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**INTEGRATED DECISION SUPPORT SYSTEM FOR PRIORITIZING SEWER SYSTEM  
REHABILITATION: A GIS-AHP APPROACH**

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## DECLARATION AND RECOMMENDATION

### DECLARATION

I, Mrs. **Rahima ARSLANE**, hereby declare that this thesis represents my personal effort, realized to the best of my knowledge. Furthermore, I declare that all information, material, methods, and software from other works presented here, have been fully acknowledged, cited and referenced in accordance with the academic rules and ethics.




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### RECOMMENDATION

This thesis is the candidate's original work and has been prepared with our guidance and assistance. It is presented for examination with our approval as official University Supervisors.



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## **Abstract**

Sewer networks form a part of modern society's critical infrastructure, due to their function that ensures public health and environmental protection in urban areas and their capital-intensive nature. These systems, however, have been undergoing deterioration, malfunctioning and overloading, mainly caused by their long lifetimes, inadequate maintenance, or population growth. These issues require repair or rehabilitation. Still, due to an insufficient sewer system rehabilitation budget, utility managers have been forced to prioritize competing projects. Therefore, prioritizing sewer rehabilitation interventions have become crucial to address these problems and optimize the allocation of limited resources. This study proposes an integrated decision support system integrating the Analytic Hierarchy Process (AHP) and Geographic Information Systems (GIS) to prioritize sewer system rehabilitation in Gdyl, Algeria based on both physical and hydraulic criteria. A set of 18 indicators were used to rank sewer network of Gdyl city, under two different scenarios. The results showed that 13% of the network in Scenario 1 and 31% in Scenario 2 require urgent intervention. In addition, a methodology was introduced to confirm the proposed approach accuracy, which effectively aligned high-priority areas with known high-risk zones.

**Keywords:** Sewer rehabilitation; Analytic Hierarchy Process (AHP); Geographic Information Systems (GIS).

## **Résumé**

Les réseaux d'assainissement constituent une composante essentielle des infrastructures modernes, car ils jouent un rôle fondamental dans la protection de la santé publique et de l'environnement en milieu urbain. Toutefois, ces systèmes se dégradent progressivement, connaissent des dysfonctionnements et sont souvent surchargés, en grande partie à cause de leur âge, d'un entretien insuffisant ou encore de la croissance démographique. Ces problèmes nécessitent des travaux de réparation ou de réhabilitation. Or, face à un budget limité alloué à la réhabilitation des réseaux, les gestionnaires sont contraints de hiérarchiser les projets en concurrence. Ainsi, la priorisation des interventions est devenue indispensable pour répondre efficacement à ces défis et optimiser l'utilisation des ressources disponibles.

Cette étude propose un système d'aide à la décision intégré, combinant la méthode Analytic Hierarchy Process (AHP) et les Systèmes d'Information Géographique (SIG), afin de prioriser la réhabilitation du réseau d'assainissement de la commune de Gdyl, en Algérie, en s'appuyant sur des critères physiques et hydrauliques. 18 indicateurs ont été mobilisés pour évaluer le réseau selon deux scénarios distincts. Les résultats montrent que 13 % du réseau dans le premier scénario et 31 % dans le second nécessitent une intervention urgente. Une méthode de validation a également été mise en place, confirmant la précision spatiale du modèle proposé en alignant efficacement les zones prioritaires avec les zones à risque connues.

**Mots-clés :** Réhabilitation des réseaux d'assainissement ; Processus hiérarchique analytique (AHP) ; Systèmes d'information géographique (SIG).

## **DEDICATION**

I would like to dedicate this thesis to my parents Mohammed and Fayrouz MOTRANI. Thank you so much for everything! Words can hardly describe my thanks and appreciation to you.

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## List of Acronyms and Abbreviations

AC	Asbestos Cement
AHP	The Analytic Hierarchy Process
ANRH	Agence Nationale des Ressources Hydriques
CI	Consistency Index
CR	Consistency Ratio
CSOs	Combined Sewer Overflows
CSs	Combined Sewers
D	Diameter
DSS	Decision Support Systems
GIS	Geographic Information System
PVC	Poly vinyl chloride pipe
RC	Reinforced concrete
RI	Random Index
RWL	Relative Water Level
S	Slope
SEOR	Société de l'Eau et de l'Assainissement d'Oran
SNs	Sewer Networks
SSS	Separate Sewer Systems
WWTPs	Waste Water Treatment Plant
$\lambda$	Lambda

# CHAPTER 1: INTRODUCTION

## 1.1. Background information

Wastewater networks form a part of modern society's critical infrastructure. (Ghavami et al., 2020; Anbari et al., 2017; Laakso et al., 2018). One of the reasons for this, aside from their function, is that these systems are considered one of the most capital-intensive infrastructures (E. Ana et al., 2009). They are complex systems that perform a critical function in wastewater management, public health protection, and environmental quality preservation. However, the majority of cities worldwide are faced with severe issues of aging and deteriorating sewer infrastructure, which is characterized by large-scale networks that have been in operation for decades (E. Ana et al., 2009; Anbari et al., 2017; Malek Mohammadi et al., 2019) The collapse of sewer systems can lead to pathogen exposure, pollution of groundwater, water ways and wetlands, damage to roads and buildings, and disruption of vital services (Anbari et al., 2017; Laakso et al., 2018; Malek Mohammadi et al., 2019).

Traditional infrastructure management policies have been predominately reactive, with the cities typically responding to extreme failures or visible damage (E. V. Ana & Bauwens, 2010; Fenner., 2000). In addition to the reactive process being economically inefficient, it can be risky because declines in underground infrastructure tend to progress invisibly prior to the disastrous failure appearing on the surface.

The deterioration of sewer systems generates substantial financial problems. Research studies revealed that repair expenses for delayed infrastructure maintenance and inadequate maintenance operations would amount to multiple times more than that of preventive rehabilitation strategy (Kaddoura, 2018). Additionally, service interruptions along with environmental contamination and linked health-related problems elevate the financial strain faced by municipal government entities (Kaddoura, 2018).

Technological advances in geospatial analysis, data management, and decision support systems now offer unmatched possibilities to transform infrastructure management from a reactive to proactive, strategic function (E. V. Ana & Bauwens, 2010). Using the combination of advanced spatial technologies and multi-criteria decision-making techniques, municipalities are able to develop more sophisticated, data-based strategies for infrastructure rehabilitation.

## **1.2.Statement of the problem**

The sewer infrastructure in urban areas in Algeria is under increasing pressure due to urbanization population growth, and climatic hazards. The deterioration of these systems can pose significant challenges, including potential failures, environmental risks and public health problems (Ghavami et al., 2020). Therefore, effective prioritization of sewer system rehabilitation is imperative to address these challenges and optimize the allocation of limited resources.

However, decision-makers struggle to prioritizing these projects as they face several challenges, including limited resources, complex decision criteria, stakeholders' engagement and changing conditions. Furthermore, the existing decision-making approaches for sewer system rehabilitation often lack a comprehensive and transparent methodology that considers multiple technical and socio-economic factors (Carriço et al., 2012; Tabesh & Saber, 2012). Classic methodologies could rely too much on subjective indicators, while not taking into account the integration of spatial data and expert knowledge in an effective way (Drafor & Amatokwu, 2020; Ryu et al., 2016). This can lead to inadequate resource allocation, failing to pay attention to vital areas that require immediate attention and potentially causing more harm to the environmental and public health (Tscheikner-Gratl et al., 2017). A decision support system that integrates advanced spatial analysis approaches with multi-criteria decision-making frameworks is urgently required to fill these gaps (Fenner & Sweeting, 1999; Tagherouit et al., 2011). The urban sewer networks management in Algeria has always been done punctually, often to answer to objectives and urgent local needs without considering the systems durability and their impacts on the environment at middle and long terms.

The case study for this research is Gdyl which is a coastal city in the north eastern region of Algeria facing significant sewer system challenges. The urban areas of Gdyl have suffered from poor wastewater management for many years, leading to severe environmental and public health problems. The existing sewer infrastructure is old and cannot support the increased load caused by rapid urban growth and industrialization.

This research aim is to address this need by proposing an integrated decision support system that leverages Analytic Hierarchy Process (AHP) and Geographic Information Systems (GIS) for prioritizing sewer system rehabilitation in Algeria. The Geographic Information Systems (GIS) is used to assess the current state of sewer networks, identifying vulnerable areas that are prone to network failures and evaluating environmental risks (Jafari et al., 2022). The model considers various factors including infrastructure, material, diameter, slope, and hydraulic

performance. By proposing this approach, this study aims to bridge the gap between technical assessments, and resource constraints, resulting in better sewer system management and better structure outcomes.

### **1.3.Objectives**

#### **1.3.1. Main Objective**

The primary aim of this research is to develop an Integrated Decision Support System (DSS) for prioritizing sewer system rehabilitation in Algeria. By integrating GIS data and AHP methodology the study aims to identify critical areas that require immediate attention due to deteriorating conditions or environmental risks.

#### **1.3.2. Specific Objectives**

- a) To assess the current condition of sewer network by using GIS and its spatial analysis.
- b) To leverage the spatial analysis capabilities of GIS to identify critical areas or hotspots within the sewer network that require immediate attention based on the integrated evaluation of multiple criteria.
- c) To identify and evaluate the criteria and sub-criteria for sewer system rehabilitation, including pipe physical characteristics, hydraulic structure, and determine their weights using the AHP methodology.
- d) To assess the effectiveness and efficiency of the proposed decision support system in prioritizing sewer system rehabilitation projects.

### **1.4.Research questions**

- a) How can an integrated decision support system combining GIS and AHP be developed and applied to effectively prioritize sewer system rehabilitation in the city of Gdyl?
- b) How can the spatial analysis capabilities of GIS be leveraged to identify and prioritize critical areas or hotspots within the sewer network that require immediate attention?
- c) What are the key criteria and spatial factors that should be considered in the decision-making process for prioritizing sewer system rehabilitation projects, and how can their relative importance be determined using the AHP method?
- d) What are the challenges and limitations associated with the implementation and adoption of the integrated decision support system in real-world sewer system management contexts?

### **1.5.Justification of the study**

The research will add value to infrastructure management since it delivers a method to assist decision-makers in their priority decision-making regarding rehabilitation projects and improve

their resource management. The final objective of this system focuses on creating better sustainable and operational sewer infrastructure throughout urban centers while strengthening infrastructure resilience across Algeria.

### **1.6.Scope and Limitation of the Study**

The research work presented here is directed towards the development of a composite decision support system for sewer network rehabilitation priority ranking in the Gdyl urban conurbation of the Wilaya of Oran, Algeria. The methodology used in this research combines Geographic Information Systems (GIS) and the Analytic Hierarchy Process (AHP) for the spatial evaluation and ranking of sewer network sections based on physical and hydraulic structure. Diagnostic data obtainable from SEOR and field inspections were used to construct a risk surface through the application of Inverse Distance Weighted (IDW) interpolation in order that areas of high risk might be ascertained. The outcome supports data-driven decision-making and planning for sewer infrastructure management.

The research contains various restrictions. Firstly, the study depends on data quality and availability. This study did not include pipe age as a criterion, as accurate and comprehensive data on the installation dates of the sewer network were not available. Second, the IDW interpolation relies on a limited set of diagnostic points, and that can influence the accuracy of spatial risk distribution. The model priority retains current conditions and does not incorporate future urban development or climatic variability that might impact network performance. Finally, while the AHP methodology is useful for multi-criteria decision-making, it involves pair-wise comparison subject to subjective judgment, which might induce bias notwithstanding efforts to remain consistent.

### **1.7.Outline of the study**

This study consists of five chapters. Chapter One introduces the background of the research, the statement of the problem, objectives, and scope. Chapter Two provides appropriate literature on sewer infrastructure management, GIS, AHP, and integrated decision-making techniques. Chapter Three summarizes the methodology, for instance, the study area, data sources, selection of criteria, and application of GIS and AHP. Chapter Four compares and gives the results, including risk maps and prioritization outcome, to SEOR. Chapter Five concludes the findings, provides recommendations, determines limitations, and suggests areas for future research.

## CHAPTER 2: LITERATURE REVIEW

### 2.1. Introduction

This chapter discusses the strength, limitation and most importantly, the gaps within the previous studies and literature related to prioritizing sewer system rehabilitation and the various methodologies employed in decision-making for sewer management with a special emphasis on approaches that integrate GIS with AHP. This chapter presents an overview on the processes of sewer pipe deterioration, highlighting the key factors that affect their degradation including physical and hydraulic factors.

Through integrating literature review findings, this chapter will seek to present the existing state of knowledge while also constructing a framework and conceptualization for the methodology and analysis to be employed in the subsequent chapters.

### 2.2. Sewer networks

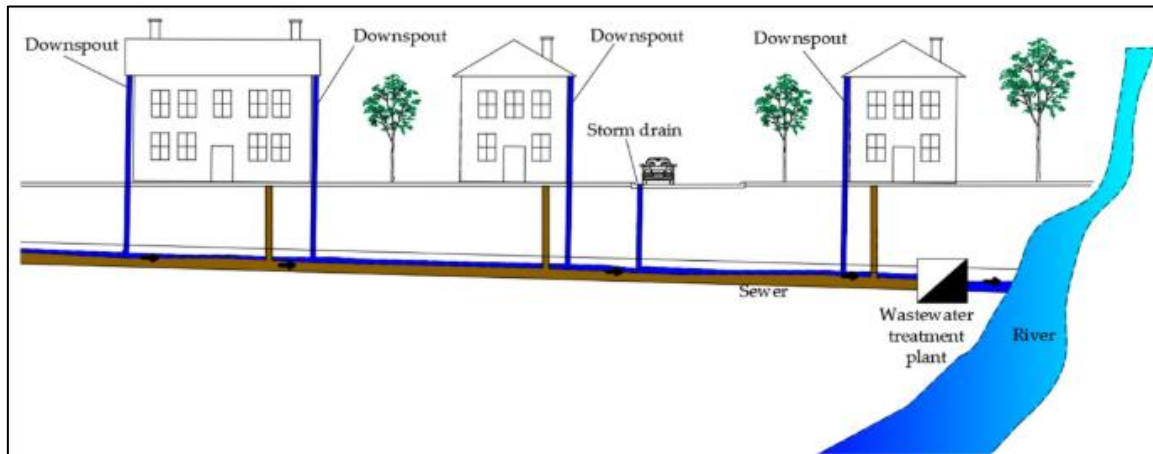
Sewer networks (SNs), also known as wastewater networks form a part of modern society's critical infrastructure. When properly maintained, a sewer system drains wastewater from residential, commercial, and industrial areas to treatment facilities. These systems play a vital role in ensuring public health, environmental protection in urban areas, preventing the spread of waterborne diseases, and act as flood prevention measures in urban environment (Barone et al., 2019; Jia et al., 2021; Vollertsen et al., 2015; Pikaar et al., 2011.). SNs essentially composed of pipes, manholes, pumping stations, overflow structures and other hydraulic that are normally buried underground (Jia et al., 2021; Joseph-Duran et al., 2014) and are capital intensive. According to the way of collection and drainage of wastewater, sewer systems can be classified into three types, combined systems, separated and partially separated systems.

#### 2.2.1. Types of sewer networks

##### a) Combined sewer systems

Combined sewer systems CSs (Figure 2.1) are designed to collect both wastewater and stormwater in a single system and transport this combined flow to WWTPs for treatment or discharge (Haghighi & Bakhshipour, 2015; Jia et al., 2021; Martin & Vanrolleghem, 2014; Obradović et al., 2023). This is the oldest type of sewer system, and it was adopted as a cost-effective solution for collecting and draining urban waste and rain waters to the recipient (Obradović et al., 2023). While CSs are highly efficient in terms of infrastructure integration, they are susceptible to sewer overflows during intense rainfall events, which will lead to

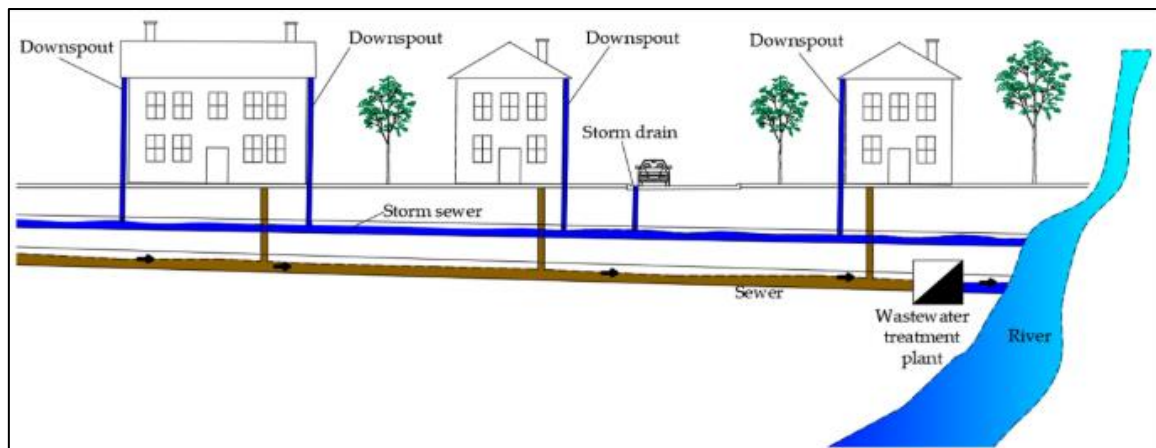
discharge of untreated sewage and stormwater into water bodies, posing environmental and public health risks (Hager & Gisonni, 2005; Jia et al., 2021; Joseph-Duran et al., 2015.). In addition, CSs are prone to sedimentation problems during dry weather due to low flow velocities which cause blockages and require frequent maintenance. Sediments deposition can also create odor issues as well as contributing to the formation of hydrogen sulfide gas responsible for corrosion of the sewer system.



**Figure 2.1: Combined sewer system (Sketch by D. Obradović, 2017).**

### **b) Separate sewer systems**

In contrast to CSs, separate sewer systems SSSs (Figure 2.2) utilize two distinct networks: one used for the drainage of rainwater and the other intended for household and industrial wastewater (if there is an industry in the area) (Jia et al., 2021; Obradović et al., 2023). Stormwater is usually discharged to natural water systems whereas wastewater is collected and discharged to WWTPs for treatment. Despite their various advantages, separate systems still face a range of issues, such as illicit connections where the pipes for a stormwater and a wastewater are improperly linked leading to a problem of either pollution of stormwater with sewage or overloading (Jia et al., 2021). Furthermore, the cost needed for establishing and maintaining two separate network is a significant economic challenge, especially for developing countries.



**Figure2.2: Separated sewer system (Sketch by D. Obradović, 2017).**

### **c) Partial sewer systems**

The partial separate system is a hybrid system with properties of both combined and fully separate sewer system (Obradović et al., 2023). In this type of network, the wastewaters and stormwaters are conveyed in separated pipelines and they may occasionally join or connect through a number of junctions or overflow facilities to prevent flooding. This design minimizes the hydraulic load on waste water treatment plants WWTP's during normal conditions, as the majority of the stormwater runoff gets directly discharged to the local water bodies. however, during intense rainfall events, overflow structures allow a portion of stormwater to enter sanitary sewer to treatment plants while the remaining storm water is carried through open drains to the point of disposal, thus reducing the chances of urban flooding. This design was developed to overcome some of the limitation of both combined and separate network offering a cost-effective solution for areas with existing combined sewer system (CSs) infrastructure, thereby minimizing the frequency of combined sewer overflows (CSOs) and their effect to the environment

### **d) Alternative sewer systems**

The above-mentioned common types of sewer systems are conventional wastewater collection systems in which sewage is transported from homes or other sources by gravity flow (Misztak-Kruk, 2016). These systems are usually reliable and consume no power. However, the slope requirements to maintain adequate flow by gravity may require deep excavations in hilly or flat terrain, in such case, alternative sewer systems are developed to address these challenges (Misztak-Kruk, 2016; Obradović et al., 2023).

### **i. Pressure sewer systems**

A pressure sewer system is one of the alternative sewer systems that are commonly used, especially in rural or semi-rural communities with challenges of implementing conventional sewer systems (Water Environment Research Foundation, 2010; Obradović et al., 2023). This system is mostly implemented in parts of sewerage network with flat or undulating terrain and where there are no conditions for gravitational drainage (Water Environment Research Foundation, 2010; Obradović et al., 2023). The typical installation for this kind of system is that every connection, or a small group of connections, are provided with a basin in which wastewater will be collected. When the basin fills to a certain level, a pump in the basin pumps the wastewater into the sewer. This process will make the sewer network pressurized, as more additional pumps introduce sewage at a certain point, wastewater is stepwise conveyed to the treatment plant.

### **ii. Vacuum sewer systems**

Vacuum sewer is another alternative sewer systems that were first established in 1860 and further expanded from 1950s in Sweden (Obradović et al., 2019, 2023; Šperac & Obradović, 2018). These systems are meant for areas with special circumstances, such as arid areas and requires special pipes, facilities and sanitary devices, so it has no wider application (Islam, 2017). This sewer system operates by the force of a negative pressure (0.6–0.7 bar) generated by vacuum pumps in a pumping station (Miszta-Kruk, 2016). The highest negative pressure is at the collection chamber or discharge point (Margeta, 2009; Obradović et al., 2023). The vacuum sewer system is best applied where the constructing environment is difficult such as flat ground, high water table, unfavorable longitudinal gradient or where the soil condition is poor (Islam, 2017; Miszta-Kruk, 2016).

## **2.3. Overview of sewer deterioration**

Sewer pipes are one of the most used types of underground infrastructure component in urban areas, they are expected to function seamlessly for decades; However, they exhibit significant problems of deterioration, malfunctioning and overloading, mainly caused by long lifetimes, inadequate maintenance, or population growth (Carriço et al., 2012).

Several studies have classified and grouped sewer pipes failures into several types based on various factors, for example Najafi & Gokhale. 2005 categorized pipe failures in two main types: structural and operational failures. (Anbari et al., 2017) further classified pipe failures

into two categories: structural and hydraulic failures. The EPA (2009) grouped wastewater pipe failures into three categories, including hydraulic restrictions (blockages), hydraulic capacity, and structural deterioration. (Opila, 2011) considered both water and wastewater systems, classifying failure modes into structural, operational, and maintenance issues, such as, hydraulic capacity, economic, and water quality. (Sami et al., 2018), divided the pipe segments into three principal components: the pipe length, the corresponding joints, and the manholes or access holes. The defects in each component were classified into three primary defect categories: structural defects, operational defects, and installation/rehabilitation defects.

According to the previous studies the deterioration mechanism of sewer pipes, can be generalized into structural, operational, and hydraulic capacity failure (Malek Mohammadi et al., 2019).

### **2.3.1. Structural failure**

Structural failure involves any physical damage or degradation on the pipe wall that reduce the structural integrity of pipe segment (Anbari et al., 2017; Malek Mohammadi et al., 2019). This type of Failure includes (PDSS, 2009):

**-Erosion:** Mechanical/physical destruction or gradual removal of some inner surface parts in a sewer pipe.

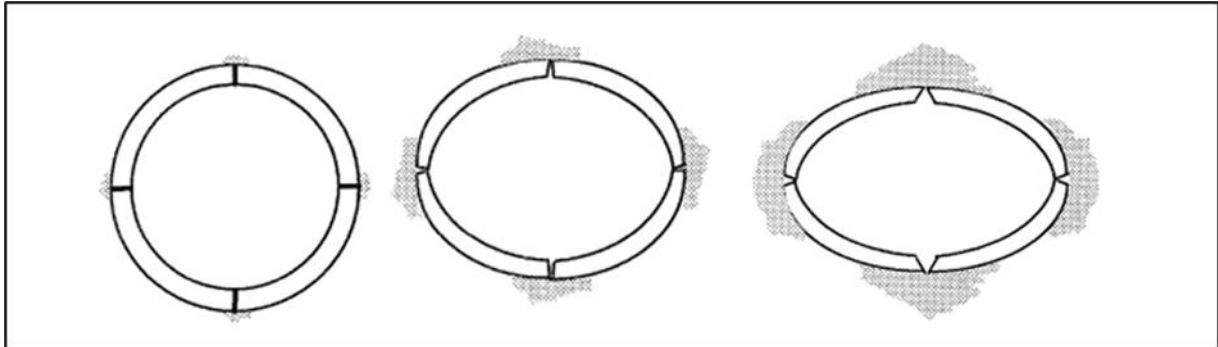
**- Corrosion:** The reaction of pipe material with its surroundings, which results in a measurable deterioration in the material's properties. Among the materials used in the sewer networks, such as cement-based components (concrete, asbestos cement, and mortar) and metals (steel and iron) are more exposed to corrosion. While synthetic pipes are more resistant, they too may experience corrosion under certain environmental conditions.

**- Deformation:** Deformation can be described as the alteration of a pipe's shape due to external forces or internal pressures that exceed its structural capacity. It only occurs in flexible pipes (usually made of synthetic materials) such as PVC.

**- Cracking, pipe fracturing or collapse:** Cracking occur generally in non-flexible pipes, including longitudinal, transverse, and point cracks. Over time these cracks expand, leading to pipe fractures. Collapse is the severest structural failure where the pipe loses its complete resistance and breaks down.

Davies et al. (2001) and E. V. Ana & Bauwens. (2010) explained Sewer pipe structural failure in three basic stages. The first stage, is where an initial defect is formed, it can be a crack caused e.g., by excessive vertical load or bad bedding, by bad construction practice or by damage

caused when making connections. The second stage involves the deterioration of the pipe, the presence of cracks combined with groundwater interaction because of the hydrostatic pressure initiates infiltration/exfiltration within the system. (Davies et al., 2001; Jaganathan et al., 2010; Kaddoura, 2018). This process leads to soil movement around the pipeline, which will cause the loss of ground and the removal of the support that the ground provides.



**Figure 2.3: Sewer pipe structural failure (Davies et al., 2001).**

At the same time, this process will lead to the deterioration of the material itself, concrete pipe may suffer from corrosion due to exposure to hydrogen sulfide, forming sulfuric acid, which accelerates chemical breakdown. As for brick-and-mortar sewers the joint material tends to erode while metallic pipe may corrode as a result of oxidation or galvanic reactions. Over time, these mechanisms weaken the structure integrity of the pipe making it more vulnerable to fracture and eventual collapse. The Third and the final stage, shown in Figure 2.3, is when the sewer pipeline is susceptible to collapse if its side support is lost and in the same process the side of the pipeline is exerted further to cause deformation of over 10% to lead to pipeline collapses.

### **2.3.2. Operational failure**

Operational failure is the most common type of failure in wastewater collection systems, it occurs when the sewer system is unable to fulfill its intended function of transporting wastewater in an efficient manner, even if the pipe remains structurally sound. These types of failures are generally caused by physical factors which may be remediated by a maintenance procedure. Examples include debris deposits, roots intrusions, infiltration, and the presences of obstacles (Malek Mohammadi et al., 2019; Opila, 2011).

### **2.3.3. Hydraulic failure**

Hydraulic capacity failure arises when the flow exceeds the pipes capacity to convey wastewater, without having any structural or operational problem, leading to surcharges, overflows, or backflows. Hydraulic capacity failures may be caused by of infiltration/inflow

(I/I), where the groundwater and storm water enter the sewer system through connections, manholes, cracks, and defects. Hydraulic capacity failure may indicate other underlying type of structural defects such as cracks, broken pipe, leaks, and other factors (Anbari et al., 2017; Malek Mohammadi et al., 2019; Opila, 2011).

#### 2.4. Factors affecting deterioration of sewer pipes

Deterioration of sewer pipes is a very complex process that is affected by several factors rather than just a single factor (Table 2.1). Understanding these factors is crucial for effective asset management, prioritization, and select the most effective rehabilitation approaches. Numerous studies including those by, Al Barqawi. (2006), E. V. Ana & Bauwens. (2010), and Davies et al. (2001) have evaluated the condition of sewer pipelines and identified the factors that influence deterioration and remaining useful life of sewer systems. Based on these studies, it is possible to categorized these factors into physical factors, environmental factors, operational factors. In general, physical factors such as material, age, and diameter are well documented by agencies and municipalities while environmental and operational factors are often unavailable because collecting this kind of data is costly and time consuming (Malek Mohammadi et al., 2019).

**Table 2.1: Factors affecting sewer pipe deterioration. (Adapted from Al Barqawi and Zayed, 2006).**

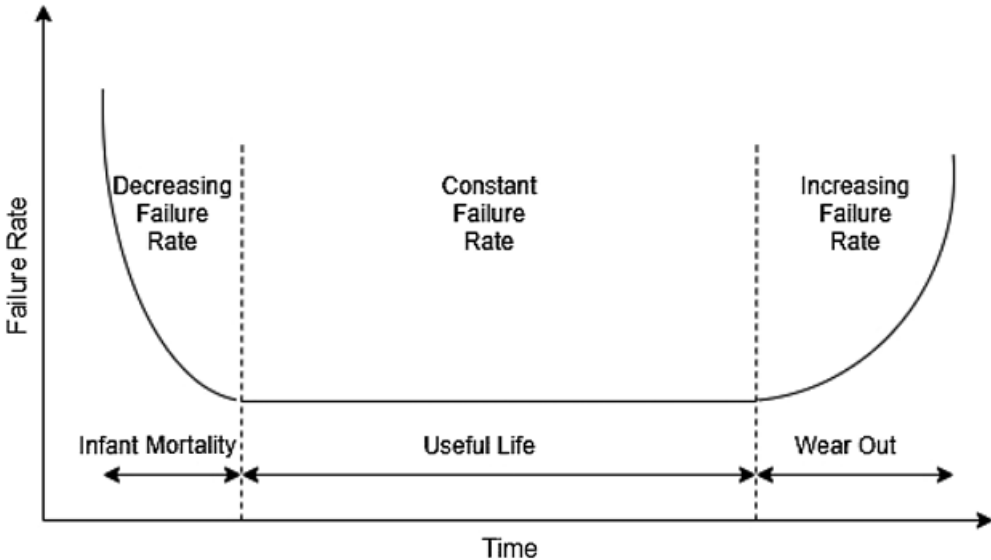
Physical Factors	Environmental Factors	Operational Factors
Connections	Backfill type	
Invert elevation	Bedding material	
Installation method	Ground movement	Blockages
Joint type	Groundwater level	Burst history
Pipe length	pH	Debris
Pipe shape	Road type	Flow velocity
Pipe slope	Root interference	Hydraulic condition
Sewer age	Soil corrosivity	Infiltration/exfiltration
Sewer depth	Soil fracture potential	Previous maintenance
Sewer pipe material	Soil moisture	Sediment level
Sewer size	Soil type	Sewer function
Start invert elevation	Sulfate soil	Surcharge
	Surface type	

**2.5. Factors Contributing to sewer pipes deterioration**

**2.5.1. Pipe age**

Pipe age is the difference between the year of installation year and date of inspection. The aging process of pipe begins the minute the sewer pipe is installed, and it’s recognized as one of the most important factors influencing the pipe deterioration as old pipes are more exposed to structural deformities, cracks, and displaced joints or connections (Malek Mohammadi et al., 2020; Najafi & Kulandaivel, 2005). Most of the condition prediction models developed in previous studies highlighted the critical role of age in the deterioration process of sewer pipes. For instance, pipe age was found to be a key variable in prediction models developed by Salman and Salem. (2012), Kabir et al. (2018), and Laakso et al. (2018).

Generally, the deterioration rate is lower during the early years of pipe service life and higher during the later years (E. Ana et al., 2009; Ariaratnam et al., 2001; Jeong et al., 2005).as sewer pipe age, root intrusion and pipe roughness increases gradually. Since there is a direct relationship between pipe roughness and friction factor, the hydraulic performance of the pipe will decline and the likelihood of pipe deterioration will increase (Malek Mohammadi et al., 2020).



**Figure 2.4: Theoretical bathtub curve of the life cycle of a buried pipe. (Data from Singh and Adachi 2013.)**

The bathtub curve is a plot that illustrates the rate of pipe failure depending on the age of the pipe (Singh and Adachi, 2013). This curve involves three distinct phases, as shown in Figure 2.4.

The first phase is the early-life period, characterized by a high failure rate right after installation. Failures during this phase can occur because of human error, pipe damage during construction or installation, or the use of inappropriate pipe materials. The second phase represent the useful life of the pipe, in which the failure rate is very low and almost constant. Failures in this phase often result from random events, such as extreme loading, earth movement, settlement, or third-party interference. And the last phase or third phase, known as the wear-out life, the frequency of failure is high due to pipe aging and deterioration. This phase is characterized by the reduction of pipe performance over time due to use and exposure to environmental conditions (Singh & Adachi, 2013).

### **2.5.2. Pipe Material**

Sewer pipes are made of different materials, which exhibits different performance characteristics and reactions to environmental factors, such as soil type, water table, and other site-specific conditions (Salman, 2010). For example, concrete pipes are known for their resistance to abrasion, while clay pipes, possess high resistance to acidic environments. Plastic pipes such as polyvinyl chloride (PVC) and high-density polyethylene (HDPE), are resistant to acidic as well as alkaline wastes, however they are exposed to excessive deformation under heavy loading (Singh & Adachi, 2013).

In condition prediction models pipe material can be used as an independent variable in order to assess its significance in pipe deterioration. Different studies have evidenced that pipe material significantly impacts the longevity and performance of sewer systems. For instance, Davies et al. (2001) identified pipe material is a critical variable and have a direct relationship with the deterioration of sewer pipes. Similarly, the study by Lubini & Fuamba (2011) indicated that reinforced concrete pipes are the most resistant against deterioration because of the reinforcing steel that makes the conduit strong enough to prevent structural deterioration. In his study, (Bakry et al., 2016) showed that vitrified clay performed better than asbestos cement and reinforced concrete pipes in their model. Laakso et al. (2018) also found concrete and high-density polyethylene pipes significant in their prediction model, attributing the variability in HDPE pipe performance to inconsistencies in manufacturing quality.

### **2.5.3. Pipe diameter**

Pipe diameter is one of the important factors affecting the deterioration of sewer pipes due to its impact on hydraulic performance, structural integrity, and maintenance challenges. Pipes with larger diameters generally have better self-cleaning capabilities when flowing partially full, because of their higher flow velocities and capabilities of carrying sediments (Montes et

al., 2019). However, during low flow periods pipes with large cross-sectional areas are likely to accumulate high level of sediments deposits as the flow spreads out more, reducing velocities below critical levels. On the other hand, pipes with smaller diameter are more susceptible to blockages and debris buildup that increase wear and chemical attack, and because of their small size and their limited accessibility their maintenance and inspection are very difficult and thus any sign of degradation goes unnoticed. Several studies investigated the relationship between sewer pipe diameter and its deterioration rate, and the results are contradictory. Some condition prediction models, indicated that sewer deterioration rate decreases with increasing the diameter. While others indicated that smaller diameter pipes have better performance and less failure. Davies et al., (2001) stated that probability of having a rigid sewer pipe in a state of poor condition decrease with increase in diameter. Micevski et al. (2002) have reported higher deterioration rates in the smaller pipes perhaps due to poor depth of cover and underestimated traffic loads during construction design. Lubini & Fuamba. (2011) observed that pipes with big diameters are able to sustain hydraulic flow in spite of the existence of some barriers than those pipes with small diameter which are more susceptible of failure. The same observation was made by Salman & Salem. (2012) and Bakry et al. (2016), who specified that greater pipe diameters are associated with lower deterioration rates. On the other hand, Baik et al. (2006) opined that large diameter pipes deteriorate faster than smaller ones because more area is exposed to sewage as well as the surrounding soil and because of the difficulties in proper installation caused by their size and weight.

#### **2.5.4. Pipe length**

In most sewer pipe inventories, pipe length is expressed as segment length between two manholes, which contains more than one pipe joint. Typically, long pipe lengths such as manhole-to-manhole length exhibit higher rates of deterioration because of possibility of defects extending over larger length, and their high vulnerability to blockages and sediment deposition, which facilitate their degradation (Malek Mohammadi et al., 2020). However, prior research has documented somewhat mixed results, which suggests that the functions between pipe length and deterioration rate are not necessarily direct or mutually reciprocal.

According to Davies et al. (2001) pipes are less likely to be in poor condition where individual pipe sections, are greater than 1.5 m (5ft) long. This is due to decrease in the number of joints per pipe segment because pipe joints are the main source of infiltration, structural instability and soil movement into the sewers. Similarly, Jeong et al. (2005), found that longer sewer pipe

segments are less likely to deteriorate than shorter ones, particularly in datasets containing large diameter pipes, blockage is less likely to occur due to the free flow of sewage.

Conversely, other researchers have pointed out the vulnerability associated with longer pipes, such as Khan et al (2010), which has indicated that pipes shorter than 70 meters (230 feet) appear to have little effect on sewer pipe conditions while pipes over 70 meters length appear to deteriorate faster due to joint density, infiltration, and exfiltration. Salman and Salem (2012) determined that longer pipes perform better in a sewer network because, as the length increases, the level of exposure to deteriorating factors such as bending stress and lateral connections also increases. Laakso et al. (2018) support these findings suggesting that sewer pipes with length greater than 40 meters (131 feet) have a faster deterioration potential attributed to bending stress, increased possibilities of defect and structural damage from lateral connections.

#### **2.5.5. Pipe slope**

Pipe slope has a strong impact on the performance and condition of sewer networks, making it an essential criterion for prioritizing rehabilitation efforts. Sewer pipes with flat slopes leads to reduced velocities, promoting hydrogen sulfide gas formation, in the presence of moisture and oxygen, this gas can be converted to sulfuric acid, which attacks cementitious pipes, such as concrete and mortar, and increases the rate of corrosion inside the sewer pipes (E. Ana et al., 2009; Ayoub et al., 2004; Malek Mohammadi et al., 2020). Moreover, sewer with flat slopes lead to sediment accumulation and clogging, increasing the risk of deterioration (E. Ana et al., 2009; Baur & Herz, 2002).

Several studies highlighted the significance of sewer pipe slope in sewer system performance. Jeong et al. (2005) indicated in his study, that pipes with steeper slope have a higher probability of failure in sewer segments, due to its higher flow rate and lower stability. Similarly, Tran et al. (2006) noted that pipes with steeper gradient are more at risk of encountering problems due to the existence of voids within the surrounding soil, soil movements and pipe joint defects. Laakso et al. (2018) in their prediction model, revealed that negative and very low slopes are the most harmful conditions for sewer pipes, causing inadequate rinsing, debris accumulation, and blockages. However, other studies such as Tran et al. (2006), Sousa et al. (2014), and Kabir et al. (2018), considered pipe slope as having no contribution to the deterioration of sewer pipes network.

### **2.5.6. Velocity**

Velocity is a vital criterion for sewer system given their significant impact in the system's functionality, efficiency, and durability. Low velocities can lead to sediment accumulation, blockage, and reduced flow capacity while high velocity exerts pressure that can cause pipe erosion and structural damage. Both scenarios impact on hydraulic performance and the durability of the network. Maintaining optimal velocity including adherence to the minimum self-cleaning velocity within the sewer network, is essential to avoid sedimentation and maintain the system self-cleansing, so that it runs efficiently. The average velocity of self-cleaning, ranging from 0.6 to 1.5 m/s depending on the design of the system, guarantees that flow is adequate to move sediments and prevent buildup. ( Hillas 2014; Arthur et al., 2009; Hafskjold & König, 2002.), amongst others, concluded that a significant number of sewer pipes in operation before the formulation of self-cleaning velocity standards have more blockage incidents compared to sewer pipes designed in accordance with minimum self-cleaning velocity requirements (Okwori et al., 2020). Another study conducted by Sep & Chinyama. (2013), investigated the poor performance of urban sewerage systems, also supported this and revealed that 68% of sewer blockages were detected in sewers with velocity below the self-cleaning velocity (Okwori et al., 2020). This was attributed to variations between conditions of the design assumptions of flow regime such as the population per household and the water consumption assumed for the peak discharge design and the operational conditions in practice (Okwori et al., 2020)

Moreover, velocities problems often indicate design flaws, including pipes whether they are undersized or oversized, which needed to be improved for better functioning. By using velocity as criterion in rehabilitation decisions, ensures an effective evaluation of the system and helps in the identification of major areas that required urgent attention. Despite the fact that many researches in extant literature have used velocity as a criterion for prioritizing the rehabilitation of water distribution networks, its application in sewer networks remains largely unexplored.

### **2.6. Sewer systems rehabilitation**

The rehabilitation of sewer systems poses a significant challenge for municipalities worldwide. It is a substantial and costly global problem often addressed through crisis-oriented approaches (Tagherout et al., 2011). With increasingly populations in cities and aging infrastructure the need for effective and efficient sewer system rehabilitation is more vital. However, lack of funds and other priorities constantly pose a challenge on the capacity of authorities to address both maintenance and rehabilitation at the same instance. In the same regard, there is growing

pressure in respect of environmental regulations which demand higher quality levels of wastewater treatment and pollution reduction. Furthermore, the constant changes in accounting standards mean that municipalities have to adopt more transparent and accurate reporting practices for their infrastructure assets, further complicating the management and renewal processes.

Given these challenges, the traditional approaches to sewer system rehabilitation, which often rely on reactive maintenance and isolated repairs, are no longer sufficient. It is therefore apparent that there is need to have more strategic and sustainable ways that would help in addressing the root causes of infrastructure deterioration, optimize the allocation of limited resources, and also meeting set standards.

In the past, the problems brought about by deteriorating drainage pipes were tackled using a reactive approach, whereby repair or rehabilitation was only done once a pipe failed. However, this type of approach was deemed unsustainable due to cost consideration, e.g. very high cost of emergency repairs, and due to increasing customer and regulatory pressures (Fenner & Sweeting, 1999). The current trend is to manage drainage pipes in a proactive manner, i.e., addressing the problems (just) before they occur. To achieve this goal, utilities began implementing some sort of asset management system (Vanier, 2001).

## **2.6. Challenges in rehabilitation decision-making**

Decision on sewer rehabilitation have long lasting effects on the functionality and quality of future services provided by these networks. It involves navigating a range of challenges that can complicate the process of identifying, prioritizing and executing necessary interventions.

Limited budget is considered one of the major constraints affecting the ability of municipalities when it comes to maintaining and rehabilitating sewer systems. Halfawy et al. (2008) highlighted the challenge of balancing rehabilitation needs with limited financial resources and other competing infrastructure priorities. In many cases, the means provided for the rehabilitation are often not enough to address renewal requirements to the extent desired. Therefore, decision on which projects to fund are very challenging. This financial pressure is further compounded by increased costs in materials, labour and compliance with stricter environmental and safety regulations.

Sewer systems are most often overlooked because they are underground infrastructure facilities, making it challenging to accurately assess their current state and predict future deterioration

rates. It is also clear that, inspecting all sewer pipes is impossible because of constraints on time, budget, and the available technologies for evaluating the state of the sewer system.

### **2.6.1. Uncertainty in Risk Assessment**

Decisions in sewer network rehabilitation is usually made under uncertainties, especially when predicting the timing and intensity of risk of failures. First of all, the deterioration of sewer infrastructure is a rather unpredictable process, which, along with the imperfection of the existing models, complicate the risk assessment and prioritization of rehabilitation efforts (Tagherout et al., 2011). However, being exposed to risks, may lead to severe outcomes, such as environmental contamination or public health crises, making risk management an important but complex part of the decision-making process.

### **2.6.2. Data Limitations**

Successful and effective rehabilitation planning of sewer network require current, valid and reliable data. However, the state of this underground assets is not fully documented. Moreover, most municipalities do not have data on the previous condition but also the current sewer situation in their management information system. The available data may be incomplete records, outdated maps and inconsistent maintenance logs. These gaps in data hinders the assessment of the existing sewer, the development of prediction models, the evaluation of the effects of rehabilitation on sewer condition, and identifying critical areas that requires immediate attention. Lack of elaborated condition assessments prevent the identification of proper priorities for interventions based on actual needs.

### **2.6.3. Stakeholder Engagement**

Rehabilitation projects involve a wide range of stakeholder groups with different professional background, experience, expectations and financial constraints. Engaging these stakeholders in the decision-making is essential in order to gain their support for rehabilitation efforts as well as to ensure that the selected interventions suit the needs of the community members. Nevertheless, managing the competing needs and claims of the various stakeholders can be quite complex especially where decisions affect the routine of the community for instance the closing of a road or a temporary shutdown of some services.

These challenges highlight the importance of more advanced decision support tools that can help prioritize rehabilitation efforts. An effective prioritization approach must take into account several criteria, including structural condition, hydraulic performance, environmental impact, criticality of the asset, and socio-economic factors.

## 2.7. Decision Support Systems in Infrastructure Management

In response to the challenges confronted by municipalities around the globe, many models and programs have been established for sewer network rehabilitation, with much focus on the development of more sustainable and better prioritization methods for the rehabilitation of sewer systems (Fenner & Sweeting, 1999). One of the most used approaches is Decision Support Systems (DSS), which have emerged as critical tools in the realm of infrastructure management. This system integrates data, models, and analytical techniques in order to support decision-making in complex systems. They allow decision-makers to consider multiple factors, explore different scenarios, assess the outcomes of decisions from various perspectives and angles.

The topic of decision support system for prioritizing sewer system rehabilitation has been widely discussed in literature, more specific in applying multi-criteria decision-making (MCDA) such as AHP, Entropy, Electre, Topsis and PROMETHEE. For example, Tagherouit et al. (2011) developed a ranking scheme for sewer rehabilitation priorities using a fuzzy expert system for the city of Laval in Canada. The system used inputs from a combined assessment of hydraulic, structural performance and potential failure consequences.

Salehi. (2017) presented a comprehensive criteria-based multi-attribute decision-making model for the rehabilitation of water distribution systems. In this model, which is called as WDSR model, using a fuzzy TOPSIS technique, it is possible to adjust the criteria based on the local conditions. and to weight them based on the group decision-making of experts. Vladeanu & Matthews. (2019) presented a structured approach to evaluating the condition of wastewater pipes by integrating multiple criteria and utilizing the AHP method for decision-making. The proposed model was applied to a small portion of a US wastewater collection system. Orhan et al. (2022) presented a methodology for determining rehabilitation priority in wastewater systems by integrating the ENTROPY, ELECTRE, and TOPSIS methods.

Another approach that has gained popularity in recent years is the integration of GIS and MCDA for the decision-making process. GIS-based MCDA, is a series of techniques and processes that transform and integrate geographical data (input or criterion maps) with the preferences of decision-makers (criterion weights) to generate an overall value for each decision or evaluation alternative, or output map. Malczewski & Rinner. (2015), Nyimbili et al. (2018), Qin. (2013). This implies that the analysis results are influenced not only by the spatial distribution of the alternatives but also by the value judgments incorporated in the decision-making process (Malczewski & Rinner, 2015; Nyimbili et al., 2018; Qin, 2013).

The motivation behind integrating GIS and MCDA stems from the need to make the capabilities of GIS more relevant for planning and decision-making (Nyimbili et al., 2018; Sugumaran & Degroote, 2010). While there exist numerous MCDA methods, this study primarily focuses on one technique: the Analytical Hierarchical Process (AHP), developed by Saaty in 1980, and its integration with GIS.

## **2.8. Arc-GIS Applications in infrastructure management**

GIS (Geographic information system) is an organized collection of computer hardware, software, and geographic data, and personnel designed to efficiently capture, store, update, manipulate, analyze, and display all forms of geographically referenced information (Environmental System Research Institute, 1994), such as spatial location, spatial distributed information (Liu et al., 2008a).

GIS has proven to be a powerful tool for spatial analysis, data management, and visualization in various infrastructure management applications, including sewer systems rehabilitation (Jafari et al., 2022). Several studies have proven GIS crucial role in the decision-making process and cost planning for urban infrastructure management. Leveraging its spatial analysis capabilities and integration of diverse data sources, GIS enables decision-makers to gain valuable insights into the condition, performance, and spatial relationships of sewer infrastructure.

One of the early applications of GIS in sewer rehabilitation was presented by Fenner and Sweeting (1999), presented a decision support model for the rehabilitation of non-critical sewers by combining sewer performance and geographic information system (GIS) data to rank variable-sized grid squares into priority zones for rehabilitation action.

Burkhard & González Lakehal. (2006) highlight GIS's significance in sewer rehabilitation planning and cost assessment. The authors developed prototype based on Geographic Information Systems (GIS) that visualizes the most urgent rehabilitation needs and facilitates cost planning. Furthermore, they advocate further research endeavors to integrate stakeholder preferences and community needs into the decision-making process, ensuring long-term sustainability.

Yang & Su. (2006) introduced an automation model for optimal sewerage rehabilitation planning in Taichung, Chinese Taiwan, by integrating image processing, clustering technology, optimization, and visualization display within a Geographic Information System (GIS). GIS played a pivotal role in the automation model by providing a spatially explicit platform for

integrating various data sources, visualizing sewer system information, and displaying rehabilitation plans graphically.

Halfawy et al. (2008) presented an integrated approach, including a GIS-based DSS, for the renewal planning of sewer networks. The approach aims to maximize return on investment by optimizing budget allocation while considering elements such as asset performance, risk of failure, and life-cycle costs. However, the model didn't focus on role of stakeholder engagement in the decision-making process for sewer network renewal planning. Additionally, it focused only on the evaluation of structural conditions without considering hydraulic conditions.

Baah et al. (2015), presented a risk-based approach using GIS (Geographic Information System) to prioritize maintenance and rehabilitation efforts in a cost-effective and proactive manner.

## **2.9. Analytic Hierarchy Process (AHP) For Decision Support**

The Analytic Hierarchy Process (AHP) has emerged as the most commonly used multi-criteria decision-making technique, particularly prevalent in the realm of water and wastewater management, accounting for 28.3% of relevant publication (Kabir et al., 2018). AHP is recognized as a valuable method for obtaining priorities among various alternatives in multiple criteria decision-making problems (Lee et al., 2009). It provides a structured approach to decision-making by breaking down complex problems into a hierarchy of criteria, sub-criteria, and alternatives. This process allows for the incorporation of expert knowledge and stakeholder preferences through pairwise comparisons and weight assignments (Vargas, 1990). Therefore, the AHP is highly dependent on human judgment.

Darko et al. (2019), performed an extensive review of AHP application in constructions management through an analysis of 77 AHP-based studies, indicating it rising application in infrastructure decision-making. According to their analysis AHP is flexible as a stand-alone tool or in conjunction with other tools to resolve decision making problems.

Given its flexibility and ability to handle both quantitative and qualitative factors, the AHP has been widely employed in infrastructure management contexts, including sewer system rehabilitation (Basupi & Kapelan, 2015). Several studies have successfully integrated AHP with other for instance Yang et al. (2005) have established an evaluation model using the Analytic Hierarchy Process (AHP) to prioritize sewerage rehabilitation projects for east Taichung, Taiwan, addressing the challenge of limited budgets by conducting a cost-benefit ratio analysis. Another study by Vladeanu & Matthews. (2019) in which they developed a Consequence-of-Failure (COF) model using the Analytic Hierarchy Process (AHP) to evaluate the economic,

social, and environmental consequences of wastewater pipe failure. The model incorporates 14 factors consisting of pipe characteristics and demographic parameters. This study revealed that economic cost factors, are the most significant in determining the COF score.

Ebrahimian et al. (2015) developed a hybrid system that integrate Analytic Hierarchy Process (AHP) with fuzzy AHP techniques. They sought input from decision-makers and technical personnel's opinions to select the most appropriate construction method for urban stormwater management in Iran. This study emphasizes the adaptability of AHP to handle complex decision-making situations. Additionally, Kessili & Benmamar. (2016) formulated a model for ranking sewer rehabilitation projects in Algiers, Algeria by combining the Analytic Hierarchy Process (AHP) with PROMETHEE II (Preference Ranking Organization Method for Enrichment Evaluations) method.

Although AHP has been extensively used for prioritizing sewer rehabilitation, its effectiveness can be significantly enhanced by integrating it with Geographic Information Systems (GIS). In this case, GIS will facilitate decision-making by providing an encompassing representation of the sewer network as well as allowing different data layers to be incorporated (Halfawy et al., 2008; Mogila et al., 2013). By incorporating both spatial and non-spatial criteria into the prioritization process through employing GIS together with AHP can help to make it a more informed and transparent approach.

### **2.10. Integration of Arc-GIS and AHP in infrastructure management**

Geographic Information System (GIS) integrated with the Analytic Hierarchy Process (AHP) incorporates the analytical properties and capabilities of GIS with GIS with the multi-criteria decision-making (MCDM) methodology of AHP.

This integrated approach, commonly known as spatial AHP, was first proposed by Siddiqui et al. in 1996. By using the strengths of both techniques, Spatial AHP allows for the enhancement of decision-making processes that use spatial data and multiple criteria (Liu et al., 2008b).

Geographic Information System (GIS) is a versatile technological tool used in managing, analyzing, and visualizing geographic data while Analytical Hierarchy Process (AHP) is a systematic decision-making technique used to handle complex decision-making problems with multiple criteria and alternatives (Liu et al., 2008b). By incorporating GIS and AHP, decision makers can consider the spatial data and geographic relationships into the decision-making process to enhance analysis and decision making since they entail spatial and non-spatial factors.

Many researchers have explored the possibility of improving decision-making through the application of GIS and AHP in different fields, pointing out the strengths of coupling geographic analysis with multi-criteria evaluation procedures. In the context of natural hazard assessment, Goumrassa et al. (2021) used GIS-AHP to assess the susceptibility to flood hazards in the Chiffa wadi in Algeria, combining qualitative and quantitative methods.

Regarding water management, Berrezel et al. (2024) developed and applied a decision-making tool for prioritizing water distribution network renovations, integrating GIS with AHP, highlighting its utility in infrastructure management. Additionally, Berrezel et al. (2023) created a decision support system for managing water distribution networks in Tourville, Algeria. This system uses GIS, AHP, and hydraulic simulation models to aid in the renovation and rehabilitation of water networks, Hammouri et al. (2022) developed a vulnerability hotspot mapping for improving sanitation services provision in Jordan based on multi-weighted criteria model, which integrated GIS and (AHP). Ghavami et al. (2020) suggested a novel approach for assessing the risk of failure in urban sewer pipelines based on a combination of GIS, AHP and Data Envelopment Analysis (DEA).

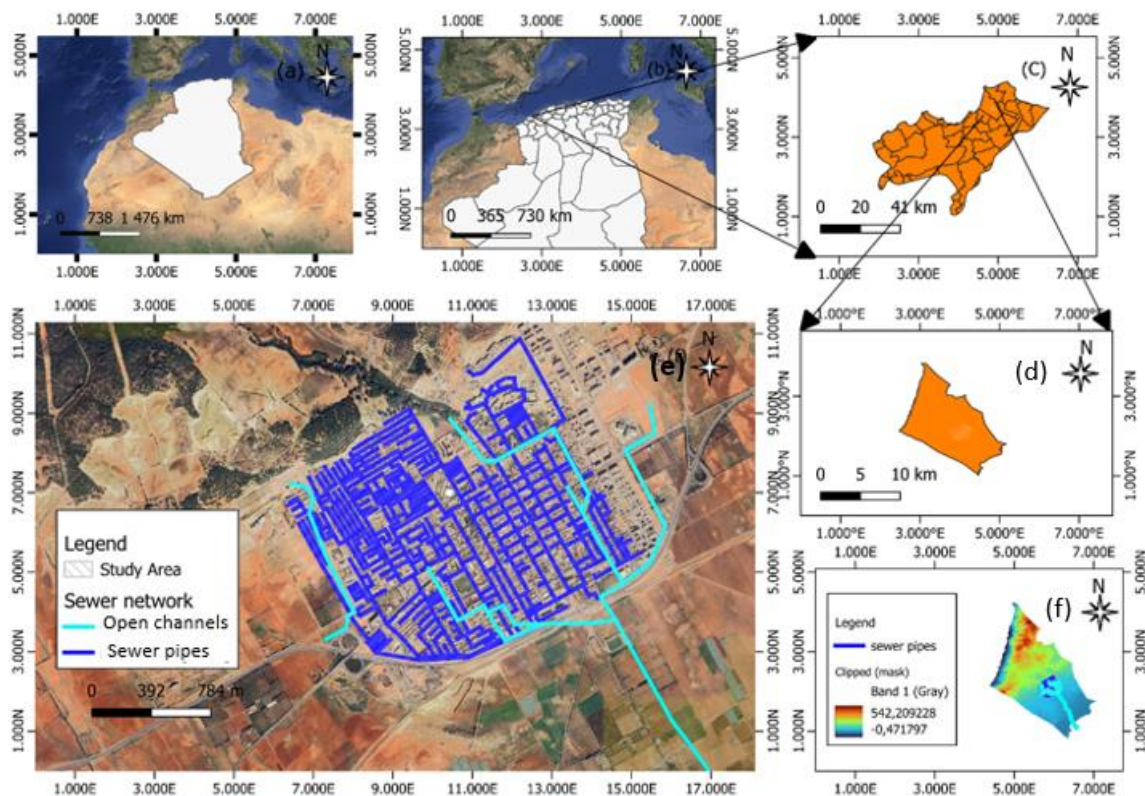
While These studies have demonstrated the effectiveness of GIS-AHP base approach for multiple application. There is lack of researches using this approach for sewer system rehabilitation. Therefore, there is a pressing need for further research on integrated decision support systems that leverage the strengths of both GIS and MCDA, specifically in the context of sewer system rehabilitation in urban areas facing rapid urbanization and aging infrastructure challenges (Younis, 2010).

## CHAPTER 3: METHODOLOGY

### 3.1. Introduction

The methodology chapter presents the approach that has been used in this study for developing a GIS-AHP-based framework to prioritize sewer system rehabilitation. It explains the systematic approach for data collection, criteria selection, and the combined use of GIS and AHP in decision making. It consists in selecting indicators characterizing the physical and hydraulic state of the sewerage system and using the AHP method to prioritize them in the form of pairwise comparisons, and using GIS tools to visualize the results.

### 3.2. Presentation of the study area



**Figure 3.1: a) Algeria’s location within the African continent; b) Oran city’s position within Algeria; c) Gdyel town’s placement within Oran city; d) The study area’s location within Gdyel, (e)The sewer network of the study area; (f)The digital elevation model (DEM) representing the study area.**

The study area of this research represented in Figure 3.1, is the urban agglomeration of Gdyel, a municipality in the northeast region of the Wilaya of Oran in Algeria, situated on National

Route No. 11, approximately 20 kilometers east of Oran. It is part of the plains and basins of the Western Tellian Atlas. Its coordinates are 35°46'56" North latitude and 0°25'25" West longitude. The municipality covers an area of 100 km and its limits are as follows:

To the North: By the Mediterranean Sea.

To the East: By the two communes of Hassi Mefssoukh and Sidi Benyebka.

To the South: By the commune of Ben Freha.

To the West: By the Mediterranean Sea and the commune of Hassi Ben Okba.

Gdyel has witnessed an increasing rate of urbanization in the last few decades (SEOR, 2023). This growth has exerted great pressure on sewerage system, especially in the areas that have been characterized by irregular constructions that lack proper sewage service connections. The municipality housing development program includes 1,629 collective housing units, and with an average household size of 7, the projected future population is estimated at 11,403 residents (ANRH, 2024). This rapid demographic expansion, combined with irregular urban development, has made Gdyel an ideal case study for testing and validating the developed system for prioritizing sewer system rehabilitation.

### **3.2.1. Topography**

The territory of the municipality is composed of five physical areas:

#### **• Gdyel Center**

The center of Gdyel is characterized by a gradual and irregular slope, ranging from an elevation of 130 meters to 170 meters over a distance of 1,500 meters, resulting in an average slope of 2.67% (SEOR; 2023; ANRH, 2024).

#### **• Coastal Massifs and Slopes**

Approximately one-third of the commune is occupied by two mountainous areas: Djebel Khar (nicknamed "the mountain of lions") and Djebel Kristel, which together represent 31.60% of the total area (SEOR; 2023; ANRH, 2024).

#### **• Gdyel Plateau**

This plateau, covering 11% of the communal area, is characterized by relatively gentle slopes ranging between 3% and 12% (SEOR; 2023; ANRH, 2024).

#### **• Plain Areas**

The plains occupy the southern part of the commune, covering 40% of the total area. They feature elevations ranging from 85 meters to 150 meters, making them suitable for various agricultural activities (SEOR; 2023; ANRH, 2024).

#### **• Hills**

The hills in the northeast of the commune are dotted with small valleys (chaabets) and cover **10%** of the total area, adding a picturesque dimension to the local landscape (SEOR; 2023; ANRH, 2024).

### **3.2.2. Climatology**

Gdyel's climat is semi-arid with mild winters and hot summers, the average annual rainfall is irregular and low, with a level of 307.1 mm per year. The region's wettest month is March with an average of 43.7 mm, whereas August is the driest with an amount of 2.4 mm of rainfall (SEOR; 2023; ANRH Alger, 2024). Torrential rains are quite frequent in this region especially during spring months. These intense rainfall events trigger large stormwater runoff levels which pressure the sewage infrastructure (SEOR; 2023; ANRH, 2024). The network system's hydraulic performance is evaluated through analysis of biennial and decennial rainfall events because these intense events typically produce localized flooding in vulnerable sections. The highly intense rainfall frequency combined with low annual precipitation levels demonstrates an urgent need to enhance stormwater infrastructure resilience against peak water flow periods (SEOR; 2023; ANRH, 2024).

### **3.2.3. Hydrology**

Hydrography of the municipality of Gdyel is characterized by two types of drainage network. The exorheic network discharges in to the sea and encompasses major rivers of Oued Chachoune (3 km) and Oued Rhadrane (2.5 km) with other streams including Chaabates Mersat Ammar and Ain-Defla (SEOR; 2023; ANRH, 2024). The endorheic network which discharges to Lake Télamine originates primarily from Djebel Kristel and includes Oued Ras El Ain and Oued Tazahrha. Furthermore, Oued El-Mohgoun starts in Gdyel fed by tributaries like Oued Gassaa Bennou and Oued Tazdout. In general water flows from the north-west to the south-east. The hydrographic network of the area is relatively sparse, with streams flowing east of the city and merging further before reaching lac Télamine, located 11 km to the south (SEOR; 2023; ANRH, 2024).

### **3.2.4. Sewer network characteristics**

The sewer network in the study area spans a total length of 68.044 km, consisting of pipes with diameters of Ø200, Ø250, Ø300, Ø400, Ø500, and Ø700, made of asbestos cement and reinforced concrete. The network operates as a combined sewer system, functioning primarily by gravity flow (SEOR, 2023). Additionally, it features three rectangular channels designed to

collect stormwater flowing through the city from north to south, which converge beyond the expressway before discharging into Lake T elamine, located 11 km to the south (SEOR, 2023).

### 3.3. Data and methods

#### 3.3.1. Methodology

The methodology of this study illustrated in Figure 3.2, consist of three phases: Data Collection and Processing, AHP-Based Prioritization, and GIS-Based Risk Mapping. The main objective of this tool is to integrate Geographic Information Systems (GIS) with the Analytical Hierarchy Process (AHP) to identify pipes in critical state, prioritize those that require immediate attention and ranking them based on their rehabilitation urgency.

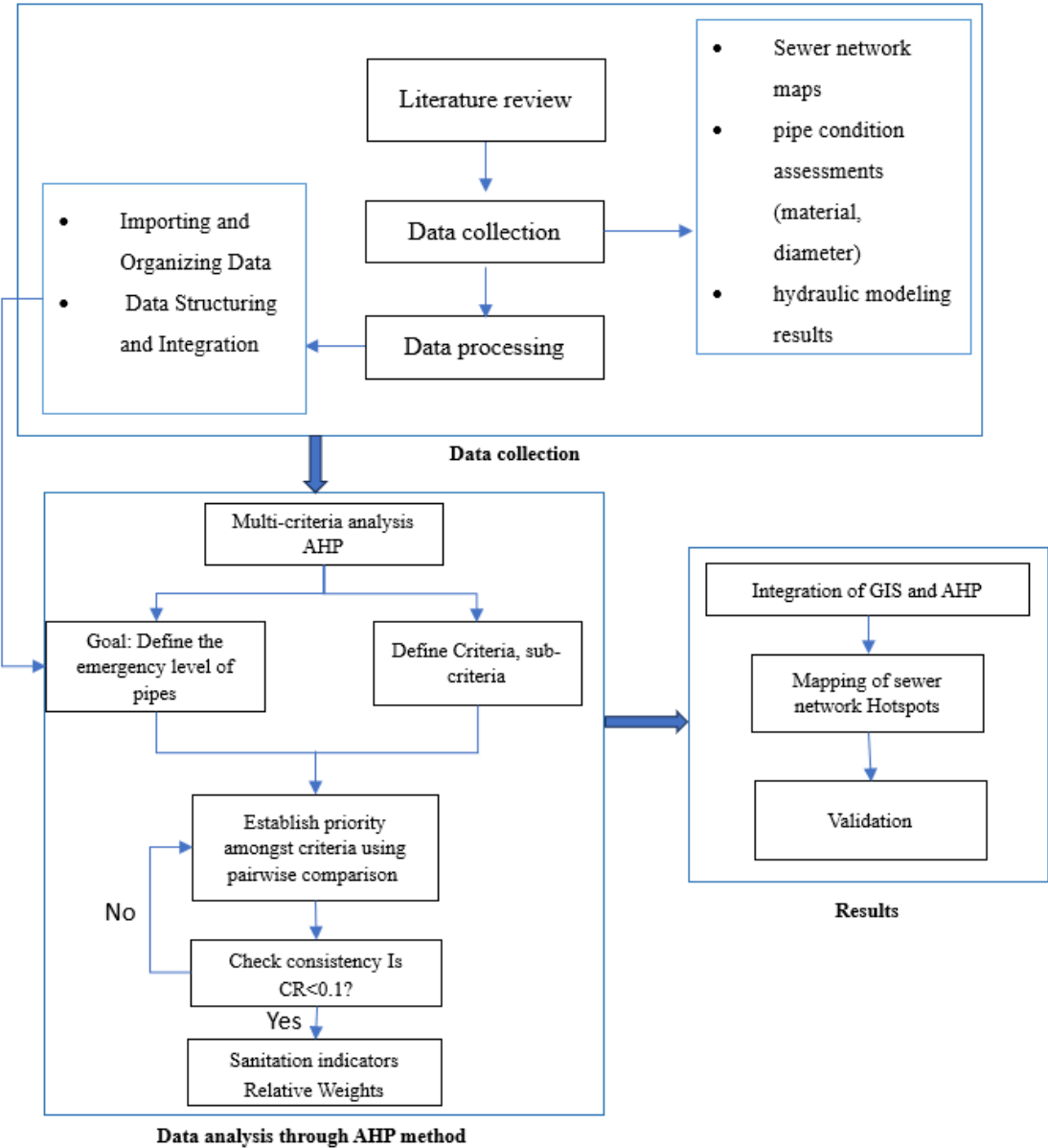


Figure 3.2: Schematic framework for the methodology of the study.

### 3.3.2. Data collection

The data gathering process consisted of two separate steps, we started by reviewing existing literature and previous studies conducted on the study area from technical reports and websites. Secondly, we consulted the Water and Sanitation Company of Oran (SEOR), where we gathered valuable information on the sewer system of the study area including detailed sewer network layouts generated through MikeUrban software, comprehensive GIS shapefiles documenting the entire network infrastructure (pipes and manholes), and hydraulic simulation results which covered various scenarios including dry weather conditions and rainfall events (both biennial and decennial). In addition, SEOR provided their research results on the study area highlighting critical areas within the network. A summary of the collected data is presented in Table 3.1:

**Table 3.1: Collected data from the SEOR company, Oran.**

	Category	Description	Data provided by SEOR
1	GIS layers of the sewer network	GIS layer of the main sewer network, including attributes such as pipe diameter, material type, and slope.	Geospatial dataset of the sewer network, structured for analysis in GIS software.
2	Hydraulic simulation results (Mike Urban)	Simulation results from Mike Urban software, providing hydraulic performance indicators such as pressure, Relative water level, and velocity.	Hydraulic analysis outputs used to assess flow capacity, network performance, and potential bottlenecks
3	Failure Notices	Sewer sections experiencing failures	sewer segments that need replacement, along with their location, current diameter, required replacement diameter, pipe length, and estimated cost.
4	Black Spots (Flood-Prone Areas)	Identified locations where flooding has been observed and recorded	PDF report with a mapped representation of flood-prone areas,
5	Estimation and Prioritization of Interventions	Assessment by SEOR experts outlining necessary interventions, ranked by urgency based on infrastructure condition and failure risk.	Expert recommendations for rehabilitation projects, prioritization criteria, and estimated costs where available

### 3.3.3. Material

The study conducted using software packages and tools represented in Table 3.2:

**Table 3.2: Overview of software and tools used and their related activities.**

Software/tool	Task
ArcGIS 10.1	Spatial analysis, data preprocessing, and visualization of GIS-based sewer network data.
MIKE URBAN 2014	Displaying hydraulic simulation results and analyzing sewer network layouts.
Excel	Organizing and analyzing tabular data, calculating AHP weights, and generating input tables.
Python	Automating data processing tasks, performing calculations for indicators, and model validation.

#### **3.3.4. Data processing**

The data processing phase involved several steps in order to analyze, organize, and transforming the data into a format suitable for GIS-AHP methodology. This process involved the manipulation of layers, and their attributes tables, The first step consisted of importing simulation results from Mike Urban, such as velocity, pressure and flooding into GIS database in forms of shapefile, then with the help of ArcGIS tools, relevant attributes (e.g., pipe diameter, material, slop) were extracted from the sewer network layer and organized in separate layers and tables. Then all these shapefiles were merged later into a single database. A geospatial analysis was used to define spatial relationship between pipes and other features (e.g., high-risk zones or critical areas), in order to identify the high-risk zones and critical infrastructure sections within the network.

#### **3.3.5. The AHP method**

Analytic Hierarchy process AHP, developed by Saaty in 1980 (Saaty, 1980), it's a well-known decision-making method, which integrates qualitative analysis with quantitative analysis. It's used to establish priorities among various alternatives in complex, multi-criteria decision-making problems (Saaty, 1980). This model is composed of four main steps:

- i. Defining and clarifying the context of the problem,
- ii. Hierarchical construction which consists of dividing the decision -making problem into hierarchical levels, starting from the objective at the top, followed by criteria and sub-criteria, and ending with a set of alternatives),
- iii. The formation of pairwise comparison matrices and the analysis of the relative importance weights of each criterion and alternative,

iv. Evaluating the consistency of the pairwise comparisons by calculating the Consistency Index (CI) and the Consistency Ratio (CR) to ensure the reliability of the judgments.

**a) Pair-wise comparison matrix**

In order to compare a set of criteria, Saaty (1980) proposed the pairwise comparison technique to determine their relative importance. This involves the development of a pairwise comparison matrix, expressed on the form of a square matrix  $n \times n$ , where  $n$  is the number of criteria. The element  $a_{ij}$  of the matrix  $A$  (3.1) indicates the relative importance of factor (i) with respect to factor (j). In order to quantify  $a_{ij}$ , we can use The Saaty’s Ratio Scaling shown in Table 3.3.

**Table 3.3: Saaty numerical scale (Saaty 1980).**

DEFINITION	INTENSITY OF IMPORTANCE
THE SAME IMPORTANCE	1
MODERATE IMPORTANCE	3
STRONG IMPORTANCE	4
EXTREME IMPORTANCE	7
ABSOLUTE IMPORTANCE	9

with respect to the  $j$ th criterion and reciprocals are assigned automatically as:

$$a_{ij} = 1$$

$$a_{ji} = \frac{1}{a_{ij}}$$

$$A = [a_{ij}] = \begin{bmatrix} 1 & a_{12} & \dots & a_{1n} \\ \frac{1}{a_{12}} & 1 & \dots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{1}{a_{1n}} & \frac{1}{a_{2n}} & \dots & 1 \end{bmatrix} \quad (3.1)$$

**b) Weight calculation**

The relative weights of criteria and sub-criteria are calculated through the AHP pairwise comparison matrix using Equation (3.2). The first step is to sum the values of each row in the comparison matrix (3.1):

$$S_i = \sum_{j=1}^n a_{ij} \quad (3.2)$$

The next step consists of normalizing the comparison matrix by dividing each element by the sum of the values in its respective column, as shown in Equation (3.3):

$$n_{ij} = \frac{a_{ij}}{\sum_{i=1}^n a_{ij}} \quad (3.3)$$

The result is a normalized matrix (N). The weight of each criterion is then obtained by determining the mean of every row of the normalized matrix, as shown in Equation (3.4).

$$W_i = \frac{1}{n} \sum_{j=1}^n n_{ij} \quad (3.4)$$

The resulting weight vector (W) represents the relative importance of the criteria.

### c) Consistency check

To assess the accuracy of the pairwise comparison matrix and ensure a logical consistency in the judgments, Saaty. (1980) defined the consistency Ratio (CR) as :

$$CR = \frac{CI}{RI} \quad (3.5)$$

Where:

RI: Random consistency index, it depends on the value of n as shown in Table 3.4.

Consistency index is calculated using Equation (3.6):

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (3.6)$$

Where:

$\lambda_{max}$ : the dominant eigenvalue of the pairwise comparison matrix.

n: the order of the matrix.

To validate the judgment matrix, the critical value of CR is defined as 0.10 (Saaty 1982). If CR exceeds 0.10, the evaluation criteria must be reevaluated. To determine the final weight, the weights assigned to elements at the lowest level must be multiplied by the weights assigned to the higher levels of criteria and dimensions.

**Table 3.4: Saaty (Saaty 1980) values of random index.**

N	2	3	4	5	6	7	8	9	10	11
RI	0.00	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49	1.52

### 3.3.6. The AHP process development

#### a) Hierarchical Structure for Sewer Rehabilitation Prioritization

The AHP process in this study is structured through a series of steps outlined in the following sections:

### **Step 1: Defining the Problem and Determining Its Goal**

The first step involves defining the decision problem and then determining the goal through AHP implementation. In the present study, the goal is to identify and rank the most critical sewer pipes requiring rehabilitation based on a series of pipe characteristics including physical and hydraulic factors. The AHP method will be used to calculate the weights of each pipe and prioritize them according to their emergency level in the sewer network

### **Step 2: Structuring the Decision Problem into the Hierarchy**

This step consists of decomposing the decision problem into multiple levels starting from the top level to the next lower level (intermediate through to the lowest levels). The goal or the objective of the problem serves as the topmost element which gets divided into criteria then sub criteria, and alternatives. This step is very important in the AHP process, as it establish the hierarchical relationship among criteria and factors.

In this study, factors that impact the deterioration process of wastewater pipes were selected based on extensive literature review and expert input from SEOR engineers, and grouped under two main criteria: pipe physical characteristics and the hydraulic performance of the network.

The physical characteristics of the network criterion is divided into five sub-criteria, which are pipe laying dates, materials, diameter, slope, and burial depth. As for the hydraulic performance of the network criterion were divided into two sub- criteria, including wastewater velocity ( $v$ ) and wastewater depth within the sewer network.

Figure 3.3 represent the hierarchical model used to define the critical parts of the network that need to be rehabilitated, using a rating-based assessment approach in which each criterion is subdivided to sub-criteria, each containing three specific indicators.

This system of rating is used in case there is multiple alternatives to be evaluated. Rather comparing each option directly against each other, the performance and the effectiveness of each alternative is assed based on specific indicators (categories).

#### **b) AHP Criteria rating system**

In this study, the ratings of each criterion were determined based on an extensive literature review and consultations with SEOR engineers. The selection of the criteria considers physical and hydraulic factors that affect the performance and deterioration of sewer systems.

##### **a) Physical criteria**

**Materials:** comparison between the least and most desirable sewer pipe material. A state-of-the-art by (Mohammadi et al., 2020) revealed that pipe material significantly impacts the longevity and performance of sewer systems. For instance, Lubini and Fuamba (2011) found that reinforced

concrete pipes are the most resistant to deterioration compared to other pipes because of the reinforcing steel that makes the conduit strong enough to prevent structural deterioration.

**Diameter:** Pipe diameter is another significant variable affecting the condition of sewer pipes after age based on the results of reviewed literature (Mohammadi et al., 2020). In this case of study smaller diameter pipes are considered as being more prone to deterioration than larger sizes.

**Slope:** Several studies including Ana et al., (2009), Ayoub et al. (2004), Laakso et al. (2018) highlighted the significance of sewer pipe slope in sewer system performance, revealing that negative and very low slopes are the most harmful conditions for sewer pipes, causing inadequate rinsing, debris accumulation, and blockages in accordance with this results, high priority will be assigned to pipe with flatter slopes.

**Burial depth:** the burial depth impacts the pipe lifespan as shallow depths result in increased live loads, while deep burial of the pipe results in increased soil over burden on the pipe (Hawari et al., 2020). According to Ennaoui and Fuamba (2013), a minimum of 2 meters in depth is required during installation to ensure structural stability and surface load resistance. However, soil conditions, water table levels, and traffic loading intensity need to be taken into consideration while determining the optimum burial depth. Based on these insights, sewer pipes with shallow depths will be given higher priority as they are more vulnerable to external loads and environmental factors, compared to deeper pipes.

#### **b) Hydraulic criteria**

**Velocity:** will be evaluated based on wastewater velocity within the pipe. Velocity has not been used before as criteria in deterioration prediction models, or investigated on its impact on sewer deterioration rate despite its importance as an indicator of failure. Researches conducted by (Hillas 2014; Chinyama., 2013; Arthur et al. 2009; Hafskjold et al. 2002) revealed that most of sewer blockages were detected in sewers with velocity below the self-cleaning velocity (Okwori at al., 2020). While high velocity water corrodes the internal walls of the pipe and causes disturbances especially when moving between pipes of different diameters (Hawari et al., 2020). Based on these results, higher priority will be given to velocities that exceed the average, and velocities smaller than standard average.

**Relative water level:** Represents the difference between the actual water level in a sewer link and its critical level, which is derived from the ground levels of the upstream and downstream nodes along the pipe's length. When no critical level is specified, the ground level is used instead.

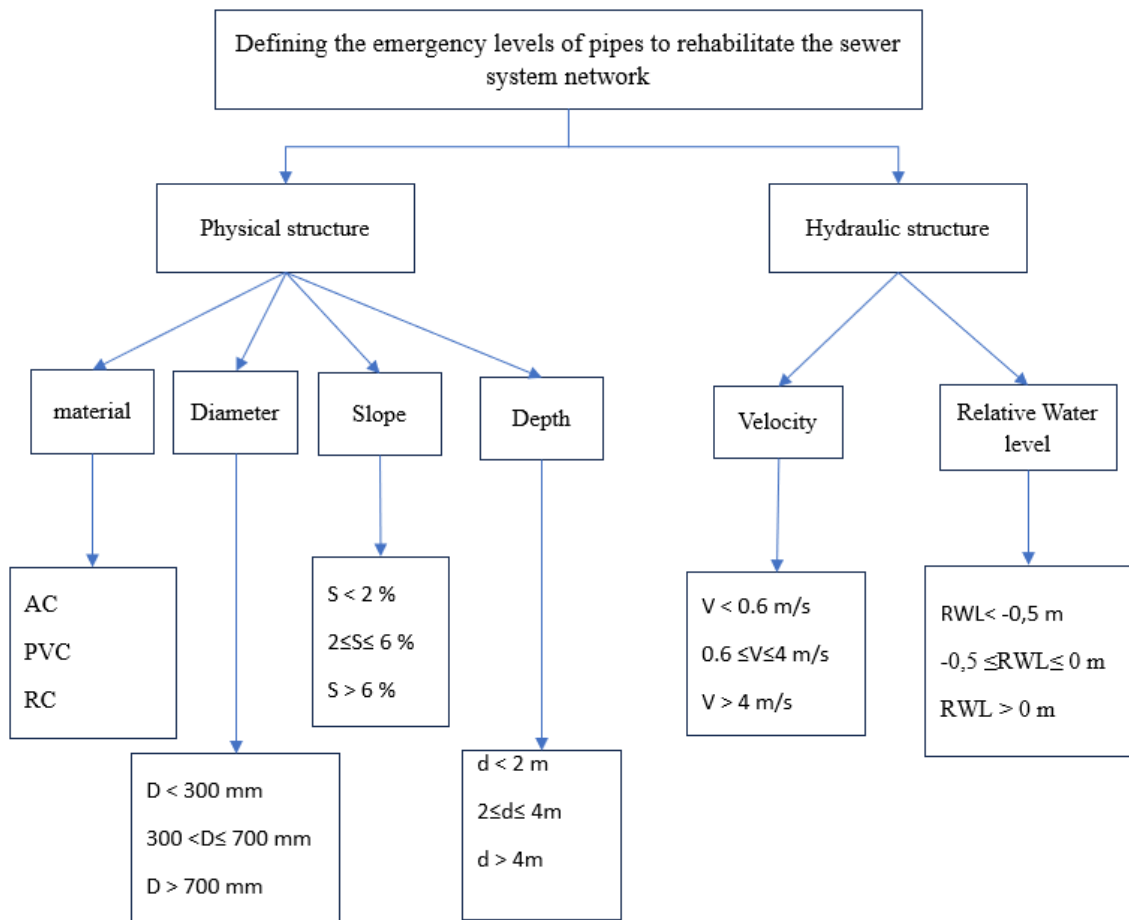
Pipes functioning at high-capacity levels have increased failure potential yet pipes used below capacity become susceptible to sediment buildup which affects hydraulic performance. The

rehabilitation strategy in this research focuses on prioritizing water pipes that operate at critical depth criteria.

The criteria and sub-criteria considered in the AHP process, along with their descriptions and assigned relative importance, are summarized in Table 3.5, while the hierarchical structure, along with the characteristics of the area’s pipe network, is depicted in Figure 3.3

**Table 3.5: Criteria and sub-criteria used in the AHP process, along with their descriptions and relative importance**

Criteria	Sub-criteria	Description and importance
Physical criteria	Pipe material	Different pipeline materials show different failure patterns.
	Diameter	The larger the pipeline diameter, the larger is its thickness, the lower is its deterioration rate and vice versa.
	Slope	Low or negative slopes cause sedimentation and blockages.
	Buried depth	Live loads impact increases at shallow depths and the soil overburden impact increases at high depths. Moderate depths increase the life of sewers.
Hydraulic criteria	Velocity	High velocity water corrodes the internal walls of the pipe and causes disturbances especially when moving between pipes of different diameters. Low velocity water causes deposition and accumulation of sediments
	Relative water level	Represents how close the water level inside a pipe is to its critical or ground level. High relative water levels indicate risk of overflow and structural stress, while low levels may suggest underuse and potential sediment buildup. Used to assess hydraulic performance and prioritize maintenance.



**Figure 3.3: The hierarchical structure and characteristics of the area pipe network.**

**c) Step 3. Making Pairwise Comparisons and Obtaining the Judgmental Matrix**

The process of evaluating criteria and sub-criteria through the pairwise comparison matrix can be demonstrated using the following steps, in which we'll focus on comparing four criteria: material, diameter, slope and depth using matrix (3.1), the elements are arranged in matrix A (3.7).

$$A = [a_{ij}] = \begin{bmatrix} 1 & 1 & 3 & 4 \\ 1 & 1 & 2 & 3 \\ \frac{1}{3} & \frac{1}{2} & 1 & 2 \\ \frac{1}{4} & \frac{1}{3} & \frac{1}{2} & 1 \end{bmatrix} \quad (3.7)$$

To determine the relative importance of these elements, we first sum up the values of each column of the matrix (3.7), this gives us the column totals: [2.6, 2.8, 6.50, 10.0]. next, we divide each value of the column by its corresponding column sum, the result will be a normalized matrix.

$$A = \begin{bmatrix} 1/2.6 & 1/2.8 & 3/6.5 & 4/10 \\ 1/2.6 & 1/2.8 & 2/6.5 & 3/10 \\ (1/3)/2.6 & (1/2)/2.8 & 1/6.5 & 2/10 \\ (1/4)/2.6 & (1/3)/2.8 & (1/2)/6.5 & 1/10 \end{bmatrix} = \begin{bmatrix} 0.387 & 0.353 & 0.462 & 0.40 \\ 0.387 & 0.353 & 0.308 & 0.30 \\ 0.129 & 0.176 & 0.154 & 0.20 \\ 0.097 & 0.118 & 0.077 & 0.10 \end{bmatrix}$$

Finally, the relative importance (weight) is determined by calculating the average value across each row of the normalized matrix using Equation (3.4):

$$\begin{bmatrix} 0.4 \\ 0.337 \\ 0.165 \\ 0.098 \end{bmatrix}$$

**a) Step 4: consistency check**

$$Det|A - \lambda I| = 0 \tag{3.8}$$

This will enable us to find the eigenvalues of the matrix A, where:

I: the identity matrix.

$\lambda$ : the eigenvalues of the Matrix.

$$Det \left| \begin{bmatrix} 1 & 1 & 3 & 4 \\ 1 & 1 & 2 & 3 \\ \frac{1}{3} & \frac{1}{2} & 1 & 2 \\ \frac{1}{4} & \frac{1}{3} & \frac{1}{2} & 1 \end{bmatrix} - \lambda \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \right| = 0 \tag{3.9}$$

$$\lambda = 4.0310$$

n: the order of the matrix, n = 4.

Using table, we get Random Consistency Index, RI = 0.89.

$\lambda_{max}$ : the principal eigenvalue of the matrix,  $\lambda_{max} = 4.0310$ ,

Consistency Index using Equation (3.6):

$$CI = \frac{\lambda_{max} - n}{n - 1} = \frac{4.3010 - 4}{4 - 1} = 0.0103$$

Consistency ratio using Equation (3.5):

$$CR = \frac{CI}{RI} = \frac{0.0103}{0.89} = 0.012$$

CR is less than 10%. Which means that, the comparison matrix is consistent.

After calculating the relative importance of each sub-criteria and indicator, the final weight of each indicator is determined by multiplying it by the weight of its corresponding sub-criteria. The final results are then visualized and analyzed spatially using GIS.

### 3.3.7. Integration of GIS and AHP

After determining the weight values of each indicator by the AHP model, the next step consists of integrating those results into the ArcGIS environment, to classify and map sewer pipes that require urgent rehabilitation. In this process attribute table functionality in ArcGIS is used, in order to manage the physical characteristics and hydraulic simulation results of the sewer network.

To rank the alternatives, ArcGIS is used to filter and select pipeline segments that meet predefined prioritization criteria. This process utilizes Attribute Query, a selection method that enables the identification of critical sewer sections based on their assigned priority levels. Queries and mass updates and visualization for spatial creations are executed within the analysis via Python scripts in order to create a consistent and effective analysis. This procedure involves several steps:

#### a) Step1: Preparing GIS Data for Integration

Before integrating the AHP results into ArcGIS, the dataset must be properly structured. During the data processing phase, all shapefiles were merged into a single geodatabase, the result is a single attribute table including the pipe Material, Diameter, Slope, Burial depth, Velocity, and Relative Water Level, as represented in Figure 3.4:

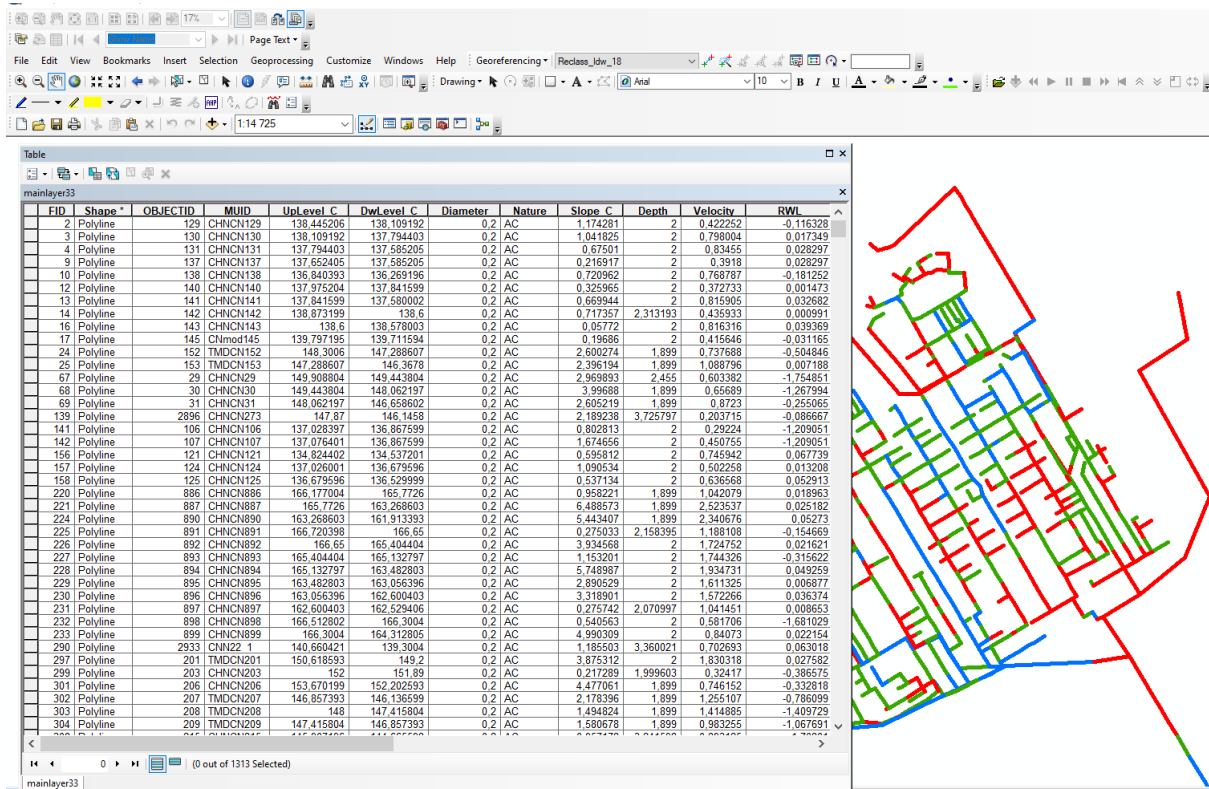


Figure 3.4: Sewer network attribute table with spatial and hydraulic parameters.

After full dataset preparation, the network is then overlaid on a base map derived from GIS features.

### **b) Step 2: Assigning Weights from AHP to GIS Layers**

This step consists of integrating the AHP weights into the GIS environment. For each criterion, an attribute field is created within the GIS layer, which stores the relevant AHP-derived weight. To facilitate the process and for a better management, a Python script utilizing ArcPy is employed, enabling systematic assignment and easy updates of the weights.

### **c) Step 3: Performing Spatial Analysis in GIS**

Once the AHP-derived weights are assigned to their respective indicators, the next process is to perform spatial analysis to rank sewer segment rehabilitation. A new attribute field in the main sewer network layer is created to store the final weight of each pipe segment. The final weight is calculated using the Field Calculator by summing all the assigned weights of the indicators for each segment.

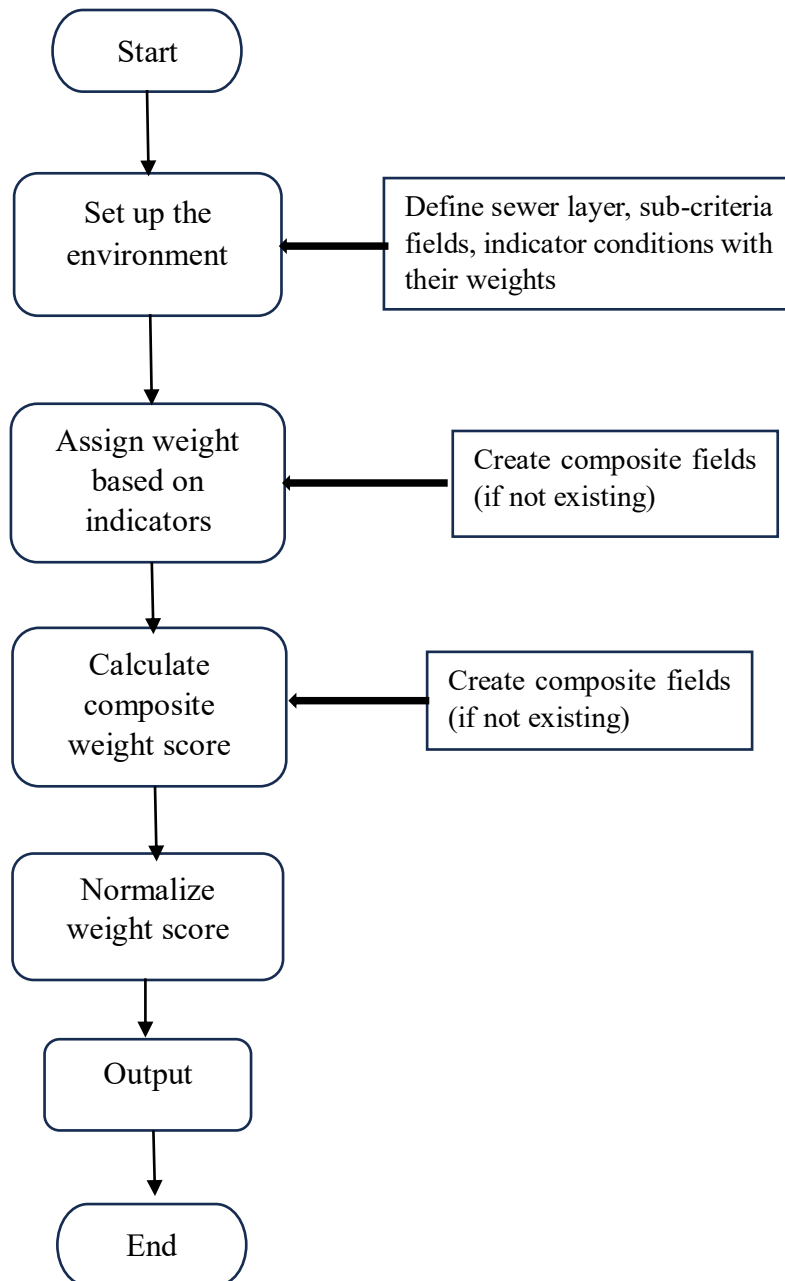
Pipes scoring high weights indicate higher rehabilitation urgency, while those scoring low indicate medium or low priority for action. In this way, decision-makers can easily determine what needs to be rehabilitated first. This process makes certain that rehabilitation priority is set on the basis of a comprehensive review of various criteria.

This GIS-based approach clearly distinguishes between:

- High-priority areas, which need immediate rehabilitation.
- Medium-priority areas, requiring intervention in the near future.
- Low-priority areas, where rehabilitation can be delayed.

This method results in a clear, detailed map that highlights exactly where resources should be directed first, greatly improving the efficiency of sewer system rehabilitation efforts.

To facilitate the prioritization process, a Python script was developed to automatically assign weight for each alternative based on predefined indicators, calculate the total risk score by summing the individual weights, and finally determine the normalized score (final weight) for each alternative based on the overall maximum value as shown in Figure 3.4.



**Figure3.5: Sewer pipe risk prioritization Algorithm, AHP results in ArcGIS.**

### 3.3.8. Validation

Validation is an important step for ensuring that the AHP-GIS-based prioritization system accurately reflects the real conditions of the Gdyl sewer system. The objective of this validation exercise is to verify if the rankings are consistent with observed sewer deterioration and expert opinions. This process enhances the validity of the presented decision-support system and ensures its applicability for practical decision-making.

To validate the results of the AHP-GIS approach, the AHP-prioritized rankings were compared with the findings of a diagnostic study conducted by SEOR to check the model's consistency. This diagnostic study includes failure notices within the network.



## CHAPTER 4: RESULTS AND DISCUSSION

### 4.1. Introduction

This chapter recapitulates the results of the GIS-AHP-based decision support system implemented to prioritize the rehabilitation of Gdyel's sewer system in Algeria. It presents key findings on the physical and hydraulic condition of the sewer network and identifies the most priority zones that need intervention.

### 4.2. General Overview

#### 4.2.1. Sewer network characteristics

The sewer network of Gdyel spans a total length of 68.04 km, consisting of pipes with diameters ranging from Ø200 mm to Ø700 mm, made of asbestos cement (AC), reinforced concrete (RC), and polyvinyl chloride (PVC).

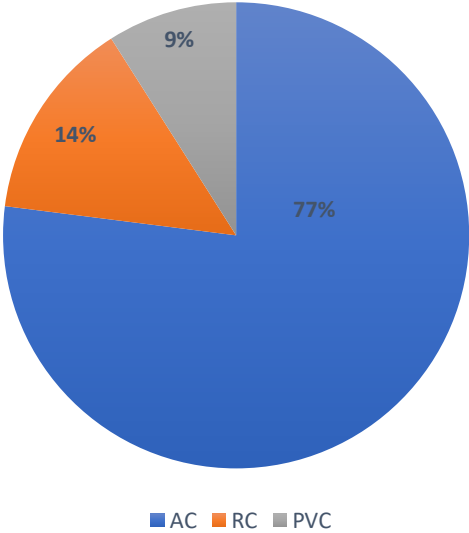
The sewer network in this area is combined operating primarily on gravity. It features three rectangular channels designed to collect stormwater flowing through the city from north to south converging beyond the expressway before discharging into Lake Télamine, located 11 km to the south.

The distribution of pipe materials and diameters is as follows:

**Table 4.1: Distribution of pipe material.**

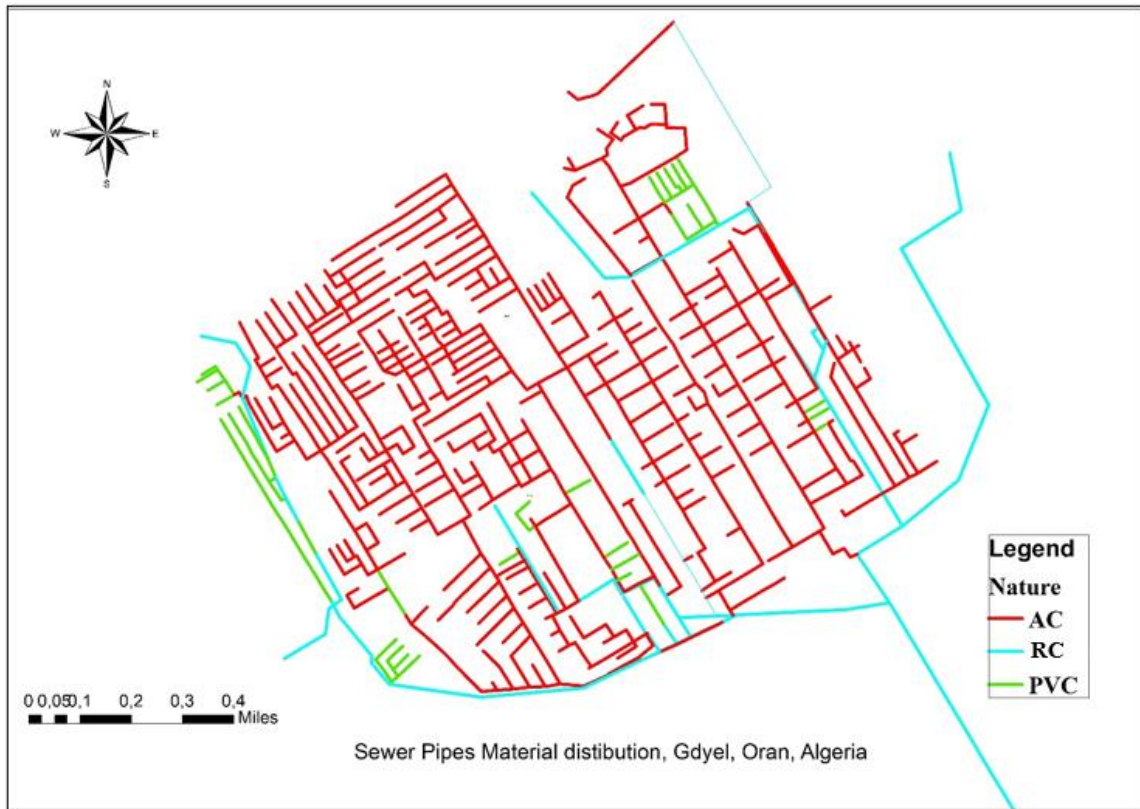
	Network element	Quantity	Description
Sewer network	Pipes Ø200	150	Asbestos Cement
	Pipes Ø250	77	Asbestos Cement
	Pipes Ø300	588	Asbestos Cement / Poly Vinyl Chloride (PVC)/ Reinforced concrete
	Pipes Ø350		Asbestos Cement
	Pipes Ø400	276	Asbestos Cement/PVC/Reinforced concrete
	Pipes Ø500	47	Asbestos Cement / Reinforced concrete
	Pipes Ø700	12	Reinforced concrete
	Pipes Ø600	2	Reinforced Concrete
Ancillary Structures	Open channels	160	Concrete, Open conduits for the transportation of stormwater or wastewater, typically visible and not enclosed
	manhole	1166	Structures for excess water discharge during heavy rains.

**4.2.2. Material Distribution**



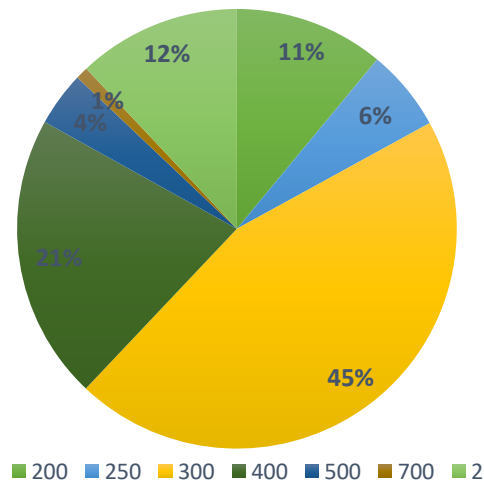
**Figure 4.1: Pipe material distribution of Gdyl sewer network.**

Figure 4.1 illustrates the distribution of pipe materials throughout Gdyl's sewer network. Asbestos cement (AC) pipes make up 77% of the total network assets, whereas reinforced concrete (RC) pipes occupy 14%, and PVC pipes make up the remaining 9%. The vast adoption of AC, a material that was commonly used in the past for water supply and sewage systems due to their durability and resistance to corrosion, has now aged significantly, thus increasing their risks of structural weakness, leakages, and reduced carrying capacities (Punurai & Davis, 2017). In simple terms, most of the sewer network is old and fragile, making it highly prone to failures. The distribution of these pipe materials throughout Gdyl is further demonstrated by the spatial map in Figure 4.2. It can be observed that AC pipes are widespread throughout the network, dominating the central and densely urbanized areas. The reinforced concrete pipes are placed mostly along major drainages and the boundary zone of the network as primary collectors, suggesting how suitable they are to accommodate larger flows of wastewater. PVC pipe, however, appears sporadically and is found mostly in disconnected segments, indicative of recent maintenance or localized repair efforts.



**Figure 4.2: Sewer pipes material distribution map, Gdyl, Oran, Algeria.**

#### 4.2.3. Diameter Distribution



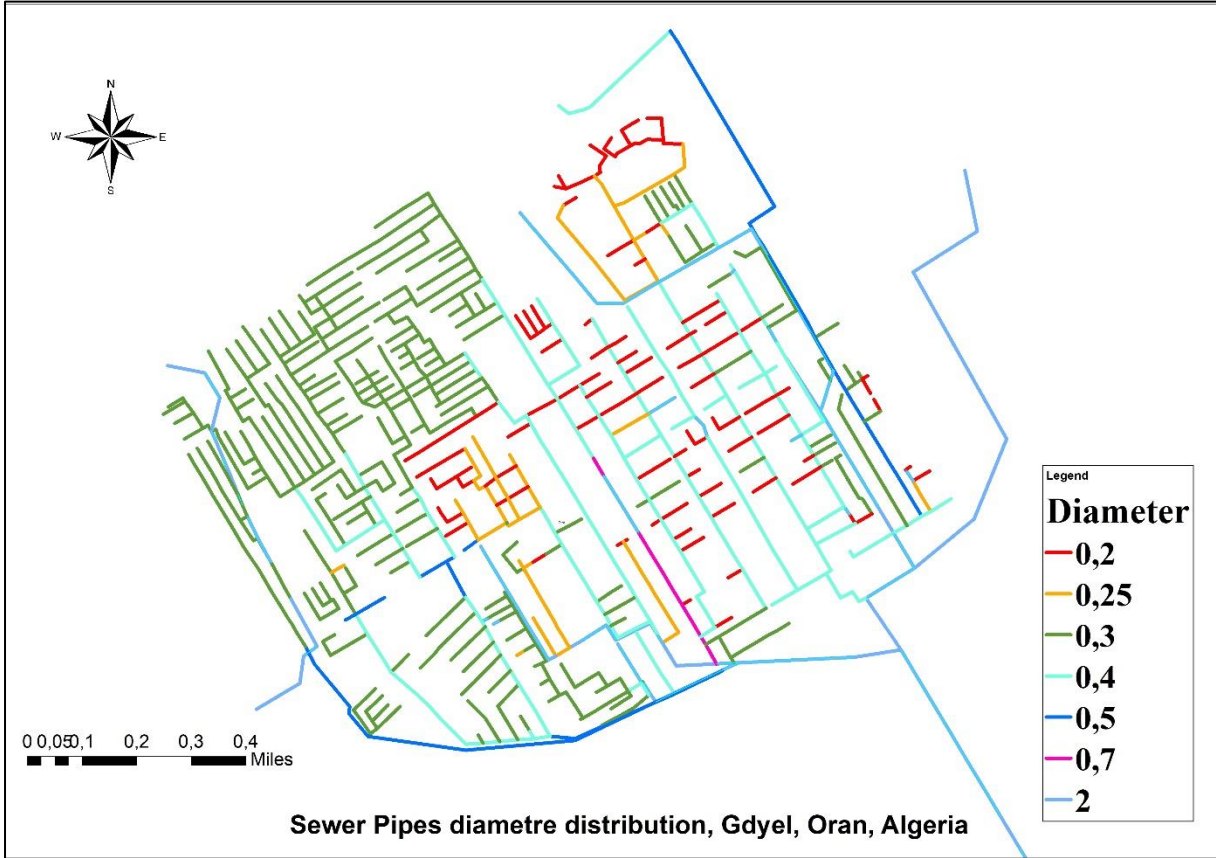
**Figure 4.3: Pipe diameter distribution of Gdyl sewer network.**

Figure 4.3 indicates the pipe diameter distribution in Gdyl's sewerage system. The largest group consists of pipes with a diameter of 300 mm, representing 45% of the network. Pipes with a diameter of 400 mm make up the second largest type and account for 21% of the system.

The larger pipes occupy a relatively small percentage of the network, with only 4% being the 500 mm diameter pipes and a paltry 1% being the 700 mm diameter pipes. Surprisingly, however, the 2-meter diameter channels occupy 12% of the network.

The smaller diameter pipes constitute 17% of the network as a whole: 11% are 200 mm diameter pipes, and 6% are 250 mm diameter pipes.

The map in Figure 4.4 shows a clear spatial distribution pattern of the sewer system. The smaller diameter pipes (200 mm and 250 mm) are highly concentrated in the eastern and central parts of Gdyel, particularly in locations like the city center (Centre Ville) and Carteaux. Conversely, the larger diameter pipes and conduits, and especially those with a 2-meter diameter, are most commonly found at the network periphery, implying their role in efficiently carrying larger volumes of wastewater from the densely inhabited central regions to treatment and point of discharge locations.



**Figure 4.4: Spatial Distribution of Sewer Pipe Diameters in Gdyel, Oran, Algeria**

### **4.3. Identifying High-Priority Zones in Gdyel's Sewer Network**

#### **4.3.1. Sewer system challenges**

According to the study conducted by the SEOR company, the sewer network faces several challenges and anomalies, including under-sizing, deteriorations and several blockages especially in the tertiary network level, likely due to malfunctions in the primary and secondary network, and this is due to multiple causes.

##### **a. Undersized infrastructure**

During the period from 1975 to 1987 Gdyel witnessed a 6% annual increase in its urban area which occurred mostly within northern and western regions of the city (El Hammar and Saint Germain). The growth in the sewer network was unable to keep pace with the rapid development which lacked proper infrastructure planning resulting in insufficient designed pipes struggling to handle present-day wastewater loads.

Most of the sewer network consists primarily of 200 mm asbestos cement (AC) pipes, which are insufficient to handle current wastewater loads and leads to continuous blocking, deterioration, and flooding. The problems exemplify the necessity for rehabilitation in order to continue operating and supporting the system.

##### **b. Aging Infrastructure**

The sewerage system consists mainly of asbestos cement (AC) pipes, representing 77% of the system. While AC pipes were durable and corrosion-resistant when installed, they have since become extremely aged, resulting in:

Structural weakness: Leaks, cracks, and collapses.

Capacity reduction: Cannot handle increased wastewater and stormwater flows.

##### **c. Unauthorized Interventions**

One of the main reasons behind those problems is the unauthorized interventions by residents, where connections are created without official approval. These unapproved modifications, were often undertaken as a quick solution to fix blockage problems and minimize connection expenses by linking to the nearest inspection chamber, which severely affect the network integrity and functionality.

#### **4.3.2. Identified High-Priority Zones**

The diagnostic study conducted by SEOR identified several zones and streets experiencing significant sewer infrastructure issues with high risk of flooding, summarized in Table 4.2 as follows:

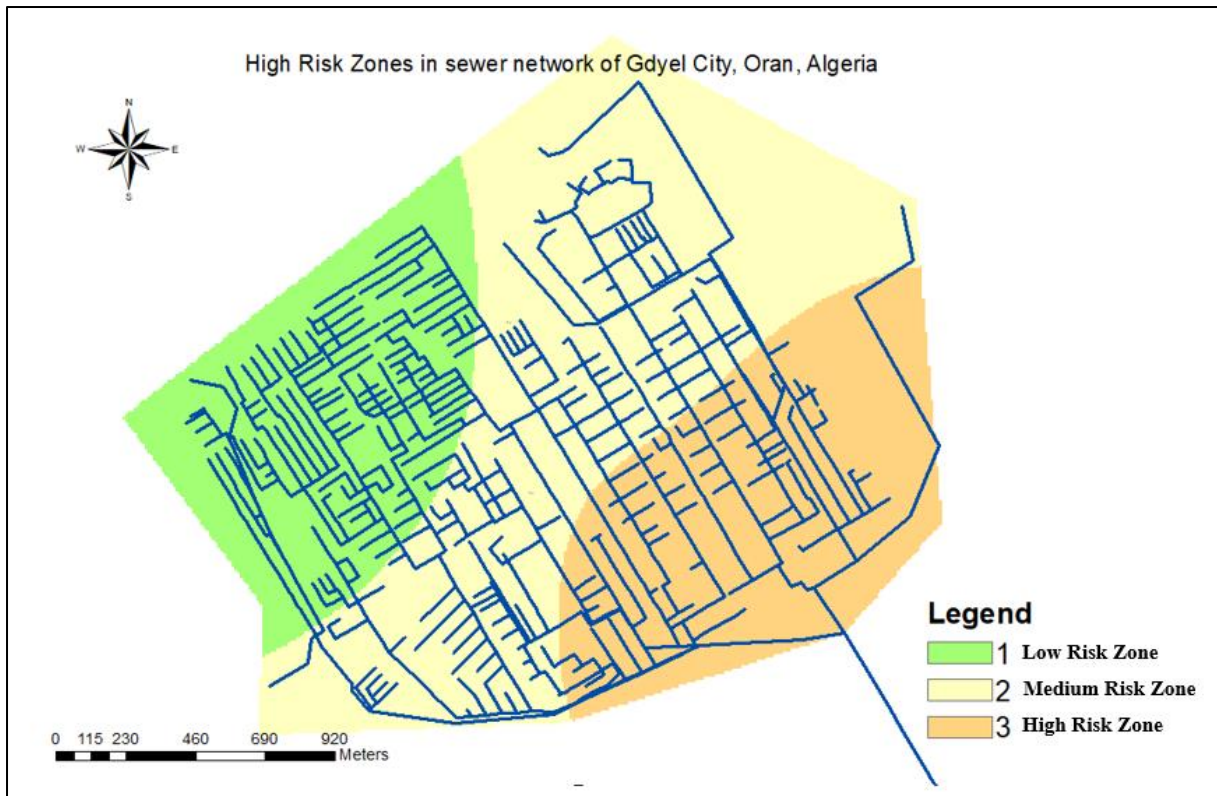
**Table 4.2: Streets and neighborhoods with identified sewer network issues.**

<b>N°</b>	<b>Neighborhood and Street</b>	<b>Existing Diameter</b>
<b>01</b>	Rue Ould Aneur	200 mm AC
<b>02</b>	Rue Djellat Habib	200 mm AC
<b>03</b>	Rue Drider Moussa	200 mm AC
<b>04</b>	Rue Pasteur	200 mm AC
<b>05</b>	Cité 266 Logements	Archaïque
<b>06</b>	Rue Benyebka	200 mm AC
<b>07</b>	220 logements Cheklaoua	300 mm AC
<b>08</b>	500 logements	300 mm AC
<b>09</b>	Boulevard du nord	300 mm AC
<b>10</b>	Nasr 1 et Nasr 2	300 mm AC
<b>11</b>	Rue de la Gare	300 mm AC
<b>12</b>	Rue Hammada et Moulin	300 mm AC
<b>13</b>	Rue Med Khemisti	300 mm AC

These segments are primarily located in key urban areas such as El Hammar, City Center, Carteaux, and Cheklaoua. These areas are frequently affected by operational issues, i.e., blockage, flooding, sewer backup, or infrastructural degradation, and thus indicate the need for priority attention and rehabilitation.

To geographically validate and enhance SEOR's diagnosis, an Inverse Distance Weighted (IDW) interpolation was performed in ArcGIS to generate a risk surface from pointwise diagnostic data.

IDW was utilized due to its being a simple, efficient, and well-liked spatial interpolation method that postulates values at unsampled locations are influenced more by nearby points than distant ones. This makes it particularly suitable for sewer network studies where conditions such as pipe deterioration or blockages are spatially correlated and tend to vary smoothly over short distances.



**Figure 4.5: Risk zones within the sewer network with high inundation risk.**

The risk map generated by the IDW indicates the areal distribution of sewer network risk based on pointwise diagnostic ratings. The interpolated surface was categorized into three levels of risk represented in Figure 4.5. These risk zones allow easy visualization of where intervention is needed. The most severe risk in the southeast quadrant of the study area (in orange) suggests the need for intensive inspection or rehabilitation on priority. Conversely, the northwest (green zone) is low in risk, suggesting good network condition. This independent risk zoning enhances SEOR's diagnostic study with a spatial verification of the key areas based on data-driven interpolation.

## **4.2. Results Section: Presenting AHP Findings**

The Analytic Hierarchy Process (AHP) was applied in this study to scientifically examine and order sewer pipes that need urgent attention in accordance with an extensive literature review and expert-guided pairwise comparisons.

### **4.2.1. Calculation example**

#### **a. Pairwise comparison matrix**

The relative importance of each sub-criterion was evaluated through a pairwise comparison matrix as shown in Table 4.3:

**Table 4.3: Comparison of the sub-criteria.**

CRITERIA	MATERIAL	DIAMETER	SLOPE	PIPE DEPTH
<b>MATERIALS</b>	1	1/2	2	3
<b>DIAMETER</b>	2	1	2	3
<b>SLOPE</b>	1/2	1/2	1	2
<b>DEPTH</b>	1/3	1/3	1/2	1
<b>SUM</b>	3,8	2,3	5,50	9,0

$$A = [a_{ij}] = \begin{bmatrix} 1 & \frac{1}{2} & 2 & 3 \\ 2 & 1 & 2 & 3 \\ \frac{1}{2} & \frac{1}{2} & 1 & 2 \\ \frac{1}{3} & \frac{1}{3} & \frac{1}{2} & 1 \end{bmatrix} \quad (4.1)$$

### b. Normalized matrix

Each column was normalized to sum to 1, and the weight of each criterion in the AHP was determined by averaging the values of its corresponding row in the normalized pairwise comparison matrix, as represented in Table 4.4:

$$A = \begin{bmatrix} 1/3.8 & (1/2)/2.3 & 2/5.5 & 3/9 \\ 1/3.8 & 1/2.3 & 2/5.5 & 3/9 \\ (1/2)/3.8 & (1/2)/2.3 & 1/5.5 & 2/9 \\ (1/3)/3.8 & (1/3)/2.3 & (1/2)/5.5 & 1/9 \end{bmatrix} = \begin{bmatrix} 0.261 & 0.214 & 0.364 & 0.33 \\ 0.522 & 0.429 & 0.364 & 0.33 \\ 0.130 & 0.214 & 0.182 & 0.22 \\ 0.087 & 0.143 & 0.091 & 0.11 \end{bmatrix} = \begin{bmatrix} 0.293 \\ 0.412 \\ 0.187 \\ 0.108 \end{bmatrix}$$

**Table 4.4: Weight calculation.**

CRITERIA	MATERIAL	DIAMETER	SLOPE	DEPTH	WEIGHT
<b>MATERIAL</b>	0,261	0,214	0,364	0,33	0,293
<b>DIAMETER</b>	0,522	0,429	0,364	0,33	0,412
<b>SLOPE</b>	0,130	0,214	0,182	0,22	0,187
<b>DEPTH</b>	0,087	0,143	0,091	0,11	0,108
<b>TOTAL</b>					1,000

### c. consistency check

- Weight sum vector:

$$\begin{bmatrix} 1 & 1/2 & 2 & 3 \\ 2 & 1 & 2 & 3 \\ 1/2 & 1/2 & 1 & 2 \\ 1/3 & 1/3 & 1/2 & 1 \end{bmatrix} \times \begin{bmatrix} 0.293 \\ 0.412 \\ 0.187 \\ 0.108 \end{bmatrix} = \begin{bmatrix} 1.1972 \\ 1.6961 \\ 0.7555 \\ 0.4365 \end{bmatrix}$$

- Consistency vector:

$$\begin{bmatrix} 4.0856 \\ 4.1186 \\ 4.0362 \\ 4.0433 \end{bmatrix}$$

- Lambda:

Lambda is the average of consistency vector:  $\lambda = 4.0709$

n: the order of the matrix,  $n = 4$ .

Using table, we get Random Consistency Index,  $RI = 0.89$ .

**Consistency Index:**

$$CI = \frac{\lambda - n}{n - 1} = \frac{4.0709 - 4}{4 - 1} = 0.0236$$

**Consistency ratio:**

$$CR = \frac{CI}{RI} = \frac{0.0236}{0.89} = 0.027$$

**Results summary:**

The results are summarized in Table 4.5

**Table 4.5: Weight calculation.**

WEIGHT SUM VECTOR	CONSISTENCY VECTOR
1,1972	4,0856
1,6961	4,1186
0,7555	4,0362
0,4365	4,0433
LAMBDA	4,0709
CI	0,0236
RI	0,89
CR	0,027

The results of the application of the AHP method, including the classification of dimensions, criteria and indicators are represented in matrices of weights in Table 4.6 to table 4.14

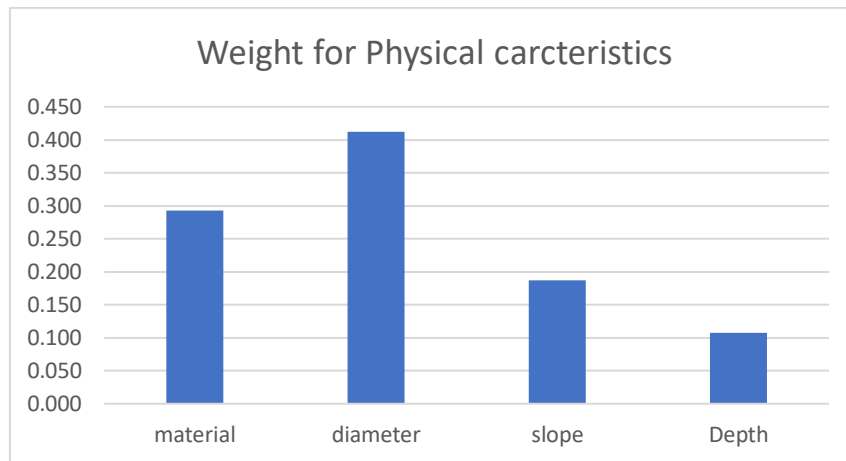
**Table 4.6: Comparison of the main criteria;  $\lambda_{max}= 2$  and  $CR=0$**

CRITERIA	PHYSICAL STRUCTURE	HYDRAULIC STRUCTURE
PHYSICAL	1	2
HYDRAULIC	1/2	1
SUM	1,50	3,00

**Table 4.7: Comparison of Subcriteria 1;  $\lambda_{max}= 4.0709$  and  $CR=0.027$**

CRITERIA	MATERIAL L	DIAMETER	SLOPE	PIPE DEPTH	WEIGHT
MATERIALS	1	1/2	2	3	0,293

<b>DIAMETER</b>	2	1	2	3	0,412
<b>SLOPE</b>	1/2	1/2	1	2	0,187
<b>DEPTH</b>	1/3	1/3	1/2	1	0,108
<b>SUM</b>	3,8	2,3	5,50	9,0	1



**Figure 4.6: Comparison of physical sub-criteria 2;  $\lambda_{max}= 2$  and  $CR=0$ .**

From Figure 4.6, it can be observed that the importance of the diameter is more than the material, although pipe material is usually given higher priority in sewer rehabilitation ranking studies, in this case, the majority of the network is made up of Asbestos Cement (AC) pipes. This introduces low heterogeneity of material in the network and thus reduces its utility as a discriminatory measure. Conversely, pipe diameters are highly variable (Figure 4.6), and lower diameters have been highly associated with repeated blockages and surcharging events. Due to this, diameter was prioritized over material within this study.

**Table 4.8: Comparison of hydraulic sub-criteria 2;  $\lambda_{max}= 2$  and  $CR=0$ .**

	Velocity	Relative Water Level	Weight
<b>Velocity</b>	1	1/2	0,3
<b>Relative Water Level</b>	2	1	0,7
<b>Sum</b>	3	1,50	1

**Table 4.9: Comparison of indicator 1;  $\lambda_{max}=3.0538$  and  $CR=0.05$ .**

Criteria	D < 300 mm	300 ≤ D ≤ 700 mm	D > 700 mm	Weight
<b>D &lt; 300 mm</b>	1	3	2	0,52

$300 \leq D \leq 700$ mm	1/3	1	1/3	0,14
$D < 700$ mm	1/2	3	1	0,33
<b>Sum</b>	1,83	7,00	3,33	1

**Table 4.10: Comparison of indicator 2;  $\lambda_{\max} = 3.054$  and  $CR = 0.052$ .**

Criteria	$S < 0,3 \%$	$0,3 \leq S \leq 4 \%$	$S > 4 \%$	Weight
$S < 0,3 \%$	1	3	2	0,52
$0,3 \leq S \leq 4 \%$	1/3	1	1/3	0,14
$S > 4 \%$	1/2	3	1	0,33
<b>Sum</b>	1,83	7,00	3,33	1

**Table 4.11: Comparison of indicator 3;  $\lambda_{\max} = 3.01$  and  $CR = 0.0089$ .**

Criteria	$d < 2m$	$2 \leq d \leq 4m$	$d > 4m$	Weight
$d < 2$	1	2	3	0,54
$2 \leq d \leq 4$	1/2	1	2	0,30
$d > 4$	1/3	1/2	1	0,16
<b>Sum</b>	1,83	3,50	6	

**Table 4.12: Comparison of indicator 4;  $\lambda_{\max} = 3.01$  and  $CR = 0.0089$ .**

Criteria	AC	PVC	RC	Weight
AC	1	3	2	0,539
PVC	1/3	1	1/2	0,164
RC	1/2	2	1	0,297
<b>Sum</b>	1,8	6,0	3,50	1

**Table 4.13: Comparison of indicator 5;  $\lambda_{\max} = 3.01$  and  $CR = 0.0089$ .**

Criteria	$V < 0.6$ m/s	$0.6 \leq V \leq 4$ m/s	$V > 4$ m/s	Weight
$V < 0.6$ m/s	1	3	2	0,54
$0.6 \leq V \leq 4$ m/s	1/3	1	1/2	0,16
$V < 4$ m/s	1/2	2	1	0,30
<b>Sum</b>	1,83	6,00	3 1/2	

**Table 4.14: Comparison of indicator 6;  $\lambda_{\max} = 3.01$  and  $CR = 0.0089$ .**

Criteria	$Rwl \leq -0,5$ M	$-0,5 \leq Rwl \leq 0$ M	$Rwl > 0$ M	Weight
$Rwl \leq -0,5$ M	1	1/2	1/3	0,16
$(-0,5 \leq Rwl \leq 0$ M)	2	1	1/2	0,30
$Rwl > 0$ M	3	2	1	0,54
<b>Sum</b>	6	3,50	1,83	1,00

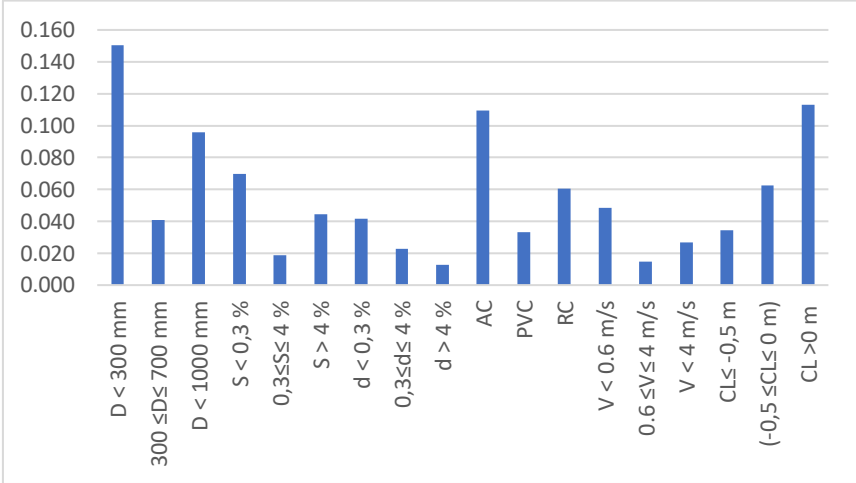
### 4.3. Scenario 1

In order to consider the influence of varying decision priorities, and in accordance with SEOR engineers, two contrasting scenarios were designed within the AHP framework. The first one

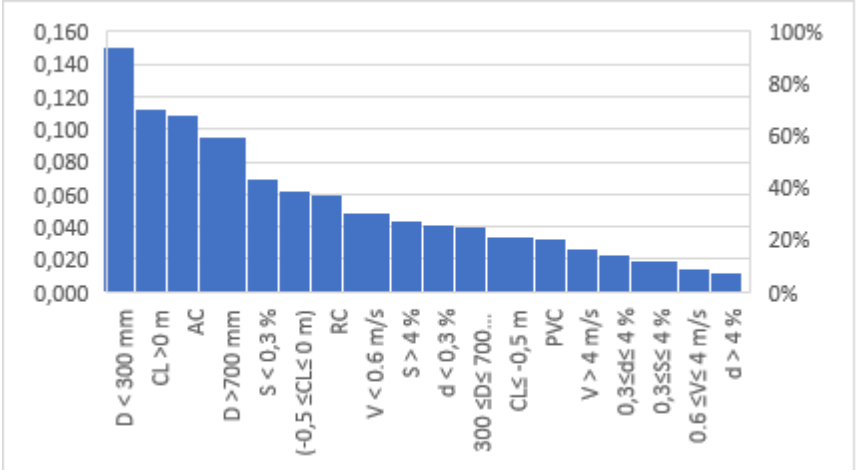
had its concentration on physical condition, assigning higher weight to physical structure components. On the contrary, the second one emphasized its concern towards hydraulic functioning, assigning higher weightage to hydraulic elements, i.e., Relative water level and velocity. Such comparative analysis enables greater insight into the influence of varied planning paradigms on prioritizing sewerage system rehabilitation.

**4.3.1. Spatial analysis results**

This scenario assigns high weights to physical aspects (pipe material, diameter, slope and burial depth).



**Figure 4.7: Ranking of all 18 indicators obtained by AHP.**



**Figure 4.8: Ranking of all 18 indicators obtained by AHP.**

Figures 4.7 and 4.8 present the different weights that was given to different pipe conditions and performance indicators when using the AHP method. From this weight distribution, it’s clear that certain factors stand out more than others. It can be seen that small-diameter pipes (<300 mm) received the heights weight, similarly, pipes made of asbestos cement (AC) and those with

a high relative water level ( $CL > 0$  m) also received high scores, indicating they're more at risk and should be prioritized for rehabilitation.

Other factors, like pipe depth or those made of PVC and reinforced concrete (RC) had much lower weights, while velocity and slope had a more balanced distribution, with mid-range values getting more attention.

Overall, these weight distribution, inform a priority ranking that highlights both physical degradation and hydraulic inefficiencies, providing a balanced approach to rehabilitation planning.

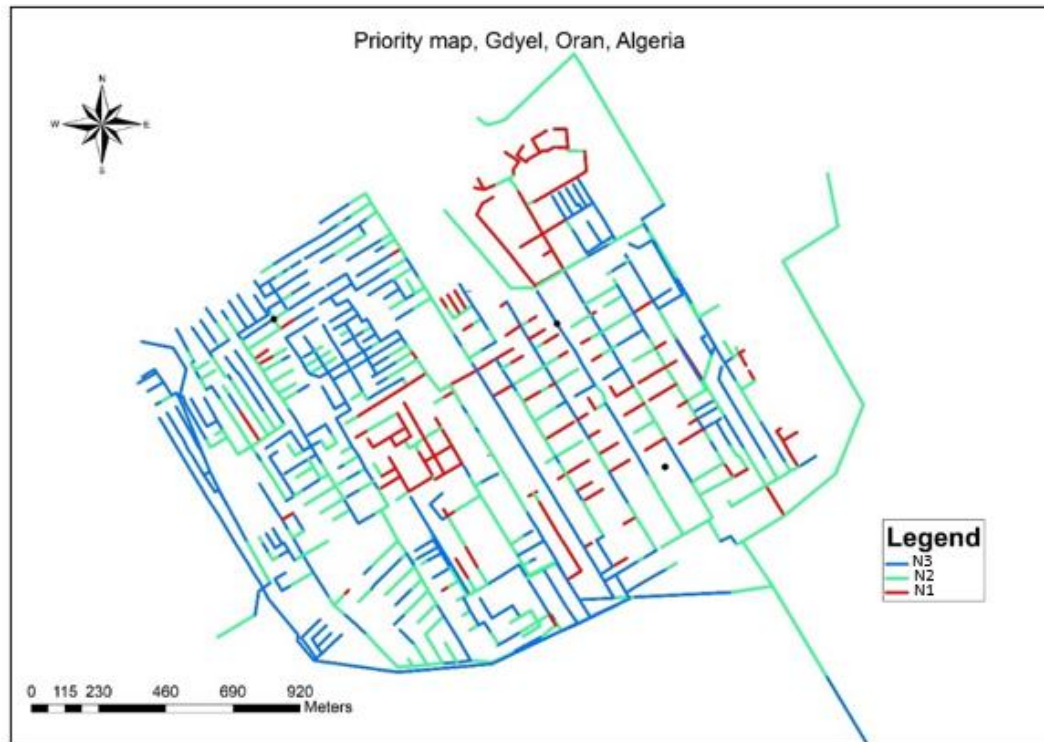
After calculating the weight of each indicator using the AHP model as shown in Figure 4.7, the next step involves the integration of these results into ArcGIS environment to classify and map out the sections in order of importance for the action of rehabilitation using the attribute table displayed in ArcGIS (Figure 4.9). To facilitate the process python program was developed with its main function being to assign weights based on indicators, and calculating the final weight for each pipe, by summing the weight of sub-criteria for each pipe and then normalizing the result.

Shape *	OBJECTID	MIJD	UpLevel C	DwlLevel C	Diameter	Nature	Slope C	Depth	Velocity	RWL	DiameterWe	NatureWe 1	SlopeWeig	DepthWeig	RWL W
Polyline	127	CN127	146.196796	145.496402	0.5	AC	1.901963	2.3	2.298283	0.014429	0.041	0.109	0.019	0.023	
Polyline	128	CN128	203.547601	198.114801	0.3	AC	13.275035	1.9	1.009766	-1.797043	0.041	0.109	0.044	0.042	
Polyline	130	CHNCN130	138.105192	137.794403	0.2	AC	1.041825	2	0.798004	0.017349	0.151	0.109	0.019	0.023	
Polyline	131	CHNCN131	137.794403	137.685205	0.2	AC	0.67501	2	0.83455	0.028297	0.151	0.109	0.019	0.023	
Polyline	138	CHNCN138	136.840393	136.269196	0.2	AC	0.720962	2	0.768787	-0.181252	0.151	0.109	0.019	0.023	
Polyline	141	CHNCN141	137.841599	137.580002	0.2	AC	0.669944	2	0.815905	0.032682	0.151	0.109	0.019	0.023	
Polyline	2934	CN199_321	140.16172	139.738	0.4	AC	1.129087	1.9	1.501001	0.021149	0.041	0.109	0.019	0.042	
Polyline	143	CHNCN143	139.6	138.578003	0.2	AC	0.05772	2	0.816316	0.039369	0.151	0.109	0.07	0.023	
Polyline	149	TMDFCN149	146.136599	144.0394	0.25	AC	2.971928	3.996199	1.594709	0.039777	0.151	0.109	0.019	0.013	
Polyline	150	CN150	206.333903	201.220001	0.3	AC	13.714521	2	1.745756	-1.865301	0.041	0.109	0.044	0.023	
Polyline	151	TMDFCN151	144.0394	141.926804	0.25	AC	2.992621	4.011596	2.095329	0.038581	0.151	0.109	0.019	0.013	
Polyline	152	TMDCN152	148.3005	147.288607	0.2	AC	2.600274	1.899	0.737688	-0.504846	0.151	0.109	0.019	0.042	
Polyline	153	TMDCN153	147.288607	145.3678	0.2	AC	2.396194	1.899	1.088796	0.007188	0.151	0.109	0.019	0.042	
Polyline	154	CN154	162.307802	161.892401	0.3	AC	1.041745	1.99	1.124254	-1.645254	0.041	0.109	0.019	0.042	
Polyline	155	CN155	161.892401	159.384802	0.3	AC	7.032069	4.497599	1.249423	0.074675	0.041	0.109	0.044	0.013	
Polyline	2870	SCHN1_895	168.183001	167.8216	0.3	AC	1.011931	1.99	2.464749	0.009574	0.041	0.109	0.019	0.042	
Polyline	160	CN160	155.549993	154.580007	0.3	AC	3.859728	1.99	0.660368	-1.807717	0.041	0.109	0.019	0.042	
Polyline	161	CN161	201.220001	195.670807	0.3	AC	13.783764	2	1.734635	-1.834838	0.041	0.109	0.044	0.023	
Polyline	164	CN164	164.834005	161.529608	0.3	AC	8.134701	1.99	0.841558	-1.76344	0.041	0.109	0.044	0.042	
Polyline	166	CN166	159.751193	159.384802	0.3	AC	0.885016	2.666391	0.689577	0.074675	0.041	0.109	0.019	0.023	
Polyline	168	CN168	189.918401	189.397604	0.3	PVC	2.08215	1.99	0.658737	-1.760054	0.041	0.033	0.019	0.042	
Polyline	1	CN1	182.15	181.86	0.4	AC	0.779343	2.002396	1.412319	0.022215	0.041	0.109	0.019	0.023	
Polyline	2	CN2	181.86	181.14	0.4	AC	1.472458	2	1.742029	0.058614	0.041	0.109	0.019	0.023	
Polyline	6	CHCN6	134.7	134.554001	2	AC	0.10552	2	0.636634	0.062205	0.096	0.109	0.07	0.023	
Polyline	2874	CN19547	151.9	151.087404	0.3	AC	2.100383	1.899	0.849793	-0.056975	0.041	0.109	0.019	0.042	
Polyline	2892	1_99986	152.189606	150.375595	0.4	PVC	2.683964	3.814011	2.417807	0.064887	0.041	0.033	0.019	0.013	
Polyline	2925	CN669	163.54	162.743395	0.3	AC	1.43264	1.899	2.028413	-0.405985	0.041	0.109	0.019	0.042	
Polyline	8	CN8	141.95	141.758804	0.3	AC	0.320027	2	0.729672	-1.772461	0.041	0.109	0.019	0.023	
Polyline	11	CN11	181.409994	179.787603	2	Beton	0.941173	1.89	2.508235	-1.682516	0.096	0.06	0.019	0.042	
Polyline	12	CN12	169.975802	167.921404	0.3	PVC	1.933977	1.899	1.231063	-1.52812	0.041	0.033	0.019	0.042	
Polyline	13	CN13	157.291995	155.907993	0.3	PVC	1.736737	2.3	1.250221	-1.840997	0.041	0.033	0.019	0.023	
Polyline	14	CN14	185.582006	183.143606	0.3	AC	3.14784	1.99	2.631439	-0.067369	0.041	0.109	0.019	0.042	
Polyline	16	CN16	147.420398	146.196796	0.5	AC	2.942032	2.3	2.37467	0.037777	0.041	0.109	0.019	0.023	
Polyline	17	CN17	194.978399	191.345602	0.3	AC	10.377229	1.99	2.710037	-1.624669	0.041	0.109	0.044	0.042	
Polyline	2880	CN1999	131.860004	131.482407	0.4	Beton	0.51275	2	0.774397	-1.465073	0.041	0.06	0.019	0.023	
Polyline	2900	2_95120	147.875601	146.1	0.5	AC	3.034271	2	2.384474	0.12065	0.041	0.109	0.019	0.023	
Polyline	24	CN24	152.355596	152.194799	0.3	AC	0.838011	1.99	0.666584	-1.850807	0.041	0.109	0.019	0.042	
Polyline	25	CN25	152.194799	150.991995	0.3	AC	4.42078	1.99	0.674159	-1.593021	0.041	0.109	0.044	0.042	
Polyline	28	CN28	191.345602	188.206396	0.3	AC	8.762235	1.99	2.644814	-0.465252	0.041	0.109	0.044	0.042	
Polyline	29	CHNCN29	149.908604	149.443804	0.2	AC	2.969893	2.455	0.603382	-1.754851	0.151	0.109	0.019	0.023	

**Figure 4.9: Sewer network attribute table displaying sub-criteria and assigned weights.**

To rank the alternative, each pipe segment was ranked by their normalized final weight, a higher weight means a higher priority for rehabilitation. The final weight was then graphed to form a spatial priority map (figure 4.10), allowing easier visualization of important segments that require immediate attention.

Figure 4.10 displays the prioritized ranking of sewer pipes in the Gdyl municipality, based on multi-criteria analysis. The map's color scheme represents the rehabilitation priority level assigned to each pipe.



**Figure 4.10: Priority map of Gdyel sewer network (scenario1).**

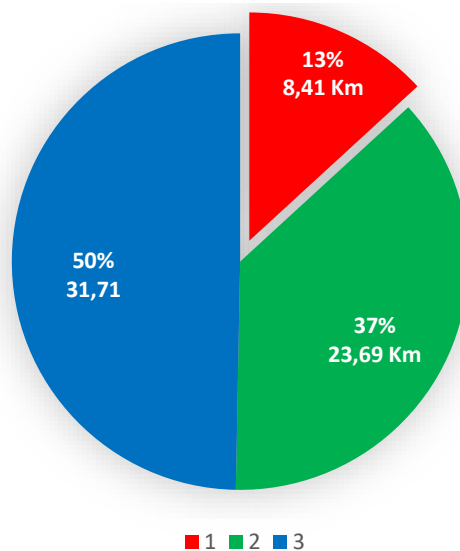
The sections prioritized for maintenance action can be identified based on the color classification, which consists of three classes, as shown in Figure 4.10:

Level 3 (N3): low priority in blue, it present pipes that are the least in need of immediate intervention.

Level 2 (N2): medium in green.

Level 1 (N1): high priority for intervention in red. It may be due to several reasons such as unfavorable hydraulic performance, or poor physical condition.

The linear of each category is divided into 3 levels. The concept of urgency level allowed us to classify the pipes in the short-, medium- and long-term to rehabilitate the sewer network. The high priority level represents 13% of the length of the network for the first scenario, which is important in terms of criticality, and it must be rehabilitated first, so the focus was on this part for both scenarios, as shown in Fig. 4.11.



**Figure 4.11: Linearity of sections by emergency level.**

Figures 4.12 to 4.17 provide a detailed breakdown of the key factors influencing the prioritization of sewer system rehabilitation. Figure 4.13 shows that 99% of the network in emergency level 1 is made of asbestos cement (AC), which represents 100% of the pipes with diameter less than 300 mm (200mm, 250mm) (Figure 4.12). AC is a material known for its age and vulnerability, and it's currently no longer utilized in the waste water network. While smaller-diameter pipes (less than 200-250 mm) are inherently more susceptible to blockages, structural failures, and hydraulic inefficiencies, which justifies their high prioritization weight (0.151). This observation also aligns with the findings of Lubini and Fuamba (2011), which have revealed that small-diameter pipes are more prone to deterioration because of their limited capacity to convey wastewater in the presence of obstacles, leading to hydraulic performance loss. Similar conclusions were reported by Salman and Salem (2012) and Bakry et al. (2016).

Further analysis, reveals that 35% of small diameters (200-250mm), have flow velocities below 0.6 m/s, a condition often linked with partial sediment blockages, under-design, or a lack of pipe slope. Such low velocities increase the risk of sediment deposition and system inefficiency, both of which accelerate deterioration and failure risk (Arthur et al., 2009; Hafskjold & Kønig, 2002.; Hillas et al., 2014; Okwori et al., 2020;.).

On the other hand, 64% of small diameters AC pipes operate with acceptable velocity range ( $0.6 \leq V \leq 4$  m/s), While from a hydraulic point of view this may be favorable, it is important to consider the pipe material AC limitation as it old, and probably isn't capable of withstanding repeated pressurization or fluctuating flow rates, which in turn could develop under peak

demand or storm events. Repeated exposure to these conditions can lead to micro-cracks formulation, failure in joints, and bursts in pipes, especially in old networks.

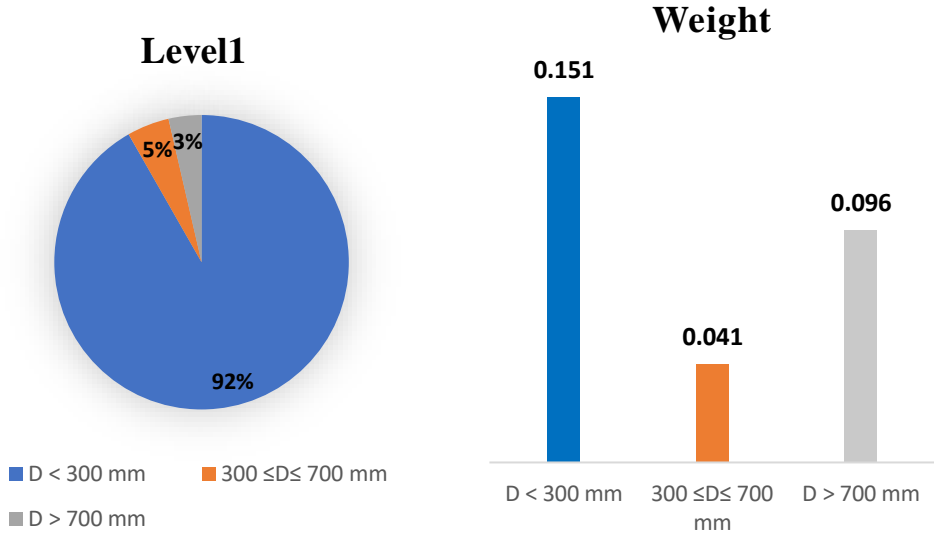


Figure 4.12: Percentage and weight of each diameter.

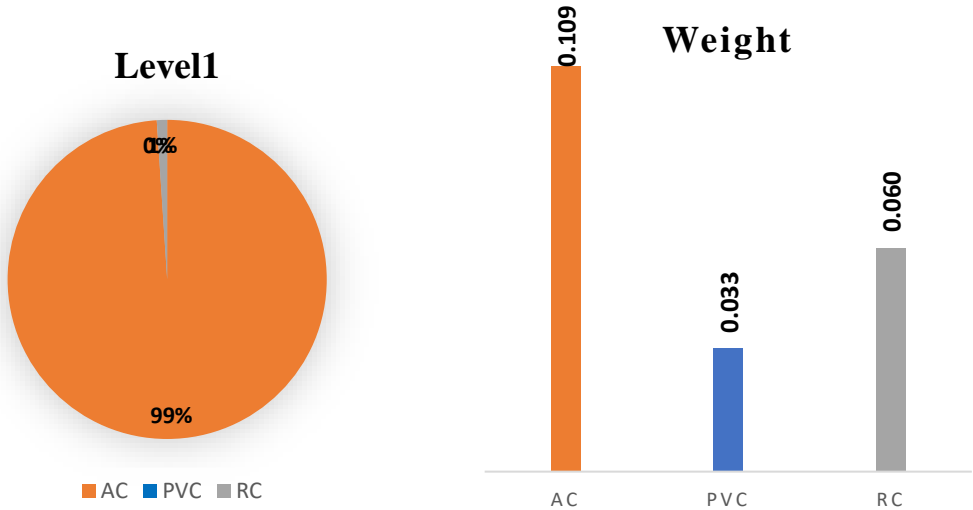


Figure 4.13: Percentage and weight of each material.

The emergency level of pipes is illustrated in Fig. 4.14 and Fig. 4.15 using slope and burial depth as parameters, respectively. It can be observed from figure 4.14, that a large portion (72%), has slopes between 0.3% and 4%, which is considered moderate. However, the heights weight (0.070) is assigned to pipes with slopes less than 0.3%, which account for 12% of the network in the emergency level 1, Low-slope pipes are emphasized in literature as they have greater chances of sediment deposition and lower velocities of flow, with the potential for blockage and maintenance issues increasing, which directly impacts the functionality and performance of the system (E. Ana et al., 2009; Laakso et al., 2018). Although pipes with slopes

greater than 4% represent 16% of the network, they may lead to scouring and structural wear due to increased flow velocities, though their risk is lower in comparison to flat pipes (Jeong et al., 2005 ; Tran et al., 2009).

Burial depth presented in Figure 4.15 is also a critical factor that contribute to pipe vulnerability. It can be observed that depths less than 2 meters constitute 37% of the network and are assigned the highest weight (0.042). These segments are at higher risk due to potential external loads and environmental exposure. Shallow burial often correlates with quicker deterioration and increased vulnerability to surface disturbances, particularly when combined with aging material and small diameter (Laakso et al., 2018; Malek Mohammadi et al., 2019; Salman & Salem, 2012).

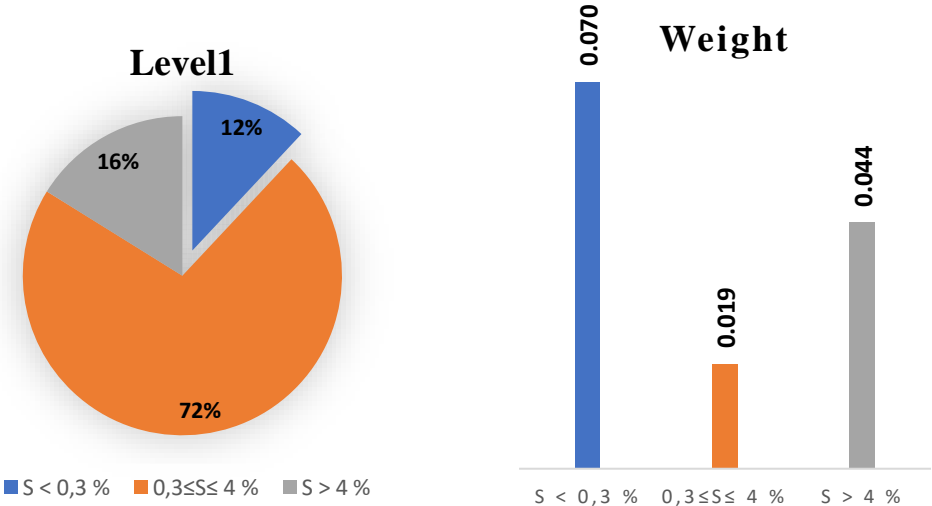


Figure 4.14: Percentage and weight of pipe slope.

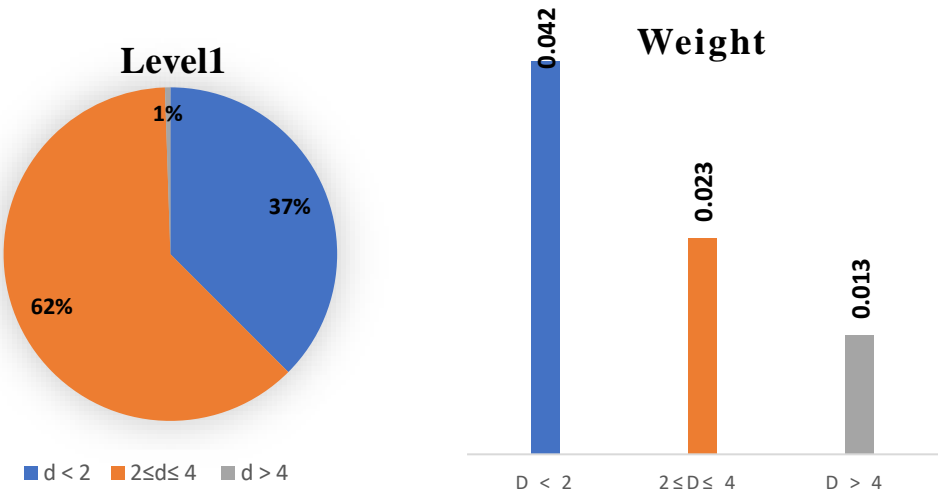


Figure 4.15: Percentage and weight of pipe burial depth.

Figure 4.16 and 4.17, illustrate the emergency level using velocity and relative water level as parameters. It is noted that 60% of the network in emergency level1 have velocity within acceptable range ( $0.6 \leq V \leq 4$  m/s, while 39% falls below the minimum range ( $v < 0.6$  m/s), which increase the risk of blockage and sediment buildup. More critically, almost half of the network is surcharging ( $RWL > 0$  m), which is an indicator of severe hydraulic stress. These results agree with the high weights assigned to low velocity and high RWL, reaffirming their significance in the AHP model. In combination with structural defects, these hydraulic risks determine the priority of rehabilitation works to ensure that the most vulnerable and overloaded sections of the network are addressed first.

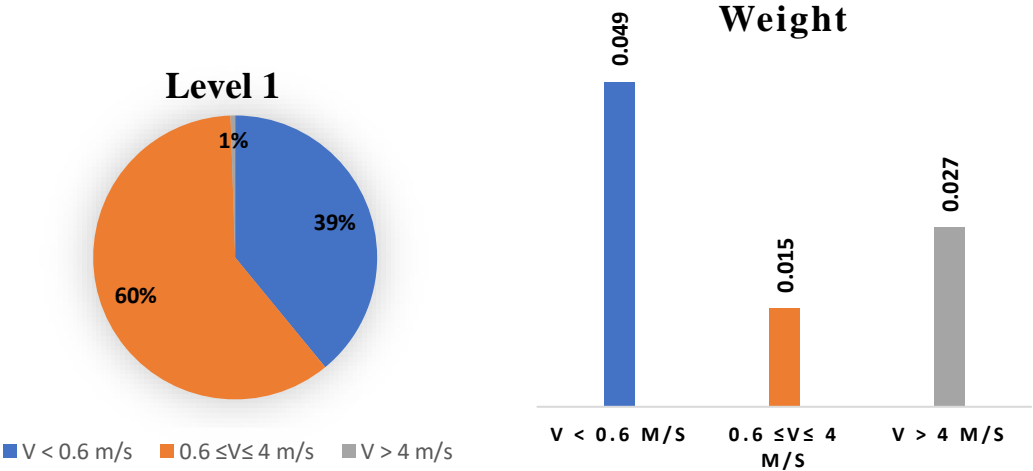


Figure 4.16: Percentage and weight of wastewater velocity.

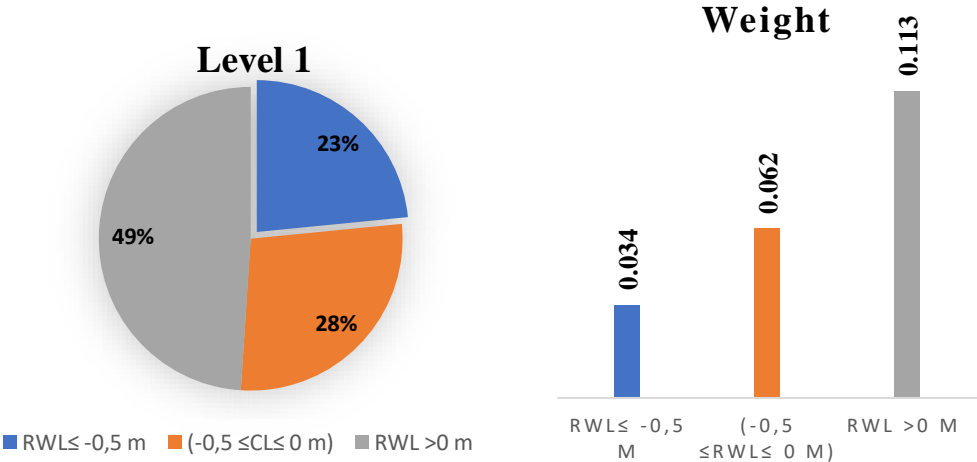


Figure 4.17: Percentage and weight of Relative water level.

The dissection of Figures 4.10 to 4.17 highlights the compound vulnerability of sewer network sections that fall under emergency level 1, with good reason for their prioritization in planning rehabilitation. The correlation of critical variables—material, pipe diameter, flow velocity, relative water level, slope, and burial depth—indicates a network most susceptible to structural failure and operational efficiency loss.

The prevalence of asbestos cement (AC) pipes, especially those below 300 mm in diameter, has a twofold susceptibility: AC's established brittleness and aging-related failures, combined with the limit of small-diameter pipes in handling clogging and pressure surges. The velocity distribution also supports this concern—while 35% of these pipes exhibit subcritical flow (< 0.6 m/s) which is vulnerable to sedimentation, the considerably high 64% operate within the acceptable range, which might be concealing underlying risks. For AC pipes, even moderate velocities and peak flow pressurization cycles are long-term structural threats because of the material's inability to withstand stress and aging (Bakry et al., 2016).

In addition, pipes with low slope and shallow burial depth within the emergency level 1, are associated with increased maintenance needs and accelerated degradation due to deposition, load effects on the surface, and exposure to the environment (E. Ana et al., 2009; Laakso et al., 2018; Tran et al., 2009).

Each of these indicators directly or indirectly affects the other indicator in a complex way, which means that the velocity can affect the aging of the pipe and material, the diameter affects the velocity and so on. Therefore, rehabilitation priority is not decided by the individual parameters but by the aggregate risk stemming from the interactive effects between them (Berrezel., 2023).

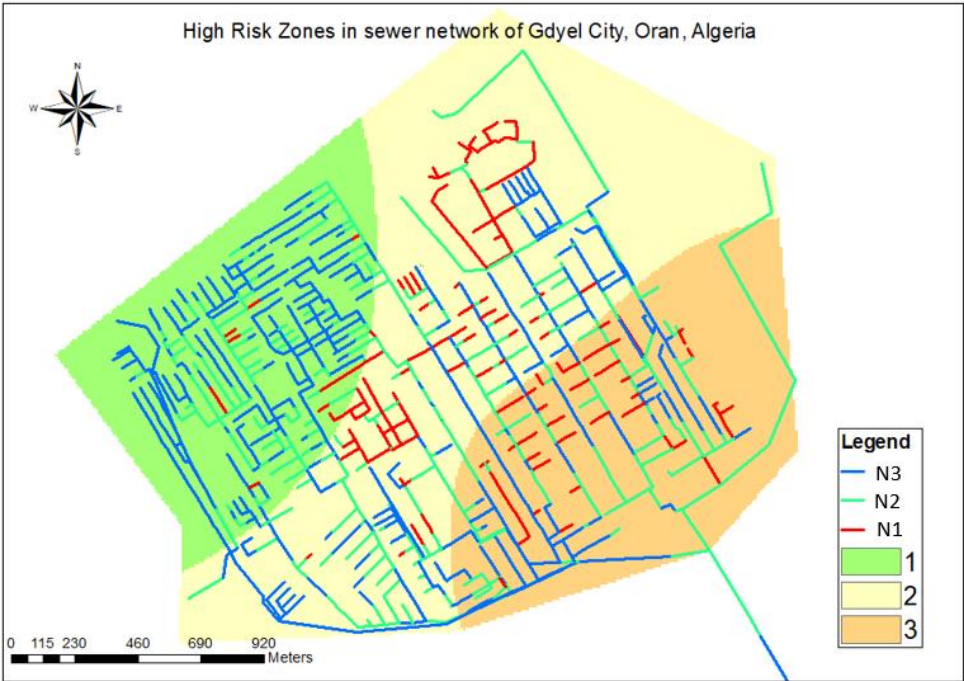
#### **4.3.2. Validation**

After identifying the priority segments for rehabilitation action, it is necessary to verify the reliability of the system and confirm that the results obtained by this prioritization approach accurately reflect the real state of the network and that the choice of the 3 emergency levels is correct and reliable. In the absence of historical maintenance or failure data, the idea is to compare the classified risk levels of individual pipes with predefined spatial zones (high-risk, moderate-risk, and low-risk areas) based on diagnostic study conducted by the SEOR company. The objective of this comparison is to assess how well the model-predicted pipe risk levels align with the broader spatial zoning strategy developed for rehabilitation planning.

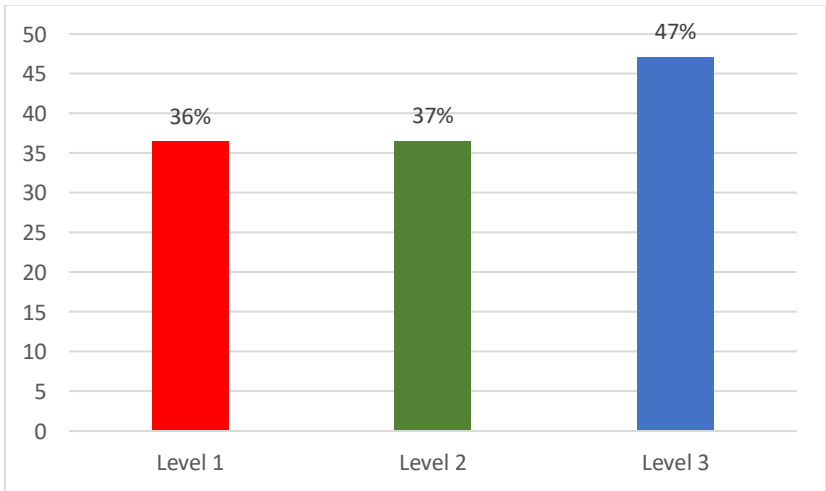
As shown in Figure 4.18, high-priority pipes identified through the AHP model (red) are predominantly located within Zone 3, which was represent the high-risk area. Likewise, most

of the pipes falling within Zone 2 are medium-risk pipes, marked in green and low-risk, marked as in blue fall most within Zone 1.

Figure 4.19 is obtained by calculating the percentage of classified pipes of the 3 levels within each zone. While 31% of high-risk pipes fall within Zone 3, 36% of moderately ranked pipes lie in Zone 2, and 47% of low-priority pipes align with Zone 1. These values indicate a meaningful alignment between the model outputs and the zonal classification, thus supporting the applicability of the GIS-AHP method in guiding prioritized maintenance interventions across the network.



**Figure 4.18: Validation Map of Sewer Pipe Prioritization and Risk Zones in Gdyl City.**

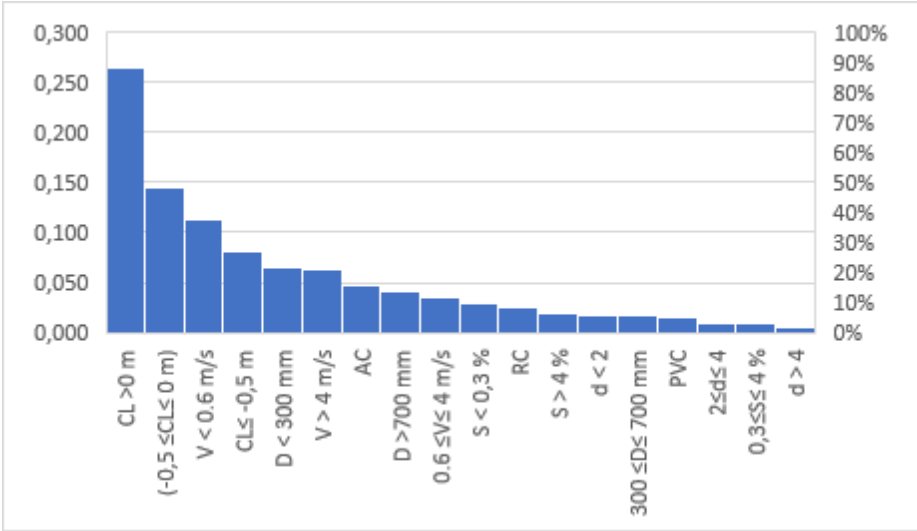


**Figure 4.19: Number of Classified Pipes Within Each Risk Zone.**

**4.4. Scenario2**

While the majority of existing studies consider physical parameters such as pipe material and pipe age as primary factors in sewer system rehabilitation sequencing, this scenario emphasizes hydraulic structure parameters such as flow velocity, and relative water level. This is with regard to situation-specific properties observed in the study area of Gdyl.

In Gdyl, the problems most in need of attention marked by SEOR's diagnostic field studies and observations are operation performance problems such as backflow, surcharging, and flooding rather than structural failure. These are normal indications of hydraulic deficiencies — more often a result of improper slopes, inadequate pipe diameters, or improper flow conditions — as opposed to material degradation or age in itself.



**Figure 4.20: Ranking of all 18 indicators obtained by AHP.**

Figure 4.20 represent the relative importance of 18 indicators of sewer pipes. It can be observed that the most influential factors include pipes with a critical level above 0 m, low velocity ( $V < 0.6$  m/s), and small diameter ( $D < 300$  mm), indicating these features play a key role in identifying high-risk segments in the sewer network under this scenario.

**4.4.1. Spatial analysis results**

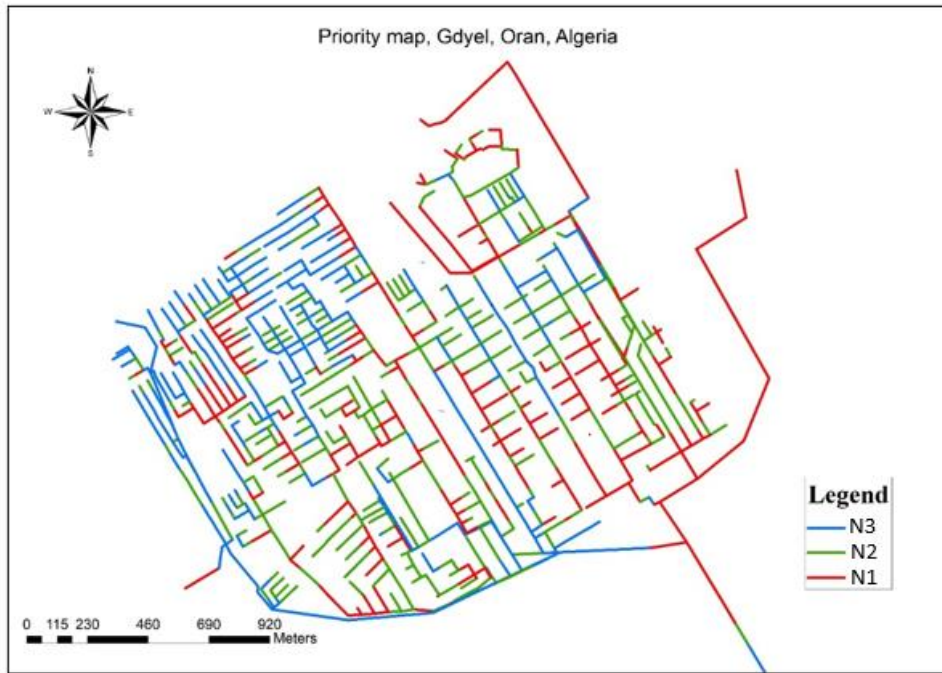
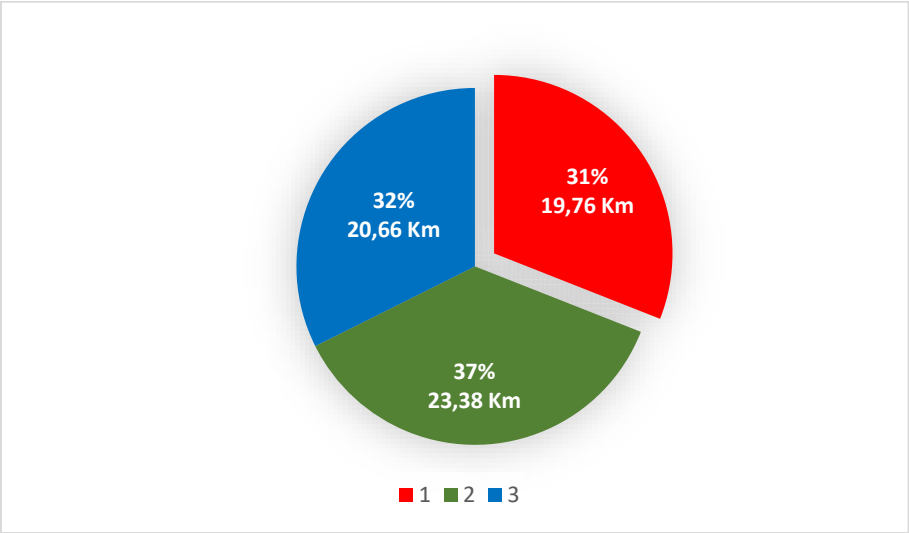


Figure 4.21: Priority map of Gdyl sewer network.



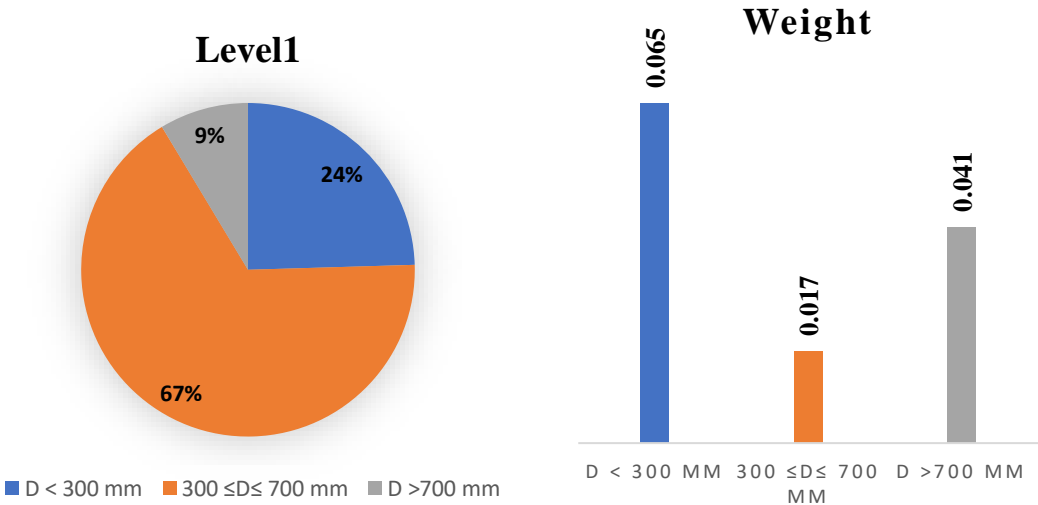
Figure 4.22: Spatial Distribution of Sewer Pipe Rehabilitation Priorities in Gdyl Municipality

The sewer network in the priority map in Figure 4.21 and 4.22 is classified into high (red), moderate (green), and low (blue) priority pipes. This classification reveals a heterogeneous spatial distribution of rehabilitation priorities throughout the sewer network of Gdyel. Dense patches of high-priority segments (red) are concentrated in eastern and northern areas of Gdyel municipality. Moderate-priority segments (green) are typically centralized, while low-priority areas (blue) are concentrated in the northwestern areas.



**Figure 4.23: Linearity of sections by emergency level.**

Figure 4.23 further quantifies these findings, 31% of the sewerage network falls under Priority 1 (19,76 Km). The majority of the network 37% (23.38 Km) is classified as priority 2, requiring medium-term interventions. The remaining 32% (20,66 Km) is classified as priority 3 considered to be in relatively better condition.



**Figure 4.24: Percentage and weight of each diameter.**

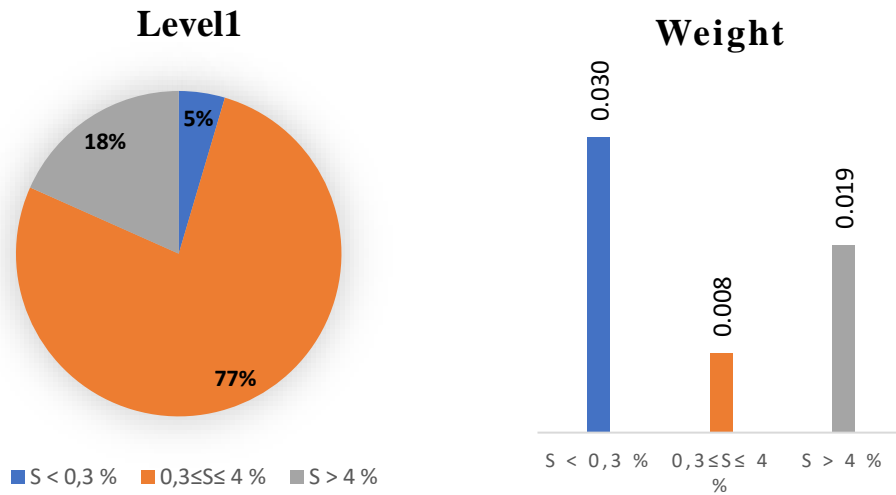


Figure 4.25: Percentage and weight of pipe slope.

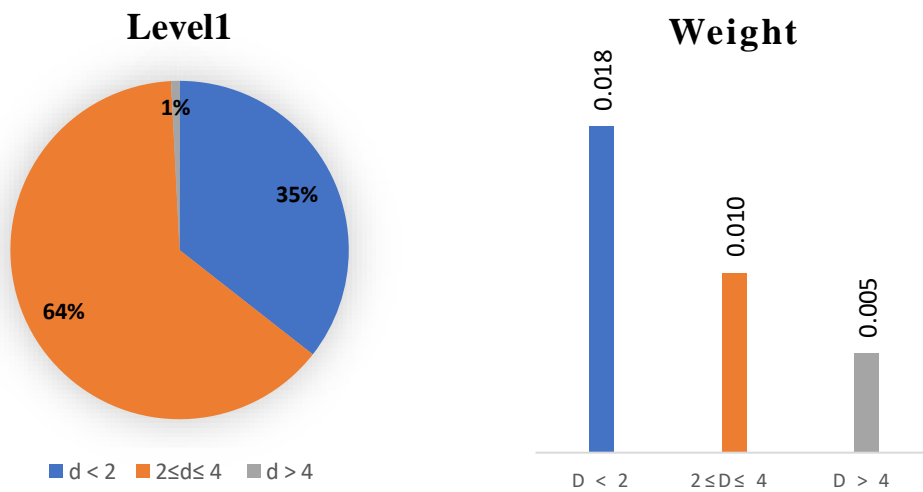
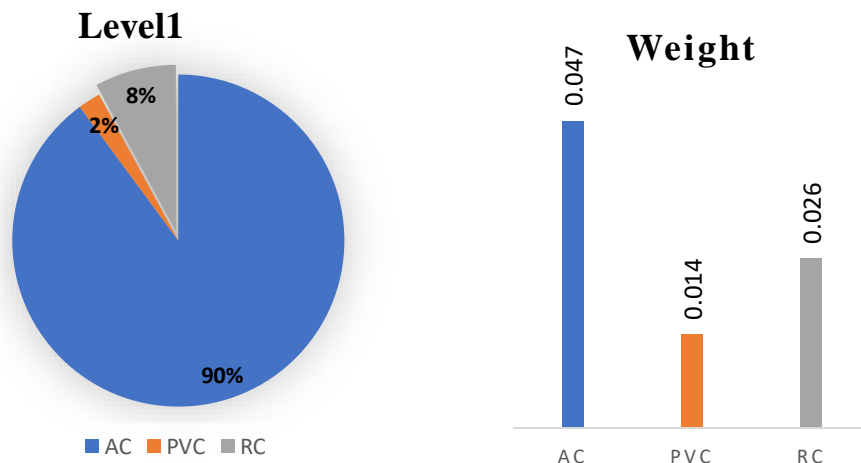


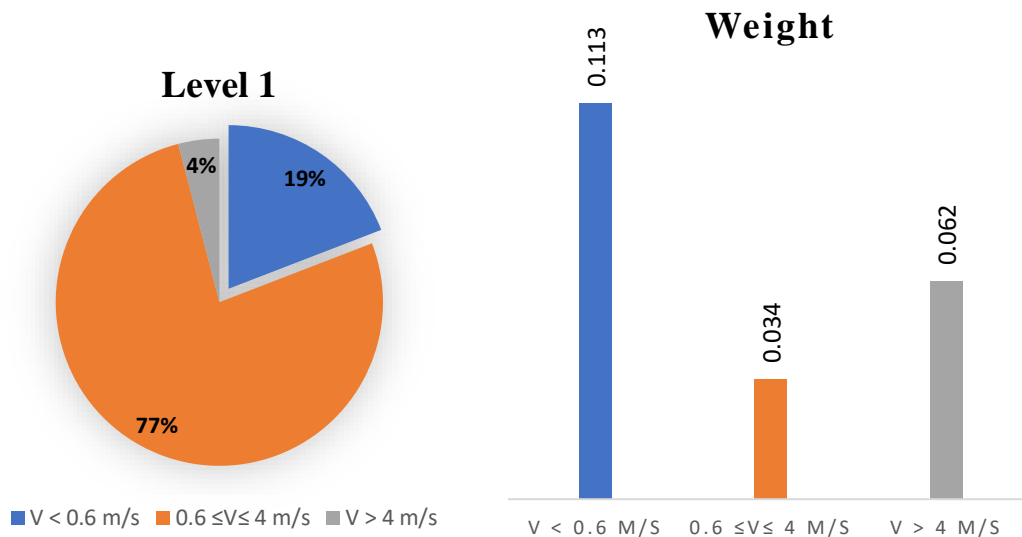
Figure 4.26: Percentage and weight of pipe burial depth.



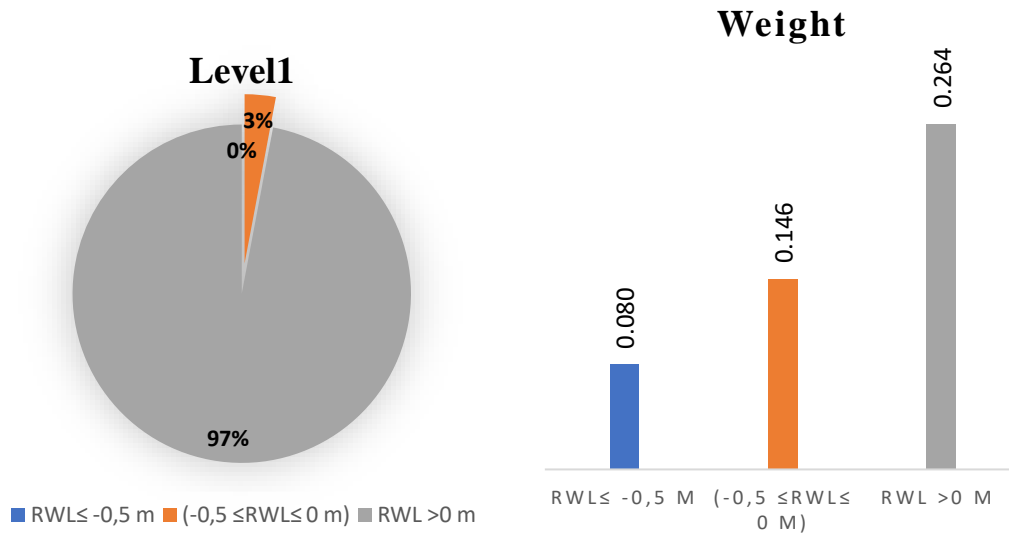
**Figure 4.27: Percentage and weight of each material.**

Figures 4.24 to 4.27 illustrate the distribution of pipes within the emergency level1 of the second scenario using diameter, pipe material, slope and burial depth as parameters. From this results, it can be observed that the majority of pipes (67%) have diameters between 300–700 mm, which is generally considered to be hydraulically adequate. Small diameters (200mm-250mm) are assigned a higher weight compared to other diameters, most likely as they are more vulnerable under severe stress conditions since they have less capacity and are most likely to block or overload (Bakry et al., 2016; Lubini & Fuamba, 2011; Salman & Salem, 2012), while in this scenario represent only 24% of Level 1 emergency pipes. Similarly, Figure 4.25 exhibits the same trend where pipes with slopes less than 0.3%, despite occupying just 5% of the network, are assigned the highest weight (0.030) to capture their strong influence on hydraulic performance. They exert high influence on self-cleaning velocity decrease and on improving sedimentation risk (E. Ana et al., 2009; Ayoub et al., 2004; Laakso et al., 2018).

As for burial depth (Figure 4.26), pipes buried at depths of less than 2 meters account for 35% of Level 1 emergency pipes and are given the highest weight (0.020). In terms of pipe material (Figure 4.27), the majority of the network (90%) is made up of Asbestos Cement (AC) pipes. As this material dominates the network, it also carries along with it aging, brittleness, and health concerns due to AC degradation structural problems. As it is, it has the largest AHP weight (0.047), which also indicates its contribution to the overall vulnerability of the network.



**Figure 4.28: Percentage and weight of wastewater velocity.**



**Figure 4.29: Percentage and weight of Relative water level.**

Figure 4.28, reveals that 77% of the network operate at velocities between 0.6m/s and 4m/s, which is generally considered to be hydraulically adequate. While 19% of the network operate with a velocity below 0.6m/s which have the highest weight among other velocities, confirming their potential for clogging and reduced transport efficiency (Okwori et al., 2020; Sep & Chinyama, 2013). As for relative water level, figure 4.26 reveals that most of high priority pipes (97%) has a relative water level  $RWL > 0$  m, which means that the hydraulic grade line is higher than the pipe crown, indicating a pressurized or surcharged flow conditions. Such conditions can be related to potential operation issues such as backflow, reduced hydraulic capacity, or risk of flooding (Arthur et al., 2009; Okwori et al., 2020). In addition, this category was assigned the highest AHP weight (0.264) among the hydraulic sub-criteria, underscoring its importance in the decision model.

#### **a) General Interpretation of Scenario 2 Results**

The result analysis revealed that the majority of high-priority pipes have standard diameters (300–700 mm), moderate slopes ( $>0.3\%$ ), and satisfactory flow velocities (0.6–4 m/s)—all factors typically supporting good performance. However, this is precisely where the power of the integrated AHP-GIS approach becomes evident.

Despite the availability of all those good performance factors, the network demonstrates severe operational challenges during critical conditions which become apparent through relative water level (RWL) results (Figure 4.29)., The relative water level measurement exceeds the pipe's crown elevation in 97% of all Level 1 priority pipes indicating that pipeline pressure exceeds

the design specification. Due to its association with overflow risks and capacity limitations and damage potential the assessment assigns the parameter the highest weight.

These findings demonstrate the need of moving beyond static design parameters and accounting for dynamic hydraulic response under real conditions of stress. It is important to note that all hydraulic input values have been derived from peak simulation results under decennial precipitation showing a strong analysis robustness. The response of the system to high-rainfall events reveals weaknesses that are not evident under mean or dry-weather flow.

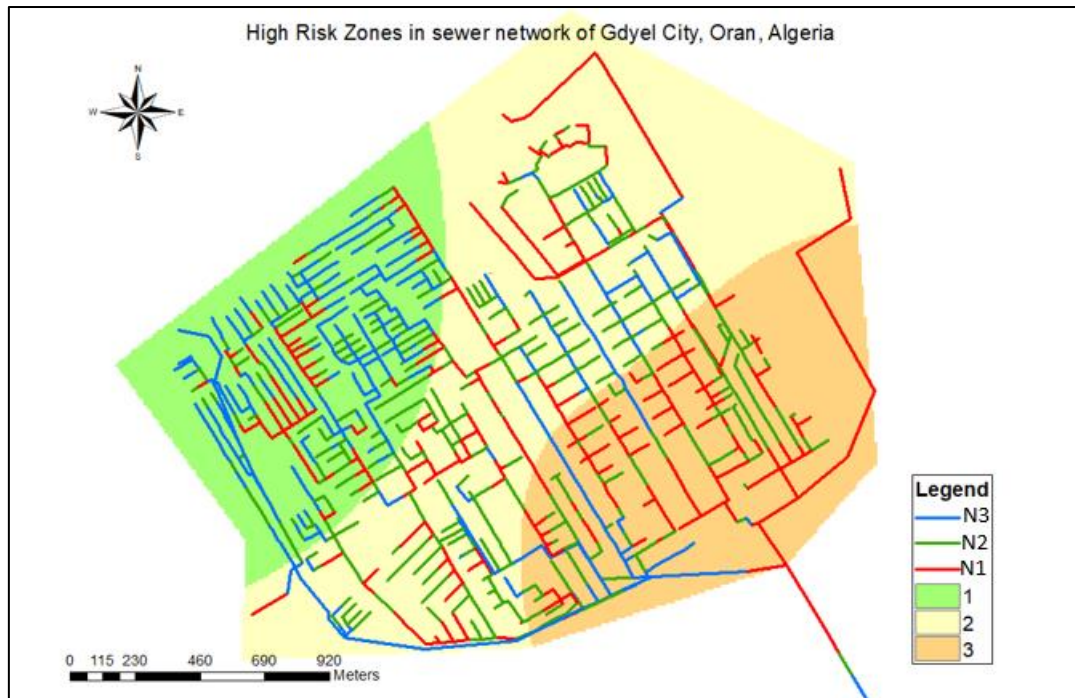
Overall, Scenario 2 demonstrates how properly designed hydraulic systems can become high-risk through contextual hydraulic behavior and environmental loading. It reinforces the significance of positioning sewer rehabilitation initially with a data-based, combined decision-making method using hydraulic simulation and multi-criteria analysis in order to assure investment in the most at-risk under real-life operating conditions.

#### **4.4.2. Validation (scenario2)**

Figure 4.30 represent the validation map of the second scenario. From this map it can be observed that most Priority level 1 pipes (high priority) are located in the southeastern part of the municipality, which corresponds closely with the previously identified high-risk zones (zone3). This spatial over-lap reinforces the accuracy of the used approach.

Priority level 2 pipes are dispersed across the entire network, with a noticeable concentration in the second intervention zone across the whole network (zone 2).

As for priority level 3 pipes (low priority) represented in blue are primely concentrated in the northwestern region of the municipality, this area corresponds with zones identified as having lower rehabilitation needs (zone3).



**Figure 4.30: Validation Map of Sewer Pipe Prioritization and Risk Zones in Gdyl City.**

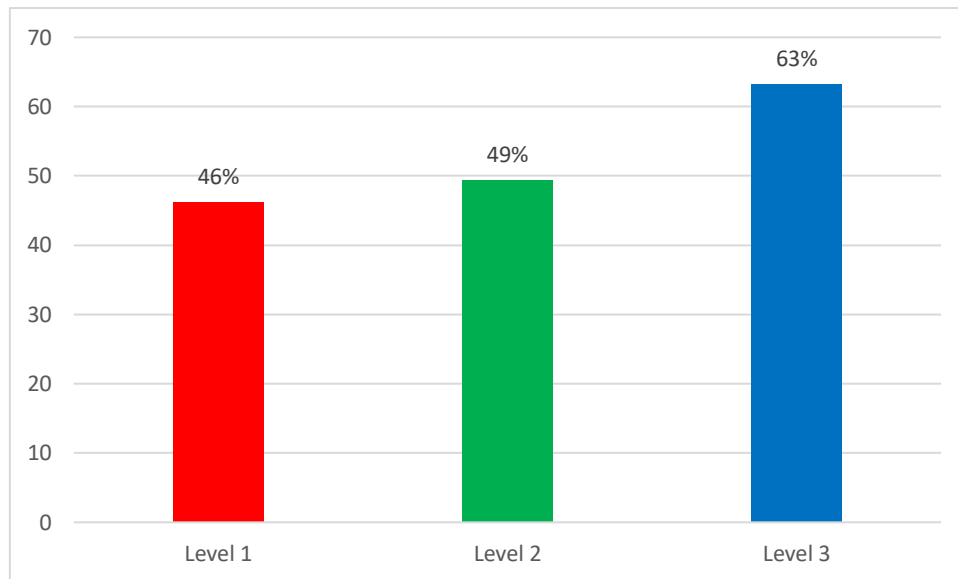
The analysis of sewer pipes spatial distribution receives statistical support from Figure 4.31 showing the configuration of pipe distribution across priority levels.

Level 1 pipes constitute 46% of those distributed in high-risk zones.

Among the pipes at Level 2 half fall into moderate-risk sections.

Level 3 pipes represent 63% of the network located in low-risk areas.

This strong alignment between pipe spatial distribution and risk classification indicates the strength of the credibility and efficacy of the prioritization approach used in this research. The results of this analysis show that the method used gives good consistency between the network evaluation and its actual state.



**Figure 4.31: Number of Classified Pipes Within Each Risk Zone.**

#### **4.5. Results discussion**

In this study the integrated approach GIS-AHP was applied on two scenarios. Both scenarios used a combination of physical and hydraulic criteria for ranking sewer pipes, However the weighting and influence of these parameters differed significantly in the two.

In Scenario 1, more emphasis was placed on physical factors—pipe material, size, and depth of burial—resulting in a set of priorities that emphasized most heavily structural weakness. Although hydraulic parameters were considered, they played relatively lesser roles. Surprisingly, some homogeneity was observed between the physical and hydraulic variables, as critical pipes that was chosen based on physical weakening also had poor hydraulic performance.

For Scenario 2, attention was diverted to hydraulic criteria, with more emphasis laid on wastewater flow velocity and relative water level. The network data used was derived from extreme simulation under decennial precipitation patterns. This facilitated the model in identifying dynamic performance and operational stress issues that are not easily detectable. For this reason, Scenario 2 highlighted pipes that may appear structurally fine visually but prove to be hydraulically performing poorly, particularly under maximum flow conditions, which weaken the sewer pipes and lead to future structural failure, especially as the majority of the network is made of Asbestos cement.

These findings support the SEOR results and reveal that the sewer network is undersized and unable to handle extreme weather events, indicating the superior accuracy and sensitivity of the approach used in reflecting real operating conditions.

## CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

### 5.1. Conclusion

The main Focus of this research was to develop an Integrated Decision Support System (DSS) for to identify critical areas or hotspots within the sewer network of the Algerian city of Gdyl that require immediate attention based on the integrated evaluation of multiple criteria. This was achieved through combining Geographic Information System (GIS) spatial analysis and the Analytic Hierarchy Process (AHP) method to analyze and rank sewer pipes based on physical and hydraulic conditions.

The study demonstrated that an integration of AHP and GIS is a powerful approach to sewer infrastructure management. The combination of GIS spatial abilities with Analytic hierarchy Process multicriteria analysis helps us to facilitate the complexity of the studied system because the difficulty is the determination of the specific sections to be renewed. GIS enabled visualization of the space with regard to areas of significance, and AHP facilitated the allocation of weights to different criteria and sub-criteria based on their relative importance to the network vulnerability and performance.

To enable effective prioritization, key criteria and sub-criteria that are relevant to sewer rehabilitation were identified and evaluated based on an extreme literature review. Their relative weights were determined using the AHP method.

Two different scenarios were developed: the first one gives high weight to physical criteria (pipe material, diameter, slope, and burial depth) and the other high weight is assigned to hydraulic criteria (wastewater flow velocity and relative water level).

The priority segments for maintenance action can be identified according to the emergency level category and the colors, which include three classes: level 3 low, level 2 medium and level 1 high priority for intervention in red color.

For scenario 1, results showed that the critical part represents 13% of the network that should be rehabilitated as soon as possible. Most of these segments are characterized by unfavorable physical characteristics, such as small diameter, shallow depths, and small slopes, as for hydraulic criteria, these critical pipes also exhibit low velocities and high relative water level. This scenario showed a focused yet balanced prioritization of the most deteriorated and hydraulically inefficient segments of the network.

As for the second scenario, results revealed that 31% of the sewer network should be rehabilitated. This significant increase is primarily due to the higher weighting assigned to hydraulic parameters—especially relative water level, which resulted in a broader extent of vulnerable areas being identified.

This comparison highlights the fact that while Scenario 1 provides a focused prioritization by structural condition, Scenario 2 provides a more reactive view to hydraulic performance under stress, indicating the current network is undersized or insufficient to handle peak flows and thus requires more extensive intervention.

Validation by spatial overlays demonstrated compatibility between the high-priority pipes the model identified and the high-risk locations identified based on the SEOR diagnostic study, which validated the model's accuracy.

Each of the indicators used in this study directly or indirectly affects the other indicator in a complex way, which means that the velocity can affect the pipe material, the diameter affects the velocity and so on.

Lastly, the developed DSS proved successful in combining complex and geographically dispersed data into simple, actionable information for sewer rehabilitation project ranking. The approach demonstrated how AHP and GIS can be combined to provide evidence-based, open, and scalable decision-making. The approach is also adaptable and can be used by other municipalities facing similar urban infrastructure challenges.

This study acknowledges the potential of the developed system, yet recognizes a number of limitations, including, data limitation such as maintenance records data, the need for regularly updated spatial data, and potential institutional adoption issues. These, nonetheless, do not undermine the potential of the system to improve planning, reduce infrastructure risk, and achieve long-term urban sewer system sustainability.

## **5.2. Recommendations**

On the basis of observations and experiences gained during this study, the following are the recommendations:

**Update and verify data regularly:** As the performance of the DSS depends to a large extent on quality input data, it is important to conduct regular field inspections and sewer attribute updates like diameter, age, material, and depth. In addition, it's very important to expanded and consider other criteria in future models, while this study employed definite physical and hydraulic

parameters, future models can integrate socio-economic measures (e.g., public health risk, land use) in order to advance rehabilitation prioritization.

It is recommended that maximum priority be assigned to the rehabilitation of small-diameter asbestos cement pipes, especially those in key areas with velocities below 0.6 m/s, in order to reduce the risk of clogging and system failure. The upgrading of these pipes using more durable materials and the optimization of pipe slopes where feasible will enhance network performance. In addition, the adoption of a GIS-based risk mapping and monitoring strategy, as illustrated here, will improve data-informed decision-making and resource utilization. Finally, the development of a long-term sewer asset management plan involving regular inspections, hydraulic performance monitoring, and rehabilitation prioritization based on risk is important in ensuring the sustainability and dependability of Gdyl's sewer system..

## References

- Al Barqawi, H. A. (2006). *Condition rating models for underground infrastructure: Sustainable water mains* [Masters, Concordia University]. <https://spectrum.library.concordia.ca/id/eprint/8720/>
- Ana, E., Bauwens, W., Pessemier, M., Thoeye, C., Smolders, S., Boonen, I., & De Gueldre, G. (2009). An investigation of the factors influencing sewer structural deterioration. *Urban Water Journal*, 6(4), 303–312. <https://doi.org/10.1080/15730620902810902>
- Ana, E. V., & Bauwens, W. (2010). Modeling the structural deterioration of urban drainage pipes: The state-of-the-art in statistical methods. *Urban Water Journal*, 7(1), 47–59. <https://doi.org/10.1080/15730620903447597>
- Anbari, M. J., Tabesh, M., & Roozbahani, A. (2017). Risk assessment model to prioritize sewer pipes inspection in wastewater collection networks. *Journal of Environmental Management*, 190, 91–101. <https://doi.org/10.1016/j.jenvman.2016.12.052>
- Ariaratnam, S. T., El-Assaly, A., & Yang, Y. (2001). Assessment of Infrastructure Inspection Needs Using Logistic Models. *Journal of Infrastructure Systems*, 7(4), 160–165. [https://doi.org/10.1061/\(ASCE\)1076-0342\(2001\)7:4\(160\)](https://doi.org/10.1061/(ASCE)1076-0342(2001)7:4(160))
- Arthur, S., Crow, H., Pedezert, L., & Karikas, N. (2009). The holistic prioritisation of proactive sewer maintenance. *Water Science and Technology*, 59(7), 1385–1396. <https://doi.org/10.2166/wst.2009.134>
- Ayoub, G., Azar, N., Fadel, M. E., & Hamad, B. (2004). Assessment of hydrogen sulphide corrosion of cementitious sewer pipes: A case study. *Urban Water Journal*, 1(1), 39–53. <https://doi.org/10.1080/15730620410001732062>
- Baah, K., Dubey, B., Harvey, R., & McBean, E. (2015). A risk-based approach to sanitary sewer pipe asset management. *Science of The Total Environment*, 505, 1011–1017. <https://doi.org/10.1016/j.scitotenv.2014.10.040>
- Baik, H.-S., Jeong, H. S., & Abraham, D. M. (2006). Estimating Transition Probabilities in Markov Chain-Based Deterioration Models for Management of Wastewater Systems.

- Journal of Water Resources Planning and Management*, 132(1), 15–24.  
[https://doi.org/10.1061/\(ASCE\)0733-9496\(2006\)132:1\(15\)](https://doi.org/10.1061/(ASCE)0733-9496(2006)132:1(15))
- Bakry, I., Alzraiee, H., Kaddoura, K., El Masry, M., & Zayed, T. (2016). Condition Prediction for Chemical Grouting Rehabilitation of Sewer Networks. *Journal of Performance of Constructed Facilities*, 30(6), 04016042. [https://doi.org/10.1061/\(ASCE\)CF.1943-5509.0000893](https://doi.org/10.1061/(ASCE)CF.1943-5509.0000893)
- Barone, L., Pilotti, M., Valerio, G., Balistrocchi, M., Milanese, L., Chapra, S. C., & Nizzoli, D. (2019). Analysis of the residual nutrient load from a combined sewer system in a watershed of a deep Italian lake. *Journal of Hydrology*, 571, 202–213. <https://doi.org/10.1016/j.jhydrol.2019.01.031>
- Basupi, I., & Kapelan, Z. (2015). Flexible Water Distribution System Design under Future Demand Uncertainty. *Journal of Water Resources Planning and Management*, 141(4), 04014067. [https://doi.org/10.1061/\(ASCE\)WR.1943-5452.0000416](https://doi.org/10.1061/(ASCE)WR.1943-5452.0000416)
- Baur, R., & Herz, R. (2002). Selective inspection planning with ageing forecast for sewer types. *Water Science and Technology*, 46(6–7), 389–396. <https://doi.org/10.2166/wst.2002.0704>
- Berrezel, Y. A., Abdelbaki, C., Rouissat, B., Boumaaza, T., & Khaldoun, A. M. (2023). DECISION SUPPORT SYSTEM FOR THE MANAGEMENT OF WATER DISTRIBUTION NETWORKS A CASE STUDY OF TOURVILLE, ALGERIA. *LARHYSS Journal P-ISSN 1112-3680 / E-ISSN 2521-9782*, 54, Article 54.
- Berrezel, Y. A., Abdelbaki, C., Rouissat, B., Boumaaza, T., Saber, M., Goosen, M., & Kumar, N. (2024). Automated GIS-based decision tool for rehabilitation of a drinking water infrastructure in Tlemcen, Algeria. *Applied Water Science*, 14(6), 1–17. <https://doi.org/10.1007/s13201-024-02190-7>
- Burkhard, R., & González Lakehal, S. (2006). Sewer rehabilitation planning—Priority and cost planning using GIS. *Water Practice and Technology*, 1(1), wpt2006015. <https://doi.org/10.2166/wpt.2006.015>
- Carrico, N., Covas, D. I. C., Almeida, M. C., Leitão, J. P., & Alegre, H. (2012). Prioritization of rehabilitation interventions for urban water assets using multiple criteria decision-aid

- methods. *Water Science and Technology*, 66(5), 1007–1014.  
<https://doi.org/10.2166/wst.2012.274>
- Darko, A., Chan, A. P. C., Ameyaw, E. E., Owusu, E. K., Pärn, E., & Edwards, D. J. (2019). Review of application of analytic hierarchy process (AHP) in construction. *International Journal of Construction Management*, 19(5), 436–452.  
<https://doi.org/10.1080/15623599.2018.1452098>
- Davies, J. P., Clarke, B. A., Whiter, J. T., & Cunningham, R. J. (2001). Factors influencing the structural deterioration and collapse of rigid sewer pipes. *Urban Water*, 3, 73–89.  
[https://doi.org/10.1016/S1462-0758\(01\)00017-6](https://doi.org/10.1016/S1462-0758(01)00017-6)
- Ebrahimian, A., Ardeshir, A., Zahedi Rad, I., & Ghodsypour, S. H. (2015). Urban stormwater construction method selection using a hybrid multi-criteria approach. *Automation in Construction*, 58, 118–128. <https://doi.org/10.1016/j.autcon.2015.07.014>
- Fenner, R. A., & Sweeting, L. (1999). A decision support model for the rehabilitation of “non-critical” sewers. *Water Science and Technology*, 39(9), 193–200.  
[https://doi.org/10.1016/S0273-1223\(99\)00233-4](https://doi.org/10.1016/S0273-1223(99)00233-4)
- Ghavami, S. M., Borzooei, Z., & Maleki, J. (2020). An effective approach for assessing risk of failure in urban sewer pipelines using a combination of GIS and AHP-DEA. *Process Safety and Environmental Protection*, 133, 275–285. <https://doi.org/10.1016/j.psep.2019.10.036>
- Goumrassa, A., Guendouz, M., Guettouche, M. S., & Belaroui, A. (2021). Flood hazard susceptibility assessment in Chiffa wadi watershed and along the first section of Algeria North–South highway using GIS and AHP method. *Applied Geomatics*, 13(4), 565–585.  
<https://doi.org/10.1007/s12518-021-00381-4>
- Hafskjold, L. S., & Kønig, A. (n.d.). *Improved assessment of sewer pipe condition*.
- Hager, W. H., & Gisonni, C. (2005). Supercritical flow in sewer manholes. *Journal of Hydraulic Research*, 43(6), 660–667. <https://doi.org/10.1080/00221680509500385>
- Haghighi, A., & Bakhshipour, A. E. (2015). Deterministic Integrated Optimization Model for Sewage Collection Networks Using Tabu Search. *Journal of Water Resources Planning and Management*, 141(1), 04014045. [https://doi.org/10.1061/\(ASCE\)WR.1943-5452.0000435](https://doi.org/10.1061/(ASCE)WR.1943-5452.0000435)

- Halfawy, M. R., Dridi, L., & Baker, S. (2008). Integrated Decision Support System for Optimal Renewal Planning of Sewer Networks. *Journal of Computing in Civil Engineering*, 22(6), 360–372. [https://doi.org/10.1061/\(ASCE\)0887-3801\(2008\)22:6\(360\)](https://doi.org/10.1061/(ASCE)0887-3801(2008)22:6(360))
- Hammouri, N., Talafha, M., Hamarneh, Q., Annab, Z., Al-Ruzouq, R., & Shanableh, A. (2022). Vulnerability Hotspots Mapping for Enhancing Sanitation Services Provision: A Case Study of Jordan. *Water*, 14(11), Article 11. <https://doi.org/10.3390/w14111689>
- Islam, M. S. (2017). Comparative evaluation of vacuum sewer and gravity sewer systems. *International Journal of System Assurance Engineering and Management*, 8(1), 37–53. <https://doi.org/10.1007/s13198-016-0518-z>
- Jafari, Zahiri, & Bozorg-Haddad. (2022). *Development of multi-objective optimization model for water distribution network using a new reliability index*. ResearchGate. [https://www.researchgate.net/publication/360037531\\_Development\\_of\\_multi-objective\\_optimization\\_model\\_for\\_water\\_distribution\\_network\\_using\\_a\\_new\\_reliability\\_index](https://www.researchgate.net/publication/360037531_Development_of_multi-objective_optimization_model_for_water_distribution_network_using_a_new_reliability_index)
- Jaganathan, A. P., Allouche, E., & Simicevic, N. (2010). Numerical modeling and experimental evaluation of a time domain UWB technique for soil void detection. *Tunnelling and Underground Space Technology*, 25(6), 652–659. <https://doi.org/10.1016/j.tust.2009.08.006>
- Jeong, H. S., Baik, H.-S., & Abraham, D. M. (2005). An Ordered Probit Model Approach for Developing Markov Chain Based Deterioration Model for Wastewater Infrastructure Systems. *Pipelines 2005*, 649–661. [https://doi.org/10.1061/40800\(180\)52](https://doi.org/10.1061/40800(180)52)
- Jia, Y., Zheng, F., Maier, H. R., Ostfeld, A., Creaco, E., Savic, D., Langeveld, J., & Kapelan, Z. (2021). Water quality modeling in sewer networks: Review and future research directions. *Water Research*, 202, 117419. <https://doi.org/10.1016/j.watres.2021.117419>
- Kabir, G., Balek, N. B. C., & Tesfamariam, S. (2018). Sewer Structural Condition Prediction Integrating Bayesian Model Averaging with Logistic Regression. *Journal of Performance of Constructed Facilities*, 32(3), 04018019. [https://doi.org/10.1061/\(ASCE\)CF.1943-5509.0001162](https://doi.org/10.1061/(ASCE)CF.1943-5509.0001162)
- Kaddoura, K. (2018). *Performance Modeling for Sewer Networks*.

- Kessili, A., & Benmamar, S. (2016). Prioritizing sewer rehabilitation projects using AHP-PROMETHEE II ranking method. *Water Science and Technology*, 73(2), 283–291. <https://doi.org/10.2166/wst.2015.490>
- Laakso, T., Ahopelto, S., Lampola, T., Kokkonen, T., & Vahala, R. (2018). Estimating water and wastewater pipe failure consequences and the most detrimental failure modes. *Water Supply*, 18(3), 901–909. <https://doi.org/10.2166/ws.2017.164>
- Lee, J. H., Baek, C. W., Kim, J. H., Jun, H. D., & Jo, D. J. (2009). Development of a Decision Making Support System for Efficient Rehabilitation of Sewer Systems. *Water Resources Management*, 23(9), 1725–1742. <https://doi.org/10.1007/s11269-008-9349-2>
- Liu, J., Zhou, N., & Wang, Y. (2008a). The Experimental Research on the Method of Integrating AHP with GIS. *2008 International Symposium on Computer Science and Computational Technology*, 2, 698–702. <https://doi.org/10.1109/ISCSCCT.2008.140>
- Liu, J., Zhou, N., & Wang, Y. (2008b). The Experimental Research on the Method of Integrating AHP with GIS. *2008 International Symposium on Computer Science and Computational Technology*, 2, 698–702. <https://doi.org/10.1109/ISCSCCT.2008.140>
- Lubini, A. T., & Fuamba, M. (2011). Modeling of the deterioration timeline of sewer systems. *Canadian Journal of Civil Engineering*, 38(12), 1381–1390. <https://doi.org/10.1139/111-103>
- Malczewski, & Rinner. (2015). *Multicriteria Decision Analysis in Geographic Information Science*. <https://www.nhbs.com/multicriteria-decision-analysis-in-geographic-information-science-book>
- Malek Mohammadi, M., Najafi, M., Kaushal, V., Serajiantehrani, R., Salehabadi, N., & Ashoori, T. (2019). Sewer Pipes Condition Prediction Models: A State-of-the-Art Review. *Infrastructures*, 4(4), Article 4. <https://doi.org/10.3390/infrastructures4040064>
- Malek Mohammadi, M., Najafi, M., Salehabadi, N., Serajiantehrani, R., & Kaushal, V. (2020). Predicting Condition of Sanitary Sewer Pipes with Gradient Boosting Tree. *Pipelines 2020*, 80–89. <https://doi.org/10.1061/9780784483206.010>

- Margeta, J. (2009). *Kanalizacija naselja ; odvodnja i zbrinjavanje otpadnih i oborionskih voda*. Split: Fakultet građevinarstva, arhitekture i geodezije Sveučilišta u Splitu. <https://www.croris.hr/crosbi/publikacija/knjiga/5976>
- Martin, C., & Vanrolleghem, P. A. (2014). Analysing, completing, and generating influent data for WWTP modelling: A critical review. *Environmental Modelling & Software*, 60, 188–201. <https://doi.org/10.1016/j.envsoft.2014.05.008>
- Micevski, T., Kuczera, G., & Coombes, P. (2002). Markov Model for Storm Water Pipe Deterioration. *Journal of Infrastructure Systems*, 8(2), 49–56. [https://doi.org/10.1061/\(ASCE\)1076-0342\(2002\)8:2\(49\)](https://doi.org/10.1061/(ASCE)1076-0342(2002)8:2(49))
- Miszta-Kruk, K. (2016). Reliability and failure rate analysis of pressure, vacuum and gravity sewer systems based on operating data. *Engineering Failure Analysis*, 61, 37–45. <https://doi.org/10.1016/j.engfailanal.2015.07.034>
- Mogila, Nguyen, M. N., Cook, S., Hieu Trung, N., & Neumann, L. E. (2013, December). *Integrated assessment of water management strategies: The case of Can Tho City, Vietnam*. ResearchGate. [https://www.researchgate.net/publication/259197316\\_Integrated\\_assessment\\_of\\_water\\_management\\_strategies\\_the\\_case\\_of\\_Can\\_Tho\\_City\\_Vietnam](https://www.researchgate.net/publication/259197316_Integrated_assessment_of_water_management_strategies_the_case_of_Can_Tho_City_Vietnam)
- Montes, C., Kapelan, Z., & Saldarriaga, J. (2019). Impact of Self-Cleansing Criteria Choice on the Optimal Design of Sewer Networks in South America. *Water*, 11(6), 1148. <https://doi.org/10.3390/w11061148>
- Najafi, M., & Gokhale, S. B. (2005). *Trenchless technology: Pipeline and utility design, construction, and renewal*. McGraw-Hill. <https://cir.nii.ac.jp/crid/1130000794815910144>
- Najafi, M., & Kulandaivel, G. (2005). Pipeline Condition Prediction Using Neural Network Models. *Pipelines 2005*, 767–781. [https://doi.org/10.1061/40800\(180\)61](https://doi.org/10.1061/40800(180)61)
- Nyimbili, P. H., Erden, T., & Karaman, H. (2018). Integration of GIS, AHP and TOPSIS for earthquake hazard analysis. *Natural Hazards*, 92(3), 1523–1546. <https://doi.org/10.1007/s11069-018-3262-7>

- Obradović, D., Šperac, M., & Marenjak, S. (2019). Maintenance issues of the vacuum sewer system. *Environmental Engineering - Inženjerstvo Okoliša*, 6(2), 40–48. <https://doi.org/10.37023/ee.6.2.1>
- Obradović, D., Šperac, M., & Marenjak, S. (2023). Challenges in Sewer System Maintenance. *Encyclopedia*, 3(1), Article 1. <https://doi.org/10.3390/encyclopedia3010010>
- Okwori, E., Viklander, M., & Hedström, A. (2020). Performance assessment of Swedish sewer pipe networks using pipe blockage and other associated performance indicators. *H2Open Journal*, 3(1), 46–57. <https://doi.org/10.2166/h2oj.2020.027>
- Opila, M. C. (2011). *Structural condition scoring of buried sewer pipes for risk-based decision making*. <https://www.semanticscholar.org/paper/Structural-condition-scoring-of-buried-sewer-pipes-Opila/50c2b53be2d93c72eed8d80bc0680c0b300fa968>
- Orhan, Firat, & Yilmaz. (2022). *Identification of priority areas for rehabilitation in wastewater systems using ENTROPY, ELECTRE and TOPSIS | Water Practice & Technology | IWA Publishing*. <https://iwaponline.com/wpt/article/17/4/835/88090/Identification-of-priority-areas-for>
- Qin, X. (2013). Local Ideal Point Method for GIS-based Multicriteria Analysis: A Case Study in London, Ontario. *Electronic Thesis and Dissertation Repository*. <https://ir.lib.uwo.ca/etd/1295>
- Reducing the Occurrence of Flooding Through the Effective Management of Sewer Blockages—ProQuest*. (n.d.-a). Retrieved April 14, 2025, from <https://www.proquest.com/openview/b4e604c93ebca9aa7f63dda6a2468378/1?cbl=2026366&diss=y&pq-origsite=gscholar>
- Reducing the Occurrence of Flooding Through the Effective Management of Sewer Blockages—ProQuest*. (n.d.-b). Retrieved April 14, 2025, from <https://www.proquest.com/openview/b4e604c93ebca9aa7f63dda6a2468378/1?cbl=2026366&diss=y&pq-origsite=gscholar>
- Saaty. (1980). *The Analytic Hierarchy Process: A New Approach to Deal with Fuzziness in Architecture: Architectural Science Review: Vol 25, No 3*. <https://www.tandfonline.com/doi/abs/10.1080/00038628.1982.9696499>

- Salehi, S. (2017). *A comprehensive criteria-based multi-attribute decision-making model for rehabilitation of water distribution systems: Structure and Infrastructure Engineering: Vol 14*, No 6—Get Access. <https://www.tandfonline.com/doi/full/10.1080/15732479.2017.1359633>
- Salman, B. (2010). *Infrastructure Management and Deterioration Risk Assessment of Wastewater Collection Systems*. <https://www.semanticscholar.org/paper/Infrastructure-Management-and-Deterioration-Risk-of-Salman/2f2db05df1d7b67f1fe54bb14beaaaa69fe10030>
- Salman, B., & Salem, O. (2012). Modeling Failure of Wastewater Collection Lines Using Various Section-Level Regression Models. *Journal of Infrastructure Systems*, 18(2), 146–154. [https://doi.org/10.1061/\(ASCE\)IS.1943-555X.0000075](https://doi.org/10.1061/(ASCE)IS.1943-555X.0000075)
- Sep, C., & Chinyama, A. (n.d.). *Understanding the Poor Performance of Urban Sewerage Systems: A Case of Coldstream High Density Suburbs, Chinhoyi, Zimbabwe*. Retrieved April 14, 2025, from [https://www.academia.edu/27933587/Understanding\\_the\\_Poor\\_Performance\\_of\\_Urban\\_Sewerage\\_Systems\\_A\\_Case\\_of\\_Coldstream\\_High\\_Density\\_Suburbs\\_Chinhoyi\\_Zimbabwe](https://www.academia.edu/27933587/Understanding_the_Poor_Performance_of_Urban_Sewerage_Systems_A_Case_of_Coldstream_High_Density_Suburbs_Chinhoyi_Zimbabwe)
- Singh, A., & Adachi, S. (2013). Bathtub curves and pipe prioritization based on failure rate. *Built Environment Project and Asset Management*, 3(1), 105–122. <https://doi.org/10.1108/BEPAM-11-2011-0027>
- Sousa, V., Matos, J. P., & Matias, N. (2014). Evaluation of artificial intelligence tool performance and uncertainty for predicting sewer structural condition. *Automation in Construction*, 44, 84–91. <https://doi.org/10.1016/j.autcon.2014.04.004>
- Šperac, M., & Obradović, D. (2018). *Odvodnja otpadnih voda alternativnim kondominijalnim kanalizacijskim sustavom* (P. Raos, Ed.; pp. 199–208). Osijek: Strojarski fakultet Sveučilišta u Slavonskom Brodu. <https://www.croris.hr/crosbi/publikacija/prilog-skup/668245>
- Sugumaran, R., & Degroote, J. (2010). *Spatial Decision Support Systems: Principles and Practices*. CRC Press. <https://doi.org/10.1201/b10322>

- Tabesh, M., & Saber, H. (2012). A Prioritization Model for Rehabilitation of Water Distribution Networks Using GIS. *Water Resources Management*, 26(1), 225–241. <https://doi.org/10.1007/s11269-011-9914-y>
- Tagherout, W. B., Bennis, S., & Bengassem, J. (2011). A Fuzzy Expert System for Prioritizing Rehabilitation of Sewer Networks: A fuzzy expert system for prioritizing rehabilitation of sewer networks. *Computer-Aided Civil and Infrastructure Engineering*, 26(2), 146–152. <https://doi.org/10.1111/j.1467-8667.2010.00673.x>
- The Components of Sustainable Development—A Possible Approach*. (n.d.). ResearchGate. Retrieved April 14, 2025, from [https://www.researchgate.net/publication/283241878\\_The\\_Components\\_of\\_Sustainable\\_Development\\_-\\_A\\_Possible\\_Approach](https://www.researchgate.net/publication/283241878_The_Components_of_Sustainable_Development_-_A_Possible_Approach)
- Tran, D. H., Perera, B. J. C., & Ng, A. w. m. (2009). Comparison of Structural Deterioration Models for Stormwater Drainage Pipes. *Computer-Aided Civil and Infrastructure Engineering*, 24(2), 145–156. <https://doi.org/10.1111/j.1467-8667.2008.00577.x>
- Tscheikner-Gratl, F., Egger, P., Rauch, W., & Kleidorfer, M. (2017). Comparison of Multi-Criteria Decision Support Methods for Integrated Rehabilitation Prioritization. *Water*, 9(2), 68. <https://doi.org/10.3390/w9020068>
- Vanier, D. (n.d.). *An evaluation of condition assessment protocols for sewer management*. Retrieved April 14, 2025, from [https://www.academia.edu/51913087/An\\_evaluation\\_of\\_condition\\_assessment\\_protocols\\_for\\_sewer\\_management](https://www.academia.edu/51913087/An_evaluation_of_condition_assessment_protocols_for_sewer_management)
- Vargas, L. G. (1990). An overview of the analytic hierarchy process and its applications. *European Journal of Operational Research*, 48(1), 2–8. [https://doi.org/10.1016/0377-2217\(90\)90056-H](https://doi.org/10.1016/0377-2217(90)90056-H)
- Vladeanu, G., & Matthews, J. (2019). Wastewater Pipe Condition Rating Model Using Multicriteria Decision Analysis. *Journal of Water Resources Planning and Management*, 145(12), 04019058. [https://doi.org/10.1061/\(ASCE\)WR.1943-5452.0001134](https://doi.org/10.1061/(ASCE)WR.1943-5452.0001134)

Vollertsen, J., Revilla, N., Hvitved-Jacobsen, T., & Nielsen, A. H. (2015). Modeling Sulfides, pH and Hydrogen Sulfide Gas in the Sewers of San Francisco. *Water Environment Research*, 87(11), 1980–1989.

*Water engineering. Reducing sewer corrosion through integrated urban water management.* (n.d.). ResearchGate. Retrieved April 14, 2025, from [https://www.researchgate.net/publication/264794929\\_Water\\_engineering\\_Reducing\\_sewer\\_corrosion\\_through\\_integrated\\_urban\\_water\\_management](https://www.researchgate.net/publication/264794929_Water_engineering_Reducing_sewer_corrosion_through_integrated_urban_water_management)

Yang, M. D., & Su, T. C. (2006). Automation model of sewerage rehabilitation planning. *Water Science and Technology: A Journal of the International Association on Water Pollution Research*, 54(11–12), 225–232. <https://doi.org/10.2166/wst.2006.805>

Yang, M.-D., Su, T.-C., & Chen, Y.-P. (2005). Priority Evaluation of Sewerage Rehabilitation By AHP. *Pipelines 2005*, 523–537. [https://doi.org/10.1061/40800\(180\)41](https://doi.org/10.1061/40800(180)41)

Younis, R. (2010). Discussion of “Integrated Decision Support System for Optimal Renewal Planning of Sewer Networks” by M. R. Halfawy, Leila Dridi, and Samar Baker. *Journal of Computing in Civil Engineering*, 24(5), 462–463. [https://doi.org/10.1061/\(ASCE\)CP.1943-5487.0000016](https://doi.org/10.1061/(ASCE)CP.1943-5487.0000016)