DOKUZ EYLÜL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

DEVELOPMENT OF A NEW DOMESTIC/URBAN WASTEWATER MANAGEMENT ACTION PLAN FOR NORTH SUDAN: A PROPOSAL FOR 2023-2030

by

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September, 2024

İZMİR

DEVELOPMENT OF A NEW DOMESTIC/URBAN WASTEWATER MANAGEMENT ACTION PLAN FOR NORTH SUDAN: A PROPOSAL FOR 2023-2030

A Thesis Submitted to the
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by

Ayman Abdulrahman Mohamed OSMAN.

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İZMİR

M.Sc THESIS EXAMINATION RESULT FORM

We have read the thesis entitled **"DEVELOPMENT OF A NEW DOMESTIC/URBAN WASTEWATER MANAGEMENT ACTION PLAN FOR NORTH SUDAN: A PROPOSAL FOR 2023-2030"** completed by **AYMAN ABDULRAHMAN MOHAMED OSMAN** under supervision of **PROF. DR. AZİZE AYOL** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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DEVELOPMENT OF A NEW DOMESTIC/URBAN WASTEWATER MANAGEMENT ACTION PLAN FOR NORTH SUDAN: A PROPOSAL FOR 2023-2030

ABSTRACT

The scarcity of vital resources is increasingly a concern given the rise in global population particularly in water resources, underlining the ever-growing importance of effective water resource management as well as the need for wastewater treatment to keep up with increasing demand. Wastewater management plans cannot be done sustainably by Sudan and similar developing nations due to ongoing armed conflicts and economic difficulties. The situation has become so critical that inadequate management has led to outbreaks of waterborne diseases and environmental degradation in Sudan. Therefore, this research aims at proposing a comprehensive urban/domestic wastewater management action plan for Sudan for the period 2024-2030 which will give insights for policy makers and researchers in the field. The report concludes by establishing an action plan that considers legal and institutional frameworks, public awareness, population growth and economics, with primary and secondary data serving as references. The suggested action plan can provide guidance for future researches in Sudan or other states in similar context.

Keywords: Wastewater management, Sudan, action plan, sustainable development, public awareness

KUZEY SUDAN İÇİN YENİ EVSEL /KENTSEL ATIKSU YÖNETİMİ EYLEM PLANININ GELİŞTİRİLMESİ: 2023-2030 YILLARI İÇİN BİR ÖNERİ

ÖZ

Dünya genelinde nüfus artışıyla birlikte, özellikle su gibi temel kaynakların kıtlığı önemli bir sorun haline gelmektedir. Bu durum, su kaynaklarının etkin yönetiminin ve artan talepleri karşılamak için atık suyun arıtılmasının önemini vurgulamaktadır. Sudan gibi gelişmekte olan ülkeler, süregelen iç çatışmalar ve ekonomik zorluklar nedeniyle sürdürülebilir atık su yönetim planları oluşturma konusunda daha büyük zorluklarla karşı karşıyadır. Yetersiz atık su yönetiminin sonuçları, hastalık salgınlarına ve çevresel bozulmalara yol açarak giderek daha kritik hale gelmektedir. Bu çalışma, Sudan için 2024-2030 dönemi için bir evsel/kentsel atık su yönetimi eylem planı sunmayı amaçlamakta ve politika yapıcılara değerli bilgiler sağlamaktadır. Hem birincil hem de ikincil kaynaklardan elde edilen verilere dayanarak, araştırma, çerçeveler, kamu bilinci, nüfus artışı ve ekonomik faktörleri dikkate alan kapsamlı bir yönetim eylem planı ile sonuçlanmaktadır. Bu plan, Sudan ve benzer zorluklarla karşılaşan diğer ülkelerdeki gelecekteki çalışmalar için bir temel teşkil etmektedir.

Anahtar kelimeler: Atık su yönetimi, Sudan, eylem planı, sürdürülebilir kalkınma, kamu bilinci

.

CONTENTS

Page

M.Sc THESIS EXAMINATION RESULT FORM ii
ACKNOWLEDGMENT iii
ABSTRACT iv
ÖZ v
CONTENTS vi
LIST OF FIGURES xii
LIST OF TABLES xiii

CHAPTER ONE - INTRODUCTION 1

1.1 Overview 1
1.2 Purpose & Scope 2
1.3 Significance of the Research 2
1.4 Objectives of the Research 3

CHAPTER TWO - PREVIOUS STUDIES 4

2.1 General literature Review 4
2.1.1 Defining wastewater: 4
2.1.2 Classification of wastewater: 5
2.1.2.1 Classification of Wastewater According to its Source: 5
2.1.3 Contaminants in Wastewater 6
2.1.4 Impact of Urban Wastewater on Public Health, Environment, and Society 8
2.1.4.1 Public Health Impact: 8
2.1.4.2 Environmental Impact: 9
2.1.4.3 Societal Impact: 9
2.1.5 The Concept of Watewater Management 9
2.1.5.1 Components of wastewater Management 10

2.1.6 Challanges and Opportunities of Wastewater Management 11
2.1.7 A Review of Common Wastewater Collection Methods 12
2.1.7.1 Combined Sewer Systems (CSS) 13
2.1.7.2 Separate Sewer Systems (SSS) 13
2.1.7.3 Onsite Wastewater Treatment Systems (OWTS).................... 14
2.1.7.4 Vacuum Sewer Systems 14
2.1.7.5 Low-Pressure Sewer Systems 15
2.1.7.6 Condominium and Cluster Systems 15
2.1.8 Treatment Processes 15
2.1.8.1 Physical Processes:.. 16
2.1.8.2 Chemical Processes: 16
2.1.8.3 Biological Processes:... 17
2.1.9 Reuse and Disposal Methods of Wastewater................................ 17
2.1.10 Wastewater Management Infrastructure: 18
2.1.10.1 Importance of Proper Infrastructure 19
2.1.11 Economic Aspects of Wastewater Management: Costs and Benefits 20
2.1.11.1 Costs of Wastewater Management 20
2.1.11.2 Benefits of Wastewater Management 21
2.1.12 Sustainable Practices in Wastewater Management........................ 21
2.2 Contextualized Review for Sudan 22
2.2.1 Introduction to Sudan 22
2.2.2 Regions and States of Sudan... 22
2.2.3 Major Sudanese Cities 24
2.2.4 Population and Population Growth Trends in Sudan 24
2.2.5 Sudan Environmental Policy and Frameworks.............................. 25
2.2.5.1 Sudan Environmental Policy and Developments 27
2.2.5.2 Regulatory Framework for Water Management 29
2.2.5.3 Institutional Framework Water Water Management............... 30

2.2.6 Sudan’s Water Resources 32
2.2.6.1 Characteristics of Nile System Tributaries............................. 34
2.2.6.2 Seasonal Rainfall-Dependent Non-Nilotic Streams................ 35
2.2.6.3 Wetlands.. 36
2.2.6.4 Lakes 37
2.2.6.5 Dams and Artificial Lakes.. 37
2.2.6.6 Groundwater Resources 37
2.2.6.7 Non-Conventional Water Resources....................................... 38
2.2.7 Surface Water Quality 38
2.2.8 Ground Water Quality 40
2.2.9 Treatments for Raw Water in Sudan 46
2.2.10 Total Water Availability 48
2.2.11 Water Availability Rates Versus Existing Needs and Consumption Patterns in Residential and Industrial Sectors 49
2.2.11.1 Water Sources Usage By Sector... 50
2.2.11.2 Water Needs for Irrigated Agriculture 51
2.2.11.3 Current Water Needs for Hydroelectric Power 52
2.2.11.4 Water Needs for Domestic and Industrial Uses 52
2.2.12 Efficiency of Current Water Usage 52
2.2.13 Data on Generated Household Wastewater in Sudan 54
2.2.14 Existing Wastewater Infrastructure in Sudan and Current Situation Analysis 55
2.2.14.1 Sanitation Systems Used in Sudan 56
2.2.14.2 Khartoum Sewage Project.. 57
2.2.14.3 Khartoum North Sewage Project: 59
2.2.14.4 Current Construction Endeavors 61

CHAPTER THREE - METHODOLOGY AND DATA ANALYSIS 64

3.1 Materials and Methodology 64

CHAPTER FOUR - RESULTS AND CONCLUSIONS....................................... 67

4.1 Evaluation of the Water Quality of Sudan's Water Resources 67
4.1.1 Water Quality of Surface Water Bodies 67
4.1.1.1 Seasonal and Geographical Variations................................... 67
4.1.1.2 Parameters for Assessing Water Quality................................ 68
4.1.2 Groundwater Quality 69
4.1.2.1 Nubian Sandstone Aquifer System 69
4.1.2.2 Water Quality Parameters in Sampled Areas.......................... 69
4.1.3 Non-Conventional Water Sources 70
4.1.4 Surface Water Treatment and Management 70
4.1.4.1 Results of Analysis and Notable Discoveries 70
4.2.1 Present Water Availability.. 71
4.2.2 Analysis of Water Availability and Consumption Patterns 72
4.2.2.1 Water Usage by Sector... 73
4.2.2.2 Water Requirements for Irrigated Agriculture 73
4.2.3 Enhancing Water Usage Efficiency and Overcoming Challenges 74
4.2.4 Significant Discoveries and Valuable Insights 75
4.3 Assessment of Sudan's Wastewater Generation and Treatment Capability 76
4.3.1 Present Volume of Wastewater Generation.................................. 76
4.3.1.1 Production of Wastewater from Households 76
4.3.1.2 Manufacturing and Farm Wastewater Generation 77
4.3.2 Current Wastewater Treatment Plants and Their Capabilities 77
4.3.2.1 Khartoum Sewage Initiative... 77
4.3.2.2 Project for Sewage Treatment in North Khartoum (Bahri)..... 78
4.3.2.3 Capacity for Treatment at Present.. 78

4.3.3 Limitations and Challenges Related to Wastewater Data.............. 78
4.3.4 Discoveries and Noticings 79
4.4 Population Growth Calculation and Estimation of Future Wastewater Generation 80
4.4.1 Estimation of Population Growth 80
4.4.2 Estimated Wastewater Production (2024-2030) 81
4.4.3 Conclusion of The Calculated Growth Rates 81
4.5 Invistigating Applicable Wastewater Management Systems for Sudan 82
4.5.1 Summary of Commonly Employed Wastewater Disposal Systems.. 82
4.5.1.1 Cost Analysisi of Possible Wastewater Treatment and Disposal Systems... 83
4.5.1.2 Selection of Suitable Wastewater Mangement System for Sudan 85
4.5.2 Cost Estimation and Implementation Timeline for Decentralized Wastewater Management System in Sudan (2024-2030).............. 86
4.5.2.1 Population Projections (2024-2030): 86
4.5.2.2 Cost Calculation for Treatment and Disposal Systems........... 86
4.5.3 Financing Method for the Proposed Decentralized Wastewater Management System in Sudan (2024-2030).................................. 88
4.5.4 Regulatory and Institutional Framework Analysis for Water Management in Sudan 89
4.5.4.1 Observations.. 90
4.6 Conclusions.. 90
4.6.1 Proposed Urban/Domestic Wastewater Management Action Plan for Sudan (2024-2030) 90
4.6.1.1 Overview 90
4.6.1.2 System Selection and Cost 90
4.6.1.3 Financial Strategy.. 91

4.6.1.4 Responsible Authorities 91
4.6.1.5 Framework Suggestions 91
4.6.1.6 Awareness and Enforcement Considerations 92
4.6.1.7 Timeline for Implementation 92
4.6.2 Action Plan Summary 93

REFERENCES 94

LIST OF FIGURES

Page

Figure 2.1. Classification of Wastewater (Mamta Tomar (1999) Quality Assessment of Water and Wastewater CRC Press, New York)....................................6
Figure 2.2 Republic of the Sudan..22
Figure 2.3 Sudanese states 24
Figure 2.4. Anticipated Population Growth and Annual Growth Rates In Sudan 1950-2030..25
Figure 2.5 Sudan's water basins (source: Fanack Water)...33

LIST OF TABLES

Page

Table 2.1 Summary of water pollutants, their sources and impact (Matma T., 2019). 7
Table 2.2 Main policies related to water and environment in Sudan 29
Table 2.2 (Continued) 30
Table 2.3 Break-down of national authorities over Sudan's natural resources.......... 31
Table 2.4 Sudan environmental policies and responsible authorities 31
Table 2.4 (Continued) 32
Table 2.5 Sudan water basins area coverage.. 34
Table 2.6 Flow characteristics of nile system tributaries.. 34
Table 2.8 Dam capacities 37
Table 2.9 Groundwater sources in Sudan 38
Table 2.10 Chemical analysis report for the main Nile, Blue Nile and White Nile (Sudan Council For Environmental Affairs, 2014)................................. 40
Table 2.11 Physical properties of soba ground water sample................................... 41
Table 2.12 Physical Properties Ground Water Samples Taken from a Site in Kalakla area 41
Table 2.13 Supply Boreholes in areas using septic tanks services (Khartoum district) 42
Table 2.14 Supply boreholes in areas using combination services (pit latrine+ septic tank) (KhartoumDistrict)... 44
Table 2.15. Water treatment plants in khartoum and employed treatment processes 47
Table 2.16. Sudan Water Availability (FAO) 48
Table 2.17 Sudan water availability (SCEA)... 49
Table 2.18: Sudan Water Usage by water Source and Sector................................... 51
Table 2.19.Summary of water needs by sector 53
Table 2.20: Part A: estimation of total generated household wastewater in Sudan, 2020 (United Nations, 2020)... 54
Table 2.21 Part B: estimation of generated household wastewater by sanitation facility type in Sudan (UN, 2020) 54
Table 2.22 Part C: household wastewater management chain (Sudan, 2020) 55

Table 3.1 Overview of cost of disposal methods 83
Table 3.2 Effluent characteristics of Ali Abdelfattah and OIU treated wastewater... 84
Table 3.3 WWT Cost of Ali Abdelfattah and OIU wastewater systems 85
Table 3.4 Summary fort he proposed Domestic Wastewater Management Action Plan 2024-2030 93

CHAPTER ONE
INTRODUCTION

1.1 Overview

Water is the most essential natural resource for supporting life and ecosystems. The continuous growth of the global population and increasing urbanization makes the efficient control and utilization of water resources and wastewater more and more vital (Silva, 2023). Efficiently managing domestic and urban wastewater is crucial for environmental management, public health, and sustainable development in densely populated areas. This involves the process of collecting, treating, and safely disposing or reusing water that has been contaminated by human activities (Kesari et al., 2021).

Urban settings pose special challenges and opportunities regarding wastewater management, and this effect is especially significant in the context of countries like Sudan, where rapid city growth and demographic changes have created unprecedented pressure on an already struggling infrastructure insufficient to meet the needs for sanitary services and water supplies (World Bank, 2021). Insufficient management of wastewater impacts the well-being of society by posing a threat to public health and the long-term viability of urban development.

Negative effects of inadequate urban wastewater mangemnt extend beyond health problems by leading to important economic consequences such as increased healthcare costs, reduced agricultural output and damage to local ecosystems. On the other hand, efficient wastewater management has the potential to create opportunities in terms of resource recovery and energy generation which can have a great role in economic growth.

Major challenges in conducting research and acquiring vital data on the matter of wastewater in Sudan were caused by prolonged political turmoil coupled with minimal investment in the field. This resulted in a limitation in the Sudanese authorities' ability to formulate informed policies and make careful decisions regarding water resource management and wastewater treatment and reuse. The situation is worsened by a severe deficiency in adequate infrastructure in Sudan.

Realizing the seriousness of these difficulties, global organizations in collaboration with local government agencies have made efforts to address the knowledge gaps regarding Sudan's complex water issues. This collaboration have played an important role in providing field data necessary to understand the nature of water and wastewater management in Sudan.

The primary goal of this study is to formulate a practical strategy for managing urban/domestic wastewater in Sudan providing comprehensive policy recommendation based on thorough analysis of the present situation, global strategies and considerations to the local context. The primary objectives are to reduce environmental hazards, protect public health, and maximize the efficient use of resources.

1.2 Purpose & Scope

This study is contextualized to the specific requirements and conditions of urban settings in North Sudan (officially the Republic of The Sudan). To encompass the essential aspects of wastewater management the study approaches the topic from various perspectives, including wastewater treatment methods, institutional and regulatory frameworks, economic factors, stakeholder involvement and community awareness. The proposed action plan is built on a synthesis of a wide range of factors to ensure providing a practical solutions that can fit the urban environment and societal setting of Sudan.

1.3 Significance of the Research

The proper handling and management of domestic/urban wastewater in Sudan is of utmost importance with the continuous urbanization and projected population growth and demographic changes in the near future. The study seeks to enhance ongoing efforts in wastewater management by offering a methodological assessment accompanied by a tailored action plan to provide guidance to policymakers, environmental agencies, and urban planners in Sudan to enable them to formulate informed policies regarding wastewater management and to address issues caused by rapid urbanization providing plans for sustainable development that enhance the quality of life in cities.

1.4 Objectives of the Research

The primary objectives of this research are as follows:

- Assess the current wastewater management practices by evaluating the existing infrastructure and management practices in Sudan. and identifying key challenges in the current system.
- Analyze environmental and public health impacts through reviewing the environmental consequences of inadequate wastewater management.and investigating the public health implications affecting urban populations.
- Explore technological solutions suitable for urban settings in Sudan and identify cost-effective and efficient technologies that can be implemented locally.
- Develop regulatory framework proposals that support sustainable wastewater management. and ensure compliance with international standards and local needs.
- Conduct an economic assessment of proposed wastewater management solutions.and identifying funding mechanisms to support implementation.
- Study stakeholder engagement and develop strategies for stakeholder collaboration.
- Increase community awareness and ınvolvement
- Formulate a comprehensive action plan applicable in the urban landscape of Sudan integrating international best practice with locally relevant solutions.

CHAPTER TWO
PREVIOUS STUDIES

The literature review for this study will consist of two separate sections. The first section will aim to develop a foundational understanding of wastewater management and will contain an overview of key definitions, categorizations and managerial elements related to the scope of wastewater and its management.

The second section of the literature will contain review of data and studies contextualized to Sudan, drawing on existing literature on Sudan’s water resources, environmental policy, water quality data, estimated water consumption and wastewater generation across various sectors. This part of the review aims to assess the local practices, policies and technologies currently in place in Sudan while also identifying knowledge gaps and areas that might be improved within the Sudanese wastewater management system.

The two sections will collectively offer a comprehensive perspective on wastewater management by integrating theoretical knowledge with real-life implementations that could tackle the specific obstacles encountered by Sudan in wastewater management.

2.1 General literature Review

2.1.1 Defining wastewater:

Wastewater can be defined as water that has become unsuitable for its original intended use as a result of human activities. It may contain many different kinds of pollutants, including organic and inorganic substances, diseases and chemicals. These contaminants can have negative impacts both environmentally and on human and animal health if not properly controlled and handled.

Wastewater, as defined in the ***United Nations World Water Development Report of 2017-Wastewater: The Untapped Resource***, refers to water that has been negatively impacted in terms of quality due to human involvement. Sewage consists of liquid waste that is released by households, businesses, factories, and farms. It can contain various types of pollutants and different levels of concentration (United Nations Educational, Scientific and Cultural Organization, 2017).

2.1.2 Classification of wastewater:

It is possible to catagorize wastewater into distinct groups based on many criteria, including the source, content, and treatment needs. Since this research focuses on urban/domestic wastewater, it would be advantageous to begin by examining the categorizations of wastewater based on its origin.

2.1.2.1 Classification of Wastewater According to its Source:

Domestic wastewater is derived from residential dwellings and encompasses both sewage and graywater. Graywater primarily pertains to wastewater generated from bathing, sinks, and laundry activities. Alongside flush toilets, it constitutes almost 65% of the wastewater generated in households. (Tilley et al., 2014). Urban wastewater is what the European Union in Council Directive 91/271/EEC defines as domestic wastewater or a combination of domestic wastewater, industrial wastewater and rain water.

Industrial wastewater is generated by industrial processes and may contain various pollutants. The classification of industrial wastewater can be further refined based on the specific industry type (Shah, 2022)

Agricultural wastewater comes from farming activities, including irrigation runoff and animal husbandry. It may contain fertilizers, pesticides, and organic matter (Nagendran, 2011).

Municipal wastewater refers to wastewater generated by a municipality, including residential, commercial, and institutional sources. It often undergoes centralized treatment before disposal or reuse (Zaibel et al., 2022).

Stormwater is generated from rainwater and surface runoff. It may carry pollutants from streets, rooftops, and urban areas (Aryal et al., 2010)

Infiltration/inflow (I/I) refers to excess water entering the sewer system from groundwater infiltration or surface water inflow. This excess water can overwhelm wastewater treatment plants (Robinson & Sandink, 2021).

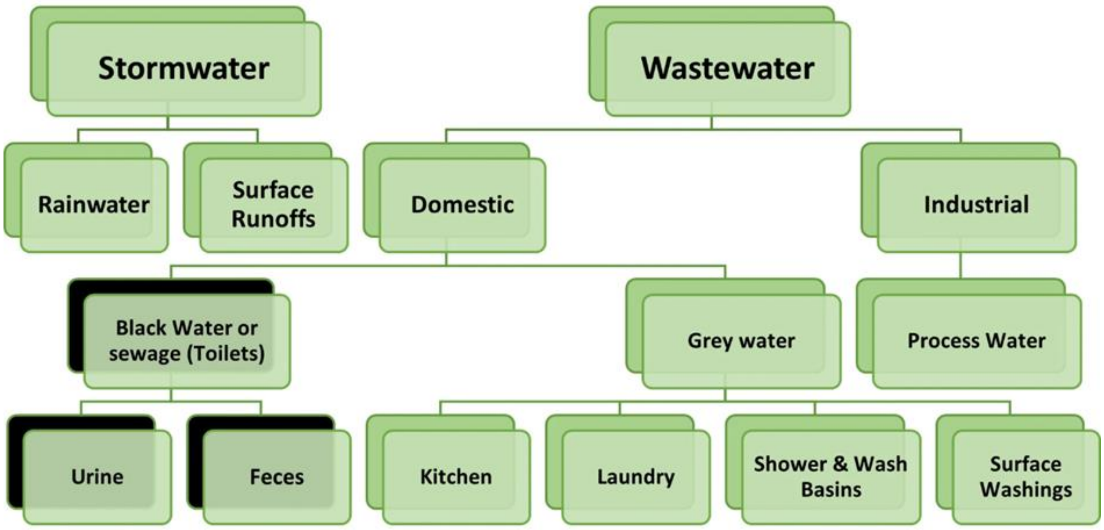

Figure 2.1. Classification of Wastewater (Mamta Tomar (1999) Quality Assessment of Water and Wastewater CRC Press, New York)

2.1.3 **Contaminants in Wastewater**

Surface water undergoes a natural self-purification process facilitated by microorganisms present in the water, resulting in its cleansing. These little organisms utilize the oxygen present in the water to decompose contaminants. Nevertheless, the introduction of diverse pollutants into the water by human activities, such as inorganic, organic, and biological chemicals, hampers the inherent purification mechanism.

Pollutants in water from any source can typically be categorized into three types, physical pollutants, chemical pollutants (organic and inorganic) and biological pollutants.

Table 2.1 summarizes the main pollutants released into natural water bodies and their effects on the environment, health, and aquatic life.

Table 2.1 Summary of water pollutants, their sources and impact (Matma T., 2019)

Pollutants	Source	Impact
Physical		
Suspended Solids	Public water supply, domestic & industrial wastes, soil erosion, infiltration/inflow	Can cause anaerobiosis due to sludge deposition at water beds & result in the generation of malodorous gases Hamper the contact between disinfectants & pathogens to kill them
Dissolved Solids	Public water supply, domestic & industrial wastes, soil erosion, infiltration/inflow	Impart hardness to water & Restrict use of treated effluent for irrigation
Chemical - Inorganic		
Nutrients (N & P)	Domestic, industrial & agriculture wastes, natural runoff	May cause eutrophication resulting in the excessive growth of algae when discharged to the sea create adverse environment for fishes if discharged to land may contaminate ground water also
Trace metals	Industrial wastes from mining, petroleum, metal industries	Mostly toxic in nature thus disturbs the ecological balance in activated sludge process Restrict the reuse of treated effluent
Gaseous inorganics	Domestic & industrial wastes	Hydrogen sulfide & ammonia Toxic and health hazardous
Chemical - Organic		
Biodegradable organics	Domestic & industrial wastes	Cause biological degradation at the expense of dissolved oxygen (DO) May deplete DO in receiving water & cause septic conditions

Table 2.1 (Continued)

Pollutants	Source	Impact
Floating materials such as grease & oil	Domestic & industrial wastes especially from dairy, food processing & slaughterhouses	Interfere with treatment process & create toxic condition for biological life May cause floating sludge/scum
	Biohazards	
Pathogenic bacteria & viruses	Domestic & hospital wastes and agriculture runoff	Transmit infectious diseases such as typhoid, polio, amoebic dysentery, paratyphoid etc. and May lead to epidemic

2.1.4 Impact of Urban Wastewater on Public Health, Environment, and Society

Insufficient management and treatment of urban wastewater can cause significant negative impacts on human health, environment and society at large. It is essential to adopt strategies that consider public health, environmental conservation and societal well-being to effectively deal with the multifaceted effects of domestic/urban wastewater. Minimizing these effects will require implementing comprehensive solutions for wastewater management that promote sustainable urban growth.

2.1.4.1 Public Health Impact:

Urban wastewater may contain pathogens including bacteria, viruses and parasites, which have the potential to cause waterborne diseases outbreaks such as cholera, dysentery and hepatitis that present a major risk to public health. (Olaolu, 2014)

Wastewater can act as breeding sites for disease vectors like mosquitoes which heightens the rates of contracting vector-borne infections such as malaria and dengue fever. (Barbazan et al., 1998)

Chemical pollutants like heavy metals, pesticides and pharmaceuticals have the potential to penetrate the food chain and affect human health. (Schriks et al., 2010; Ternes et al., 2002).

2.1.4.2 Environmental Impact:

When there is an excessive amount of nutrients such as phosphorus and nitrogen in wastewater it can cause eutrophication leading to hazardous algal blooms and oxygen depletion which in turn lead to reduction in aquatic life (Paerl & Otten, 2013).

Chemically contaminated water can harm aquatic species and reduce biodiversity in rivers, lakes, and coastal areas (Dudgeon et al., 2006).

2.1.4.3 Societal Impact:

Untreated wastewater can affect economy by leading to significant costs in healthcare expenses, decreased tourism dıue to reputation and harm to fishing and agriculture businesses. (Sien et al., 2001)

Poor management of wastewater usually have a greater impact on disadvantaged areas making socioeconomic inequalities and access to clean water and sanitation services worse (UNESCO World Water Assessment Programme & UNESCO. Director-General, 2016).

Inappropriate disposal of wastewater can result in social behavioral problems and the marginalization of affected communities in regions lacking adequate sanitation infrastructure (Owusu, 2010).

2.1.5 The Concept of Watewater Management

Effective management of wastewater is a crucial part of environmental governance with important consequences in maintaining ecological balance, protecting public health and promoting economic growth. It involves a thorough strategy that includes gathering, processing, and properly disposing or reusing water contaminated by human activities (UNESCO, 2017).

2.1.5.1 Components of wastewater Management

Collection of wastewater from multiple sources, including residential areas, industrial facilities, and commercial establishments, is the primary element of wastewater management. This proper collection is essential to reduce the risk of adverse environmental or public health impacts. Insufficient hydraulic capacity in collection systems can lead to sewer overflows, which can damage private property or discharge untreated wastewater into receiving waters (Feeney et al., 2009). Collection systems vary in complexity, ranging from simple gravity sewers to more advanced systems that include pumping stations (Zhao et al., 2016). Urban areas typically have sewer networks specifically designed to transport wastewater to treatment facilities (Cheremisinoff, 2002).

Wastewater treatment is the process whereby collected wastewater undergoes impurity and pollutant elimination. Wastewater must be treated after collection to meet specified standards prior to its release into the environment or reuse for other purposes. Primary treatment, secondary treatment, and tertiary treatment stages are involved in wastewater treatment processes. Physical methods like screening and sedimentation are used in primary treatment to eliminate solids and some organic matter. The second stage involves further organic matter breakdown in activated sludge. Advanced technologies such as filtration and sterilization are employed under tertiary treatments to get desired quality in situations where necessary (Baresel et al., 2016).

After properly treating wastewater, the subsequent part focuses on its safe disposal or beneficial use. Ways of disposing off include treated wastewater discharges into receiving bodies such as rivers and oceans. However, for such discharges to be undertaken there are often stringent regulations imposed to protect aquatic life and human health. In addition, it can be used again as a non-potable water source for instance irrigation and industrial usages in which case it would involve treatment that is advanced enough to make it potable (Baresel et al., 2016)

Wastewater management might involve otheromponents as dictated by the local needs and environmental factors apart from the major components stated above. these include management of sludge**,** as **t**he process of treating wastewater generates sludge, which should be disposed of, handled, and treated properly (Mara, 1998).

In some cases stormwater runoff is incorporated into wastewater systems and this necessitates special treatment considerations.

Specialized treatment may be required for nitrogen and phosphorus removal in areas that are experiencing nutrient pollution (Nie et al., 2018).Some new trends aim to obtain useful resources from wastewater such as energy production from biogas or nutrient-rich biosolids (Wang et al., 2023)

2.1.6 Challanges and Opportunities of Wastewater Management

For the conservation of environment and protection and public health, it is important to manage wastewater efficiently. However, this is hindered by many factors including technological limitations, inadequate infrastructure, financial constraints and legal complications among others. These challenges might slow down or even completely stop the progress towards effective wastewater systems (Morris et al., 2021) leading to pollution of the environment thus endangering lives of people. In many regions, problems related to proper sewage system are worsened by out-dated structures, insufficient funding and weak enforcement of regulations (Corcoran et al., 2010).

On another note, there is a great opportunity for better efficiency in treatment and disposal methods through technological advancements, innovative management approaches as well as policy changes. Some modern solutions can solve past dilemmas brought about by outdated technology like advanced biological treatments or smart monitoring technologies (Moretti et al., 2024). Moreover, wider understanding on sustainable water use together with integrated water resource management adoption creates room for stronger and more adaptable systems for treating wastewater within different settings (Marlow et al., 2013).

Wastewater collection is a complicated process with different sources that can lead to pollution if not managed properly. Failing to treat enough during treatment stages may cause waterborne diseases, environmental pollution and reduced levels of purity in water. Using treated wastewater, as underlined by Morris et al (2021), creates challenges because it must be strictly regulated and its acceptance by the public may need careful handling. Inadequate investment and maintenance can lead to system failures and environmental hazards.

The research conducted by Wang et al. (2023) highlights potential avenues for extracting valuable resources from wastewater management, including the creation of energy from biogas and nutrient-rich biosolids. These practices have the potential to contribute to economic growth.

(Mara, 1998) highlight the significance of proper sludge management within wastewater treatment for environmental protection.

Finally, it is important to note that regulations and policies in wastewater management impact treatment standards discharge limits, and reuse practices.

2.1.7 A Review of Common Wastewater Collection Methods

Wastewater collecting systems differ in various respects, such as their implementation, considerations, and applicability in different circumstances. It is important to acknowledge that the methods used for collecting wastewater can differ depending on the region and local circumstances.

This section provides a comprehensive discussion of different wastewater management methods, including Combined Sewer Systems (CSS), Separate Sewer Systems (SSS), Onsite Wastewater Treatment Systems (OWTS), Vacuum Sewer

Systems, Low-Pressure Sewer Systems, Condominium and Cluster Systems, Onsite Greywater Reuse Systems, Fecal Sludge Management (FSM) Systems, Smart and Sensor-Based Systems, as well as combinations or hybrid systems.

2.1.7.1 Combined Sewer Systems (CSS)

When they were first introduced in 1855, combined sewer systems were highly regarded as a notable improvement over the urban cesspool ditches that ran down city streets and caused overflow during rainfall (Tibbetts, 2005). Combined Sewer Systems (CSS) are designed to gather both household wastewater and stormwater runoff in a single pipeline, which is subsequently sent to treatment facilities. This method is frequently used in older metropolitan regions, primarily because of limited space for individual systems or the existence of outdated infrastructure. Nevertheless, CSS has the potential to result in combined sewer overflows (CSOs) in the event of intense precipitation, which can lead to water contamination and pose a threat to public health and the ecosystem. Notwithstanding these difficulties, CSS is appropriate in situations where it is not feasible to install separate systems and if measures to mitigate combined sewer overflow (CSO), such as storage tanks and real-time control systems, are already implemented.

2.1.7.2 Separate Sewer Systems (SSS)

Separates the movement of dry and wet weather into distinct networks. Separate Sewer Systems (SSS) employ separate conduits for domestic wastewater and stormwater, each of which is sent to its appropriate treatment or disposal facility (Mannina & Viviani, 2009). This approach is highly preferred in contemporary urban design because to its ability to mitigate pollution and combined sewer overflows (CSOs), hence safeguarding water quality. Nevertheless, the implementation and maintenance of separate infrastructure for wastewater and stormwater via SSS can incur significant costs. Sustainable stormwater systems (SSS) are especially well-suited for new urban projects or areas with sufficient money for infrastructure, where the long-term advantages of less pollution and improved water management outweigh the initial financial commitment.

2.1.7.3 Onsite Wastewater Treatment Systems (OWTS)

Onsite Wastewater Treatment Systems (OWTS), such as septic tanks, process wastewater at individual properties. They handle and disperse wastewater from individual households or other buildings or structures (Links, 1994), either by releasing it into the soil or collecting it for future transportation. These systems are prevalent in rural regions lacking access to centralized sewer systems. Ensuring appropriate maintenance and strict adherence to laws is essential in order to prevent the pollution of groundwater. This contamination can arise if the systems are not effectively handled. Onsite wastewater treatment systems (OWTS) are appropriate in areas with low population density when centralized systems are not economically feasible. They offer a cost-efficient method for treating wastewater in isolated areas.

2.1.7.4 Vacuum Sewer Systems

In the last 25 years, a new method of collecting wastewater known as vacuum system has proven to be efficient and convenient in some situations such as mountainous areas, places with a high water table and unstable soil (Islam, 2017). A centralized collection point for waste is reached by using the suction created by creating vacuum pressure through the pipes. Such technology is suitable where there are flat or rocky landscapes that cannot accommodate gravity-based solutions. Therefore, regular maintenance must be done on vacuum systems while ensuring that they have a reliable source of power supply so as to achieve their highest levels of performance (Islam, 2017). These systems offer flexibility over difficult terrains hence can serve as good alternatives to conventional sewage treatments which may not work well in certain regions.

2.1.7.5 Low-Pressure Sewer Systems

Pressure dewatering is currently regarded as a highly developed and sophisticated method (Dohse & Eckstädt, 2003). Low-pressure sewer systems utilize narrow pipes and grinder pumps to convey effluent to treatment facilities. They are economically efficient in difficult terrains where conventional gravity-based systems are impractical, such as mountainous or isolated regions. Nevertheless, grinder pumps necessitate periodic maintenance, and power outages have the ability to interrupt the system, potentially resulting in backlog or overflows. Low-pressure systems are a viable option for transporting wastewater in regions where the landscape or financial limitations make gravity systems unfeasible. They serve as a dependable alternative (Dohse & Eckstädt, 2003).

2.1.7.6 Condominium and Cluster Systems

Condominium and cluster systems streamline the collection of wastewater in residential complexes (Jones et al., 2001), making wastewater management easier by eliminating the need for separate systems for each unit. Cluster wastewater systems allow for the development of smaller lot sizes and give planners with an effective way to preserve the green spaces and rural atmosphere of small communities (Jones et al., 2001). These systems are especially advantageous in residential projects that have common infrastructure, as they can simplify maintenance and enhance efficiency. System failures can be avoided and dependable functioning can be ensured through proper design and frequent maintenance.

2.1.8 Treatment Processes

Gaining a thorough understanding of wastewater treatment techniques is crucial for comprehending their function in eliminating impurities and pollutants from wastewater. The scientific literature offers useful insights into these processes and their efficacy.

2.1.8.1 Physical Processes:

Physical processes in wastewater treatment consists of physical elimination or segregation of solid particles from the wastewater, they consist of screening, sedimentation and filtration. Screening involves using screens or grids with various opening sizes to remove large debris, such as sticks, leaves, and plastics, from wastewater. Sedimentation allows suspended solids to settle at the bottom of a tank or basin due to gravity. It separates solids from liquid.

Filtration uses porous media, such as sand or membranes, to remove fine particles and impurities from wastewater. Types include sand filtration and membrane filtration).

2.1.8.2 Chemical Processes:

Chemical processes in wastewater treatment involve the addition of chemicals to alter the properties of wastewater and facilitate the removal of contaminants, they include coagulation, percipitation and disinfection.

Coagulation involves the addition of chemicals, known as coagulants (e.g., aluminum sulfate or ferric chloride), to destabilize particles in wastewater and make them clump together for easier removal (Sukmana et al., 2021).

Chemical precipitation is used to remove dissolved metals and other contaminants by adding chemicals that cause them to form solid particles (precipitates) that can be separated from the water (Harper & Kingham, 1992).

Disinfection involves the use of chemicals (e.g., chlorine or UV radiation) to kill or inactivate pathogens (bacteria, viruses) present in wastewater (Amin et al., 2013).

2.1.8.3 Biological Processes:

Biological processes in wastewater treatment use microorganisms to break down organic matter and remove pollutants.

Activated sludge is a biological process where microorganisms (activated sludge) are used to consume organic matter and nutrients in wastewater. It is widely used in secondary treatment (Orhon et al., 2009) .

In aerobic treatment, microorganisms break down organic matter in the presence of oxygen. It includes processes like extended aeration and sequencing batch reactors (SBRs)(Chan et al., 2009).

Anaerobic treatment occurs in the absence of oxygen and involves microorganisms that decompose organic matter and produce biogas. Anaerobic digestion is an example (Chan et al., 2009).

Trickling filters use a bed of rocks or plastic media to support the growth of microorganisms that degrade organic pollutants in wastewater (Daigger & Boltz, 2011) .

Biofilm processes involve microorganisms attached to surfaces (e.g., biofilm reactors or submerged fixed-film reactors) (Van Loosdrecht & Heijnen, 1993).

2.1.9 Reuse and Disposal Methods of Wastewater

Several techniques have been created for the recycling and elimination of processed wastewater, providing numerous advantages and uses. These methods are specifically designed to suit the specific characteristics of the local area, taking into account environmental factors and the accessibility of water resources.

Treated wastewater is often directly discharged into rivers, lakes or oceans. This method is common due to its simplicity and cost-effectiveness.

Treated wastewater can be utilized for agricultural irrigation, promoting water conservation and nutrient recycling. This method supports sustainable farming practices (Ofori et al., 2021)

Injecting treated wastewater into aquifers helps to replenish groundwater resources. This practice is essential in regions facing groundwater depletion .

Wastewater treated to meet industrial standards can be reused in various manufacturing processes, significantly reducing the demand for freshwater (Ofori et al., 2021)

2.1.10 Wastewater Management Infrastructure:

Wastewater management infrastructure is a complicated and varied bunch of physical structures and establishments that are made with the aim of collecting, treating, and getting rid of or reusing wastewater from homes, industries, and commercial activities. Though it may vary in size and shape, this essential infrastructure mainly consists of a number of key components as discussed below:

The system of collection, which may be referred to as the sewerage or sewage system, acts as a primary conduit for transporting wastewater from its initial point to treatment plants. It is made up of an extensive underground network consisting of pipelines, canals and pump stations that collect wastewater from various origins including households, industries and business premises. Proper operation of this infrastructure helps prevent surface water contamination with effluents thus minimizing environmental risks (Akunna & Bartie, 2014).

In wastewater infrastructure, treatment plants are the core that eliminates contaminants and other pollutants from water through a series of physical, chemical or biological processes (Akunna & Bartie, 2014). The aim of these techniques is to reduce the concentration of harmful substances up to the standard specified by regulations in order to protect public health as well as environment safety. Screening, sedimentation or coagulation; activated sludge systems plus anaerobic digestion among others are some methods used during primary treatment stage.

Called outfall or effluent systems, distribution networks play an important role in getting treated wastewater to where it needs to go (Reyes-Silva et al., 2020). Depending on local regulations and environmental factors, treated wastewater may be discharged into natural water bodies, reused for various purposes such as irrigation or industry, or further purified to meet drinking water standards (Kara et al., 2016). Such systems ensure that processed sewage is transported efficiently so that it can be used safely and responsibly.

According to Kara et al. (2016), it is important to have real-time monitoring and control systems in place for the smooth operation of wastewater management infrastructure. These systems help assess the quality of raw as well as treated water continuously so that necessary changes in treatment processes can be made and emergency situations handled immediately by operators (Kara et al., 2016). Observance with environmental regulations is ensured through monitoring which allows proactive measures towards maintaining safe levels of water quality.

2.1.10.1 Importance of Proper Infrastructure

Inefficient infrastructure can lead to the spread of waterborne diseases and infections through contact with untreated or poorly treated sewage (Tariq & Mushtaq, 2023). Such risks are prevented by robust infrastructures.

Infrastructure that functions well prevents the release of toxic substances into the atmosphere thus; Protecting habitats, freshwater organisms and maintaining ecological balance. Additionally, it plays an important role in minimizing pollution from water bodies which helps in the preservation of a healthy aquatic system.

An effective system of wastewater management is essential for a country's economic stability and development. It cuts down on health care spending linked to diseases caused by unclean drinking water, enhances farm productivity through preserving the quality of water used for irrigation purposes and ensures that businesses relying on clean sources of fresh water remain viable. In addition, recycling wastewater could help recover some valuable resources besides saving significant amounts of money.

Sufficient infrastructure guarantees adherence to local, national, and global rules that control the management of wastewater and the protection of the environment. Adhering to regulations is important for preventing legal repercussions and retain a favorable public image.

2.1.11 Economic Aspects of Wastewater Management: Costs and Benefits

2.1.11.1 Costs of Wastewater Management

The costs of wastewater management include:

- Infrastructure Development Costs
- Operation and Maintenance Costs
- Environmental and Health Costs
- Financing and Investment:
- Tariffs and Pricing Policies

The financial aspect of wastewater management involves funding strategies and investment mechanisms. Governments, international organizations, and private investors contribute to financing wastewater projects through grants, loans, or public-private partnerships (Koppenjan & Enserink, 2009)

2.1.11.2 Benefits of Wastewater Management

Effective wastewater management can result in economic advantages by enabling the recovery of valuable resources. The water that has been treated and recycled, along with organic content and gas generated in the treatment process, can be reused or sold, which can reduce the expenses associated with the operation (Healy et al., 2015).

Research indicates that allocating funds towards the development of wastewater infrastructure has the potential to boost economic growth and generate employment opportunities, especially in underdeveloped areas (Van Leeuwen & Sjerps, 2015).

Recent research highlights the growing importance of ecosystem services in wastewater treatment, particularly in terms of nitrogen removal and water purification (Barbier et al., 2017). By assigning economic values to these services, it is possible to provide a justification for investing in enhanced wastewater infrastructure.

2.1.12 Sustainable Practices in Wastewater Management

The importance of sustainable wastewater management is growing as urbanization, population increase, and environmental deterioration present significant problems. This method prioritizes both the efficient treatment of wastewater and the reduction of its harmful effects on the environment. It also aims to maximize the recovery of valuable resources and ensure economic sustainability. Sustainable practices in the contex of wastewater include:

- Wastewater Reuse
- Energy Generation from Wastewater
- Eco-Friendly Treatment Methods
- Importance of Sustainability in Modern Wastewater Management

2.2 Contextualized Review for Sudan

2.2.1 Introduction to Sudan

The Republic of Sudan is positioned in Northeast Africa. It is bordered to the southwest by the Central African Republic, to the west by Chad, to the northwest by Libya, to the north by Egypt, to the northeast by Eritrea, to the southeast by Ethiopia and to the south by South Sudan; additionally having coastline on the Red Sea. Covering an area of 1,886,068 square kilometers it is regarded as Africa's third largest country and also that of Arab League after Algeria and Saudi Arabia respectively. In 2024, Sudan had a population close to 50 million people (CIA World Fact Book.

Figure 2.2 Republic of the Sudan

2.2.2 Regions and States of Sudan

Sudan has 18 states consisting of 133 districts.

- **Central and Northern States:**

1) Gezira
2) Khartoum
3) Northern
4) River Nile

5) Sennar
6) White Nile
7) Al Qadarif

- **Darfur Region:**

1) Central Darfur
2) East Darfur
3) North Darfur
4) South Darfur
5) West Darfur

- **Eastern Region:**

1) Kassala
2) Red Sea

- **South Kordofan and Blue Nile States:**

1) Blue Nile
2) South Kordofan
3) West Kordofan
4) Abyei Area

Figure 2.3 Sudanese states

2.2.3 Major Sudanese Cities

The major Sudanese cities are as follows:

- Omdurman
- Khartoum
- Khartoum North (Bahri)
- Nyala
- Port Sudan
- Ubayyid

2.2.4 Population and Population Growth Trends in Sudan

Urbanization and population increase are closely connected phenomena that have significant consequences for wastewater management in Sudan. The country is currently undergoing fast urbanization, mostly because of the migration of people from rural regions to urban centers(United Nations, 2020) . Urban regions operate as hubs for employment opportunities and other amenities, drawing in those who are in search of better living conditions. Khartoum, the capital, and other important cities have experienced substantial population expansion. In recent years, the population of Sudan has been consistently growing, with estimates exceeding 44 million. This expansion is driven by high fertility rates and a primarily youthful population. The growing population exerts increased pressure on urban infrastructure, specifically on wastewater management systems (United Nations, 2020).

The figures presented below were gathered from a study conducted by **Macrotrends**, which integrated the population growth forecasts provided by the **United Nations**:

- Population of Sudan as of 2024 = **49,358,228**, **2.6% increase** from 2023.
- Population in 2023 = **48,109,006**, **2.63%** growth rate.
- Population in 2022 = **46,874,204**, **2.67%** growth rate.
- Population in 2021 = **45,657,202**, **2.74%** growth rate.

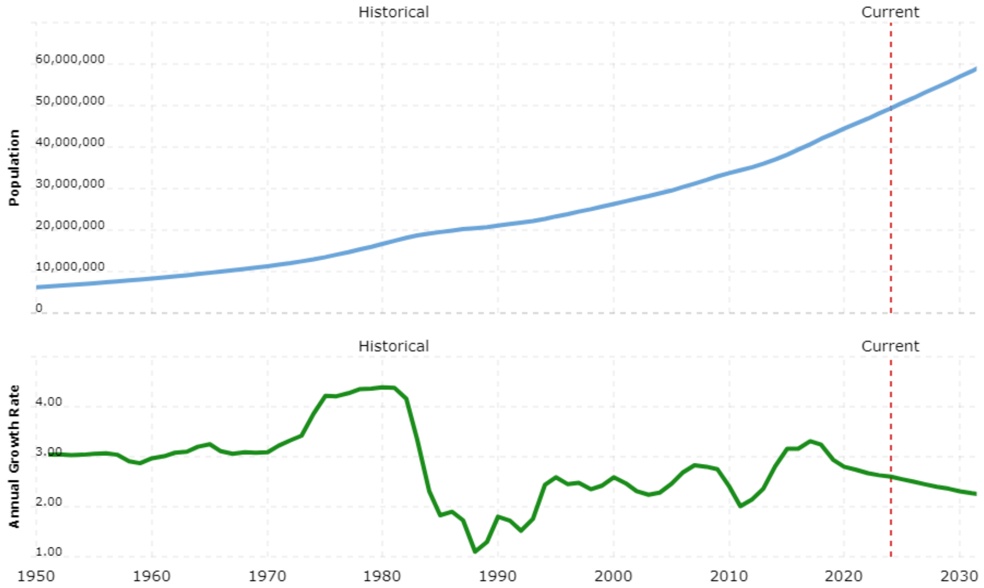

Figure 2.4. Anticipated Population Growth and Annual Growth Rates In Sudan 1950-2030

2.2.5 Sudan Environmental Policy and Frameworks

In 2018, the Sudanese Ministry of Information stated that Sudan is a federal country with eighteen states (United Nations, 2020). The foundational government setup was formed through the Interim National Constitution of 2005 which echoed the

Comprehensive Peace Agreement (CPA) between Khartoum's central government and Sudan People's Liberation Movement (SPLM) signed in January 2005 (United Nations, 2020). It transferred various powers from the national level to regional governments and created several levels where power is exercised:

- State level, the highest office is the governor supported by ministers.
- Locality level, headed by the commissioner and is supported by the executive director and related committees.
- Administrative units where each unit is led by an administrative officer, who is assisted by various committees.
- Neighborhood and village councils, neighborhood councils operate in urban areas, while in rural areas, village councils are established.

The primary source of Sudan's environmental legislation is the Environment Protection Act of 2001. This act outlines regulations, guidelines, and allows states the power to form environmental councils and enact local policies and laws **(Ministry of Environment and Physical Development 2001)**. In addition, Sudan has pledged to several international environmental agreements, while other legislations safeguard natural resources. The country also fulfills the criteria set by international investors, including the World Bank, the African Development Bank, USAID, and the UK's Department for International Development (DFID).

The Ministry of Environment, Natural Resources, and Physical Development was established in 1995 and obtained its power from a constitutional order. The Higher Council for Environment and Natural Resources (HCENR) functioned as the ministry's technical section, responsible for supervising the alignment of environmental policy across several sectors and managing international environmental agreements.

In September 2018, a presidential decree was issued to abolish the environment ministry and create the National Council for the Environment, while maintaining the duties of the HCENR. The Transitional Supreme Council made amendments to the

Environment Protection Act of 2001 on 30 April 2020. The amendment led to the creation of a new governing entity known as the Higher Council for Environment and Natural Resources (United Nations, 2020).

2.2.5.1 Sudan Environmental Policy and Developments

After gaining independence, Sudan made a notable error by embracing a Western paradigm of "development." The country chose to pursue capital-intensive, large-scale agriculture initiatives primarily aimed at exporting unprocessed resources (United Nations, 2020). The objective of this method was to facilitate Sudan's economic convergence with the global community. However, the country's actual requirement was a conventional and alternative development framework. The implementation of a centralized planning system, influenced by Western practices, resulted in some adverse outcomes. These include the exclusion of indigenous farming techniques and a lack of consideration for environmental sustainability and the preservation of natural resources. The implementation of extensive initiatives, including as the anti-thirst campaign during the 1960s, the enlargement of rain-fed and irrigated agriculture, and the establishment of dams on the Nile and other waterways, played a substantial role in the deterioration of the environment. The government's attention towards natural resource conservation, including soil conservation, reforestation, and resource protection, started with the implementation of the Six-Year Plan of 1977-83 (Bayoumi, 1996). During the subsequent twenty years, numerous attempts were made to incorporate environmental conservation into governmental policies. Participants at the 1986 National Economic Conference expressed significant apprehensions over ecological and environmental concerns. The significance of effective environmental management and alleviation of poverty was emphasized in the Salvation Recovery and Development Programme from 1988 to 1992 (Bayoumi 1996). The 1992-2002 national strategy placed a high importance on reducing poverty and promoting sustainable development. It emphasized the active participation of local people and the utilization of indigenous knowledge.

The National Comprehensive Strategy faced substantial obstacles including institutional, budgetary, and structural issues, as well as disagreements between federal and state administrations and limited public knowledge of environmental concerns (Mohamed, 2001). Despite the previous regime's development of several plans to combat poverty and preserve natural resources, a significant portion of these projects were not put into action. Similar to several initiatives during Sudan's period after gaining independence, these plans were impeded by internal strife, centralized decision-making, limited involvement of local communities, and inadequate determination from governmental authorities.

To help in the creation of development plans, Sudan has like other underdeveloped countries received aid from the international entities. The World Bank and International Monetary Fund started a program in 1996 which was meant to reduce the debt burden of the Least Developed Countries (Nwonwu, 2008). At that time, Sudan was among ten to fifteen nations with least developed levels. Governments could relieve some of their responsibilities through “Environmental Debt Swap” schemes where they made commitments on conserving nature. (Nwonwu, 2008)

In 1999, the World Bank and the IMF implemented a new effort that established a connection between debt relief and the reduction of poverty. Nations were obligated to prepare Poverty Reduction Strategy Papers describing their strategies for diminishing poverty. After receiving permission, countries became eligible to receive debt relief and aid. This program received widespread acclaim as an important step taken by the international community to prioritize poverty reduction in development planning and finance, while also promoting the idea of nations taking responsibility for their own development policies. Furthermore, civil society organizations played a role in formulating and executing these strategies, indicating a favorable change. In 2012, Sudan made progress by creating its Interim Poverty Reduction Strategy Paper, which is a step towards completing its comprehensive Poverty Reduction Strategy Paper (Sudan’s Ministry of Finance and Economic Planning Assessment, 2011).

2.2.5.2 Regulatory Framework for Water Management

Sudan's strategy for overseeing natural resources may be traced back to the early 20th century, which was closely linked to the establishment of the country's forestry service. The Forests and Woodlands Service was established by the government immediately after the foundation of the Anglo-Egyptian Condominium in 1902. Later, in 1908 and 1917, laws were passed to encourage the preservation of nature (Badi et al. 1989). In 1932, the country implemented its inaugural national forest policy, and by 1935, the Wildlife Act was enacted, resulting in the establishment of multiple national parks (Badi et al., 1989).

Nevertheless, the enforcement of environmental laws in Sudan has been disjointed, lacking a unified and sustainable long-term plan. Presently, there exist around 150 rules and regulations that pertain to several facets of natural resource management, including health, water provision, land ownership, safeguarding of animals, and fisheries (Ali, 2007).

The following in (Table 2.2) is a list of the existing national, regional, and international legislation and treaties that pertain to Sudan's environmental governance and water management.

Table 2.2 Main policies related to water and environment in Sudan

Category	**International and Regional Conventions/Treaties**	**Key Sudanese National Policies/Laws**
Conservation & Nature Protection	African Convention on Conservation of Nature and Natural Resources (1968)	Central Forest Act (1932), Wildlife Protection and National Parks Act (1986)

Table 2.2 (Continued)

Category	International and Regional Conventions/Treaties	Key Sudanese National Policies/Laws
Wetlands & Water Management	Ramsar Convention on Wetlands (1971)	National Water Policy (1992), Integrated Water Resources Management Policy (2007), Water Resources Act (1995)
Cultural & Natural Heritage	Convention on Protection of World Cultural and Natural Heritage (1972)	Antiquities Protection Act (1999), Archaeology Protection Act (1999)
Environmental Protection	United Nations Convention on Biological Diversity (1992), Basel Convention on Hazardous Wastes (1989)	Environmental and Natural Resources Act (1991), Environment Protection Act (2001), Environmental Health Act (2009)
Climate Change	United Nations Framework Convention on Climate Change (1994), Kyoto Protocol (2005)	National Adaptation Programme of Action (2007), Desertification Control Act (2009)
Water Supply & Sanitation	-	Water Supply and Sanitation Policy (2010), Regulation for Ground Water Control (2016), Regulation for Surface Water Control (2016)
Land & Forests	-	Land Settlement and Registration Ordinance (1925), Forestry Act (1989)

2.2.5.3 Institutional Framework Water Water Management

The authorities over the natural resources management can be listed as in (Table 2.3)

Table 2.3 Break-down of national authorities over Sudan's natural resources

Category	Responsibilities
Federal Authorities	Oversight of national land and natural resource management; Administration of the Nile and other transboundary water bodies, including resolution of disputes related to interstate waters and national protected ecosystems
State Authorities	Governance of local government affairs; Management, leasing, and use of state-owned land; Implementation and enforcement of state-specific laws; Regulation of agricultural practices within the state; Application of traditional and customary laws
Shared Federal and State Authorities	Environmental stewardship, including conservation efforts and pollution control; Regulation of land rights, tenure, and usage; Management of water resources, excluding interstate waters; Disaster response and preparedness, including management of relief efforts and epidemic control; Oversight of pastures, veterinary services, and control of animal and livestock diseases; Urban planning, development, and housing initiatives

The institutional bodies responsible for Sudan's key policies on the environment and natural resources are shown in (Table 2.4) bellow:

Table 2.4 Sudan environmental policies and responsible authorities

Policy/Plan	Responsible Entity
National Development Strategy (1992–2002)	Higher Council for Strategic Planning
Decentralization Policy (1997)	Local, state, and federal government bodies
Sudan National Adaptation Plan (2015)	Government, non-government, and private institutions at state and national levels
Quarter Century Strategy (2007–2031)	Higher Council for Strategic Planning
National Climate Commitment (INDC) (UNFCCC Contribution)	Higher Council for Environment and Natural Resources

Table 2.4 (Continued)

Policy/Plan	Responsible Entity
National Water Policy (1999; revised 2006)	National Water Corporation
Water and Sanitation Policy (2009)	Ministry of Water Resources
Biodiversity Strategy (2015)	Higher Council for Environment and Natural Resources, supported by UNDP
National Forest Policy (2006; updated from 1986)	Forests National Corporation, Ministry of Agriculture and Forestry
Poverty Reduction Strategy (2012)	Ministry of Finance and Economic Planning, technical ministries, donor community
SDGs and 2030 Agenda	National Population Council

2.2.6 Sudan's Water Resources

Rain, rivers, seasonal streams, lakes and wetlands are Sudan's main water resources in terms of surface water. Non-conventional sources like groundwater, wastewater reuse and desalination also contribute significantly to the country's total water supply. Erratic rainfall patterns and short rainy seasons limit internal renewable waters in Sudan thereby exposing it to high vulnerability especially in the rain-fed areas (FAO 2015).

Surface waters mainly originate from the Nile River system; with Sudan covering 43% of the Nile basin and 72% of the country within the Nile basin (FAO, 2015). Sudan possesses six main basins shared with its neighbors: the Nile basin with an area of about 1.37 million Km^2 which is equivalent to 72 percent of total landmass; Northern Interior basins measuring approximately 310.89 thousand km^2 at the northwest corresponding to 16.5%; Lake Chad Basin situated at western part at border with Chad and Central African Republic area stretching up to approximately101.05 km^2 which accounts for around 4 %; Northeast Coast basins along Red Sea coast line occupying a length of about83.84 km^2 equaling to a contribution by approximately4%; Baraka basin beside Eritrean boundary representing a territory extending over24.14 square miles that is about one point three percent & Mareb Gash basin also bordering Eritrea with an area coverage amounting to8.82 square kilometers or roughly half a percent (FAO,1997; UNEP,2007).

Figure 2.5 Sudan’s water basins (source: Fanack Water)

The table bellow summarizes the area coverage of basins in Sudan:

Table 2.5 Sudan water basins area coverage

Resource Type	Area (km²)	Percentage
Nile Basin	1,350,616 km²	(72%)
Northern Interior Basins	310,888 km²	(16.5%)
Lake Chad Basin	101,048 km²	(5.4%)
Northeast Basins	83,840 km²	(4.5%)
Baraka Basin	24,141 km²	(1.3%)
Mareb Gash	8,825 km²	(0.5%)

2.2.6.1 Characteristics of Nile System Tributaries

The Nile system in Sudan is composed of several tributaries, each with unique flow characteristics influenced by rainfall patterns and seasonal variations. These tributaries include the Blue Nile, White Nile, Atbara River, Setit-Tekeze River, and the Main Nile. The Blue Nile has a distinct seasonal flow, reflecting the rainfall over the Ethiopian highlands, while the White Nile experiences flow obstruction during the flood period caused by the Blue Nile. The Atbara River and Setit-Tekeze River are highly seasonal, with flows primarily during the flood period between July - October. The Main Nile, which forms downstream of the confluence of the Blue Nile and White Nile, has a significant annual flow at the Sudan-Egypt border.

Table 2.6 Flow characteristics of nile system tributaries

River	Flow Characteristics	Average Annual Flow (million m³)	Seasonal Flow Pattern
Blue Nile	Reflects seasonality of Ethiopian highlands rainfall; wet season (July-Oct), dry season (Nov-June).	52,600	Bell-shaped hydrograph pattern
White Nile	Average annual flow entering Sudan from South Sudan; flood period obstructed by Blue Nile.	34,000	Flood period causes upstream flooding
Atbara River	Highly seasonal with steep slope; flow mainly during July-October.	4,370	Peaks in August-September

Table 2.6 (Continued)

River	Flow Characteristics	Average Annual Flow (million m³)	Seasonal Flow Pattern
Setit-Tekeze River	Highly seasonal; originates in Ethiopia and forms border with Eritrea before entering Sudan.	7,630	Peaks in August-September
Main Nile	Downstream of Blue and White Nile confluence; Atbara is the last tributary joining.	84,000 (at Sudan-Egypt border)	

2.2.6.2 Seasonal Rainfall-Dependent Non-Nilotic Streams

Sudan features numerous non-Nilotic streams, comprising both permanent and seasonal varieties. The seasonal streams, locally referred to as wadis or khors, flow for brief periods between July-October and stays dry for the year remaining. The flow of these streams is dependent on rainfall, and most are not systematically monitored. On average, these seasonal streams contribute about 5.5 BCM annually.

The primary non-Nilotic streams in Sudan include the Mareb-Gash and Baraka, both originating from Eritrea. These streams have an average annual flow of 700 million m³ and are noted for their considerable yearly flow variations and heavy silt loads.

Table 2.7 Sudan non-nilotic streams

Stream	Origin	Average Annual Flow (million m³)	Characteristics
Mareb Gash	Eritrea	700	varries in annual flow, cobtains significant silt loads
Baraka	Eritrea		
Azum	Chad	***Not Monitored***	
Hawar	Chad	***Not Monitored***	
Khor Abu Habil	Sudan	***Not Monitored***	Seasonal stream, local wadi

Table 2.7 (Continued)

Stream	Origin	Average Annual Flow (million m^3)	Characteristics
Wadi El Mugaddam	Sudan	***Not Monitored***	Seasonal stream, local wadi
Wadi Kaja	Sudan	***Not Monitored***	Seasonal stream, local wadi
Wadi Nyala	Sudan	***Not Monitored***	Seasonal stream, local wadi
Alawataib	Sudan	***Not Monitored***	Seasonal stream, local wadi
Alhawad	Sudan	***Not Monitored***	Seasonal stream, local wadi
Annual Total Average Water Contribution (BCM)		***5,5***	

2.2.6.3 Wetlands

Across the Sudan, there are a variety of wetlands and thirty different types have been identified within its territory. Three of these have been recognised as Ramsar sites, underlining their importance globally. One notable type of unique Sudanese wetland is mayas or ox-bow lakes found in Dinder National Park.

Sudan's wetlands are different kinds. In western Sudan for instance, Er-Rahad, Kundi, Keilak and Abyad freshwater Lakes have a high level of biodiversity due to the presence of waterfowl and micro-invertebrates. Other temporary lakes around include Butu Rayia, Um Badir, al-Fula, Ras Amir, Um Baggara, Kibbew Undur and Nzeli. On the other hand saline crater lakes such as Dariba and Malha can be found in volcanic areas like Jebel Marra and Meidoub Hills within this country. Other streams that contribute to its diversity are Wadi Shalengo which drains the western side of Nuba Mountains while Arbaat being the only permanent stream in Red Sea Hills. In addition to that there are numerous hot springs in Sudan with Akasha hot springs being the most accessible located near Lake Nubia on one hand while others can be found at Quella (Jebel Marra), al-Harra (Wadi Azum), and the Meidoub Hills.

2.2.6.4 Lakes

Various fresh water lakes like Abyad in Southern Kordofan, Turdat el-Rahad in Kordofan and Kundi located in the southern Darfur exist on Sudan. Moreover salty lakes such as Malha located in Northern Darfur and Dariba crater located at Jebel Marra in western Sudan are found here. The north parts of the country have oases such as Nikheila, Natroon, and Saleema.

2.2.6.5 Dams and Artificial Lakes

In Sudan, different dams have created artificial reservoirs. A few examples include the Sennar and Roseires dams on the Blue Nile, the Jebel Aulia dam built across White Nile, the Khashm El-Girba and Upper Atbara and Setit Complex in River Atbara, Northern state's Merowe dam, as well as Lake Nubia at the topmost part of Sudan which is a constituent of Egyptian High Aswan Dam's reservoir.

Table 2.8 Dam capacities

Dam	River	Built Year	Capacity (BCM)	Additional Info
Sennar	Blue Nile	1925	0.07	-
Jebel Awlia	White Nile	1937	3.0	-
Khashm al-Girba	Atbara	1964	0.8	-
Roseires	Blue Nile	1966, heightened in 2014	7.0	Heightened in 2014
Merowe	Nile	2009	12.0	-
Atbara/Setit Complex	Atbara	Under Construction	-	-

2.2.6.6 Groundwater Resources

Groundwater is an essential resource in Sudan, particularly during the extended dry season. Over 80% of the population relies almost exclusively on groundwater. Beyond the Nile basin and other non-Nilotic river wells, groundwater remains the sole water source. The groundwater reserves are estimated at 900 BCM, with an annual recharge rate of 1,563 BCM.

The Nubian Sandstone Aquifer System, which Sudan shares with Egypt and Libya, receives recharge from the Nile within Sudan and spans nearly 29% of the country, making it the most significant aquifer. Details of other major aquifers, including their annual recharge and abstraction rates, are provided below:

Table 2.9 Groundwater sources in Sudan

Aquifer	Storage (km^3)	Annual Recharge (km^3)	Annual Abstraction (km^3)
Nubian Sandstone	503	1	0.7
Um Ruwaba	60	0.6	0.15
Alluvial deposits	1	0.375	0.16
Total	**564**	**1.975**	**1.01**

2.2.6.7 Non-Conventional Water Resources

As of 2020, Sudan operated five desalination plants in Port Sudan, collectively producing 0.02 million cubic meters (MCM) per day. The reuse of wastewater remains limited, primarily used for irrigation in the suburbs of Khartoum.

Historically, before the advent of UNICEF's small bore hand pumps, villagers in western Sudan utilized the hollowed trunks of giant baobab trees (Adansonia digitata) for water storage. In various regions, water is also collected and stored in haffirs—simple water harvesting structures used for domestic, pastoral, and animal needs in Darfur and Kordofan. These haffirs vary in storage capacity, with some able to hold thousands of cubic meters.

2.2.7 Surface Water Quality

There is a limited amount of data available on the quality of surface water, and the existing data is outdated. The majority of existing data is primarily located along the White and Blue Nile rivers. The qualities of water depend on the source and the types of soil through which the water flows. Water contamination arises from the presence of agricultural leftovers and the sugar industry, while the inherent ability of natural systems to cleanse themselves is considerable. In addition, the 1975 Public Health Law prohibits the discharge of any untreated, treated, or partially treated water into natural water bodies.

The amount of water pumped during different seasons is contingent upon the water level of the Blue Nile. During the flood season, the water table level of surface water often reaches a depth of approximately 30-40 feet. During the dry season, the water table level typically ranges from 45 to 55 feet. Furthermore, its level of salinity is lower compared to groundwater. The water is extensively utilized in agriculture and is also consumed by humans, both treated and untreated.

Sinada (1972) observed that the nutrient levels in the White Nile vary with the seasons, with changes in the White Nile at Khartoum being linked to the flood patterns. These floods are influenced by the Ethiopian Plateau via the Sobat River and the seasonal growth of phytoplankton in the Jebel Aulia reservoir upstream. They reported a notable rise in the concentrations of nitrate, phosphate, silicon, and iron in Khartoum during the rainy season between July and September.

This study will analyze the quality of surface water in the Nile Basin because there is a lack of data for other surface water basins in the country. The Nile Basin, which encompasses 72% of Sudan's land area, serves as a substantial and representative example for studying the features of surface water across a large portion of the country. The choice to prioritize this basin is based on the fact that the existing data mostly comes from the White and Blue Nile rivers, which are crucial elements of the Nile Basin. The consolidation of data in this particular area offers a more dependable basis for analysis in contrast to other regions where data is either obsolete or limited. Furthermore, considering the significant impact of the Nile on Sudan's water system and its massive utilization in farming and human consumption, discoveries obtained from this basin are expected to provide vital understanding into the wider trends and difficulties of water quality control in Sudan.

The following water quality data in (Table 2.10) were provided within the **Khartoum State Environmental Strategic Assessment and Evaluation Project 2014** by the Sudanese **Council For Environmental Affairs.**

Table 2.10 Chemical analysis report for the main Nile, Blue Nile and White Nile (Sudan Council For Environmental Affairs, 2014)

Parameter	Blue Nile (Max/Min)	White Nile (Max/Min)	River Nile (Max/Min)
Turbidity N.T.U	39000 / 8	288 / 55	22000 / 30
pH	8.7 / 7.8	8.7 / 7.7	8.4 / 7.7
E.C µ S\cm	321 / 222	370 / 187	349 / 207
T.D.S mg\I	176 / 127	185 / 93	192 / 112
T.S.S mg\I	27000 / 10	260 / 47	24000 / 35
Total Alkalinity as caco3 mg\I	125 / 80	170 / 80	128 / 95
Phenolphthalein ph Alkalinity as caco3 mg\I	5 / 0	15 / 0	5 / 0
Total Hardness as caco3 mg\I	132 / 100	99.2 / 50	148 / 60
Phosphate mg\I	0.13 / 0.07	0.63 / 0	0.25 / 0.08
Chloride mg\I	8 / 3	16 / 9	16 / 6
Fluoride mg\I	0.45 / 0.14	0.16 / 0	0.44 / 0.09
Sulfate mg\I	23.7 / 14	25.2 / 0	23 / 0.1
Ammonia mg\I	0.168 / 0.022	0.268 / 0	0.615 / 0.028
Nitrite mg\I	0.032 / 0.007	0.051 / 0	0.126 / 0.014
Iron mg\I	0.45 / 0.14	0.8 / 0.11	0.1 / 5.28
Calcium mg\I	32 / 19.2	15.5 / 5	36.8 / 9.6
Magnesium mg\I	15.36 / 10.56	15.36 / 6.24	13.44 / 9.6
Sodium mg\I	10.78 / 5.46	33 / 16	24.48 / 10.38
Potassium mg\I	3.21 / 2.29	13 / 7.7	13.8 / 4.19
Nitrate mg\I	7.48 / 2.64	8.8 / 0	28.36 / 4.19

2.2.8 Ground Water Quality

The following (Table 2.11) and (Table 2.12) give sample pysical properties provided by the **Higher Council of Environmental Affairs** in Sudan while (Table 2.13) and (Table 2.14) provide chemical analysis.

Table 2.11 Physical properties of ground water samples taken from a site in SOBA WEST area

Sample Date	11/9/90
Latitude	15°35'00" N
Longtitude	32°40'00" E
Colour	Normal
Taste	Normal
Turbidity	Normal
Odour	Normal
pH	8.9
Electrical conductivity	364 us/cm
T.D.S	252
Total Hardness	16
T.Alk (CaCO3)	56.2
E.ALK (Na2CO3)	254.6
CO3	0.00
CL	3.4
SO4	19.9
K	N.A
Ca	6.42
Mg	0.00
Na	N.A
HCO3	256.2
F	0.2
NO3	1.10
NO3	10.019
NH3	0.00
Alb (N)	N.A.
As	N.A.
Pb	N.A.
Se	N.A.

Table 2.12 Physical Properties Ground Water Samples Taken from a Site in Kalakla area

Sample Date	16/12/99
Latitude	15°14'00" N
Lontitude	32°32'00" E
Colour	Normal
Taste	Normal
Turbidity	Normal
Odour	Normal
pH	7.3

Table 2.12 (Continued)

Electrical conductivity	460 us/cm
T.D.S	322.0
Total Hardness	194.9
T.Alk (CaCO3)	256.2
E.ALK (Na2CO3)	66.2
CO3	0.00
CL	9.94
SO4	22.2
K	8.6
Ca	46.4
Mg	26.9
Na	68.5
HCO3	256.2
F	0.5
NO3	1.10
NO2	0.019
NH3	N.A.
Alb (N)	N.A.
As	N.A.
Pb	N.A.
Se	N.A.

Table 2.13 Supply Boreholes in areas using septic tanks services (Khartoum district)

Parameter	Standard (SSMO)	Al Riyad Office	ElManshia Mosque	ElManshia New	Al Riyad Block 10	Elgeraif West	Almamora Block 69	Almamora Block 55
APPEARANCE	CLEAR	CLEAR	CLEAR	CLEAR	CLEAR			
TURBIDITY (NTU)	5	0.7	1.8	0.5	0.5	1.9		
COLOR (TCU)	15	NIL	NIL	NIL	NIL	NIL		
ODOUR	Nil	NIL	NIL	NIL	NIL	NIL		
pH	6.5-8.5	8	7.51	7.3	7.9	7.58	7.62	7.5
TEMP.		23.3	31.8	24.1	27.2	26.4		
CONDUCT. µs	1500	298	322	326	559	626	403	287
TDS (mg/l)	1000	178.8	179.3	307.4	373	240	157.8	285
TSS (mg/l)		NIL	NIL	NIL	NIL	NIL		
T. ALKALINITY (mg/l)	170	110	165	200	250	180	145	180
pH. ALKALINITY (mg/l)		NIL	NIL	NIL	NIL	NIL		
T.HARDNESS (mg/l)	500	136.8	156	172.8	281.6	278	189	157.6
H. SULFIDE (mg/l)	0.05	NIL	NIL	NIL	NIL			
CALCIUM (mg/l)	200	16.64	42.4	35.68	42.88	40	39.2	32.8
MAGNESIUM (mg/l)	22.8	12.15	20.06	41.8	43.254	21.384	18.14	27.65
SODIUM (mg/l)	200	24.58	2	11.33	31	14	9	29.95
POTASSIUM (mg/l)		1.94	1	1.37	2.35	5	3	2.52
SULPHATE (mg/l)	250	15	16.7	82	21.8	67.5		
CHLORIDE (mg/l)	250	12	15	14	44	39	24	9
FLUORIDE (mg/l)	1.5	0.1	0.46	NIL	0.09	0.38		
AMMONIA (mg/l)	1.5	NIL	--	NIL	-	-	--	
NITRITE (mg/l)	2	0.002	0.002	0.002	0.173	0.007		

Table 2.13 (Continued)

Parameter	Standard (SSMO)	Al Riyad Office	ElManshia Mosque	ElManshia New	Al Riyad Block 10	Elgeraif West	Almamora Block 69	Almamora Block 55
NITRATE (mg/l)	50	4.4	4.4	3.9	6.6	7.04		
PHOSPHATE (mg/l)	1.5	0.53	0.09	0.72	0.1	0.04		
IRON (mg/l)	0.3	0.1	0.26	0.08	0.1	0.16		
TOTAL COUNT /5ml	1500	5	29	7	128	166	23	30
TOTAL COLIFORM colony/100 ml	zero	Zero	zero	Zero	Zero	zero	Zero	Zero
D.O (mg/l)		1.8	8.9	7.2	1.5	3.4	1.2	1.2
B.O.D (mg/l)	0.2	Nil	1.18	1.6	Nil	Nil	Nil	Nil
C.O.D (mg/l)		Nil	Nil	Nil	Nil	Nil	Nil	6.72
Radon (Bq/L)	70	50.6	51.1	48.6	166.5	106.4	73.1	101.7
0.25	0.09	0.09	0.08	0.28	0.18	0.12	0.17	
DDT								
Aldrin/Dieldrin		0.0						

Table 2.14 Supply boreholes in areas using combination services (pit latrine+ septic tank) (KhartoumDistrict)

Parameter	Standard	Alkalakla East Block 6	Alklakla Altrya East Block 7	Alkalakla Soog Allafa	Wad Ageib	Gabra Block 9	Gabra Block 15	Abu Adam Alsehreg Block 4
APPEARANCE	CLEAR	CLEAR	CLEAR	CLEAR	CLEAR	CLEAR		
TURBIDITY (NTU)	5	1	2	2.6	1.5	3.1	3.36	1.1

Table 2.14 (Continued)

Parameter	Standard	Alkalakla East Block 6	Alklakla Altrya East Block 7	Alkalakla Soog Allafa	Wad Ageib	Gabra Block 9	Gabra Block 15	Abu Adam Alsehreg Block 4
COLOR (TCU)	15	--	-	--	--	-	--	
ODOUR	Nil	+VE	NIL	+VE	+VE	+ve	+VE	
pH	6.5-8.5	7.77	7.8	8	7.7	7.7	7.4	7.6
TEMP.		33	33	32.9	32.4	33.5	32.7	
CONDUCT. µs	1500	489	1067	800	343	471	740	431
TDS (mg/l)	1000	294	533	400	171.6	236	371	216
TSS (mg/l)	--	--	--	--	--	--		
T. ALKALINITY (mg/l)	250	325	270	170	225	220	210	
pH. ALKALINITY (mg/l)	NIL	NIL	NIL	NIL	NIL	NIL		
T.HARDNESS (mg/l)	500	154	239.2	177.2	113.2	150.4	292	138
H. SULFIDE (H2S) (mg/l)	0.05	0.006	NIL	0.006	0.007	--	0.007	
CALCIUM (mg/l)	200	36	54.24	36.32	26.4	33.28	60	32.96
MAGNESIUM (mg/l)	15.552	24.86	18.34	11.33	16.13	34.08	13.34	
SODIUM (mg/l)	200	26	136.6	107.46	31.75	53.04	77.7	84.4
POTASSIUM (mg/l)	15	5.46	5.17	4.6	4.89	5.69	4.37	
SULPHATE (SO4) (mg/l)	250	73.5	46.2	0.3	4.6	47	0.7	
CHLORIDE (mg/l)	250	46	96	66	12	20	120	16
FLUORIDE (mg/l)	1.5	NIL	0.59	0.16	0.23	0.08	0.01	
AMMONIA (mg/l)	1.5	--	--	--	--	--	--	
NITRITE (mg/l)	2	0.006	0.607	0.003	0.003	0.009	0.007	
NITRATE (mg/l)	50	3.52	7.6	5.28	3.96	3.08	4.4	
PHOSPHATE (mg/l)	1.5	0.16	0.27	0.15	0.2	0.3	0.16	
IRON (mg/l)	0.3	0.45	0.35	0.46	0.42	0.7	0.31	
TOTAL COUNT /5ml	1500	3	4	17	Zero	14	2	zero

Table 2.14 (Continued)

Parameter	Standard	Alkalakla East Block 6	Alklakla Altrya East Block 7	Alkalakla Soog Allafa	Wad Ageib	Gabra Block 9	Gabra Block 15	Abu Adam Alsehreg Block 4
TOTAL COLIFORM colony/100 ml	zero	Zero	Zero	Zero	Zero	Zero	Zero	Zero
D.O (mg/l)		1.4	1.5	7.6	2.4	1.7	0.2	1.4
B.O.D (mg/l)	1.5	3	2.3	0.5	1.6	0.3	0.6	
C.O.D (Mg/l)	2	8	4	Nil	12	Nil	6	
Radon (Bq/L)	70	3	0.25					
DDT	1.5							
Aldrin/Dieldrin	0.02							

2.2.9 Treatments for Raw Water in Sudan

The raw water from the Nile, characterized as outlined in the tables above, undergoes several conventional treatment processes.

Primary treatment includes primary disinfection and chemical treatment. Then in primary settlement the water undergoes coagulation and flocculation, where chemicals are added to help particles in the water clump together before it enters the sedimentation tanks. After settling, the water is directed to filters.

In filtration, rapid gravity sand filters are employed, and the filters are typically washed every 24 hours. After filtration, the water is mixed with chlorine gas for disinfection.

In disinfection, chlorination is applied with the output from the chlorinator ranging between 2 to 4 parts per million.

The chemicals utilized in the water purification process include Aluminum Sulphate (Alum**),** used as the primary coagulant in the treatment process, Polymer (Poly-aluminium chloride, liquid) applied at a concentration of 23% and Chlorine Gas (in cylinders) used at a concentration of 99%, or alternatively, Calcium Hypochlorite at a concentration of 65%. (Table 2.15) highlights treatment plants in Khartoum.

Table 2.15. Water treatment plants in khartoum and employed treatment processes

Plant name	Design capacity (m3/day)	Operation capacity (m3/day)	Construction date (age)	Process	Source
Mogran	90000	84750	1964	Flash mixer, Circular Clariflocculator, Sand filter, storage tank, H.L. Pump	B.N
Burry	16920	18200	1925	Flash mixer, Circular Clariflocculator, Sand filter, storage tank, H.L. Pump	B.N
Soba	100000	101516	2009	Flash mixer, Circular Clariflocculator, Sand filter, storage tank, H.L. Pump	B.N
Jabal Awlia	68000	28000	2010	Flash mixer, Pulsater, Sand filter, storage tank, H.L. Pump	W.N
Toty	4800	4000	1983	Flash mixer, Circular Clariflocculator, Sand filter, storage tank, H.L. Pump	B.N
Bait almal	27000	0	1964	Flash mixer, Circular Clariflocculator, Sand filter, storage tank, H.L. Pump	W.N

Table 2.15. (Continued)

Plant name	Design capacity (m3/day)	Operation capacity (m3/day)	Construction date (age)	Process	Source
Bahary(A)	9600	0	1954	Flash mixer, Circular Clariflocculator, Sand filter, storage tank, H.L. Pump	B.N
Bahary(AB)	180000	186850	1976-1999	Flash mixer, Circular Clariflocculator, Sand filter, storage tank, H.L. Pump	B.N
Shamal Bahary	50000	41000	2010	Flash mixer, Rect. Cal., Sand filter, storage tank, H.L Pump	M.N
Um kutty	1200	415	2010	Compact	M.N

2.2.10 Total Water Availability

Sudan's water allocation from the Nile is 20.5 BCM, measured at Sennar. Additionally, non-Nilotic rivers contribute 7 BCM, and groundwater sources provide another 4 BCM. According to the Food and Agriculture Organization of the United Nations (FAO), the annual per capita water withdrawal is estimated to be 1,020 cubic meters.

Table 2.16. Sudan Water Availability (FAO)

Water resources	Quantity (BCM)	Constraints
Sudan present share from the Nile water agreement (at central Sudan)	20.5	Seasonality, limited storage facilities, expected to be shared with riparian's.
Water from wadis	5.0 -7.0	High variability in amounts, short duration flows, difficult to monitor or harvest, some shared with neighbors.

Table 2.16. (Continued)

Water resources	**Quantity (BCM)**	**Constraints**
Renewable groundwater	4.0	Deep water, high cost of abstraction, remote areas, lack of infrastructure.
Present total	30.0	
Expected from reclamation of swamps	6.0	High capital investment social and environment problems expected.
Total	**36**	

But according to the ***Sudanese Council for Environmental Affairs,*** the volume of the Internal Renewable Water Resources (IRWR) and Inflow in Sudan is as follows:

Table 2.17 Sudan water availability (SCEA)

Description	**Volume (million m³/year)**
Internal Renewable Water Resources (IRWR)	4,000
Total Inflow (mainly Nile system, from Eritrea)	99,300
Total Natural Renewable Water Resources	103,300
Natural Surface Water Outflow to Egypt	84,000
Estimated Evaporation	19,300
Accounted Water Resources	***37,800***

2.2.11 Water Availability Rates Versus Existing Needs and Consumption Patterns in Residential and Industrial Sectors

The water resources in Sudan are significantly influenced by various climatic and geographical factors. These factors affect both the spatial and temporal distribution of water resources, consequently influencing their usage in different regions. The key characteristics are as follows:

Sudan has a continental climate, with annual rainfall varying widely from about 800 mm in the southern regions to nearly zero in the northern desert areas.

Approximately 65% of Sudan falls within an arid zone, experiencing water scarcity for most of the year.The Nile River traverses Sudan from south to north. Sudan is divided into three primary drainage basins: the Nile Basin, the Red Sea Basin, and the Lake Chad Basin, which together cover around 92%, 4.3%, and 3.4% of the country's total area, respectively.

Scattered groundwater basins are found beneath approximately 60% of Sudan's surface area.About 80% of the Nile's water flow occurs within a three-month period (August-October) due to the hydrological cycle. Water scarcity during most of the year affects major rain-fed agricultural regions, including the extensive mechanized farming sector (about 100 million hectares). Rainfall distribution is uneven, averaging only 70 mm in populated and traditionally farmed areas (observed at stations like El-Obeid, Nyala, and Gedaref). Rainfall is directly utilized for cultivating around 30 million feddans annually, in addition to sustaining vegetation cover and recharging groundwater.

In summary, the efficient use of water resources is vital for development and is governed by their spatial and temporal characteristics.

2.2.11.1 Water Sources Usage By Sector

Water resources in Sudan are vital across various sectors, including agriculture, drinking water, domestic use, electricity generation, transportation, industry, and other human welfare needs such as tourism and environmental conservation. As in most countries, agriculture is the dominant consumer of water resources. However, as Sudan develops and lifestyles change, water demand for other purposes is increasing. The table bellow illustrates the various uses of water resources in Sudan.

Table 2.18: Sudan Water Usage by water Source and Sector

Water Source	Usage	Current Quantity (billion m³/year)
Nile Water	Agriculture, forests, human and livestock drinking water	12.56
	Industry and others	0.27
Subtotal		**12.83**
Surface Water (other)	Agriculture, forests, human and livestock drinking water	0.40
	Industry and others	0.07
Subtotal		**0.47**
Groundwater (annual recharge)	Agriculture, forests, human and livestock drinking water	0.30
	Industry and others	0.40
Subtotal		**0.70**
Total		**14.00**

These figures represent the current usage of water resources across different sectors within Sudan.

2.2.11.2 Water Needs for Irrigated Agriculture

The area equipped for irrigation in Sudan is approximately 4 million feddans (around 13% of the total cultivated area). However, this accounts for more than 50% of the total agricultural production value. Crops such as cotton, sugar, wheat, and various types of sorghum are produced in these areas. The annual water consumption for irrigation is estimated at around 12.85 billion cubic meters (BCM) from the Nile and its tributaries, 0.4 BCM from non-Nile surface water, and approximately 0.3 BCM from groundwater. Water availability is a limiting factor for agricultural expansion in Sudan, which has extensive areas suitable for irrigation estimated at over 80 million feddans. The country plans to fully utilize its share of Nile water, reduce losses in southern swamps, and fully exploit renewable groundwater and non-Nile surface water to potentially increase irrigated land to about 6.8 million feddans by 2020, an increase of around 3.5 million feddans over the current area.

2.2.11.3 Current Water Needs for Hydroelectric Power

In 1993, the National Electricity Corporation of Sudan conducted a study to develop a comprehensive plan for increasing hydroelectric power generation. The study indicated that it is feasible to generate about 5,800 megawatts (MW) of electrical capacity and approximately 36,000 gigawatt-hours (GWh) annually by utilizing suitable sites on the Nile and its tributaries by 2020. Key projects include the construction of dams such as the Merowe Dam on the main Nile, which was completed in March 2009 and generates 4,500 GWh/year. However, this additional storage will result in an increase in evaporation of about 6.15 BCM/year. Additionally, there are plans to construct smaller dams on the Nile's tributaries for electricity generation.

2.2.11.4 Water Needs for Domestic and Industrial Uses

Other water needs, including drinking water, industrial uses, and livestock, are relatively minimal, amounting to no more than 0.74 BCM per year.

2.2.12 Efficiency of Current Water Usage

As shown in (Table 2.18) , approximately 94.7% of total water consumption is allocated to agriculture, while domestic and industrial uses account for 4.60% and 0.40% respectively. This highlights the significant role of agriculture in water consumption and the necessity to focus water conservation policies on the agricultural sector. The four major irrigation schemes (Gezira, Managil, Rahad, and Suki) along with government-operated pump projects consume about 11 BCM, which is about 72% of the total water used for irrigation (or about 69% of the total water consumption).

It is important to note that agricultural production policies have negatively impacted water usage and the efficiency of irrigation projects. Some of these issues include:

- Misconceptions among beneficiaries about the abundance of water and the belief that it can always be supplied upon request, leading to careless use.
- Underestimation of the value of water and its exclusion from project efficiency evaluations.
- Increased pressure on irrigation canals, leading to prolonged flow periods and increased risk of canal breaches.
- Expansion of cultivated areas, which reduces the time available for canal drying and increases the growth of weeds beyond the capacity of removal equipment.
- Early withdrawal from reservoirs, reducing hydroelectric power generation potential during the dry season and lowering the stored water needed to cope with annual variations and weather changes.
- Over-exploitation of water in the field due to competition for water from a single canal, leading to persistent opening of outlets and making it difficult to maintain levels in small canals.
- Addition of large areas outside the design capacity of canals, resulting in water shortages in some areas within the planned scheme.

These negative impacts have affected water usage efficiency and the economic return per unit of water used. For example, the efficiency of major irrigation projects is estimated at around 54%. Improving water use efficiency in irrigation could provide substantial additional water that could be used to cultivate more land or for other uses.

Table 2.19.Summary of water needs by sector

Sector	**Current Quantity (billion m³/year)**
Agriculture (Nile Water)	12.85
Agriculture (Non-Nile Surface Water)	0.40
Agriculture (Groundwater)	0.30
Subtotal (Agriculture)	**13.55**
Hydroelectric Power	-
Domestic, Industrial, Livestock	0.74
Total	**14.29**

2.2.13 Data on Generated Household Wastewater in Sudan

Table 2.20: Part A: estimation of total generated household wastewater in Sudan, 2020 (United Nations, 2020)

Population [1000s]	On-premises* water supply [%]	Off-premises* water supply [%]	On-premises* water supply [litres/person/day]	Off-premises* water supply [litres/person/day]	Total domestic water use [million m3/year]	Proportion of domestic water use converted into generated wastewater [%]	Total generated household wastewater [million m3/year]
43.849 (E1)	38.8% (E2)	61.2% (E3)	159 (R4)	20 (A5)	1.184,118 (C6)	80% (A7)	947,294 (C8)

Table 2.21 Part B: estimation of generated household wastewater by sanitation facility type in Sudan (UN, 2020)

Sanitation facility coverage				Estimated household wastewater generated by sanitation facility type					
Type of sanitation facility	**Proportion of population [%]**			**Volume [million m^3/year]**			**Proportion by volume [%]**		
Stream 1: Piped sewers	1,0%	E	[9]	21,018	C	[14]	2,2%	C	[14] / [8]
Stream 2: Septic tanks	6,3%	E	[10]	127,475	C	[15]	13,5%	C	[15] / [8]
Other improved facilities	38,0%	E	[11]	658,626	C	[16]	69,5%	C	[16] / [8]
Unimproved facilities	30,7%	E	[12]	78,697	C	[17]	8,3%	C	[17] / [8]
Open defecation	24,0%	E	[13]	61,479	C	[18]	6,5%	C	[18] / [8]
			TOTAL:	**947,294**	C	[8]	100,0%	C	

Table 2.22 Part C: household wastewater management chain (Sudan, 2020)

Stream	Description	Volume (million m^3/year)	Proportion (%)
Estimated Household Wastewater Generated			
Stream 1	Households connected to sewers	21,018	2.2%
Stream 2	Households connected to septic tanks	127,475	13.5%
Other Households	Households using all other types of sanitation	798,802	84.3%
Total Generated		947,294	100%
Estimated Household Wastewater Collected			
Stream 1	Collected from piped sewers	21,018	2.2%
Stream 2a	Collected at septic tanks and off-site treatment	31,869	3.4%
Stream 2b	Collected at septic tanks and on-site treatment	31,869	3.4%
Total Collected		84,755	8.9%
Estimated Household Wastewater Safely Treated			
Stream 1	Treated from piped sewers	0	0%
Stream 2a	Treated at septic tanks and off-site treatment	0	0%
Stream 2b	Treated at septic tanks and on-site treatment	31,869	3.4%
Total Safely Treated		31,869	Insufficient Data

2.2.14 Existing Wastewater Infrastructure in Sudan and Current Situation Analysis

Sudan has only one fully operational sewerage system, which was established in 1959 in the older districts of Khartoum, excluding areas like Omdurman and Khartoum North. The majority of other areas rely on open-air and pit latrines. In more affluent residential neighborhoods, septic tanks and soak-away wells are utilized, but these systems carry the risk of contaminating both subsurface groundwater and deeper aquifers.

There are two sewage treatment plants in the region, but only one is currently functional, serving a small portion of Khartoum's older districts. This plant was initially designed as a trickling filter system. The treated effluent was diluted and used to irrigate the Green Belt, a 7,000-feddan eucalyptus plantation located south of the city. Around 30 years ago, the Green Belt was removed, and evaporation ponds were introduced to the treatment process.

2.2.14.1 Sanitation Systems Used in Sudan

The majority of sanitation systems used in Sudan and Khartoum State are traditional on-site systems, which include the following:

1. Pit Latrine
2. Aqua Privy
3. Septic Tank and Well
4. Bucket System, phased out in central Khartoum in areas serviced by sewage networks long ago because it is unhealthy, expensive, labor-intensive, and requires large areas for burying fecal material.
5. Open Defecation still exists in the outskirts of cities and villages. Wastewater in some areas of Khartoum is still disposed of using one of the three methods including Cesspool and Scattering System, Evaporation Beds System and Kana Beds System

These mentioned systems are considered unsuitable for public health requirements as they contribute to the breeding of mosquitoes, flies, and harmful insects, leading to environmental degradation and the spread of environmental diseases. It is unfortunate that 90% of the population in the densely populated capital continues to use traditional systems that degrade the environment and promote the spread of flies, mosquitoes, and other insects harmful to human health, often leading to air, water, and food contamination by pathogenic germs.

Given this situation and the importance of the capital, the government, represented by the Khartoum Municipal Council, initiated the first phase of a sewer network project in central Khartoum. This project still only covers about 6% of the population and the area of Khartoum. The project was designed to serve only 80,000 people, providing 40 gallons of water per person per day, with a daily flow rate of 3.2 million gallons per day before the recent network extensions. Below is a brief overview of the project.

2.2.14.2 Khartoum Sewage Project

To implement the Khartoum Sewage Project, a contract was signed with the British company Marples and Ridgeway around 1953 to execute the project, with the British consulting firm Horden Hanfres designing and overseeing the project's execution.

This company executed the project in a small area in central Khartoum, bordered to the north by Nile Street, to the south by the railway and Khartoum (1, 2, 3), plus the industrial area. In 1962, the Al-Amarat extension was added, with the area bordered to the west by Al-Mugran and to the east by the Khartoum International Exhibition. The network was recently extended to cover the areas north of the central and local markets and Al-Dioum and other areas.

Any sewage project typically consists of the network, pumping stations, treatment fields, and final discharge. The company completed a network extending 146 km with asbestos pipes ranging in diameter from 7 to 32 inches, most being 7 inches. There were over 1,186 manholes placed every 100 meters or at direction changes, distributed over approximately 13 zones, each served by a pumping or lifting station.

The most important pumping stations are Station 6 near the Al-Muslimiyah Bridge, which receives flows from most small stations; Station 9 on Freedom Street; Station 10 in Al-Mugran; Station 12; Station 4 near the Satellite Station; Station 5 near the electricity station on Parliament Street; Station 3 (Sheikh Fayed) on University Street;

Station 1 inside the Ministry of Defense; Station 7 at the electricity station near the old police college in Al-Shati' neighborhood; Station 21 in Al-Qouz; Station 30 in Soba; Station 20 in Al-Intisar; Station 8 in Khartoum (1, 2); and Stations 15 and 14 in Al-Intisar.

The number of stations exceeds 16 after recent additions, with the length of the sewage network in Khartoum now over 325 km and the pumping lines over 66 km. The number of manholes is estimated at 3,445, all of which were added through the efforts of the Khartoum Water and Services Company. It is noteworthy that the large number of stations increases the cost of the project as each station consists of a dry well, a wet well, and three pumps that operate alternately. The project was designed contrary to the natural slope, leading to deeper excavations and thus more lifting stations. The purpose of all this was to avoid discharging into the Nile, which is used for drinking water.

The British company also implemented the treatment field in the Al-Qouz area, using a traditional treatment system (Conventional Filtration Plant). The field includes administrative offices, a chemical analysis lab, an entrance to the units with screens and grit channels to capture sand and dirt, two sedimentation tanks, 16 filters, four secondary sedimentation tanks, a station to pump treated water to the green belt, which was then located south of Khartoum, sludge digesters, and several drying beds.

Sewer services continued to operate well in this part of Khartoum until the city expanded horizontally and vertically, tripling the amount of wastewater. As a result, the Al-Qouz treatment field was closed due to its limited capacity, and the current treatment field in Soba, which operates using oxidation ponds, was used instead. To improve treatment and address some shortcomings, the Khartoum Water and Services Company attempted to establish a new field using the activated sludge system, known for its high efficiency, but this field was never operational due to technical and civil engineering errors.

It is noteworthy that this project began in 1953, and the lifespan of asbestos pipes is no more than 15 to 20 years. This project has been operating for over 55 years with an asbestos network, which has deteriorated, leading to overflows and blockages and increasing maintenance and operational costs. Repeated power outages complicate the situation further.

This project was designed to serve only 80,000 people, but due to the unexpected vertical and horizontal urban expansion of Khartoum and the massive increase in population, the network's capacity has significantly decreased. Therefore, it has become necessary to replace the current network with a new one that considers the current and future population growth and pressure, and to extend the network to cover as many residents as possible, replacing the outdated traditional systems that are the primary cause of environmental degradation and disease spread.

In Khartoum North (Bahri), the sewage system covers only about 2% of the city's area, limited to the industrial area and part of the Kober residential area. This project was designed, funded, and executed by the American aid program around 1961. Recently, the Nabta network, extending over 70 km, was added.

2.2.14.3 Khartoum North Sewage Project:

The Khartoum North Sewage Project was designed to be executed in three phases:

- Residential Area of Khartoum North
- Industrial Area
- City outskirts and suburbs

The project was designed by the American company Daniel Mann Johnson and Mendenhall, funded by American aid, and executed by C.H. Level, the contractor. Only the first phase, the industrial area, was executed. The company stopped working in 1967 after Sudan severed relations with the United States during the Suez Crisis. The project included a network that was initially 29,300 meters long, now extended to 43,844 meters after recent additions, with asbestos pipes ranging from 8 to 32 inches in diameter. The network has 669 manholes, connecting over 300 factories with 6,325 meters of 6-inch pipes. The company also established three stations: two lifting stations and one main pumping station. One lifting station serves the southern part of the industrial area, the second serves the northern part, and a third station was added later to serve the Kober area. These three stations discharge into the main station, which pumps the industrial wastewater through two pipelines, 16 and 18 inches in diameter, over a distance of seven kilometers to the Haj Yousif treatment field. The company established the Haj Yousif treatment field on a 900-acre site, including the following:

- Administrative offices, a chemical analysis lab, a warehouse, and bathrooms.
- An entrance to the units with screens and a water measurement device.
- An aerated grit chamber to remove sand.
- Two clarifiers, four digesters, and 16 drying beds.
- Three sludge pumps and two compressors for washing sand and digesters.
- A well to supply water to the farm and units.

This field was designed to handle 6 million gallons per day and included the construction of stabilization ponds for biological treatment in three stages: the first four ponds are anaerobic, the second are facultative, and the last two are maturation ponds. A final station for final disposal was also built, originally intended to discharge into the Helat Koko project canal. However, as the industrial wastewater lacked microorganisms necessary for biological treatment, it was not suitable for agriculture or irrigation, and the Helat Koko authorities refused to use it for irrigation or agriculture. Therefore, the water was left to evaporate and be absorbed by the vast lands west of the farm. It is also worth noting that the Nabta area’s water was connected, with its network extending about 74 km, and the Haj Yousif treatment field was converted to a new field using the SBR system, with treated water being pumped to Hattab.

The treatment field for the Khartoum North sewage project began operation in October 1971 and was inaugurated by Engineer Abdel Rahman Ahmed Al-Aqib and Minister of Labor and Administrative Reform, Mr. Abdel Rahman Abdullah. It has been operating with industrial wastewater, which is difficult to treat due to the lack of microorganisms, affecting the network and equipment over the years. The second phase, covering the residential area

2.2.14.4 Current Construction Endeavors

The Khartoum Authority has given high importance to the management of wastewater, particularly with the creation of the Khartoum State Sanitary Corporation (KSSC) in 2009. The KSSC has assumed the duties previously held by the Sewage Administration. The swift growth of recently designed neighborhoods in Khartoum has emphasized the necessity for strong and secure wastewater disposal systems.

Three essential projects have been conceived, formulated, and are presently in the process of being built since the establishment of KSSC:

Khartoum North (Bahri) Sewerage Network (part of the old city) includes 900mm diameter rising mains. The length of these mains is 6.5 km and they have a pressure rating of 16 bars while having a stiffness of 5000.

The trunk mains have different sizes, beginning from 1000mm at the upper sections and increasing downstream to 1400mm, then 1800mm and finally 22000mm.

The project includes four pump stations for lifting waste water and one primary pumping station which all serve the purpose of conveying collected wastewater to Wad Dafea Treatment Plant through a 6.5 km long trunk sewer that is connected to a network of pressure mains with a diameter of 900mm.

Installation works for sewers are also planned over a distance of 24km with pipe diameters ranging between 200 mm – 800 mm. Moreover, there is another phase in this project where an additional hundred kilometer network will be constructed together with six extra pumping stations as well as more trunk main lines.

Another endeavor is upgrading and rehabilitation of the Wad Dafea Wastewater Treatment Plant which will include restoration of the headworks for initial treatment.

The current biological treatment lagoons will be replaced by a Sequential Batch Reactor (SBR) system, which will make use of four cylindrical sludge tanks that were previously utilized for sludge digestion.

The facility has been specifically engineered to process 17,000 cubic meters per day of wastewater, which contains 3,000 milligrams per liter of chemical oxygen demand (COD) and 1,500 milligrams per liter of biochemical oxygen demand (BOD). After undergoing treatment, it is anticipated that the effluent will contain around 40 mg/L of BOD and 90 mg/L of COD.

Wad Dafea Hatab Pressure Mains is another project that consists of a pipeline with a diameter of 500mm that spans a distance of 24 km. The objective of these ascending conduits is to convey processed sewage from the Wad Dafea Treatment Plant to a site situated in the northeastern vicinity of Hattab Village. The reclaimed wastewater will be utilized for the purpose of irrigating a forest belt spanning an area of 6,000 feddans.

The pipeline was originally constructed with a diameter of 1,000mm and a length of 33 km to transport wastewater to the specified location northeast of Hattab. Nevertheless, the project is being implemented in stages.

The primary objective of the initial phase is to convey the existing quantities of wastewater, which vary from 13,000 m^3/day to 17,000 m^3/day, via a 500mm pipeline to a temporary forest site situated 24 km away from the Wad Dafea Treatment Plant.

The project is projected to have a cost of 35 million SDG, which was equivalent to around $10 million.

To sum up, Sudan’s wastewater infrastructure requires immediate and significant investment, renovation and extension to cope with rapid urbanization and population explosion. These enhancements are essential not only for the betterment of public health but also to protect water resources and conserve the environment in the country. There is only one plant serving a small part of Khartoum currently while another one does not function at all. However, there is almost no such thing as an effective sewage treatment system in Sudan.

CHAPTER THREE
METHODOLOGY AND DATA ANALYSIS

3.1 Materials and Methodology

The study used a mixed methodology incorporating both quantitative and qualitative procedures. Understanding reality in an objective way requires approaching it from different angles, as individual representations may not be comprehensive enough to reflect the complexity of reality (Hesse-Biber & Johnson 2022). The combination of these methods provide a good insight into the meaning and necessity of a public policy as well as evaluating and providing realistic frameworks to enforce it. To develop a practical and feasible strategy, it is important to acknowledge that national policy for domestic wastewater management is complex and multifaceted hence using a mixed-methods approach.

The study aimed at having a methodology which combines qualitative and quantitative methods to effectively reflect the complex nature of wastewater management systems. The data used in this study encompass various key aspects:

- Investigation of Water Sources and Basins: This gives the background context by investigating water sources and basins in Sudan thereby providing insights into the geographical/hydrological foundations upon which wastewater management systems operate.
- Water Availability, demands, and Consumption Patterns Analysis: This involves examining data and statistics on water availability rates, current demand levels, consumption patterns in residential areas as well as industrial sectors. This helps us understand demand dynamics and resource use patterns.
- Evaluation of current wastewater management infrastructure: A detailed evaluation of already existing wastewater management infrastructures was conducted including collection, treatment, disposal or possible reuse mechanism . It shows how these systems can work optimally under certain conditions.

- Evaluation of Past Wastewater Management Projects: Focusing on past program initiatives related to wastewater handling, treatment or reuse specifically within Sudanese framework. These projects are highlighted particularly in order to get relevant insights from them towards new action plans.

An exponential growth model was used to predict Sudan's population growth between 2024-2030. It involved starting with a population of 49,358,228 people by 2024 at an annual rate of growth of 2.6 %. This model assisted in determining the population estimates of each year, which served as the basis for projection of future wastewater generation to ensure that the wastewater management approach is in line with expected demographic shifts.

The next step of analysis was to examine how much it would cost to have an appropriate wastewater management system in place within Sudan. The estimates were made using figures supplied by the Sudanese Higher Council for Environmental Affairs while also taking into consideration likely changes in population size and waste water generation.

In conclusion, the study consolidates these appraisals to come up with a comprehensive national action plan for Sudan on wastewater management between 2024 and 2030. The proposed plan is all-encompassing touching on economic aspects, regulatory framework, public awareness as well as enforcement strategies.

This research aimed at conducting an extensive review of water resources, infrastructure development, investments and environmental factors thereby producing practical recommendations that may be used to inform policy making and enhance sustainable development initiatives in Sudan. The paper discusses a variety of datasets and mixed research methods so as to have a comprehensive evaluation of wastewater management in Sudan. The study collected primary data from authoritative documents and reports obtained from key institutions in Sudan like Ministry of Irrigation and Water Resources; Ministry of Electricity and Dams; Higher Council for Environmental Affairs; regional water authorities among others while secondary data was acquired from reputable international bodies such as United Nations Environment Programme (UNEP), Food And Agriculture Organization (FAO) and World Health Organization (WHO).

Resources from Fanack Water platform were accessed online including articles on water resources, water quality, water use, water management and future prospects for water sector in Sudan. These data provided significant insights into the current state and challenges facing Sudan’s water resources and wastewater infrastructure..

CHAPTER FOUR
RESULTS AND CONCLUSIONS

4.1 Evaluation of the Water Quality of Sudan's Water Resources

Sudan is in mainly arid and semi-arid regions, thus having water as its critical source for agriculture and human consumption. These water sources include rivers, lakes, seasonal streams as surface waters; groundwater and other non-conventional resources which include desalination or wastewater reuse. The strategic nature of this resource necessitates that appraisal of its condition towards sustainability especially when there are problems such as lack of enough water due to increases in population and water damend.

4.1.1 Water Quality of Surface Water Bodies

Mainly, Sudan depends on surface water which comes from the Nile and its tributaries. In Sudan, the complexity of the Nile system is characterized by major tributaries like Blue Nile, White Nile and Atbara River that serve as important water sources for the country. Surface water quality is controlled by many factors such as seasons, rainfalls or agricultural activities along with other human activities such as industries.

4.1.1.1 Seasonal and Geographical Variations

Blue Nile river has a typical fluctuation during the year, represented by a hydrograph in the shape of a bell that is associated with rains in Ethiopian highlands. The highest flows are recorded during rainy season which start from July till October and then there is a sharp decrease until November when dry season starts and lasts until June. These temporal variations affect mainly water quality through turbidity, which can rise up to 39,000 NTU at times of increased flow.

White Nile experiences obstructions during the flood season. This is frequently caused by blue Nile which often leads to flooding in higher regions. Even though it has stable water quality in general; nitrogen levels can change greatly at times of seasonal floods.

Atbara and Setit-Tekeze rivers do not flow throughout the year because they are highly affected by slopes and contribute mainly during floods. They may have moderate flow volumes but carry huge quantities of mud that make the water become unclear and degrade its quality as a whole..

Near Sudanese-Egyptian border (around 84 km3 or 33 billion gallons), where it receives about 84000 million cubic meters annually at its peak discharge; the main nile varies greatly over time due to various factors such as upstream contributions and local sources of pollution which affect both quantity and chemical composition.

4.1.1.2 Parameters for Assessing Water Quality

The Blue Nile has high turbidity affecting the Nile with average annual values ranging from 8 to 39,000 NTU. These turbidity variations show a remarkable presence of suspended sediments, especially during the rainy season. Furthermore, Main Nile and White Nile generally indicate high levels of turbidity during peak flows.

The pH ranges for the waters of the Nile are between 7.7 and 8.7 which is good for drinking purposes but might affect aquatic life and disinfection efficacy in water treatments.

The electrical conductivity levels are below 370 µS/cm, indicating the presence of a moderate amount of dissolved salts. This range is generally acceptable for most uses but can be problematic for some particular agricultural crops.

Water is moderately fresh with total dissolved solid concentrations ranging from 93 to 192 mg/L. Gradual accumulation of salt resulting from the presence of minerals in the irrigation water necessitates continuous monitoring; otherwise, soil salinization could occur over a long period of time.

Seasons influence the levels of nitrates, sulphates and phosphates which are nutrient concentrations. In most cases, nitrates, phosphates and sulfates will reach peak levels during the rainy season due to agricultural runoff. To note, major Nile has a potential nitrate level of 28.36 mg/L that can lead to eutrophication and subsequent health hazards.

4.1.2 Groundwater Quality

Groundwater is a critical resource in Sudan, especially during the dry season when surface water is scarce. The quality of groundwater is influenced by geological factors, human activities, and natural recharge processes.

4.1.2.1 Nubian Sandstone Aquifer System

This aquifer, which Sudan shares with Egypt and Libya, is the largest and most important in the country. It has a significant water storage capacity of 503 km^3 and receives an annual recharge of 1 km^3. The water quality in this aquifer is generally good, with minimal contaminant levels. However, concerns exist regarding over-extraction and potential surface contamination.

4.1.2.2 Water Quality Parameters in Sampled Areas

Soba West Area groundwater has a slightly alkaline pH of 8.9, with a TDS level of 252 mg/L, indicating moderate mineralization. Nitrate levels, currently at 1.10 mg/L, are within acceptable limits. However, continuous monitoring is necessary to prevent potential contamination.

Kalakla Area groundwater has a pH of 7.3, with higher electrical conductivity (460 µS/cm) and TDS (322 mg/L) compared to Soba West. Total hardness is significantly higher at 194.9 mg/L, which may result in scaling in pipes and household appliances. Additionally, the higher concentrations of chloride (9.94 mg/L) and sulfate (22.2 mg/L) require attention to prevent long-term impacts on human health and the environment.

4.1.3 Non-Conventional Water Sources

Currently, Sudan's reliance on non-conventional water sources, such as desalination and wastewater reuse, is limited but holds promise for future expansion, particularly in urban areas like Khartoum. The current desalination output is low, at 0.02 million cubic meters per day, and wastewater reuse is primarily used for agricultural purposes. Expanding these resources could significantly ease the pressure on traditional water sources.

4.1.4 Surface Water Treatment and Management

The water from the Nile that is used in many urban areas like Khartoum undergoes different treatment processes before it can be distributed. These treatments involve primary treatments, coagulation, flocculation, filtration, and chlorination. Therefore, the effectiveness of these measures depends on the quality of raw water which varies with season as well as upstream pollution.

4.1.4.1 Results of Analysis and Notable Discoveries

During the peak of the wet season, turbidity levels in the Blue Nile reach 39,000 NTU, making it extremely challenging to treat water. To manage this level, a treatment plant must employ effective coagulation and sedimentation processes which are expensive to run.

Seasonally, nutrient levels such as nitrates and phosphates tend to change in both White and Blue Niles. Such variations can lead to sporadic problems with water quality particularly during rainy seasons that increase runoff moisture loading nutrients.

Majority of groundwater sampled from different areas meets drinking water standards with higher degrees of hardness and dissolved solids noticed in places like Kalakla thereby becoming potential long-term human consumption or agricultural use limitations.

The broad-based water management response is hindered by lack of adequate up-to-date information on water quality especially for non-Nilotic streams and smaller drainage basins. Comprehensive monitoring urgently needs be started along with updated data collection for support of effective water management strategies.

There is an insufficient treatment capacity: For instance, existing aging infrastructure for water treatment may not meet rapidly expanding urban areas where water demand is rising considerably. There are critical needs to expand and upgrade treatment plants besides adopting advanced technologies to maintain required quality standards.

4.2 Evaluation of Present Water Availability, Requirements, and Utilization in Sudan

Water is a vital resource in Sudan; however, it is challenging to manage water sustainably because of its adverse climatic conditions and complex geography of the country. Understanding current trends of water accessibility, requirements and use will help address problems associated with water scarcity, agriculture needs as well as demands for urbanization worldwide. This report presents an overview of Sudan’s water situation highlighting the gaps between what is available and what is being used then gives an insight into the future needs and potential areas for improvement.

4.2.1 Present Water Availability

Sudan’s Nile River allocation determines much of its overall water availability together with other contributions from non-Nilotic rivers as well as aquifers. At Sennar, official records put this figure at about 20.5 billion cubic meters on an annual basis (BCM). In addition to this, non-Nilotic rivers contribute approximately 7 BCM while underground sources account for about 4 BCM out of these totals.Thus making current supply for the nation to be close to 30 billion cubic meters per annum. Nevertheless, increase in reclamation efforts such as marshlands would raise this level by up to 36 BCM. However, this would be at great cost in terms of economics, social impacts and environmental implications.

It is crucial to acknowledge that the accessibility of these water resources is contingent upon several limitations. For example, the water supply of the Nile River is extremely dependent on the seasons, with 80% of its volume being discharged during a concentrated three-month period from August to October. The presence of seasonal variations, along with the scarcity of storage infrastructure and the need to distribute water among neighboring nations, adds complexity to water management endeavors. Rivers that are not part of the Nilotic system, although they provide a substantial amount of water, are known for their unpredictable and brief periods of flow, which makes it challenging to efficiently monitor and utilize their resources. Groundwater encounters difficulties stemming from its significant depth, the exorbitant expense associated with extraction, and the absence of infrastructure in distant regions.

In addition, the Sudanese Council for Environmental Affairs presents an alternative viewpoint on water availability. They highlight that the Internal Renewable Water Resources (IRWR) are estimated to be 4,000 million cubic meters per year, with total inflows, primarily from the Nile system, reaching 99,300 million cubic meters annually. Once the natural outflows of surface water to Egypt and the expected losses due to evaporation are taken into consideration, the overall amount of water resources is reduced to 37,800 million cubic meters.

4.2.2 Analysis of Water Availability and Consumption Patterns

The availability and location of water resources in Sudan are highly influenced by the country’s continental climate and geographical considerations. Rainfall amount varies widely: it is about 800mm in the southern parts and nearly zero in the northern deserts. The availability of water differs, however, this also affects its utilization across various industries.

4.2.2.1 Water Usage by Sector

Agriculture in Sudan is the primary user of water resources, consuming around 12.56 billion cubic meters (BCM) of Nile water each year for purposes such as irrigation, forestry, and animal drinking. Furthermore, an extra 0.67 billion cubic meters (BCM) of water is extracted from various surface water and groundwater sources, resulting in a cumulative agricultural water use of 13.55 BCM annually. Considering that agriculture accounts for more than 94% of the overall water usage in the country, it is evident that any water management policies should give priority to this sector.

Domestic, industrial, and livestock sectors combined require around 0.74 billion cubic meters (BCM) of resources each year. Although this accounts for a relatively modest portion of overall water use, the demand in these regions is projected to increase as the nation continues to urbanize and industrialize.

Sudan's hydroelectric power plans have substantial ramifications for water utilization. The Merowe Dam, a project that produces 4,500 GWh/year, causes a rise in evaporation losses. These losses are projected to be around 6.15 BCM per year, resulting in a decrease in the total amount of water available for other purposes.

4.2.2.2 Water Requirements for Irrigated Agriculture

The irrigated area of Sudan covers roughly 4 million feddans, which represents around 13% of the total cultivated area. However, this relatively small portion of land contributes to more than half of the country's agricultural production value. The present irrigation water usage is approximately 12.85 billion cubic meters (BCM) sourced from the Nile and its tributaries, with an additional 0.4 BCM obtained from non-Nile surface water and 0.3 BCM from groundwater.

Sudan possesses significant capacity for the expansion of irrigated agriculture, as it has more than 80 million feddans that are considered appropriate for irrigation. However, harnessing this potential necessitates the complete utilization of the nation's Nile water allotment, minimizing water losses in the southern wetlands, and fully capitalizing on renewable groundwater and non-Nile surface water resources.

4.2.3 Enhancing Water Usage Efficiency and Overcoming Challenges

The efficiency of water utilization in Sudan, specifically in the agricultural domain, is a crucial concern. The primary irrigation schemes, including Gezira, Managil, Rahad, and Suki, in addition to government-operated pump projects, utilize around 11 billion cubic meters (BCM) of water each year. This represents around 72% of the water utilized for irrigation, or 69% of the overall water consumption.

Nevertheless, there are various obstacles that hinder the effectiveness of water utilization in agriculture.

A mistaken belief held by beneficiaries that water is an infinite resource that can be easily supplied as needed. This misconception leads to wasteful and non-productive utilization of water.

More often than not, water is under-appreciated, with its assessment in projects being done without considering it, leading to wastage and poor management.

High pressures against the irrigation canals cause longer flow duration thus increasing the chances of canal breaching and subsequent loss of water. Increase in cultivated areas without consideration on existing infrastructure lead to over-abstraction from water resources thus additional inefficiency.

The general effectiveness of big irrigation projects in Sudan stands at about 54%, indicating a significant room for improvement in this sector. A better use of water within the irrigation framework can generate additional water resources that can be used to expand farming land or support other businesses.

4.2.4 Significant Discoveries and Valuable Insights

The availability of water in Sudan is characterized by significant seasonal and geographical constraints because most of the Nile's water flows occur within three months only. Thus, efficient management as well as storage alternatives aimed at guaranteeing year-round supply of water are required.

Agriculture is the main consumer of water with over 94% of total domestic withdrawals. Water policies should therefore prioritize improvements in efficiency here so that other allocations may be made.

: In large, Sudanese irrigation schemes, the extent of utilization is quite low at about 54%. Improved efficiencies could derive from addressing issues like mismanagement, underassessment and infrastructure constraints.

There are hydroelectric power and evaporation losses. For example, the Merowe Dam project experiences substantial evaporation losses estimated to be around 6 billion cubic meters per annum. This underscores the importance of careful planning and administration to achieve a delicate balance between energy production and conservation.

As Sudan progresses there will be increased demand for water for purposes beyond agriculture. This therefore points out to need for sustainable implementation strategies on how to manage waters towards meeting expanding population needs as well as growing economies demands.

4.3 Assessment of Sudan's Wastewater Generation and Treatment Capability

Sudan is confronted with major difficulties in controlling its wastewater, especially due to its increasing population, swift urban growth, and insufficient infrastructure. The available information on wastewater generation and processing, while incomplete, establishes a basis for comprehending the present situation and pinpointing areas that need enhancement. This study will measure the current amount of wastewater produced by different sectors (households, factories, agriculture) and assess the capacity of current treatment plants. Furthermore, we will acknowledge the constraints of the existing data, mainly obtained from United Nations publications due to the lack of thorough government documentation.

4.3.1 Present Volume of Wastewater Generation

Sudan's generation of wastewater is strongly associated with its varying water consumption patterns in different sectors. The nation's 43.849 million people produce a significant volume of household wastewater, which is impacted by the access to different types of water supply and sanitation facilities. The information given provides a glimpse into the extent of sewage generation, especially from households.

4.3.1.1 Production of Wastewater from Households

Estimations suggest that Sudan used around 1,184.118 million cubic meters (MCM) of domestic water in 2020. Approximately 80% of the water is transformed into wastewater, resulting in a yearly household wastewater production of approximately 947.294 MCM. This wastewater is classified further according to the sanitation facilities type.

Around 2.2% (21.018 MCM/year) of the overall domestic wastewater comes from homes that are linked to piped sewage systems. Septic tanks contribute to 13.5% (127.475 MCM/year) of the total wastewater produced by households.

Pit latrines and other sanitation systems on-site contribute approximately 69.5% (658.626 MCM/year) of the overall household wastewater. Unmaintained amenities and outdoor defecation together, account for 14.8% (140.176 MCM/year) of household wastewater.

4.3.1.2 Manufacturing and Farm Wastewater Generation

Regrettably, the existing data does not offer precise numbers for the production of industrial and agricultural wastewater. Nevertheless, considering the large amount of water used in agriculture and industry, it is logical to believe that these sectors play a substantial role in generating wastewater, especially in regions with high levels of farming and industrial operations. The absence of specific information in these areas points out a crucial deficiency in Sudan's water management and planning endeavors.

4.3.2 Current Wastewater Treatment Plants and Their Capabilities

Sudan's current wastewater infrastructure is greatly lacking in development and requires immediate upgrades and expansion. At present, there is solely one functional sewage system situated in the historic areas of Khartoum. Established in 1959, this system caters to a limited number of people.

4.3.2.1 Khartoum Sewage Initiative

The Khartoum Sewage Project, which started in the 1950s, still serves as the main support for the city's sewage treatment system. Nevertheless, it was specifically planned to accommodate just 80,000 residents, which is a small portion of the present populace. The setup consists of a series of pipes, pumping stations, and a treatment plant that first used trickling filters and then switched to oxidation ponds. Even with these attempts, the system is old and faces challenges in keeping up with the needs of a quickly expanding city. The initial plant in Al-Qouz was closed later because it reached its capacity limit, leading to the transfer of operations to the Soba facility, which also encounters major obstacles.

4.3.2.2 Project for Sewage Treatment in North Khartoum (Bahri)

In Bahri, in the northern part of Khartoum, the sewage infrastructure is even more restricted, servicing just 2% of the city's total area. The current system mainly caters to the industrial zone and a section of the Kober residential area. The main treatment facility in this area is the Haj Yousif treatment field, which has been created to process 6 million gallons every day. Nonetheless, the industrial wastewater processed in this facility does not have the required microorganisms for efficient biological treatment, leading to difficulties with the quality and disposal of the effluent.

4.3.2.3 Capacity for Treatment at Present

Sudan has very restricted capacity for treating wastewater, and only a small percentage of the wastewater produced is properly treated.

None of the 21.018 MCM/year of waste produced by households connected to sewers is documented as being properly treated, revealing a significant deficiency in the treatment system.

Approximately 31.869 MCM/year is gathered from septic tanks, with on-site treatment being the main approach. Yet, the effectiveness and safety of this therapy are not well-established, leading to worries about possible groundwater pollution.

A large majority of households (84.3%) depend on alternative sanitation methods, a lot of which do not include any official treatment, causing considerable risks to the environment and public health.

4.3.3 Limitations and Challenges Related to Wastewater Data

A precise assessment and planning is hindered by lack of comprehensive government reports on wastewater generation and management in Sudan. The use of estimates and assumptions in United Nations reports underscores the need for more accurate data collection and monitoring systems. Difficulty arises when plans are to be developed without adequate information about the state of things concerning wastewater management and infrastructure expansion.

4.3.4 Discoveries and Noticings

Sudan's present wastewater treatment facilities are highly inadequate because only small fraction of wastewater is adequately treated. There has been rapid growth in population numbers as well as urbanization trends, with the result that existing sewerage systems cannot cope with these.

Common sanitation practices such as open defecation and pit latrines pose major environmental dangers as well as risks to public health. Because septic tanks and soak-away wells are widely used, there is a serious concern about possible groundwater contamination.

To make efficient decisions or controls, there is not enough information on wastewater generation specifically from industries and agriculture sectors in place. As such, evidence-based decision making requires urgent development of comprehensive data gathering strategies.

A lot of money needs to be availed quickly for repair works as well as future expanding the sewerage network in Sudan. These existing systems will not function effectively if they have to take care of an increasing population's needs. In order to update them, new sewage treatment plants should be built while current ones extended.

In summary, Sudan generates a significant amount of wastewater; nonetheless, its treatment capability remains quite low. Public health risks along with environmental hazards rise when relying on outdated ways of sewage disposal services. Developing extensive data collection capabilities; huge investments into infrastructural resources; creation of modernized facilities for wastewater processing – all these aspects must be addressed immediately if the country wants to overcome those challenges. This is very crucial in ensuring that Sudan's water sources are protected and development sustained as the population continues to grow coupled with urbanization process.

4.4 Population Growth Calculation and Estimation of Future Wastewater Generation

Projecting the future requirements for water and wastewater require knowing population growth dynamics. Sudan's population has increased progressively due mainly to high fertility rates and significant movement of people from rural to urban areas. Proper forecasting of population growth is very important when predicting how much waste water will be generated in future, this data is essential for any efforts of infrastructure development and environmentall management plans.

4.4.1 Estimation of Population Growth

To project population growth, the exponential growth formula was used for population estimation for years 2024-2030 as it is a suitable method for demographic studies:

$$P(t) = P_0 \times e^{(rxt)} \tag{4.1}$$

- **P(t)** = Population at time t
- **P_0** = Initial population
- **r** = Growth rate (annual)
- **t** = Time in years

a) Given Data:

- Population in 2024 (P_0) = 49,358,228
- Annual growth rate (r) = 2.6%

b) Population Projections:

For 2024 to 2030, the population is calculated as follows:

- $P(2025) = 49,358,228 \times e^{(0.026\times1)} \approx 50,642,563$
- $P(2026) = 49,358,228 \times e^{(0.026\times2)} \approx 51,954,877$
- $P(2027) = 49,358,228 \times e^{(0.026\times3)} \approx 53,295,710$
- $P(2028) = 49,358,228 \times e^{(0.026\times4)} \approx 54,665,611$
- $P(2029) = 49,358,228 \times e^{(0.026\times5)} \approx 56,065,139$
- $P(2030) = 49,358,228 \times e^{(0.026\times6)} \approx 57,494,862$

4.4.2 Estimated Wastewater Production (2024-2030)

The wastewater for 2020 was modified in order to correspond with the expected population growth every year. The data on initial wastewater from 2020 allowed projecting oncoming waste for years 2024-2030. In 2020, it was estimated that approximately 947.294 million m3 of domestic wastewater is released annually. Henceforth, future wastewater generation would be:

1. **Wastewater in 2024** = 947.294 x $\frac{49,358,228}{43,849,000}$ ≈ 1,067.12 million cubic meters
2. **Wastewater in 2025** = 947.294 x $\frac{50,642,563}{43,849,000}$ ≈ 1,094.74 million cubic meters
3. **Wastewater in 2026** = 947.294 x $\frac{51,954,877}{43,849,000}$ ≈ 1,122.97 million cubic meters
4. **Wastewater in 2027** = 947.294 x $\frac{53,295,710}{43,849,000}$ ≈ 1,151.82 million cubic meters
5. **Wastewater in 2028** = 947.294 x $\frac{54,665,611}{43,849,000}$ ≈ 1,181.29 million cubic meters
6. **Wastewater in 2029** = 947.294 x $\frac{56,065,139}{43,849,000}$ ≈ 1,211.41 million cubic meters
7. **Wastewater in 2030** = 947.294 x $\frac{57,494,862}{43,849,000}$ ≈ 1,242.19 million cubic meters

4.4.3 Conclusion of The Calculated Growth Rates

The calculations underscore the significance of preparing for wastewater control in order to cater to the increasing population in Sudan. The forecasts suggest a significant rise in wastewater production by 2030, requiring substantial funding in infrastructure for sustainable environmental stewardship and protection of public health.

4.5 Invistigating Applicable Wastewater Management Systems for Sudan

Various wastewater treatment systems are used worldwide, each with distinct benefits and constraints, designed to accommodate different population sizes and urban environments. When choosing a suitable system, it is important to take into account the specific conditions of the site, the objectives of the treatment, and the cost-effectiveness.

4.5.1 Summary of Commonly Employed Wastewater Disposal Systems

Onsite System processes wastewater from individual residences without being connected to a sewer system that serves the entire community. Generally, it consists of a septic tank that is divided into two chambers. The primary chamber facilitates the settling of sizable solid particles, while the secondary chamber acts as a barrier to prevent the entry of scum and grease into the drain field. In Sudan, it is common to discharge effluent from septic tanks into deep wells, which poses a potential risk of contaminating groundwater. Although septic systems are uncomplicated and only need limited upkeep, their effectiveness can be subpar without additional treatment.

Cluster System caters to multiple dwellings by utilizing separate septic tanks or aerobic treatment units. The wastewater is then transported to a relatively compact treatment facility. Cluster systems provide a financially efficient solution for small communities or collections of buildings.

Decentralized systems are specifically engineered to handle relatively small amounts of wastewater originating from clusters of residences or communities. These systems generally consist of smaller pipes and less extensive sewer networks, which makes them economically efficient and flexible in accommodating urban expansion.

Centralized Systems are characterized by the presence of extensive sewer networks that efficiently convey wastewater from residential and commercial properties to a central treatment plant. Although centralized systems are efficient in densely populated urban areas, their high cost is attributed to the requirement of extensive trunk sewers and pumping stations.

4.5.1.1 *Cost Analysisi of Possible Wastewater Treatment and Disposal Systems*

The following table of cost analysis was provided within the third volume of **Khartoum State Environmental Strategic Assessment and Evaluation Project 2014,** it contains cost of several disposal systems, three from Pegram, Tennessee, USA and the other three are from Khartoum which are serving student hostels. Costs include the money needed to install the system (collection + treatment) and the annual cost to operate and maintain it.

Table 3.1 Overview of cost of disposal methods

System Type	Initial Capital Investment	Annual Maintenance & Operation Costs	Total Yearly Expense	Average Monthly Cost per Household/Person
Centralized System (USA)	$2,585,600 – $4,176,590	$33,110 – $44,830	$241,480 – $381,410	$149 – $235 per household or $44.78 – $70.51 per person
Small Cluster System (USA)	$666,040	$8,120	$61,800	$38 per household or $11.4 per person
Onsite System (USA)	$567,940	$14,920	$60,690	$37 per household or $11.1 per person
Small Cluster System (Ali Abdelfattah Student Hostels, 400 m³/day)	$380,000	$51,360	$124,886	$3.1 per person or $0.86/m³
Small Cluster System (Ribat University, 600 m³/day)	$619,000	$63,600	$183,370	$3.1 per person or $0.84/m³

Table 3.1 (continued)

System Type	**Initial Capital Investment**	**Annual Maintenance & Operation Costs**	**Total Yearly Expense**	**Average Monthly Cost per Household/Person**
Small Cluster System (Islamic University)	$833,000	$72,000	$233,177	$3.9 per person or $1.06/m³

Two of the student hostels previously mentioned are utilizing the MBR (Membrane Bioreactor) technique, which combine biological treatment with membrane filtration, are shown efficacy in the dorms at Omdurman Islamic University. These devices are small in size and provide high-quality processed wastewater.

The advanced treatment facilities in these hostels are effectively generating wastewater effluents that match the criteria for reuse in irrigation. The following data in (Table 3.2) presents the effluent characteristics of two chosen plants:

Table 3.2 Effluent characteristics of Ali Abdelfattah and OIU treated wastewater

Test Results	**Average BOD mg/l**	**Minimum BOD mg/l**	**Maximum BOD mg/l**	**Average SS mg/l**	**Minimum SS mg/l**	**Maximum SS mg/l**
Ali Abdelfatah 400 m³/day	11.0	3.6	41	12	8.0	30
Islamic University 600 m³/day	3.0	1.2	30	Nil	Nil	20

Cost of wastewater treatment by these facilities are shown by (Table 3.3) below:

Table 3.3 WWT Cost of Ali Abdelfattah and OIU wastewater systems

Sewerage Facility	**Total Construction Cost in $**	**Operation Cost in $/month**	**Total Annual Cost in $**	**Cost/m³ in $**	**Year of Operation**	**Description**
Ali Abdelfatah 400 m³/day	380000	4280	124886	0.86	2006	Cost of plant + collection but negligible cost for reclamation
Islamic University 600 m³/day	833000	6000	233177	1.06	2010	Cost of plant + collection but negligible cost for reclamation

4.5.1.2 Selection of Suitable Wastewater Mangement System for Sudan

Khartoum, the swiftly expanding capital of Sudan, encounters difficulties associated with its level terrain and disorderly urban development. Considering the fragmented layout of urban development and the expensive nature of centralized systems, a decentralized wastewater system (DWWS) seems to be the most appropriate choice. Decentralized systems can be implemented incrementally, are flexible in terms of financial limitations, and can be scaled up as required. Additionally, when MBR treatment methods used, they provide the benefit of repurposing treated wastewater for irrigation and other purposes, which is in line with the local regulatory inclination to avoid releasing effluent into the Nile.

Thus the choosen wastewater management method for Sudan consist of the following:

1- Decentralized cluster systems

2- MBR treatment

4.5.2 Cost Estimation and Implementation Timeline for Decentralized Wastewater Management System in Sudan (2024-2030)

4.5.2.1 Population Projections (2024-2030):

The projected population growth in Sudan from 2024 to 2030 is as follows:

- **2024:** 49,358,228 (base year)
- **2025:** 50,642,563
- **2026:** 51,954,877
- **2027:** 53,295,710
- **2028:** 54,665,611
- **2029:** 56,065,139
- **2030:** 57,494,862

4.5.2.2 Cost Calculation for Treatment and Disposal Systems

The cost of treating wastewater using the Membrane Bioreactor (MBR) technology, as employed by the **Islamic University system**, is calculated at **$1.06 per cubic meter**. The projected treatment costs for each year, based on the expected wastewater production volumes, are as follows:

- **2024:** $1,131.15 million (1.131 Billion)
- **2025:** $1,160.42 million
- **2026:** $1,190.35 million
- **2027:** $1,220.93 million
- **2028:** $1,252.17 million
- **2029:** $1,284.10 million
- **2030:** $1,316.72 million

The disposal system costs are based on the average annual cost per person, which is estimated at **$37.2**. The estimated total disposal costs for each year are:

- **2024:** $1,835.11 million (1.835 Billion)
- **2025:** $1,883.91 million
- **2026:** $1,933.85 million
- **2027:** $1,984.92 million
- **2028:** $2,037.17 million
- **2029:** $2,090.62 million
- **2030:** $2,145.26 million

The cumulative cost for the implementation of the wastewater management system including both treatment and disposal components is presented below:

- **2024:** $2,966.26 million (comprising $1,131.15 million for treatment and $1,835.11 million for disposal)
- **2025:** $3,044.33 million (comprising $1,160.42 million for treatment and $1,883.91 million for disposal)
- **2026:** $3,124.20 million (comprising $1,190.35 million for treatment and $1,933.85 million for disposal)
- **2027:** $3,205.85 million (comprising $1,220.93 million for treatment and $1,984.92 million for disposal)
- **2028:** $3,289.34 million (comprising $1,252.17 million for treatment and $2,037.17 million for disposal)
- **2029:** $3,374.72 million (comprising $1,284.10 million for treatment and $2,090.62 million for disposal)
- **2030:** $3,462.00 million (comprising $1,316.72 million for treatment and $2,145.26 million for disposal)

The timeline proposed for the introduction of a decentralized cluster wastewater management system is as follows:

- **2024-2025:** Initiation phase including construction decentralized systems in urban regions. Attention should be given to areas with highest projected wastewater generation and population density.
- **2026-2028**: Expansion phase where efforts will be made towards replicating the same in other regions.
- **2029-2030**: Finalization phase encompassing expansion and coverage of all areas. To ensure high quality effluent meeting reuse standards, an advanced MBR treatment technology would be installed in all units.

$22,467,700,000 (22.467 Billion) is the total cost of implementing the decentralized wastewater management system in Sudan over the period 2024-2030.

4.5.3 Financing Method for the Proposed Decentralized Wastewater Management System in Sudan (2024-2030)

It would be most beneficial for the decentralized sewage system in Sudan to combine domestic government funds, international development loans, and public-private partnerships (PPPs) to raise $22,4689 billion (22467.70 million USD). To address its current economic situation, Sudan needs low-interest loans and grants from institutions like the World Bank and African Development Bank. The availability of these funds may be enhanced by means of government contributions through a dedicated national infrastructure development fund which would ensure that this project remains as one of the top priorities in the country's budget. By using international aid and soft loans, Sudan can lessen the pressure on its own financial capabilities and gain supervision by global organizations.

Financial support is also intensified with Public-Private Partnerships which offer diverse alternatives for resource mobilization and operational efficiency. For instance, private enterprises could enter into contracts to build as well as manage waste water treatment plants under arrangements such as Build-Operate-Transfer (BOT) concessions. User fees will enable cost recovery over time. Additionally, this stimulates private capital while reducing immediate burden on state budgets. The use of green bonds may attract investors who are interested in environmental concerns into contributing towards enhancing its financial sustainability. Also carbon credit schemes could earn extra income.

4.5.4 Regulatory and Institutional Framework Analysis for Water Management in Sudan

It has been a long time since Sudan started handling natural resources in the early 20th century when the Forests and Woodlands Service was formed under the Anglo-Egyptian Condominium. During this period, numerous legislations were made including but not limited to 1932 National Forest Policy and the 1935 Wildlife Act as a means of starting to protect environment. However, it is clear that environmental regulations in Sudan have never been well coordinated and lack consistency or achievable long-term plan. As things stand, there are over one hundred fifty rules and regulations overseeing different aspects of natural resource management, which include water, land ownerships, and wild life conservation.

Sudan has ratified several international and regional agreements related to water management among them being Ramsar Convention on Wetlands and UN Convention on Biological Diversity. Apart from these international agreements, many national policies such as National Water Policy Environmental and Natural Resources Act etc have been passed through legislature over years while others were formulated for instance Nile Water Pumps Control Act Groundwater & Wadis Directorate Act which are acts specialized in water management. There is an overlap in jurisdiction between federal and state agencies regarding issues like environmental management, land control as well as disaster preparedness thereby resulting in duplication of efforts. They designate sustainable development policies administration responsibilities climate change adaptation activities along with biodiversity protection guidelines to several governmental bodies.

4.5.4.1 Observations

Federal and state powers on water management significantly intersect and might not agree. The implementation of Sudan's several environmental laws is not consistent and fragmented at times.

Despite the existence of extensive global agreements, the execution of water management plans is impeded by insufficient coordination and insufficient funding.

4.6 Conclusions

4.6.1 Proposed Urban/Domestic Wastewater Management Action Plan for Sudan (2024-2030)

4.6.1.1 Overview

Sudan encounters substantial obstacles in effectively handling its wastewater as a result of swift urbanization, population expansion, and inadequate infrastructure. In order to tackle these difficulties, a thorough plan for managing wastewater is suggested for the timeframe of 2024-2030. This strategy centers around the implementation of a decentralized wastewater management system utilizing Membrane Bioreactor (MBR) technology. This technique is well-suited to the specific conditions of Sudan, where the urban growth is dispersed and the population densities vary. It is necessary to have solutions that are adaptable and can be expanded as needed.

4.6.1.2 System Selection and Cost

The decentralized system, along with MBR technology, provides numerous benefits such as effective treatment, the possibility of water reuse, and less environmental impact. The projected expenditure for installing this system over the course of seven years is approximately $22,5 Billion. This statistic encompasses the expenses related to both the infrastructure for treating wastewater and the infrastructure for disposing of it, ensuring complete coverage over the urban areas of Sudan.

4.6.1.3 Financial Strategy

To meet the huge financial requirements, a multifaceted approach to financing is going to be utilized. This includes availing foreign developmental loans and grants from sources like the World Bank and the African Development Bank, using local government funds as well as establishing Public Private Partnerships (PPPs). By combining these sources, Sudan can reduce its own resource-based financial burden and utilize international knowledge and oversight. Funding will also involve green bond issuance and exploration of carbon credit schemes which attract investors with eco-priorities for additional finance.

4.6.1.4 Responsible Authorities

Several crucial government entities will need to participate in the implementation of this wastewater management plan. This effort will be led by National Water Corporations in Localities, Ministry of Water Resources and Higher Council for Environmental Affairs, while at the same time providing oversight and coordination on national and regional scales. They will ensure that it is in line with such national policies as National Water Policy and Environmental and Natural Resources Act. Moreover, these institutions shall oversee the incorporation of decentralized systems into existing infrastructure as well as ensuring compliance with regulatory requirements.

4.6.1.5 Framework Suggestions

To guarantee that the strategy is implemented effectively, the regulatory framework should be strengthened to prevent duplication of federal and state duties thereby creating a clear-cut system of water resources governance. This will entail relooking at existing legislation and rules so that they correspond to new decentralization approach. Additionally, it is vital to improve enforcement mechanisms in order to ensure adherence to environmental laws especially concerning illegal discharges and pollutions.

4.6.1.6 Awareness and Enforcement Considerations

A major determinant of the wastewater management system's viability is the level of public awareness. Informed by this, a countrywide outreach should be launched to inform citizens about the merits of the new system, sustainability in water use as well as the importance of community engagement to sustain it. Therefore, there need to be more stringent environmental regulations within which compliance can be ensured and thus prevent any activities that may hinder the effectiveness of its operations through tougher implementation terms.

4.6.1.7 Timeline for Implementation

The proposed action plan will be implemented in three phases:

1. **Initiation Phase (2024-2025):**
   - Be centered on decentralized approach in the urban region with highest projected wastewaters generation and population density.
   - Prioritize regions for MBR adoption.
2. **Expansion Phase (2026-2028):**
   - Ascend up the roll-out to include more areas.
   - Maintain the process of embedding MBR technology alongside enhancing extant wastewater management infrastructure.
3. **Finalization Phase (2029-2030):**
   - Carry out an expansion for full coverage of all city areas;
   - Get all the units fully embedded with Modern MBR technology and make sure that treated waste water meets reuse quality specifications.

4.6.2 Action Plan Summary

The table below (Table 3.4) summarizes the key components of the proposed action plan and the responsible authorities:

Table 3.4 Summary fort he proposed Domestic Wastewater Management Action Plan 2024-2030

Phase	Timeline	Key Activities	Responsible Authorities	Cost (Million USD)
Initiation Phase	2024-2025	- Construct decentralized systems in high-priority urban areas - Begin MBR technology integration	National Water Corporation, Ministry of Water Resources	5,960.59
Expansion Phase	2026-2028	- Scale up infrastructure to additional regions - Continue MBR integration and facility improvements	Higher Council for Environment and Natural Resources	9,619.39
Finalization Phase	2029-2030	- Complete coverage in all urban areas - Fully integrate MBR technology across all systems	National Water Corporation, Ministry of Water Resources	6,887.72
Total Cost	**2024-2030**			**22.468 Billion USD**

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