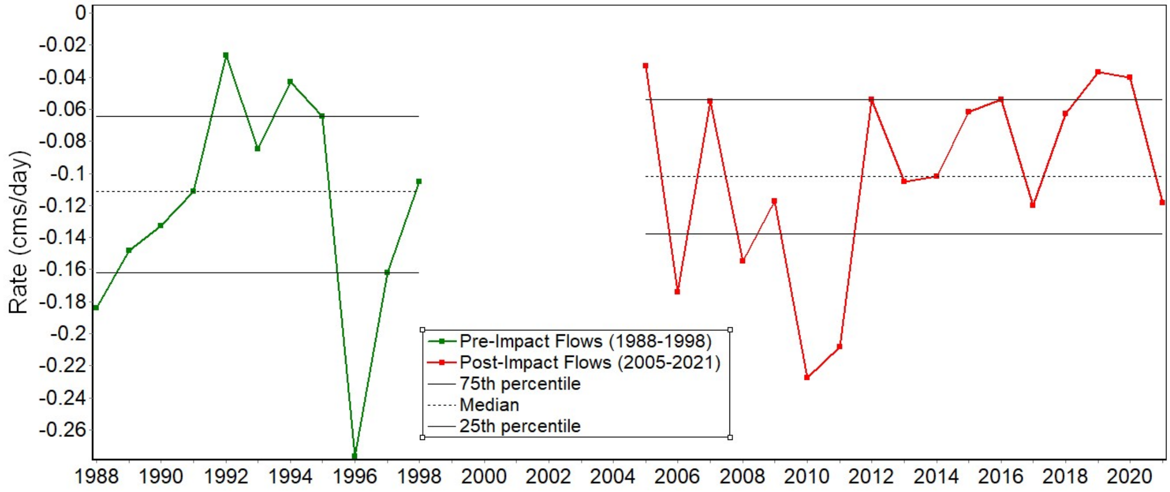

Figure B9: The pre- and post-impact on Fall rate

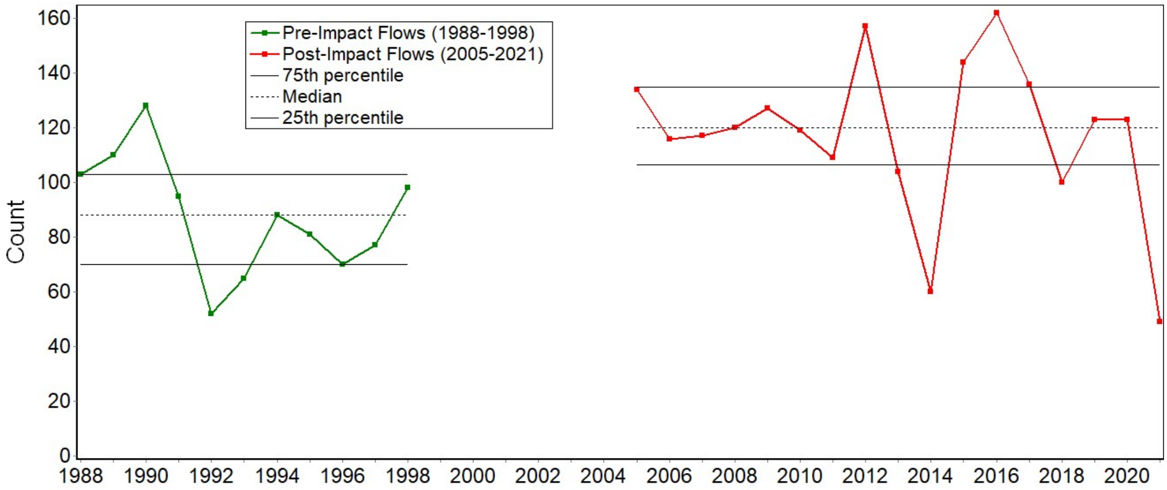

Figure B10: The pre- and post-impact on Revesals

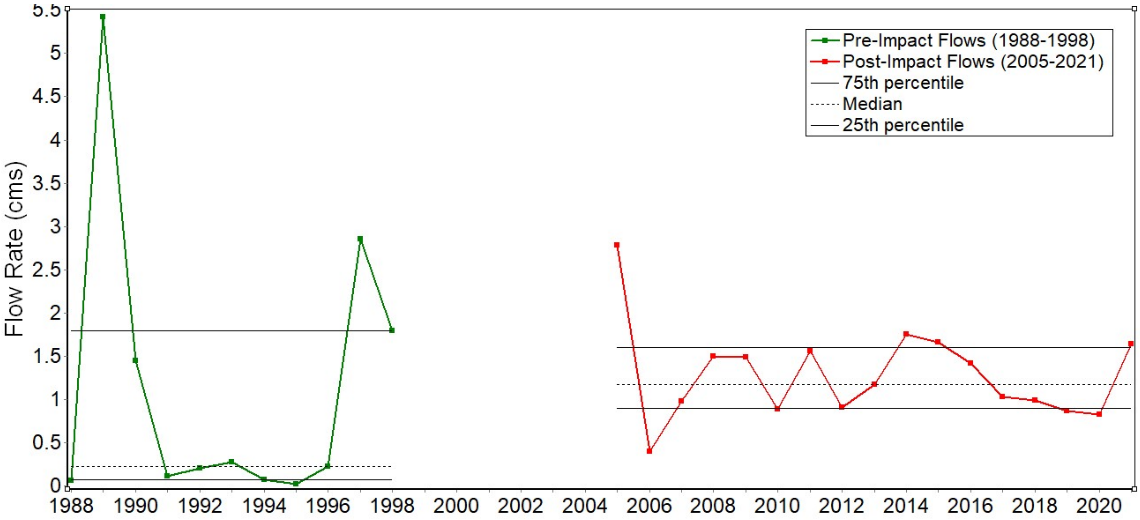

Figure B11: Example of changes in the hydrological regime, with 75th percentile and 25th percentile RVA targets downstream of Nandoni dam in the month of November.

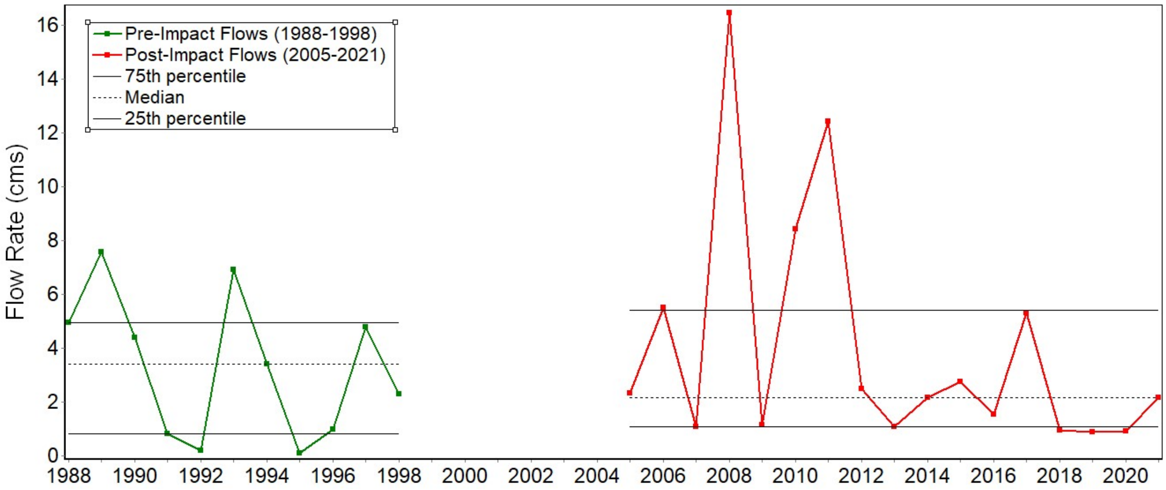

Figure B12: Example of changes in the hydrological regime, with 75th percentile and 25th percentile RVA targets downstream of Nandoni dam in the month of December.

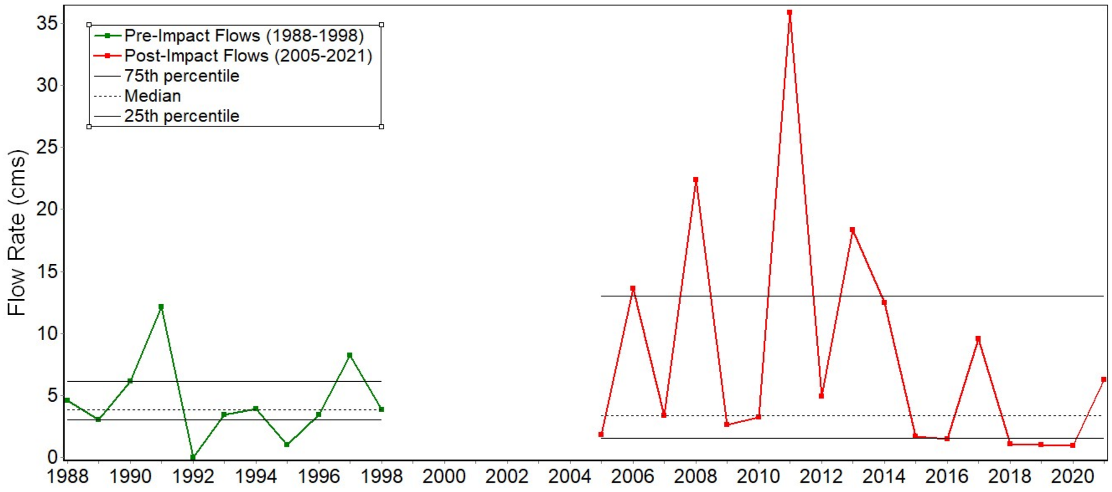

Figure B13: Example of changes in the hydrological regime, with 75th percentile and 25th percentile RVA targets downstream of Nandoni dam in the month of January

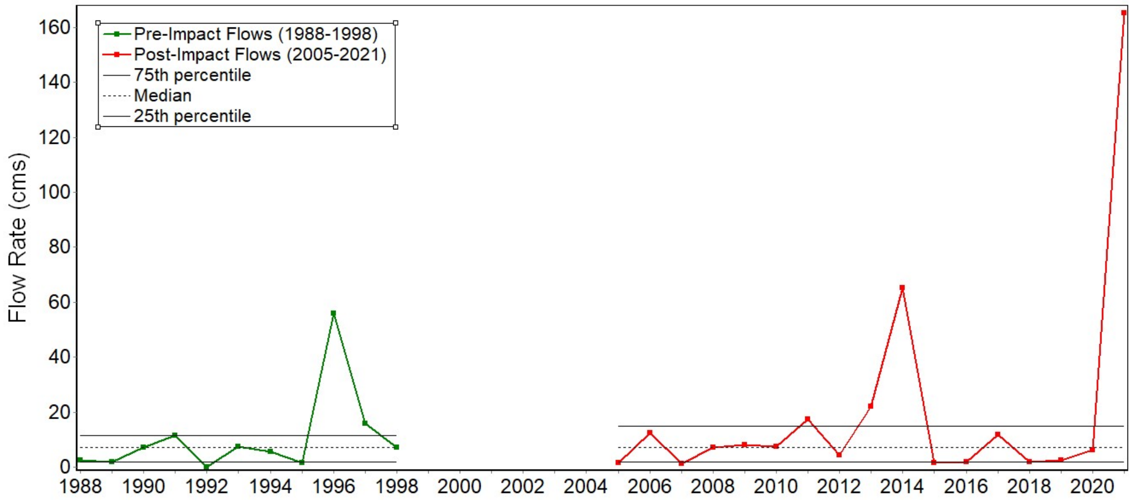

Figure B14: Example of changes in the hydrological regime, with 75th percentile and 25th percentile RVA targets downstream of Nandoni dam in the month of February.

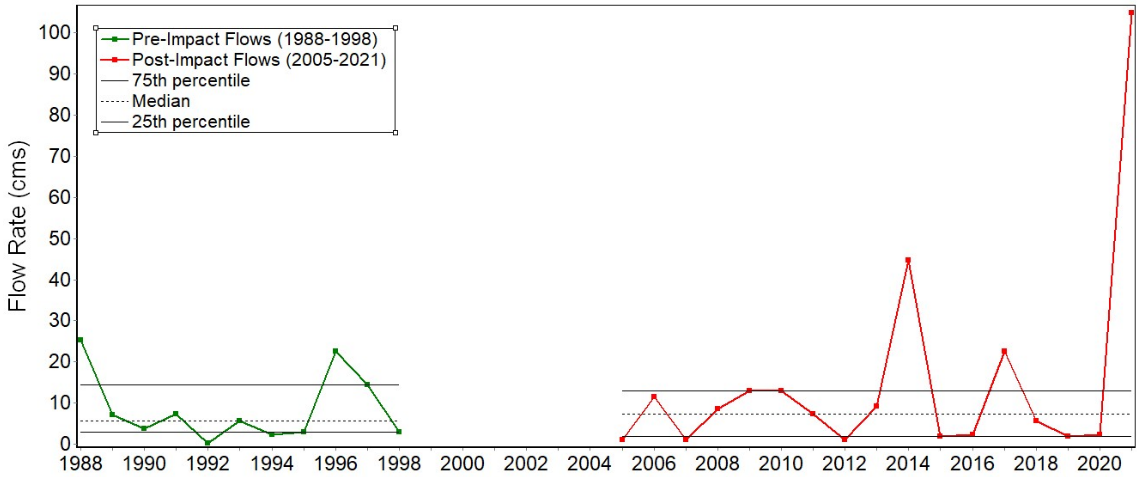

Figure B15: Example of changes in the hydrological regime, with 75th percentile and 25th percentile RVA targets downstream of Nandoni dam in the month of March.

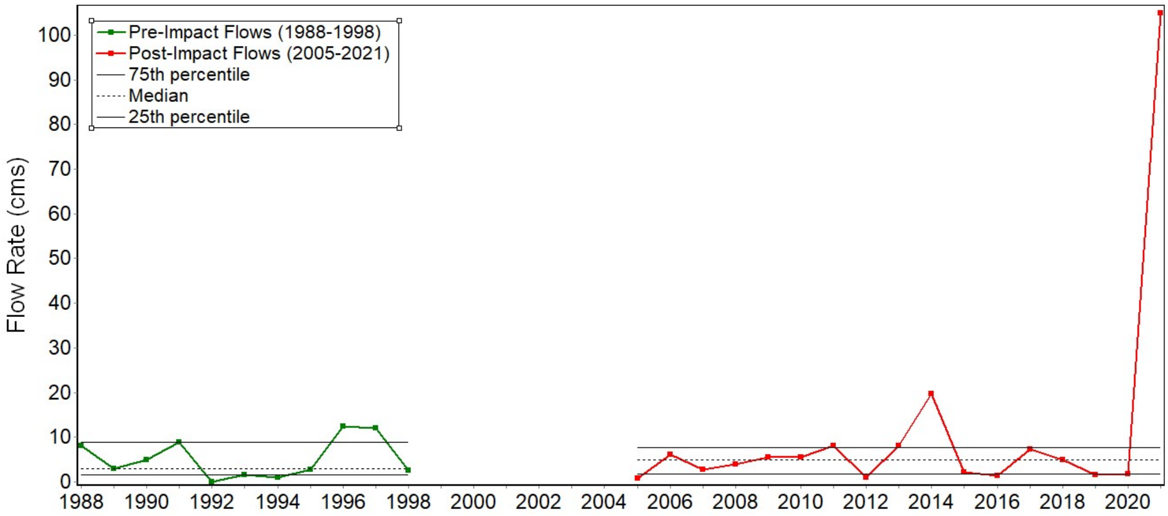

Figure B16: Example of changes in the hydrological regime, with 75th percentile and 25th percentile RVA targets downstream of Nandoni dam in the month of April.

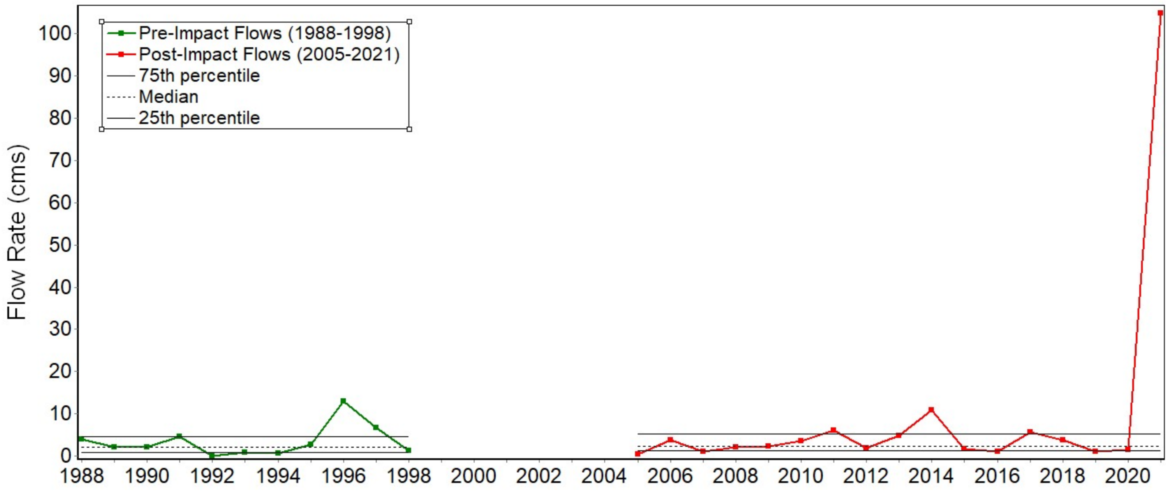

Figure B17: Example of changes in the hydrological regime, with 75th percentile and 25th percentile RVA targets downstream of Nandoni dam in the month of May.

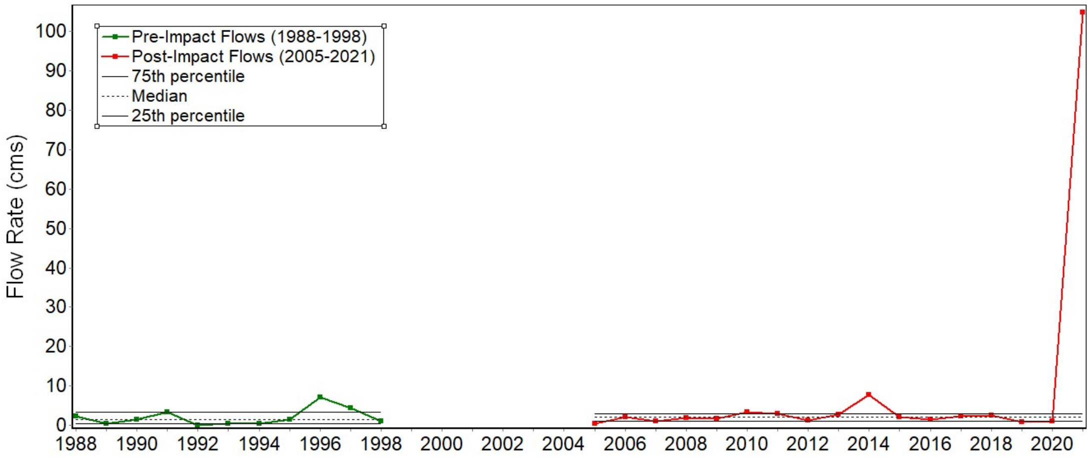

Figure B18: Example of changes in the hydrological regime, with 75th percentile and 25th percentile RVA targets downstream of Nandoni dam in the month of June.

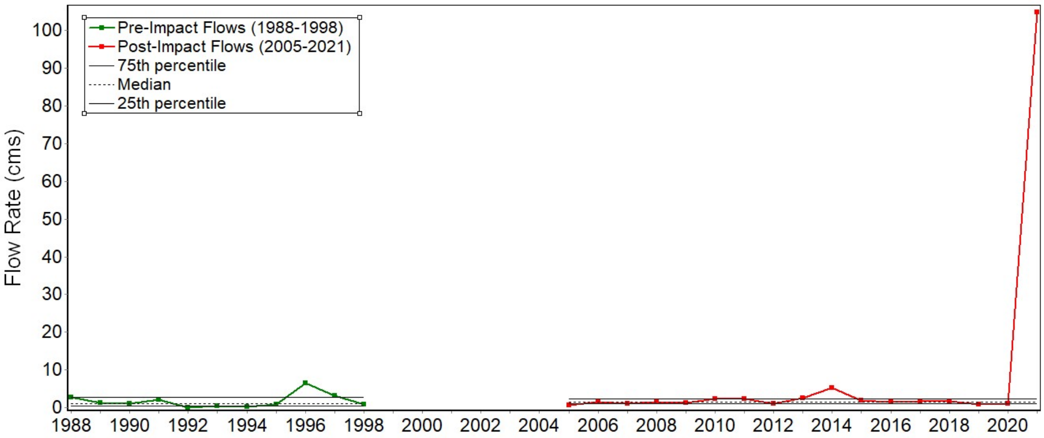

Figure B19: Example of changes in the hydrological regime, with 75th percentile and 25th percentile RVA targets downstream of Nandoni dam in the month of July.

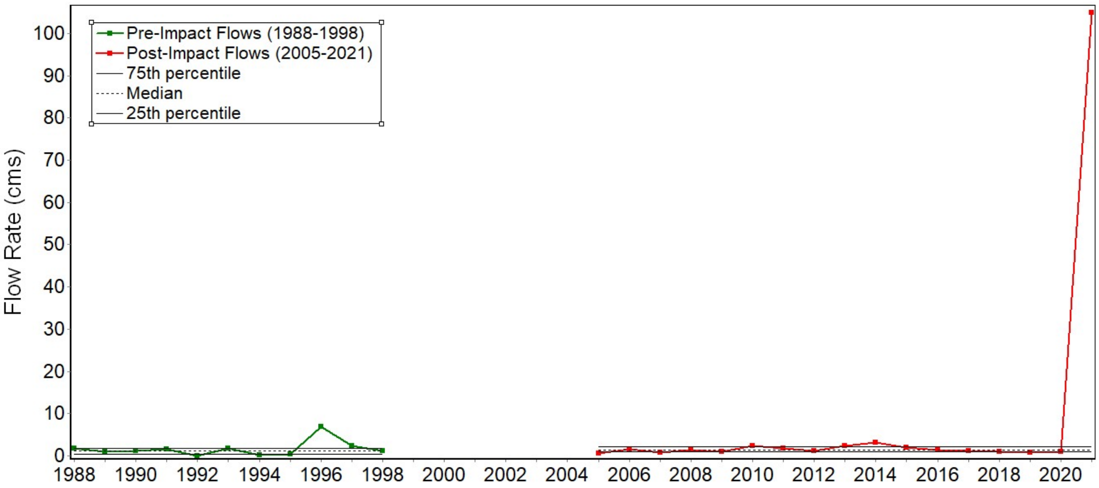

Figure B20: Example of changes in the hydrological regime, with 75th percentile and 25th percentile RVA targets downstream of Nandoni dam in the month of November August

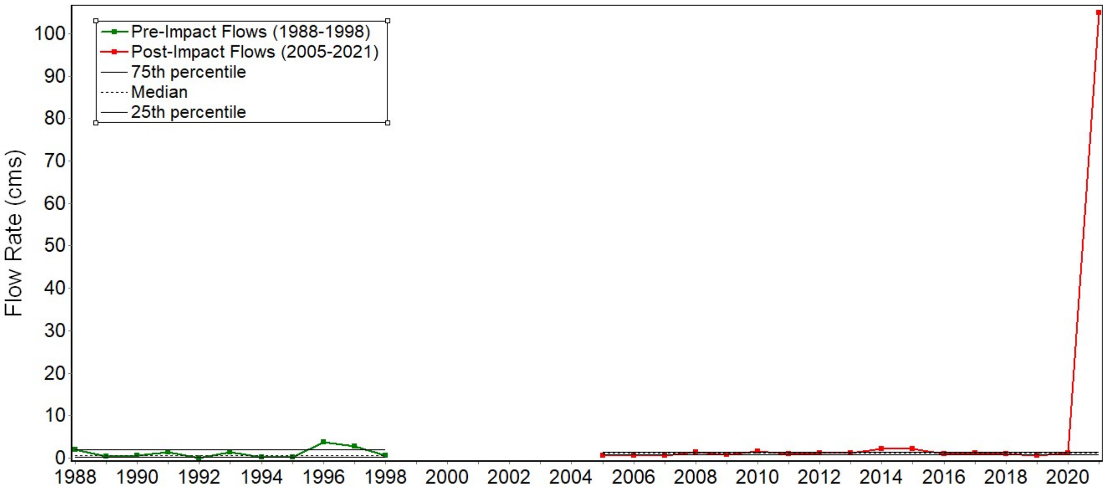

Figure B21: Example of changes in the hydrological regime, with 75th percentile and 25th percentile RVA targets downstream of Nandoni dam in the month of September.