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Sujet

Integration of GIS, AHP and Hydraulic models for Optimizing the Rehabilitation of Water Distribution Networks: Case Study of Tlemcen and Arzew Networks

Couplage entre SIG, AHP et modèles hydrauliques pour l'optimisation de la réhabilitation des réseaux d'alimentation en eau potable, Cas des réseaux d'AEP de Tlemcen et Arzew

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Dedication

“I dedicate this thesis to the memory of my father, whose wisdom, love, and guidance continue to inspire me every day. Though he is no longer with us, his presence is felt in every accomplishment and milestone.

I also dedicate this work to my mother, whose unwavering support and encouragement have been a source of strength throughout my academic journey.

Additionally, I express my heartfelt appreciation to my loving wife for her endless patience, understanding, and encouragement.

To my siblings, relatives, and friends who have stood by me through thick and thin, thank you for your unwavering belief in me. Your love and support have been invaluable.”

Yacine

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المخلص: تستكشف هذه الأطروحة تطبيق عملية التسلسل الهرمي التحليلي (AHP) ونظم المعلومات الجغرافية (GIS) في عملية اتخاذ القرار لتجديد وإعادة تأهيل شبكات توزيع المياه في الجزائر. تشمل الدراسة تحقيقين متميزين ولكنهما مترابطين. أولاً، مع التركيز على شبكة توزيع المياه في منطقة تورفيل في وهران شمال غرب الجزائر، يجمع التحليل بين مختلف نظم دعم القرار (DSS)، بما في ذلك نظم المعلومات الجغرافية والتحليل متعدد المعايير ونماذج المحاكاة الهيدروليكية. من خلال هذا النهج المتكامل، تم إنشاء نظام إدارة خبير لتحسين إدارة شبكة المياه والصرف الصحي من حيث التجديد وإعادة التأهيل. تكشف النتائج أن 26% من الشبكة تتطلب إعادة تأهيل عاجلة. ثانياً، يتعمق البحث في تطوير وتطبيق أداة برمجة نصية داخل نظام المعلومات الجغرافية ArcGIS لاتخاذ القرارات في شبكة توزيع مياه الشرب، باستخدام شبكة توزيع مياه الشرب في تلمسان، الواقعة في شمال غرب الجزائر، كدراسة حالة. توضح الدراسة فعالية أداة AHP في تحديد أولويات جهود تجديد البنية التحتية وإعادة التأهيل. تشير النتائج إلى أن 25% من الشبكة في حالة حرجة وتتطلب اهتماماً فورياً، بينما 62% و 13% في حالة طوارئ متوسطة ومنخفضة على التوالي. إن المعايير الرئيسية التي تؤثر على تحديد أولويات الأنابيب من حيث إعادة التأهيل هي المواد وعمر الأنبوب وضغط المياه، حيث يساهم كل منها بشكل كبير في العامل الإجمالي. بالإضافة إلى ذلك، يقوم البحث بالتحقق من صحة النتائج باستخدام البيانات الملاحظة في الفصل الرابع، والذي يتناول تنفيذ وتحقيق الأداة. تساهم هذه الأطروحة في هذا المجال من خلال توفير أدوات ومنهجيات عملية يمكن تكييفها وتطبيقها بسهولة من قبل المهندسين ومسؤولي إدارة المياه وصناع القرار والمخططين لإدارة المياه المناطق الحضرية. يمكن أن تكون الرؤى المكتسبة من هذه التحقيقات بمثابة إرشادات قيمة ليس فقط لإدارة شبكات المياه في تورفيل وتلمسان ولكن أيضاً في سياقات مماثلة في جميع أنحاء العالم.

الكلمات المفتاحية: بايثون؛ البرمجة نصية؛ تحليل القرار متعدد المعايير؛ عملية التسلسل الهرمي التحليلي؛ النمذجة، نظم المعلومات الجغرافية؛ شبكة توزيع المياه؛ إدارة مياه الشرب.

Abstract: This thesis explores the application of the Analytic Hierarchy Process (AHP) and Geographic Information Systems (GIS) in decision-making for the renovation and rehabilitation of water distribution networks (WDN) in Algeria. The study encompasses two distinct yet interconnected investigations. Firstly, focusing on the Arzew district water distribution network in Oran, Northwest Algeria, the analysis combines various Decision Support Systems (DSS), such as GIS, multi-criteria analysis, and hydraulic simulation models. Through this integrated approach, an expert management system is established to optimize WDN management in terms of renovation and rehabilitation. Findings reveal that 26% of the network requires urgent rehabilitation. Secondly, the research delves into the development and application of a scripting tool within ArcGIS for decision-making in WDN, using the drinking water distribution network of Tlemcen, located in Northwest Algeria, as a case study. The study demonstrates the effectiveness of the AHP tool in prioritizing infrastructure renovation and rehabilitation efforts. Results indicate that 25% of the network is in critical condition and requires immediate attention, while 62% and 13% are in medium and low states of emergency, respectively. Key criteria influencing pipe prioritization include material, laying date, and pressure, each contributing significantly to the overall weight. Additionally, the thesis validates the results with observed data, implementation and validation of the tool. This thesis contributes to the field by providing practical tools and methodologies that can be readily adapted and applied by engineers, water management officers, decision-makers, and planners for urban water management. The insights gained from these investigations can serve as valuable guidance not only for the management of water networks in Arzew and Tlemcen but also for similar contexts worldwide.

Keywords: Python; Scripting; Multi-Criteria Decision Analysis (MCDA); Analytic Hierarchy Process (AHP); Modeling, Geographic Information Systems (GIS); Water Distribution Network (WDN); Drinking Water Management.

Résumé : Cette thèse explore l'application de la méthode de hiérarchie multicritère et des Systèmes d'Information Géographique (SIG) dans la prise de décision pour la rénovation et la réhabilitation des réseaux de distribution d'eau en Algérie. L'étude englobe deux investigations distinctes mais interconnectées. Tout d'abord, en se concentrant sur le réseau de distribution d'eau de la ville de Arzew à Oran, dans le nord-ouest de l'Algérie, l'analyse combine différents

Systèmes d'Aide à la Décision, comme les SIG, l'analyse multicritère et les modèles de simulation hydraulique. Grâce à cette approche intégrée, un système de gestion expert est établi pour optimiser la gestion des réseaux de distribution d'eau en termes de rénovation et de réhabilitation. Les résultats révèlent que 26% du réseau nécessite une réhabilitation urgente. Deuxièmement, la recherche se penche sur le développement et l'application d'un outil de script au sein d'ArcGIS pour la prise de décision dans les réseaux de distribution d'eau, en utilisant le réseau de distribution d'eau potable de Tlemcen, situé dans le nord-ouest de l'Algérie, comme étude de cas. L'étude démontre l'efficacité de l'outil AHP dans la priorisation des efforts de rénovation et de réhabilitation des infrastructures. Les résultats indiquent que 25% du réseau se trouve dans un état critique et nécessite une attention immédiate, tandis que 62% et 13% se trouvent dans des états d'urgence moyen et faible, respectivement. Les critères clés influençant la priorisation des conduites incluent le matériau, la date de pose et la pression, contribuant chacun de manière significative au poids global. De plus, la thèse valide les résultats avec des données observées, mise en œuvre et validation de l'outil. Cette thèse contribue au domaine en fournissant des outils et des méthodologies pratiques qui peuvent être facilement adaptés et appliqués par les ingénieurs, les responsables de la gestion de l'eau, les décideurs et les urbanistes pour la gestion urbaine de l'eau. Les perspectives tirées de ces investigations peuvent servir de précieux conseils non seulement pour la gestion des réseaux d'eau à Arzew et à Tlemcen, mais également pour des contextes similaires dans le monde entier.

Mots-clés : Python ; Scripting ; Analyse décisionnelle multicritère ; Processus hiérarchique analytique ; Modélisation, Systèmes d'information géographique ; Réseau de distribution d'eau ; Gestion de l'eau potable.

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Abbreviation List

AHP	Analytic Hierarchy Process
GIS	Geographic Information Systems
WDN	Water distribution networks
WDS	Water Distribution Systems
DSS	Decision Support Systems
MCDA	Multi-Criteria Decision Analysis
MCM	Monte Carlo methods
CI	Consistency Index
CR	Consistency Ration
RI	Random Consistency Index
λ_{max}	The largest or the principal eigenvalue of the matrix
DMA	District Metered Area
PEHD	Polyethylene High-Density
SEOR	Oran Water and Sanitation Company
ADE	Algérienne Des Eaux

GENERAL

INTRODUCTION

General Introduction

Water distribution systems (WDS) play a crucial role in ensuring a reliable and sustainable water supply to communities worldwide. However, the management of these intricate systems can become increasingly complex due to various challenges, such as leakage, pipe aging, and deteriorating infrastructures. These issues are often exacerbated by water scarcity and growing population demands, highlighting the need for effective decision-making tools and strategies. (Brentan et al. 2022)

One of the paramount concerns in water management revolves around addressing the challenges posed by aging and deteriorating water distribution networks. Water pipe corrosion is a grave issue that managers must comprehend before deciding on solutions or new developments (Amorocho-Daza et al. 2019). The use of multi-criteria decision models and decision support systems (DSS) can address the complexity of decision-making for the rehabilitation planning of water distribution networks (Aşchilean et al. 2017a).

Several studies have explored the integration of Geographic Information Systems (GIS), Multi-Criteria Decision Analysis (MCDA), and hydraulic simulation models to support effective drinking water network management. These approaches have demonstrated their potential in facilitating data-driven decision-making, enabling the diagnosis of network malfunctions, and supporting the prioritization of pipeline renewal and rehabilitation efforts (Şener et al. 2010; Aşchilean et al. 2017a; Al-Ghobari and Dewidar 2021; Alrayess 2015; Chérifa Abdelbaki et al. 2014; Brentan et al. 2022).

In recent years, the use of mathematical models, software, and analytical tools has become increasingly important in decision-making processes for water distribution networks. These tools can provide valuable insights into complex systems and help identify the best courses of action for network rehabilitation and management. Techniques such as the Analytic Hierarchy

Process (AHP) have shown promise in water management and can aid stakeholders in developing more effective strategies. (Greco, Ehrgott, and Figueira 2016; Tarigan et al. 2018; Amorocho-Daza et al. 2019),

This thesis aims to develop and apply a GIS-based multi-criteria decision support system for the rehabilitation and management of water distribution networks. The proposed system will integrate GIS, multicriteria analysis, and hydraulic simulation models to create a comprehensive decision-making framework. The primary objective is to enhance network management by identifying and prioritizing critical sections of the network for rehabilitation, preventing potential problems, and optimizing resource allocation.

The research involved the development of a Python-based tool within the ArcGIS environment, implementing the AHP method for decision-making in water distribution network management. The tool's algorithm and script were designed to simplify the process of identifying pipes that need rehabilitation or renewal by considering multiple criteria and conducting pairwise comparisons based on Saaty's nine-point scale.

To validate the practical application and accuracy of the developed tool, it was applied to a case study area in the southern urban agglomeration of Tlemcen, Algeria. This region faces severe management challenges due to its aging water distribution network, high water losses, and inadequate infrastructure design. The study provided a detailed walkthrough of the tool's application, illustrating the step-by-step process of data preparation, criteria selection, weight assignment, and decision analysis.

Furthermore, the results obtained from the AHP tool were analyzed and compared with existing condition assessments or expert opinions to validate the tool's decision-making capabilities. This process not only showcased the tool's practical utility but also identified potential areas for improvement or future enhancements.

By developing and applying this GIS-based multi-criteria decision support system, this research aims to contribute to the field of water infrastructure management by providing a comprehensive and reliable decision-making framework for prioritizing rehabilitation efforts and optimizing resource allocation in water distribution networks.

This thesis is divided into four main chapters:

1. Literature Review: This chapter provided a comprehensive review of existing literature and research related to the use of Geographic Information Systems (GIS), Python scripting language, Multi-Criteria Decision Analysis (MCDA), Analytic Hierarchy Process (AHP), hydraulic modeling, and water distribution systems (WDS).
2. Decision Support System for the Management of Water Distribution Networks: In this chapter, the AHP method was applied to the water supply network of the Arzew district in Oran, northwest of Algeria, to demonstrate its applicability in decision-making for water distribution network management.
3. Development of the Multi-Criteria Decision-Making Tool: This chapter focused on the development of an algorithm and a Python-based script tool, dedicated to the decision-making process related to water management. The tool was GIS-based and utilized the AHP method for multi-criteria analysis.
4. Implementation and Validation of the Tool: In this chapter, the developed tool was applied to another case study in the city of Tlemcen, northwest of Algeria. The chapter aims to provide a detailed walkthrough of the tool's application, illustrating the step-by-step process of data preparation, criteria selection, weight assignment, and decision analysis. Furthermore, the results obtained from the AHP tool were analyzed and compared with existing condition assessments to validate the tool's decision-making capabilities.

**CHAPTER I:
LITERATURE
REVIEW**

I.1. Geographic Information Systems

GIS is becoming an increasingly important tool for spatial decision support system, due to its diversity of applications in many areas such as military, tourism, agriculture, zoology and of course, geography. The integration of geography information in computer systems was first created by Dr Roger Tomlison “The father of GIS”, who worked as a photo-interpreter for Spartan Air Services in Canada. He is the first one who could pass from the manual overlay to the digital overlay. The Canada Geographic Information System was the first computerized GIS in the world in 1963 by Dr Tomson. (Tomlinson, Calkins, and Marble 1976; Sebert 1999; Rura-Porterfield, Marble, and Alvarez 2014).

The early growth of GIS happened in some principally different areas, and it was between 1960s and 1970s .The need to integrate data and the relationships between features such as the Chicago Area Transportation Studies, editing maps during the cartographic production represent a big problem leading the government of Canada to make a major investment in this field. (Tomlinson 1974; Goodchild and Haining 2003). In the late 1960s a group of archaeologists used a primitive version of GIS to generate maps that interpolated the distribution of data based on a limited number of observations.(Knoerl 1991) By the mid-1970s to the 1980s the microprocessors were developed and improved and personal computer (PC) is lunched, the progress in computer memory and graphic capabilities facilitate the use of the pc and this was a reason of the increasing acceleration in the use of GIS and led to the creation of commercial GIS Software. (Fazal 2008) This era is known as the commercialization. ARC/INFO, Esri's first commercial software package is released to the public in 1982 , Esri is one of these GIS software companies (‘The History of Geographic Information Systems (GIS) | BCS’, n.d.). At the beginning of 1990s the internet became available in PCs which led to the use of data networks for geographical data search and distribution. (Fazal 2008) The integration of remote sensing technology, the data collected from space could be consumed in GIS (GISGeography 2015).

The Internet explosion of the late 1990s permitted the data sharing, Open Source GIS was born. Currently, any individual can use GIS and spatial analysis.

I.1.1. Definition of GIS

Geographic information systems (GIS) are computer applications designed for the acquisition, storage, analysis, modeling, archiving, and sharing of geographic information in digital form. (Goodchild 2012) A GIS is a computer-based system that provides sets of professional capabilities for capture, storage, manipulation and data analysis. (Aronoff 1989) The difference between a GIS and a map-making program are the data, which are geographically referenced, means can come from many sources, and can be manipulated and analyzed in a variety of ways. Geographically referenced data are also known as Geospatial data where the location and the attributes of spatial features are indexed. (Greenberg, Logsdon, and Franklin 2002; Chang 2017) Many researchers defined GIS (Maguire 1991), however all of the definitions have one thing in common which is a decision support system dedicated to manage the geospatial data.

Other definitions

'A geographic information system is a facility for preparing, presenting, and interpreting facts that pertain to the surface of the earth. This is a broad definition . . . a considerably narrower definition, however, is more often employed. In common parlance, a geographic information system or GIS is a configuration of computer hardware and software specifically designed for the acquisition, maintenance, and use of cartographic data.' - **C. Dana Tomlin**

'The purpose of a traditional GIS is first and foremost spatial analysis. Therefore, capabilities may have limited data capture and cartographic output. Capabilities of analyses typically support decision making for specific projects and / or limited

geographic areas. The map data-base characteristics (accuracy, continuity, completeness, etc.) are typically appropriate for small-scale map output. Vector and raster data interfaces may be available. However, topology is usually the sole underlying data structure for spatial analyses. - **William Huxhold**

I.1.2. The nature of geographic data

Data format is how data element are presented and stored in records.(Tomlinson 1974) GIS data are the information used which has geographical and non-geographical records. In GIS Systems there are two types of data: Raster and vector data.

Raster data: Raster is a method for the storage of spatial data, it is a representation of the real world where data is represented as a matrix of cells or pixels, each cell must be rectangular in shape (Escobar et al. 2008) the square cells are the most commonly used.(Huisman 2009)

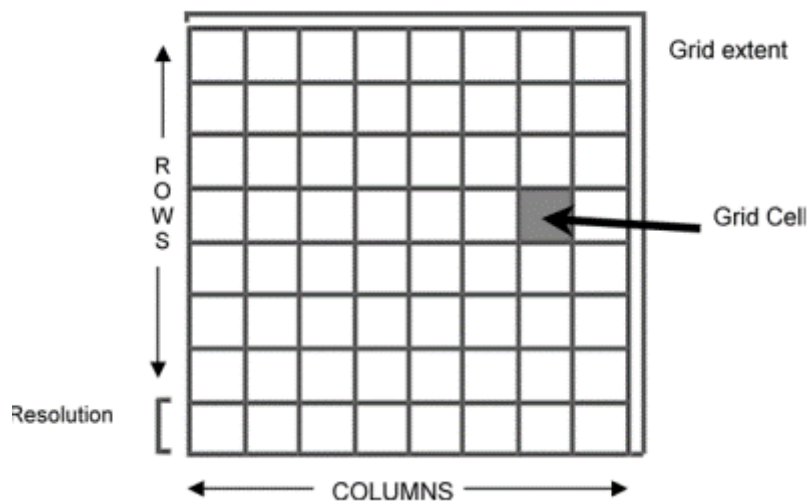


Figure I.1 : Genetic structure for a greed (Fazal 2008)

Each pixel represents a geographical area, and the value in that pixel represents some characteristic of that area.

Applications of raster data: Raster data is used in a GIS application when we want to display information that is continuous across an area and cannot easily be divided into vector features.

Vector data: a vector is used to represent points, lines and areas Figure I.2 . Vector features have attributes, each attribute has its description and geometry. ('A Gentle Introduction to GIS — QGIS Documentation Documentation', n.d.)

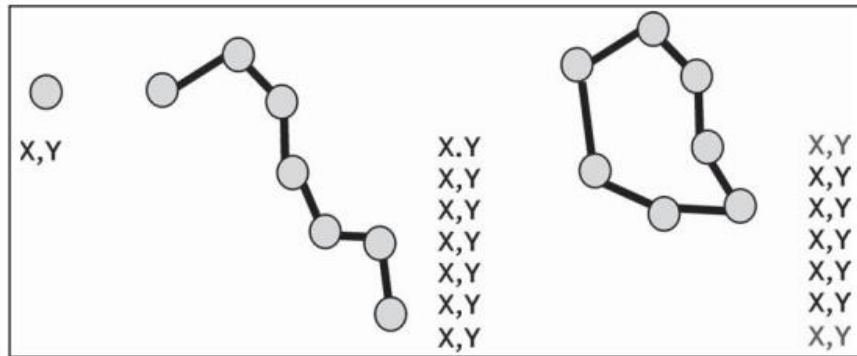


Figure I.2 : The vector data model (Fazal 2008)

The points representation is defined as single coordination pairs compared to lines and polygons representation which is defined by multiple coordination pairs.

Table I.1: Comparison of raster and vector data formats(Fazal 2008).

Raster model	Vector model
Advantages	Advantages
Simple data structure	Compact data structure
Easy and efficient overlaying	Efficient for network analysis
Compatible with RS imagery	Efficient projection transformation
High spatial variability is efficiently represented	Accurate map output
Simple for own programming	
Same grid cells for several attributes	

Disadvantages	Disadvantages
Inefficient use of computer storage	Complex data structure
Errors in perimeter, and shape	Difficult overlay operations
Difficult network analysis	High spatial variability is inefficiently
Inefficient projection transformations	Not compatible with RS imagery
represented	
Loss of information when using	
large cells Less accurate (although	
interactive) maps	

I.1.3. Application of GIS

Geographic information systems support a vast range of applications. In commerce, they are widely used to maintain inventories of distributed assets in the utility industry, to manage marketing efforts and to determine optimal locations for retail businesses and services, and to schedule delivery and pickup services. In science, they are particularly useful for examining patterns of phenomena on the Earth's surface, formulating, and testing hypotheses about the spread of disease, the distribution of plant species and the behavior of animals, and the spatial organization of society. In government, they are used to make choices between alternative planning options and to manage social services. In the military, they are essential to battlefield control.(Goodchild 2009)

GIS can be used to map locations. Through automated mapping, data collecting, and surveying analytic tools, GIS enables for the generation of maps.

People map amounts to locate places that fit their requirements and act, or to see the links between places, such as where the most and least are. This adds to the information provided by directly mapping the positions of features.

While we may observe concentrations by simply mapping the locations of features, it can be difficult to see which places have a larger concentration than others in areas with multiple characteristics. A density map allows us to count the number of features in a uniform areal unit, such as acres or square miles, so that the distribution may be seen clearly.

GIS can be used to determine what is occurring within a certain distance of a feature.

GIS can be used to map change in an area in order to predict future circumstances, choose a course of action, or evaluate the consequences of an activity or policy.(Escobar et al. 2008)

I.1.4. GIS applications in water resources

The spatial nature of data related to water resources is the single most important factor contributing to data management complexity. GIS software has the potential to revolutionize the way engineers model water resources. GIS with and without model interface has been applied to numerous areas including surface water hydrologic and groundwater modeling, water supply and sewer line design, and stormwater and nonpoint source pollution modeling for urban and agricultural areas.(Tsihrintzis, Hamid, and Fuentes 1996) Water network operators can use a management tool that combines GIS and modeling to investigate problems, respond to any incidents that may occur, and make it easier to understand the work done on the network.(Chérifa Abdelbaki et al. 2017)

I.1.5. Automating GIS Work

When some of GIS tasks become repetitive, it is necessary to automate these tasks to save time work. Spatial scripting languages are becoming increasingly important in automating workflow-based geoprocessing and map production in the GIS domain.(Zhang, Yue, and Guo

2014) Scripting allows tools to be run repeatedly by looping over the same part of code several times.('How To: Use Scripting in ArcGIS Desktop to Run Custom Tools and Repetitive Geoprocessing Workflows and Tasks', n.d.)

Programming languages are typically used to create programs from scratch; however, scripting languages are used to connect components written in various system programming languages. There are numerous commercial software such as ArcGIS and open source tools such as Quantum GIS using Python as a scripting tool, and developed package dedicated for each software, Arcpy for example is a Python site package for ArcGIS includes tools, functions, classes, and modules, which serves a tool development.(Zhang, Yue, and Guo 2014)

I.2. Python for scripting language

I.2.1. Definition

Van Rossum wanted to create a language that would allow for easier code development and testing, easy (or at least understandable) grammar, and results with fewer lines of code in less time. Python's first was released in 1991 and was freely available from the start.(Toms 2015) Python is a computer language that is available for free. Python is a widely, high-level programming language that is interpreted. Python offers a simple syntax and an integrated development environment.(Dobesova 2011) Python shares the same set of features as other general-purpose scripting languages but varies from others in its fundamental object-orientation and because the core language provides class formation, multiple inheritance, method declaration, operator overloading, and throw and catch exceptions.(Sorokine and Ackermann 2000) Python is a programming language that is object-oriented. An object-oriented program is made up of interacting objects. Object-oriented programming is supported by many modern programming languages. Python is compatible with ArcGIS since it is built to interact with object-oriented languages.(Zandbergen 2015) Geometry classes in object-oriented languages can represent spatial objects. Geometry classes (such as Point, Line, Polygon, MultiPoint,

MultiLine, MultiPolygon, and so on)(Zhang, Yue, and Guo 2014) Scripting with Python seems to be immensely beneficial to the users. Scripts also reduce the amount of manual work required when processing big amounts of data.(Dobesova 2011)

I.2.2. Using scripting in ArcGIS

Esri developed a Python package dedicated to ArcGIS users named Arcpy, it permits the coupling of ArcGIS and Python with the objective of making Python scripting simpler and more sophisticated. Using the ArcPy module, Python may be used to manipulate ArcGIS tools and Map Documents in order to produce geospatial data and maps in an organized and timely manner. There are several Arcpy modules such as cartographic module (arcpy.mapping), spatial analysis module (arcpy.sa), and the geostatistical analysis module (arcpy.ga).(Zhou et al. 2019) Arcpy is a wrapper module, which means it allows Python to communicate with other programs. Wrappers, for example, allow users to extract data from an Excel spreadsheet and transform or load it into ArcGIS.(Toms 2015)

I.3. Modelling

I.3.1. Definition

A model, or something that simulates important components of the situation being examined, is important to the theoretical and scientific analysis of a situation. A road map, a geological map, and a plant collection, for example, are all models that represent different parts of the earth's surface.(Bender 1978)

Models are descriptions of our ideas about how the world works. We transfer those views into mathematical language in mathematical modeling. There are numerous advantages to this.

- Math is an extremely precise language. This aids in the formulation of concepts and the identification of underlying assumptions.
- Mathematics is a clear and well-defined language with well-defined manipulation rules.

- The access to all the results that mathematicians have proven over hundreds of years.
- Numerical calculations can be done on computers.(Marion, Lawson, and Marion 2008)

In addition to their success in physical system design, fabrication, analysis, and improvement, modeling and simulation techniques are frequently used in organizational and operational systems.(Yin and Mckay 2018)

Experimentation that would otherwise be difficult or impossible is also possible due to modeling and simulation approaches. Computer simulations, for example, have aided several advances in domains such as biology, meteorology, cosmology, population dynamics, and military effectiveness.(‘Introduction to Modeling and Simulation’ 1995)

I.3.2. Classifications of models

Identifying model categories is important. One way to classify models is by the type of outcome they predict. In deterministic models, the output of the model is well known so there is no randomness in this system. Stochastic models possess some inherent randomness.(Marion, Lawson, and Marion 2008) The hybrid model is mixture of both without any doubt.

I.3.3. Modeling process

There are many definitions of the steps to modelling or the process of simulation, but it is noted that they all have some common steps where are given below:

- Define research problem
- Design experiments and collect data.
- Select simulation method
- Calibrate and Test the Model
- Validate the simulation model

I.3.4. Modeling and simulation methods

Simulation models can be generally classified into one of three major types, namely, continuous event simulation, discrete event simulation, and Monte Carlo simulation or Monte Carlo methods (MCM).(Muralidhar 2003) One technique to develop models in a top-down architecture and monitor time-based behaviors within a system is to use discrete-event simulation.(Yin and Mckay 2018)

MONTE CARLO METHODS are a type of simulation approach that allows to study and comprehend complicated situations. MCM can refer to any process that solves a problem by using randomly generated numbers.(Muralidhar 2003)

Continuous simulations are used to represent physical events (processes, behaviors, and situations) that are described by a set of constantly changing dependent variables.(Fortier and Michel 2003)

I.3.5. Model Calibration and Verification

Calibration is determined by comparing the output of the model with the measured values. The verification is a phase in the process of evaluating the model more globally, and it necessitates a distinct set of measurable data for verifying the model's performance. The model validation process consists of a combination of calibration and verification stages. The Figure I.3 illustrates the process of model calibration.(Benedini and Tsakiris 2013)

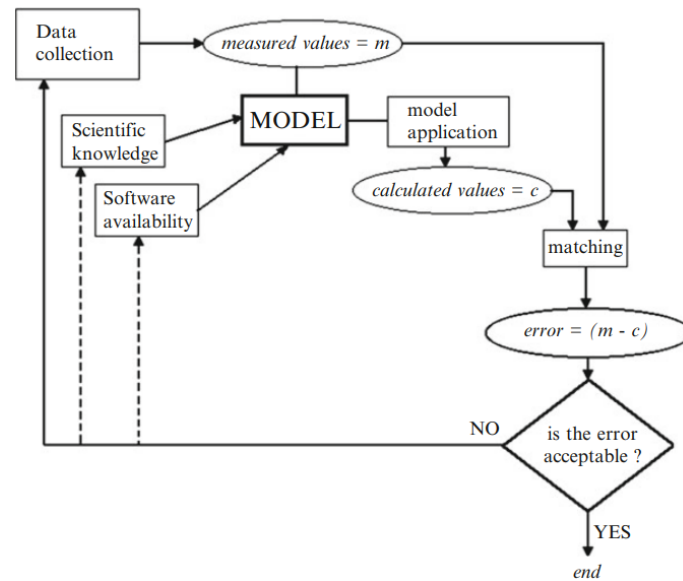


Figure I.3: The mathematical model's calibration process (Benedini and Tsakiris 2013)

I.3.6. Hydraulic modelling of water supply distribution

Water distribution network (WDN) hydraulic models are excellent decision tools for developing various management scenarios to improve the efficiency and reliability of existing networks and to build new ones. (Kara et al. 2016) Water distribution system difficulties such as deteriorating systems, leakage and pipe line disruption, inability to meet demand, poor system design and water abuse/mismanagement have necessitated water distribution system modeling, which is quickly becoming a crucial and critical aspect of the WDSs. (Awe, Okolie, and Fayomi 2019)

I.3.7. Water modelling software

Water modeling software is a powerful tool for simulating and predicting water transportation and behavior in distribution systems, which can assist preserve system resources, maintain water quality, and meet consumer needs (Farina, Creaco, and Franchini 2014).

Progress in the field of water supply and the use of computers in it have inspired experts, scientists, research scholars, developers, and programmers to create a variety of softwares for

the design and modeling of water distribution networks such as EPANET, Branch, and LOOP, as well as commercial softwares such as Aquis, H2O map, KYPipe, WaterCAD, WaterGEMS, and others.(Sonaje and Joshi 2015)

I.4. Multi-criteria decision making

I.4.1. Background

Making decisions in the face of several different criteria is what Multiple Criteria Decision Making (MCDM) is all about. MCDM has emerged as one of Operations Research/Management Science's most important and fastest-growing subfields.(Köksalan, Wallenius, and Zionts 2011) MCDM is an ancient field and have been used for centuries. The practice of decision making is ancient, Aristotle (384–322 BC) the Greek philosopher established a link between rational decision-making and human desires (preferences) however Benjamin Franklin (1706–1790), who had a simple paper system for selecting his judgement on an important topic, is the first recorded reference to Multiple Criteria Decision Making.(Köksalan, Wallenius, and Zionts 2013) The diversity of the MCDA applications is due to the multiple researcher disciplines contributing in this fields. In politics, Antoine Nicolas Caritat (1743–1794) presented several interesting results about the conduct of fair elections. In economics Vilfredo Pareto (1848–1923), an economist, was most likely the first researcher whose work may be formally classed as MCDM and conclude that 20% of the population of Italy owned 80% of the property. Many other developments in the field were made by major contributors such as mathematics, automatics, management science and other area.(Köksalan, Wallenius, and Zionts 2011; 2013)

I.4.2. Definition

MCDM is dealing with organizing and managing decision and planning problems using many criteria.(Majumder 2015) The decision-making process is an activity in which the decision-maker cannot avoid being influenced by a variety of variables that, in the end, determine what

will become the winning decision.(Munier, Hontoria, and Jiménez-Sáez 2019) MCDM refers to the process of selecting the best possible solution based on specified criteria and difficulties encountered in everyday life.(Jahan, Edwards, and Bahraminasab 2016)

I.4.3. MCDM approaches

Some mathematical elements are shared by the following MCDM approaches: For each criterion, values for alternatives are assigned, which are then multiplied by corresponding weights and eventually combined to produce a total score.(Kabir, Sadiq, and Tesfamariam 2014)

- Weighted sum model (WSM) (Fishburn, 1967),
- Weighted product model (WPM) (Bridgman, 1922; Miller & Starr, 1969),
- Compromise programming (CP) (Zeleny, 1982),
- Analytical hierarchy process (AHP) (Saaty, 1980),
- ELECTRE (Benayoun, Roy, & Sussman, 1966),
- TOPSIS (Hwang & Yoon, 1981),
- PROMETHEE (Brans & Vincke, 1985) and
- VIKOR (Opricovic, 1998).

I.4.4. Classification of MCDM Methods

The MCDM methods can be classified in many ways.(Düzce 2017) This classification style is expressed in Figure I.4.

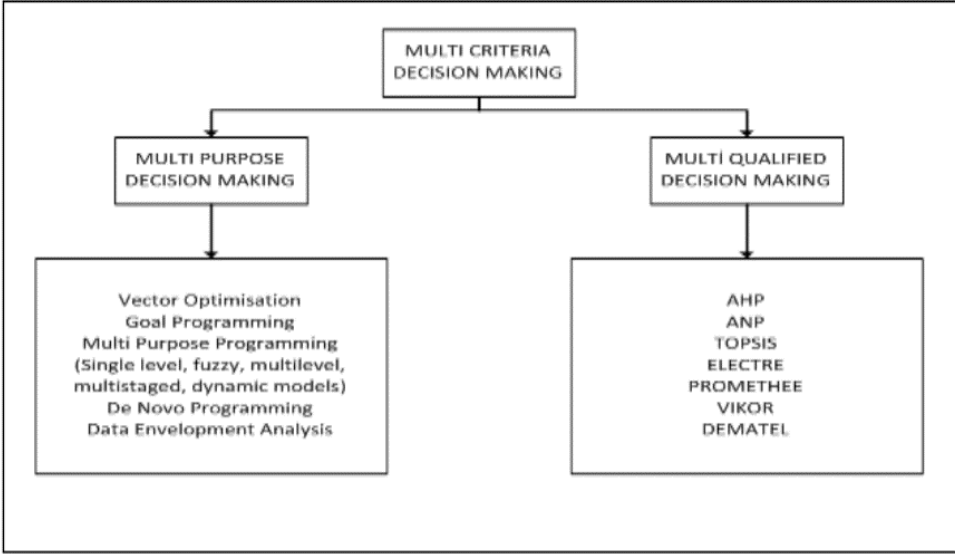


Figure I.4: Classification of MCDM methods (Tzeng and Huang, 2011: 3)

This classification has relation with the number of alternatives, if a decision problem contains an infinite number of continuous alternatives, it can be considered as a MPDM method, if it contains limited and discrete alternatives it can be considered as MPDM method. Other example of classification (Figure I.5), MCDA techniques can be classified in categories such as outranking methods, multi-attribute utility and value theories (MAUT and MAVT), pairwise comparison methods, distance-based methods, and fuzzy set theory.(Amorocho-Daza et al. 2019)

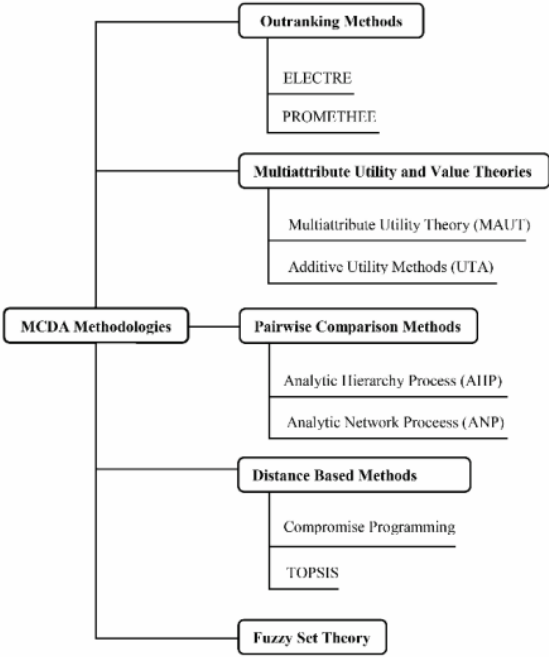


Figure I.5: General multi-criteria decision analysis (MCDA) technique classification (Greco, Ehrgott, and Figueira 2016)

I.5. Analytic Hierarchy Process

The Analytic Hierarchy Process (AHP) is a theory of measurement based on pairwise comparisons that depends on expert judgment to generate priority scales.(Saaty 2008) The Analytic Hierarchy Process has been used to solve a wide range of decision problems since its introduction in the mid-1970s. The AHP's capacity to rank decision alternatives based on both qualitative and quantitative considerations has resulted in several applications in fields as diverse as health care, politics, urban planning, and space exploration.(Golden, Wasil, and Harker 1989) The AHP works fundamentally by defining priorities for alternatives as well as the criteria used to evaluate the alternatives. A decision maker chooses the criteria. Priorities are established for the criteria based on their significance in achieving the goal, and then priorities are defined for the performance of the alternatives on each criterion. These priorities are obtained from pairwise comparisons using judgment or measurement ratios.(Saaty 2001)

To generalize, the AHP technique has eight primary applications. It enables the decision maker to 1) design a form that represents a complex problem; 2) measure priorities and choose between alternatives; 3) measure consistency; 4) predict; 5) formulate a cost/benefit analysis; 6) design forward/backward planning; 7) analyze conflict resolution; and 8) develop resource allocation based on the cost/benefit analysis.(Saaty 1988)

I.5.1. Methodology of AHP

The first stage in an AHP analysis is to create a decision hierarchy (Figure I.6). This is known as decision modeling, and it simply includes creating a hierarchy to analyze the decision.(Mu and Pereyra-Rojas 2017) The decision hierarchy is structured from the top with the goal, then the objectives from a broad perspective, via the intermediate levels (criteria on which following elements depend) to the lowest level (which usually is a set of the alternatives).(Saaty 2008)

The second stage is deriving Priorities (Weights) for the Criteria and alternatives, to calculate the weights of the priorities we need to do a pairwise comparison using the scale of Saaty (Table I.2) Each element in an upper level is used to compare the components in the level below it to it.

The final stage is the consistency checking, the consistency ratio C. R. provides a way of measuring how many "errors" were created when providing the judgments of the pairwise comparison.(Golden, Wasil, and Harker 1989)

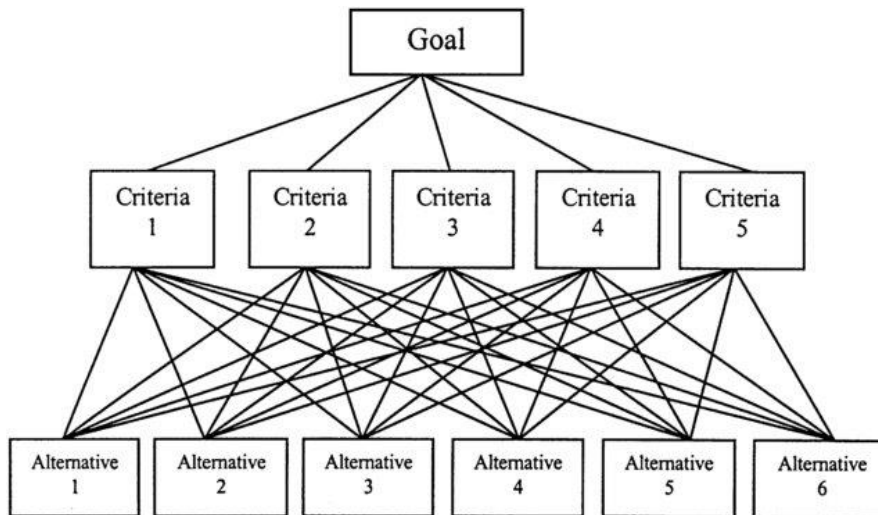


Figure I.6: Structure of the AHP model.(Badri 2001)

Table I.2: Scale of Measurement for AHP(Golden, Wasil, and Harker 1989)

Numerical Values	Definition
1	Equally important
3	Slightly more important
5	Strongly more important
7	Very strongly more important
9	Extremely more important
2,4,6,8	Intermediate values to reflect compromise
Reciprocals	used to reflect dominance of the second alternative as compared with the first.

To check the reliability of the pairwise comparisons, (CI) and (CR) allow us to know at what point the judgments are consistent and they are calculated by Equation (I.1):

$$CR = \frac{CI}{RI} \tag{I.1}$$

where:

RI: Random Consistency Index,

(RI) can be determined from Table I.3

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{I.2}$$

where:

λ_{max} : the largest or the principal eigenvalue of the matrix.

n: the order of the matrix.

Table I.3: Saaty (Saaty 1980) values of random 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

I.5.2. Application of Analytical Hierarchy Process in Water field

Since its introduction in the mid-1970s the AHP method has been applied in several applications in water field. In water policy, paper research was done about the application of the AHP to help power company decision makers predict a national acid rain policy and which acid rain policy will be selected for the United States. In water management the AHP was used to develop a Master Plan for Research in surface hydrology and surface water resources for South Africa.(Golden, Wasil, and Harker 1989) In 1987, a research was made by X. Mei et al. it was

about using the AHP to solve the water scarcity so that the city of Beijing, China can resume its normal cultural and economic growth activities.(Mei et al. 1987) In 2000 El Awar et al. combined GIS and AHP to rank possible reservoir sites based on a Reservoir Suitability Index (RSI) calculated for each of these sites in Lebanon region.(El-Awar et al. 2000) To avoid the negative impacts of wastewater on the environment, Anagnostopoulos et al. (2007) present a multicriteria approach based on the Analytic Hierarchy Process (AHP) for township wastewater facility selection.(Anagnostopoulos, Gratziou, and Vavatsikos 2007) From 2010 to now the application of AHP method have been increasingly used in different fields not only in water management with the combination of other decision support system tools such GIS. In 2010 a research by Şener et al. demonstrate the use of AHP and GIS to examine several criteria, including geology/hydrogeology, land use, slope, height, aspect, and distance from settlements, surface waters, roads, and protected areas, to determine the most suitable landfill site.(Şener et al. 2010) Another paper in the same field was about the determination of the most suitable water storage locations using a multi-criteria evaluation technique based on GIS(Ahmad and Verma 2018). The AHP method was used also in water supply Infrastructure, a research made in 2019 by Amorocho et al. to determine the preferences of various stakeholders to enable the ranking of alternatives to provide water in the city of Santa Marta, Colombia.(Amorocho-Daza et al. 2019) The AHP method has become wildly used in water management, wastewater, hydrology, drinking water supply network, and have been combined with several methods and models to support the decision making and to have the best alternative choice.

I.6. Water distribution systems

I.6.1. Definition

A water supply system transports water from sources to customers and offers services critical to the operation of a modern civilization.(Wang 2013) Water distribution systems are big and complicated networks that are designed and built to meet an urbanized area's water supply

needs.(Christodoulou et al. 2018) Water distribution systems (WDSs) have a long and interesting history. As early as the second millennium B.C., the first piped water supply, including pressure pipes, were recognized in ancient Greece.(Mala-Jetmarova, Barton, and Bagirov 2015; Crouch 1993) Pipes, pumps, valves, storage tanks, reservoirs, meters, couplings, and other hydraulic equipment that connect treatment facilities or water supplies to consumers are classified distribution system infrastructure.(National Research Council 2006)

I.6.2. Pipe-Network Configurations

Branched and looped network systems are the most common types of water supply systems. The major difference between these two systems is that the flow inside each pipe in a branched network system is a known value, whereas the flow within each pipe in a looping network system is an unknown value.(Yoo et al. 2015) Smaller pipes branch off bigger pipes across the service area, creating a branch system similar to that of a tree branch, allowing water to travel only one path from the source to the customer. In rural locations, this type of system is most employed. The most common configuration in big municipal areas is a grid/looped system, which consists of connected pipe loops throughout the region to be served. Water can go through numerous paths from the source to the user in this type of system.(National Research Council 2006) Looped systems are preferred over branched systems because, when combined with adequate valving, they can provide an extra level of reliability. Considering a main break near the reservoir in each of the systems represented in Figure I.7 That break can be isolated and fixed in the looped system with minimal impact on consumers outside of the immediate vicinity. Customers downstream from the break in the branching system, on the other hand, will have their water service stopped until the repairs are completed.(Alrayess 2015)

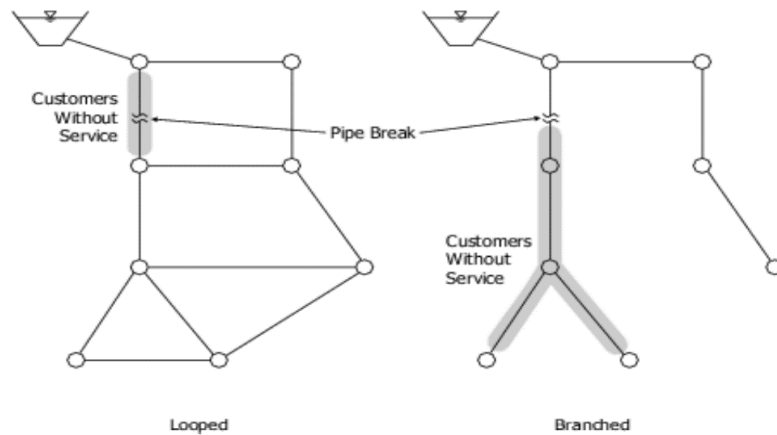


Figure I.7: Looped and branched networks after network failure (Alrayess 2015)

I.6.3. Water distribution networks management

Water services must be planned and maintained in a way that combines the goals and interests of various user groups as well as external service providers to meet people's diverse water needs. (Dlamini 2009) Advanced techniques and strategies for the analysis, monitoring, planning, and operation of water distribution networks are required for efficient and sustainable management of water distribution systems (WDNs) (Kanakoudis and Tsitsifli 2019). Within the WDN domain, sustainable management is defined as the use of strategies for the operation and management of WDNs that allow them to thrive while benefiting both current and future generations and limiting water resource depletion. (Christodoulou et al. 2018) Deep understanding of a distribution system's infrastructure is required for operation, maintenance, extension planning, and adaptation to changing restrictions. (Klingel and Deuerlein 2009)

I.6.4. District Metered Area (DMA)

Water supply networks should be separated into parts named "District Metered Areas" for the best and most simplified network management. These sections can be thought of as network parts that contain independent regional water meters. (Christodoulou et al. 2018) Place isolation valves along select pipes linking one DMA to another (closed links) and a flow meter in the remaining connecting pipes to create these districts (open links). It is possible to determine the

DMA's water balance and monitor minimal night flows using the measured inflow and outflow.(Alvisi and Franchini 2014)

By creating DMAs in an existing network, several criteria are taken into account. Some of the criteria or factors to consider when forming DMAs are as follows:

- **The number of users or connections:** typically ranges from 1000 to 2500.
- **Topography:** It is recommended that DMAs be formed using naturally occurring topographical features such as rivers, lakes, geographical differences, and even important roadways, since these will enable easy isolation.
- **Isolation and inter - connectivity:** the DMAs should be well isolated from one another for precision in measurements, they should also be interconnected using Isolation Valves .(Solutions 2019)

1.6.5. Data Loggers and Modeling

The goal of data loggers is to capture meaningful information from the pipeline system for continuous monitoring of the network state. They are permanently fixed onto crucial points of the network. The volume of water flow, the water pressure within the pipeline, and the water quality within the pipe are all examples of data acquired by data loggers. Pressure data loggers have to be installed at critical points in DMA however the flow data loggers must be at the interval.(Alves et al. 2014) There is utilization of data logger which is measuring and monitoring the water lever in a tank. Data loggers were also used to characterize real-time hourly and daily consumption profiles that represented residents' lives.(Guragai et al. 2018) Additionally, data loggers that also serve as noise correlators are employed to locate water leaks.(Christodoulou et al. 2018)

I.6.6. Water Losses

Water loss occurs in all distribution systems; the amount of leakage varies. This is dependent on the pipe network's features and other local conditions. ('Understanding and Managing Losses in Water Distribution Networks' 2003) The volume of water flowing through the distribution system is divided into two categories: "revenue water" and "nonrevenue water." The nonrevenue water which refers to water losses due to network problems, as well as other criteria that result in revenue loss for water authorities, such as unbilled or unauthorized water consumption. (Christodoulou et al. 2018) The losses caused but the network problems are called Real losses. (AL-Washali et al. 2020) The volume lost will be mostly determined by the pipe network's characteristics. ('Understanding and Managing Losses in Water Distribution Networks' 2003) However unauthorized water consumption caused by the illegal connections which are unknown parameters so it is difficult to quantify them. (Klingel and Deuerlein 2009)

CHAPTER II:

DECISION SUPPORT

SYSTEM FOR THE

MANAGEMENT OF

WATER DISTRIBUTION

NETWORKS

II.1. Introduction

Water distribution networks (WDNs) are intricate hydraulic systems that comprise nodes that are connected by pipes with non-linear hydraulic behavior. Making decisions for such a complex system requires accurate data on the hydraulic state and other relevant variables. The task of preventing pipeline renewal and diagnosing network malfunctions can prove to be challenging, and it requires competent network managers equipped with the necessary decision-making tools. These decision-making tools are mostly reliant on models such as hydraulic simulation models that simulate the behavior of WDNs to evaluate their hydraulic state, and geographic information systems (GIS) that support decision-making in WDN management. As per the study by (Patel and Mehta 2022), the design of a water distribution network capable of meeting the growing demand for water as the population increases is of utmost importance. A water-efficient distribution system is necessary to ensure a continuous water supply service 24/7 throughout the year.

According to (Pandey, Mishra, and Chauhan 2022), there is potential for utilizing sensor technologies to monitor and identify issues in water distribution networks. Their study focuses on implementing a real-time smart water supply management and water quality monitoring system. By continuously monitoring water quality and flow rate, pipeline defects can be detected early, enabling prioritized maintenance and repair activities to prevent further deterioration and ensure a dependable water supply system.

In recent years, the use of mathematical models, software, and other analytical tools has become increasingly important in decision-making processes. According to studies conducted by (Greco, Ehrgott, and Figueira 2016; Tarigan et al. 2018; Amorocho-Daza et al. 2019), these tools can provide valuable insights into complex systems and help identify the best courses of action. For instance, (Zyoud et al. 2016) found that the analytic hierarchy process (AHP)

method was particularly useful for water management and could help stakeholders develop more effective strategies. Meanwhile, (Blindu 2004) explored the use of multicriteria analysis and geographic information systems to evaluate behavior rehabilitation programs over different timeframes. Another study by (Aşchilean et al. 2017b) recommended the use of AHP to prioritize water distribution network rehabilitation projects.

In this chapter, we explored the creation of a knowledgeable management system that merges GIS, multicriteria analysis, and a hydraulic simulation model. The system is intended to make informed and strategic decisions when it comes to renovating and rehabilitating a water distribution network. Its primary objective is to enhance network management while preventing potential problems.

II.2. Study Area

In this chapter, we studied the water distribution network in the East Arzew district, which is strategically located in the Western Mediterranean and lies about 350 km west of Algiers and 40 km east of Oran (see Figure II.1). The Gulf of Arzew surrounds the region, which has a semi-arid climate characterized by moderate winters and dry, humid summers (El Abidine and Abdelmansour 2019; Chabi et al. 2023). The district has a population of 86000, according to data provided by ONS 2019. The area is characterized by a rugged terrain with altitudes ranging from 1 to 200 meters above sea level. The urbanized area represents 50% of the total surface in this region (5.25 km² from 10.2 km²), the vegetation represents only 5% of the total area and the rest 45% are Bare ground and range lands. The East Arzew sector receives its water supply from an elevated tank. The water distribution network stretches across a distance of approximately 35 kilometers and comprises pipes made of cast iron, steel, and polyethylene high-density (PEHD) with nominal diameters ranging from 63 to 300 mm.

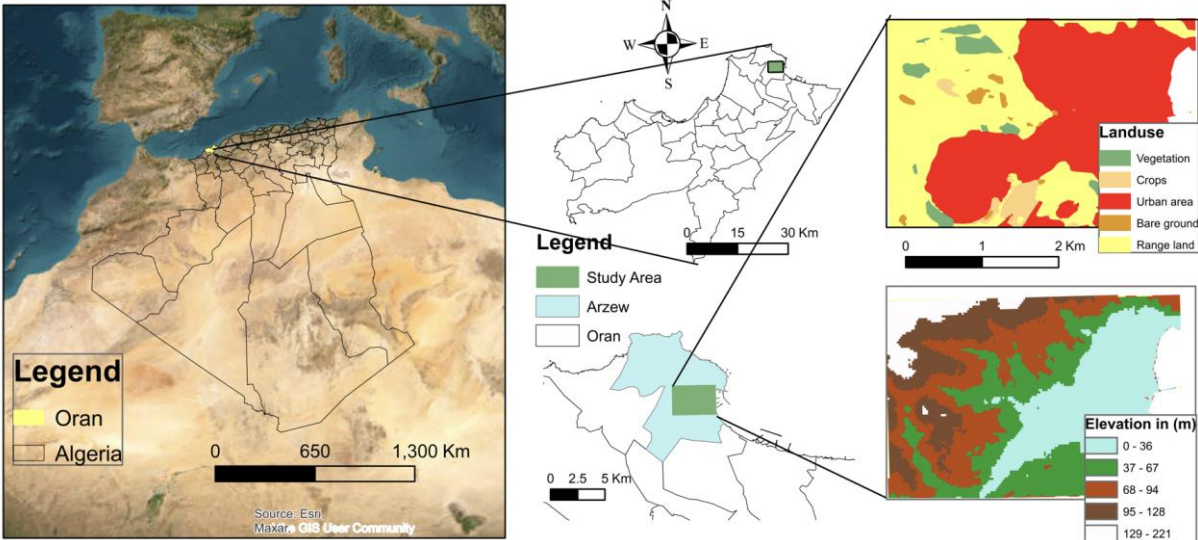


Figure II.1: Geographical location of the study area (Algeria Map - Resources | Simplemaps.Com, n.d.) (Google Earth, n.d.)

Land use resolution: 10m, Elevation resolution: 30m

II.3. The application of the AHP in the water distribution networks of East Arzew district

The water distribution network in East Arzew district is one of the fundamental infrastructures that serve the community. It is crucial to ensure that the network operates efficiently and effectively. The AHP method is a reliable tool that can help achieve this goal. Divided into two primary categories, namely data collection and decision-making, the AHP method utilizes various tools and methods such as databases, GIS, hydraulic modeling of the network, and multicriteria studies, as illustrated in Figure II.2. The hydraulic modeling process is a crucial aspect of designing databases for managing the water distribution network. By collecting the characteristics of the system's components, such as tanks, pipes, and junctions, the flow of water through the pipes can be simulated, reflecting the physical characteristics of the system (Abrunhosa, 2015).. With the help of mapping data, the pipe sections can be identified and categorized according to their priority, leading to significant advancements in network

management. Thus, the AHP method can be an effective and persuasive way to manage the water distribution network in East Arzew district, ensuring it serves the community efficiently and effectively.

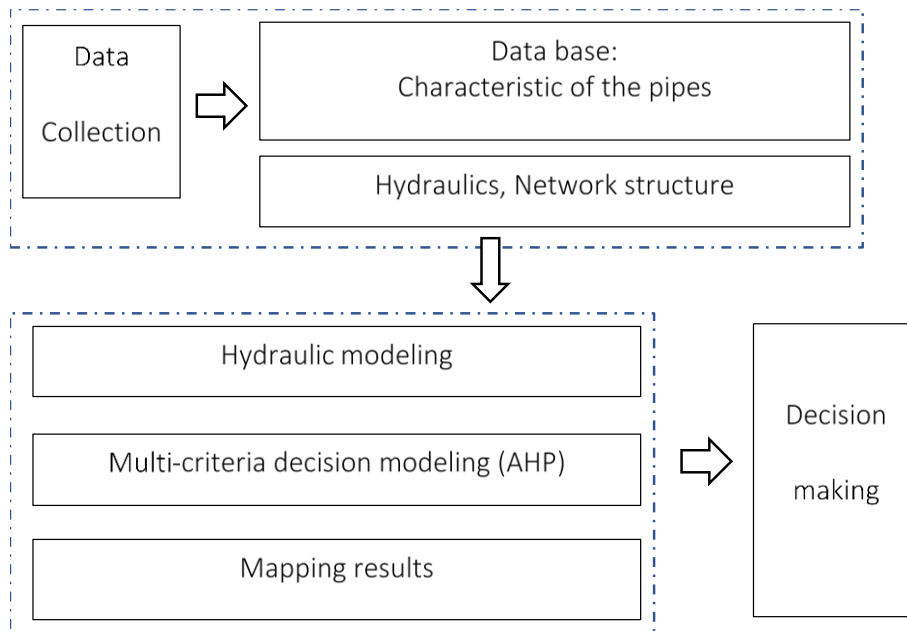


Figure II.2: Implementation of AHP in Managing the Drinking Water Supply Network

II.3.1. Hydraulic modeling

In this study, we used MIKE URBAN software to simulate the behavior of the DWS network in East Arzew district. MIKE URBAN is a highly effective program for modeling urban water, as it covers all kinds of water networks in a city, such as water delivery, stormwater and sewer systems (Abrunhosa 2015). Ingeduld et al. 2008 revealed that MIKE URBAN was more appropriate for modeling the water delivery system in Dhaka, Bangladesh, than traditional EPANET-based models. This was because of the low pressures and dry pipes in the city. The research indicated that MIKE URBAN is able to model complex and hard water networks. (Hountondji and Codo 2019) reported that the application of EPANET software allowed the evaluation of the current functioning of the Monzoungoudo drinking water delivery network and the recommendation of necessary actions. The characteristics of the network under study,

such as the digital elevation model and the properties of pipes, nodes and tanks, are given by Oran Water and Sanitation Company (SEOR), which uses ArcGIS and MIKE URBAN software. MIKE URBAN is an EPANET-based calculation model that has many advantages over typical modeling tools. For example, standard data formats, the integrated interface under GIS and the calculation engine used for modeling is EPANET. Connecting MIKE URBAN with ArcGIS offers a number of new beneficial GIS functionalities focused on topological data analysis (Metelka 2006).

II.3.2. The hierarchical structure of multicriteria decision making

The goal is to define the emergency levels of pipes to rehabilitate the water supply network. The AHP method is used to break down the goal into hierarchical criteria and sub-criteria. These criteria and sub-criteria are then weighted based on their importance to the overall goal. Finally, the alternatives (different pipes) are evaluated against the criteria and sub-criteria, and a score is calculated for each alternative. The alternative with the highest score is considered the most in need of rehabilitation, the hierarchical structure is illustrated in Figure II.3

- **Goal:** Identify pipes that are most in need of repair or replacement.
- **Criteria:** 2 criteria are used to evaluate the condition of the pipes, hydraulic, and physical structure

The five sub-criteria are:

1. **Pipe Material:** Different pipe materials have varying lifespans and susceptibility to corrosion. Cast iron pipes, for example, may be prioritized for replacement compared to PVC pipes.
2. **Laying Date:** The age of the pipes is a major factor. Older pipes are more likely to have deteriorated and require maintenance.

- 3. **Pipe Diameter:** The diameter of the pipe is crucial for water flow. Bigger diameter pipes are more important when it comes to rehabilitation of the network
- 4. **Water Pressure:** Water pressure is essential for delivering water to consumers. Low pressure can indicate leaks or inadequate pipe size.
- 5. **Water Velocity:** Excessively high or low water velocity can damage pipes and lead to problems like bursts or mineral buildup.

Each sub-criteria is further divided into levels. For example, the sub-criteria for pipe diameter is divided into three levels: less than or equal to 50 mm, 50 mm to 100 mm, and greater than 100 mm.

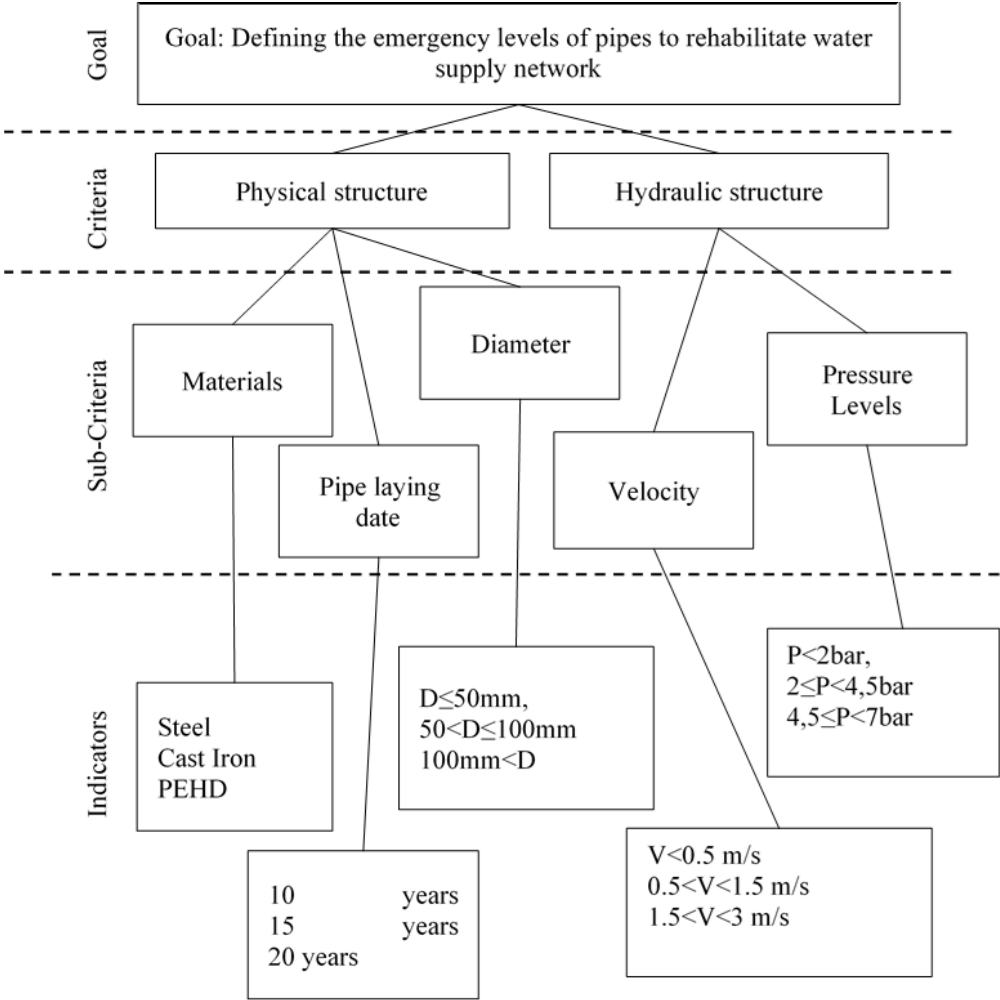


Figure II.3: The hierarchical structure of multicriteria decision making

II.3.3. Pairwise comparison

A crucial step in AHP involves pairwise comparisons, reflected in Tables II.1-II.8, which establish weights for various criteria influencing pipe condition assessment. This analysis divides the potential content of these tables and their contribution to the overall decision-making process.

Tables II.1-II.8 represent the pairwise comparisons undertaken for the main criteria, sub-criteria and indicators.

Table II.1: Comparison of the main criteria

Criteria (c)	Hydraulic structure	Physical structure
Hydraulic structure	1	1/3
Physical structure	3	1

$\lambda_{\max}=2$ and CR=0

Table II.2: Comparison of Sub-criteria 1

SC1	Materials	Pipe laying date	Diameter	Weight
Materials	1	1/2	3	0.333
Pipe laying date	2	1	3	0.528
Diameter	1/3	1/3	1	0.140

$\lambda_{\max}=3.0536$ and CR=5.15

Table II.3: Comparison of Sub-criteria 2

SC2	Pressure	Velocity	Weight
Pressure	1	3	0.75
Velocity	1/3	1	0.25

$\lambda_{\max}=2$ and CR=0

Table II.4: Comparison of indicator 1

Indicator i1.1	PEHD	Cast Iron	Steel	Weight
PEHD	1	1/4	1/3	0.122
Cast Iron	4	1	2	0.558
Steel	3	1/2	1	0.320

$\lambda_{\max}=3.018$ and $CR=1.73$

Table II.5: Comparison of indicator 2

Indicator i1.2	10 years	15 years	20 years	Weight
10 years	1	1/3	1/5	0.105
15 years	3	1	1/3	0.258
20 years	5	3	1	0.637

$\lambda_{\max}=3.038$ and $CR=3.65$

Table II.6: Comparison of indicator 3

Indicator i1.3	<100mm	100≤D<150mm	150≤D<300mm	Weight
<100mm	1	1/4	1/5	0.097
100≤D<150mm	4	1	1/2	0.333
150≤D<300mm	5	2	1	0.570

$\lambda_{\max}=3.0246$ and $CR=2.36$

Table II.7: Comparison of indicator 4

Indicator i2.1	P<2bar	2≤P<4.5bar	4.5≤P<7bar	Weight
P<2bar	1	2	1/3	0.249
2≤P<4.5bar	1/2	1	1/3	0.157
4.5≤P<7bar	3	3	1	0.594

$\lambda_{\max}=3.0536$ and $CR=5.15$

Table II.8: Comparison of indicator 5

Indicator i2.2	v<0.5 m/s	0.5<v<1.5 m/s	1.5<v<3 m/s	Weight
v<0.5 m/s	1	3	2	0.528
0.5<v<1.5 m/s	1/3	1	1/3	0.140
1.5<v<3 m/s	1/2	3	1	0.333

$\lambda_{\max}=3.0536$ and $CR=5.15$

To demonstrate how pairwise comparisons of various criteria were calculated, matrix A was formed by regrouping the elements of Table II.4. This approach was adopted to determine the relative importance of indicator 1.

The elements of table 6 are regrouped in matrix A.

$$\mathbf{A} = \begin{bmatrix} 1 & 1/4 & 1/3 \\ 4 & 1 & 2 \\ 3 & 1/2 & 1 \end{bmatrix} \quad (\text{II.1})$$

The weight of these elements is calculated by summing the columns of matrix A then dividing each of the values in the column by the sum of the columns. The weight is obtained by calculating the average of each row.

$$\text{The sum of each column: } [8 \quad 1.75 \quad 3.33] \quad (\text{II.2})$$

Dividing each of the values in the column by the sum of the columns:

$$\begin{bmatrix} 1/8 & (1/4)/1.75 & (1/3)/3.33 \\ 4/8 & 1/1.75 & 2/3.33 \\ 3/8 & (1/2)/1.75 & 1/3.33 \end{bmatrix} = \begin{bmatrix} 0.13 & 0.14 & 0.10 \\ 0.50 & 0.57 & 0.60 \\ 0.38 & 0.29 & 0.30 \end{bmatrix} \quad (\text{II.3})$$

The weight is the average of each row:

$$\begin{bmatrix} 0.122 \\ 0.558 \\ 0.320 \end{bmatrix} \quad (\text{II.4})$$

The equation of the **Det** $|\mathbf{A} - \lambda\mathbf{I}| = 0$ allows to find the **eigenvalues** of the matrix A.

Where:

I: the identity matrix

λ : the eigenvalues of the Matrix

$$\text{Det} \left| \begin{bmatrix} 1 & 1/4 & 1/3 \\ 4 & 1 & 2 \\ 3 & 1/2 & 1 \end{bmatrix} - \lambda \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \right| = 0 \quad (\text{II.5})$$

$$\text{Det} \begin{vmatrix} 1 - \lambda & 1/4 & 1/3 \\ 4 & 1 - \lambda & 2 \\ 3 & 1/2 & 1 - \lambda \end{vmatrix} = 0$$

$$= 1 - \lambda \cdot \begin{vmatrix} 1 - \lambda & 2 \\ 1/2 & 1 - \lambda \end{vmatrix} - 1/4 \cdot \begin{vmatrix} 4 & 2 \\ 3 & 1 - \lambda \end{vmatrix} + 1/3 \begin{vmatrix} 4 & 1 - \lambda \\ 3 & 1/2 \end{vmatrix}$$

$$= 1 - \lambda [(1 - \lambda) \cdot (1 - \lambda) - (2) \cdot (1/2)] - 1/4 [(4) \cdot (1 - \lambda) - (2) \cdot (3)] + 1/3 [(4) \cdot (1/2) - (1 - \lambda) \cdot (3)]$$

$$= 1 - \lambda [(1 - \lambda)^2 - 1] - (1 - \lambda) + 3/2 + 2/3 - (1 - \lambda)$$

$$= (1 - \lambda)^3 - (1 - \lambda) - (1 - \lambda) - (1 - \lambda) + 3/2 + 2/3 = (1 - \lambda)^3 - 3(1 - \lambda) + 13/6$$

$$= \lambda^3 + 3\lambda^2 - 3\lambda + 1 - 3 + 3\lambda + 13/6 = \lambda^3 + 3\lambda^2 + 1/6 = 0$$

$\lambda = 3.018$

n: the order of the matrix, n = 3,

RI: Random Consistency Index, RI = 0.52,

λ_{max} : the principal eigenvalue of the matrix, $\lambda_{\text{max}} = 3.018$,

Consistency index: $CI = (\lambda_{\text{max}} - n) / (n - 1) = (3.018 - 3) / (3 - 1) = 0.009$

Consistency ratio: $CR = CI / RI = 0.009 / 0.52 = 1.73\%$

Once weights are assigned to all indicators, a scoring system is likely implemented. Each pipe segment is evaluated based on the specific indicators it exhibits (e.g., cast iron pipe laid 15

years ago). The weights (Figure II.4) are then factored into the scoring system to arrive at a final score for each pipe segment. This process is efficiently conducted within ArcGIS, utilizing its analytical capabilities and spatial data handling features. Pipes with higher scores are likely ranked as being in greater need of rehabilitation compared to those with lower scores.

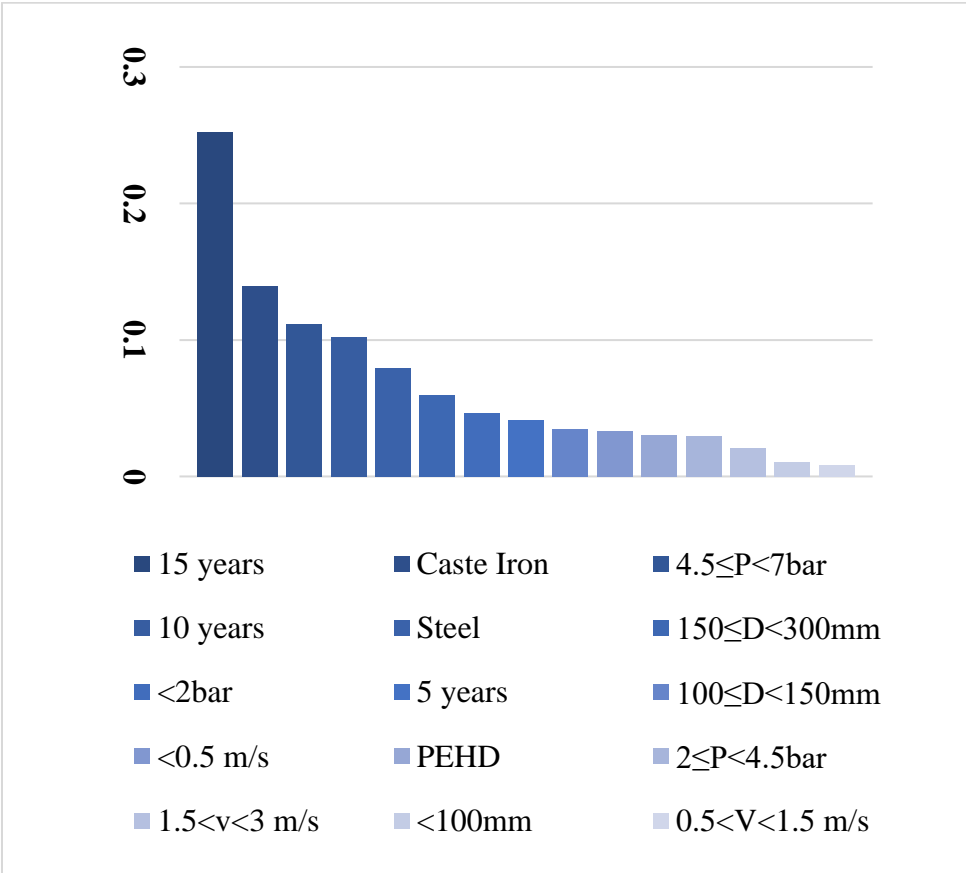


Figure II.4: Ranked Indicators for Water Pipe Rehabilitation Prioritization using AHP

II.4. Spatial Prioritization of Pipe Rehabilitation (mapping)

To rank the alternatives, ArcGIS is used to select features that match the selection criteria. One of the selection methods used to select features in a layer is to select features using an attribute query. Displaying the results as shown in Figure II. 5 helps to identify the sections and rank them in order of priority to generate real progress in network management. The maintenance action's priority sections can be identified based on their order and emergency category. These

sections are color-coded into three classes, as shown in Figure II.5. The three classes are: level 3 low in yellow, level 2 medium in orange, and level 1 high priority for intervention in red.

After displaying the map, the linear of each category is divided into 3 levels. The concept of urgency level allowed to classify the pipes into short-, medium-, and long-term categories for the rehabilitation of the water distribution network. The first level represents 26% of the length of the network, which is the most critical and requires immediate attention. The second level comprises 32%, while the remaining 42% constitutes the last level. This classification aids in prioritizing rehabilitation efforts, with a focus on the most critical sections, as illustrated in Figure II.6.

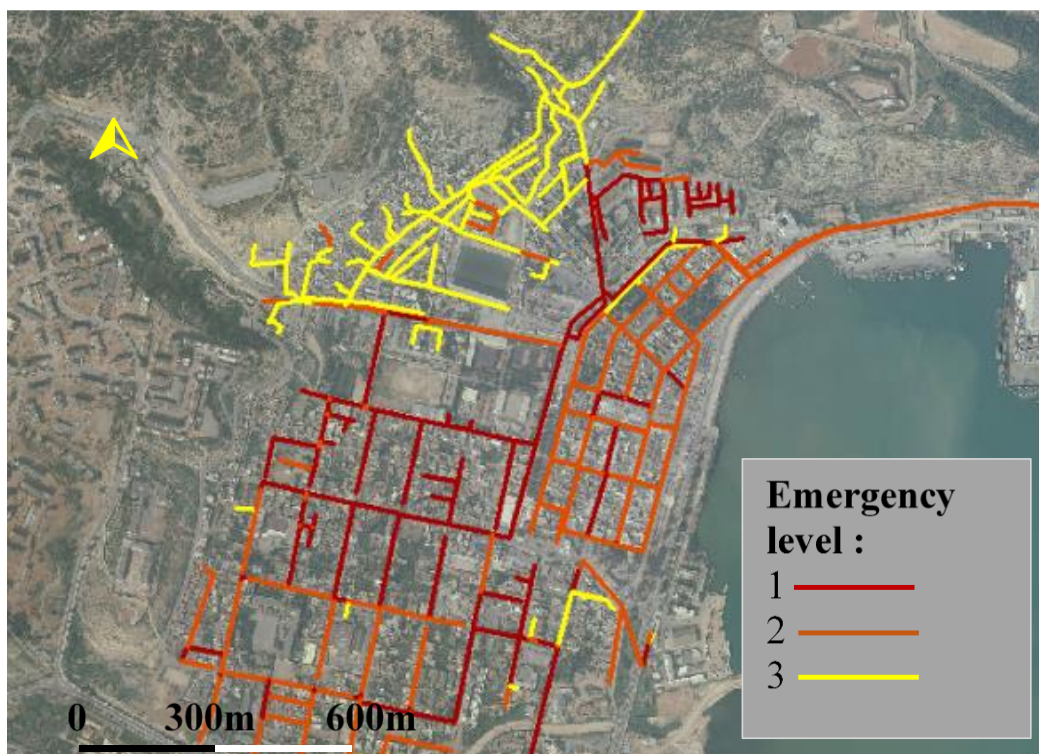


Figure II.5: Ranked pipes for Water Rehabilitation in East Arzew district

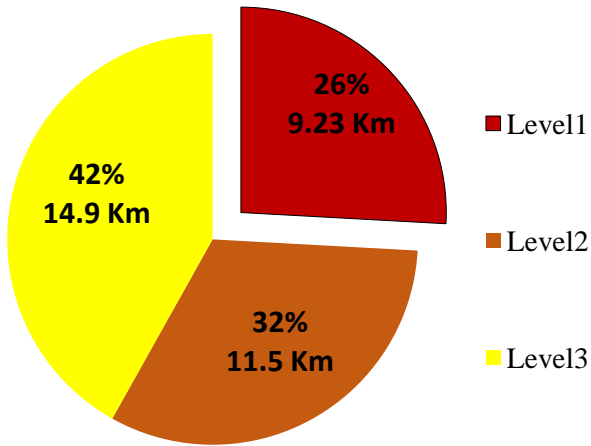


Figure II.6: Linear of sections by emergency level

In Figure II.7, it can be seen that 97% of the pipes in level 1 of the network are made of cast iron, which accounts for all pipes that are 100 mm and below in size. The majority of the failures occur in cast iron (CI) and steel (ST) pipes, which are no longer used in the water network. On the other hand, the newer polyethylene (PE) pipes have fewer failures (Tscheikner-Gratl et al. 2017).

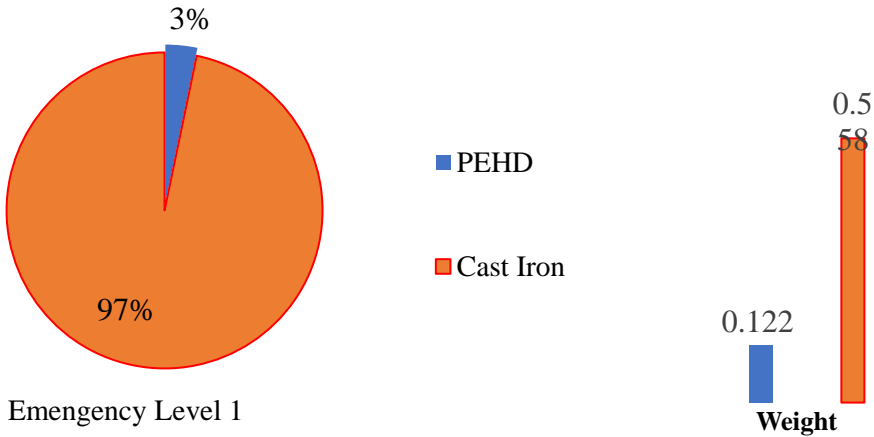


Figure II.7: Percentage and weight of each material

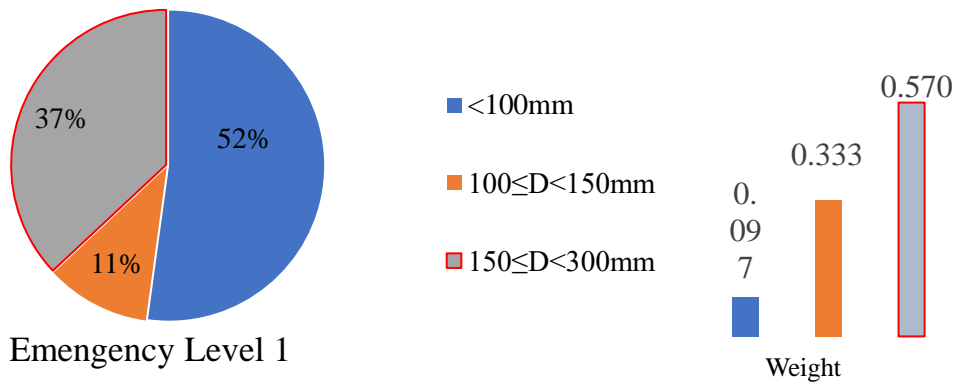


Figure II.8: Percentage and weight of each Diameter

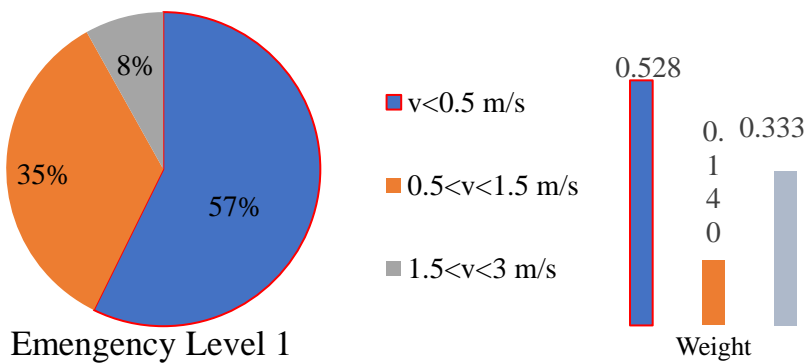


Figure II.9: Percentage and weight of velocity

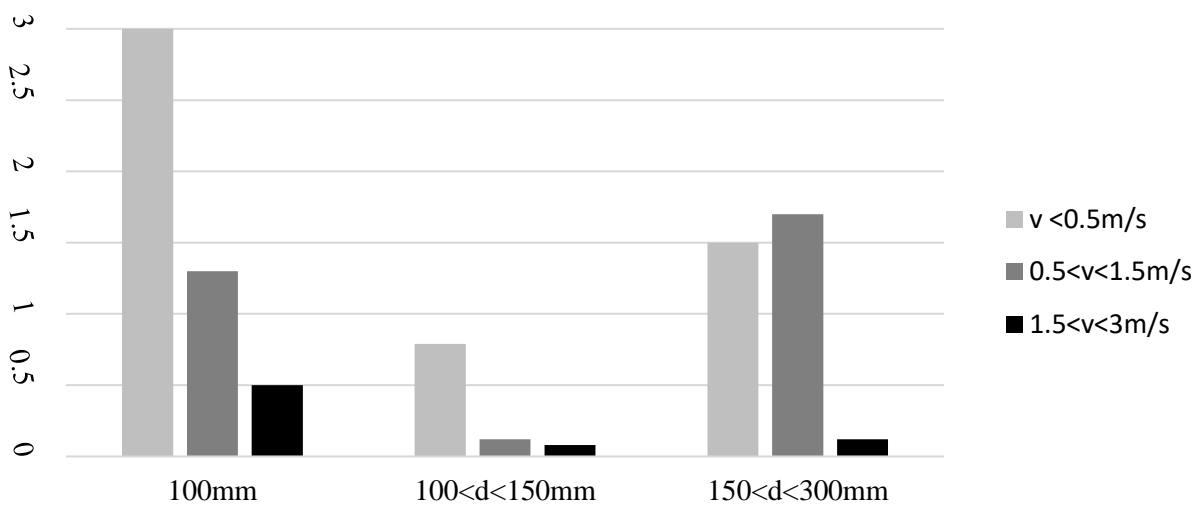


Figure II.10: Range of different flow velocities in the pipes

Figure II.8 illustrates the emergency level of pipes based on their diameter, while Figure II.9 depicts the emergency level based on flow velocity. Figure II.10 combines the results from Figures II.8 and II.9, showing different diameter sizes alongside various flow velocities. It's noteworthy that over 50% of the pipe length exhibits low velocities below 0.5 m/s, particularly in pipes with diameters of 100 mm and smaller. The network is a combination between loop main pipes and branched sections, the looped sections have pipes with diameters ranging from 100 mm and larger. The branched sections are flowing ends with a decreasing diameter. Pipes located at distribution dead-end mains typically experience low flow velocities and prolonged stagnation times (Barbeau et al. 2005). This scenario can lead to the settling of suspended materials within the pipes when flow velocities drop below approximately 0.06 m/s (Vreeburg and Boxall 2007). Prolonged residence times within pipes can exacerbate issues such as iron uptake due to corrosion and the reduction of disinfectant residuals (Mutoti et al. 2007), potentially allowing microbial pathogens to regrow (Abokifa et al. 2016). Furthermore, aging pipes may exhibit increased concentrations of particulate elements, highlighting the importance of analyzing suspended particle composition for detecting pipe deterioration (Fujita et al. 2014).

It is observed that diameters less than 100 mm often cause stress on the network. A considerable portion of the network (4.8 km) is made of cast iron, and around two-thirds of it experiences speeds lower than 0.5 m/s. This is due to the number of branches or dead-ends on this part of the network. In terms of pressure, Figure II.11 indicates that 84% of the network maintains pressure standards between 2 and 4.5 bar. Additionally, the minimum pressure in a network is generally set at 2 bar at the point of connection to a house or dwelling. It's important to note that these indicators are interrelated, which means that changes in one can affect the others in a complex way. For instance, the velocity can affect the aging of the pipe and material, and the diameter can affect the velocity, among other factors.

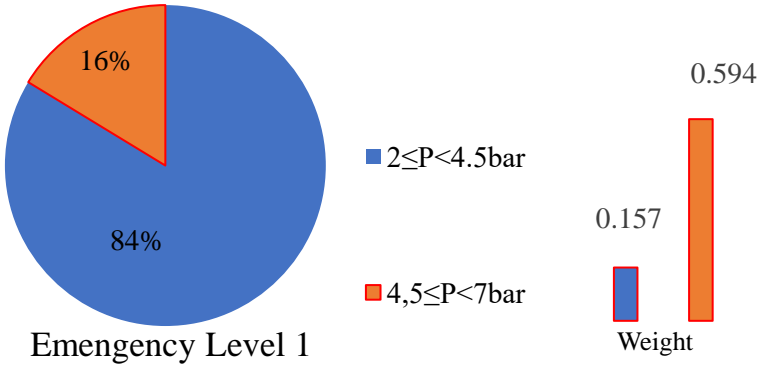


Figure II.11: Percentage and weight of pression

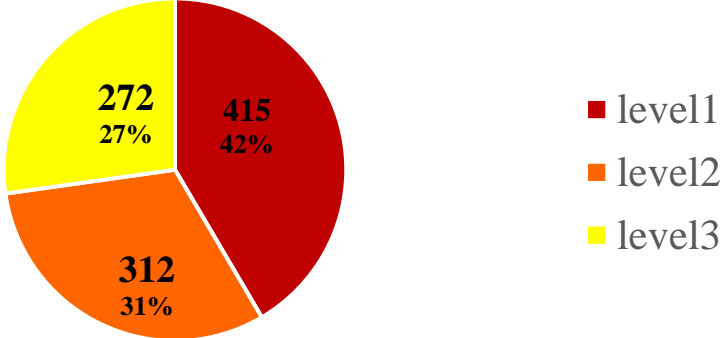


Figure II.12: Number of leaks per level

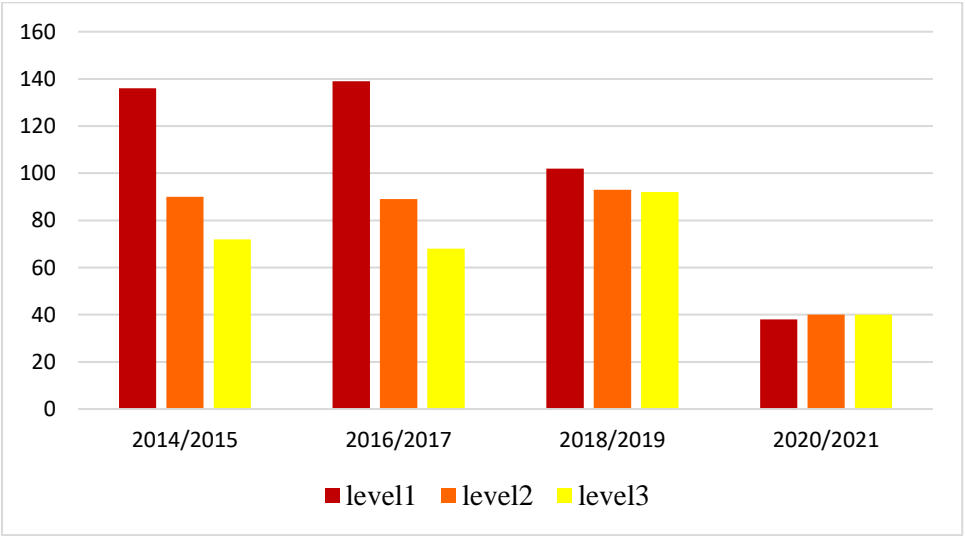


Figure II.13: Number of leaks per year per level

Once the priority sections for maintenance have been identified, it is crucial to verify the system's reliability and ensure that the results accurately reflect the network's actual state. This involves confirming the appropriateness and reliability of the chosen emergency levels by analyzing leak occurrence dates and locations. Since leaks in the network indicate potential failure, they were used to identify areas requiring current, medium, and long-term maintenance without being introduced as indicators in the study. The appearance of leaks is directly related to the hydraulic and physical network structure (Pérez-Pérez et al. 2021), so corrective and preventive application is necessary to reduce leakage rates (Carnero and Gómez 2018). We imported leakage data as nodes into ArcGIS, which allowed us to determine the location and date of each leak and classify them by urgency level. Figure II.12 shows the total number of leaks distributed across the three levels. Note that Emergency Level 1 has the highest number of leaks. Figure II.13 displays leak frequency over the past eight years, categorized by level.

It has been observed that the number of leaks in the three levels of emergency decreases over time as repair and rehabilitation applications are carried out on the networks. The analysis results indicate that the method used provides good consistency between the network evaluation and its actual condition. We compared our findings with the technical report of SEOR (2021).

II.5. Conclusion

This section discusses the development of a method for decision-making to renovate and rehabilitate distribution water networks. To simplify the complexity of the system, a combination of decision support tools such as geographic information systems (GIS), multi-criteria analysis, and hydraulic simulation model were used. The method utilizes physical characteristics of pipes like diameter, materials, and laying date, along with the hydraulic structure of the network such as water velocity and pressure to select criteria. By applying the

AHP method, dimensions, criteria, and indicators were classified. The priority sections for maintenance action were identified based on the emergency levels category and colors, where level 3 is low priority, level 2 is medium priority, and level 1 is high priority for intervention in red color. The result showed that 26% of the network is critical and requires immediate rehabilitation.

CHAPTER III:

DEVELOPMENT OF THE

MULTICRITERIA

DECISION MAKING

TOOL

III.1. Introduction

Water network management faces a significant challenge in maintaining and dealing with ageing and deteriorating infrastructures, as per (Aşchilean et al. 2017a). Water pipe corrosion is a grave issue that managers must comprehend before deciding on solutions or new developments, as stated by (Amorocho-Daza et al. 2019). Therefore, dependable decision support processes are an essential tool in this regard, as highlighted by (Chérifa Abdelbaki et al. 2017). Drinking water network management studies have been reported that use decision support systems (DSS) such as multi-criteria decision analysis (MCDA) and geographic informatics systems (GIS). (Aşchilean et al. 2017a) examined technologies for the rehabilitation of water supply systems using multi-criteria analysis. Similarly, (Amorocho-Daza et al. 2019) developed a methodology using MCDA for systematic evaluation of alternatives in water supply planning. (Chérifa Abdelbaki et al. 2017) reported that introducing GIS to water infrastructure management allows for the diagnosis of the network and prediction of future situations.

Decision-making systems and models have been developed for numerous applications. (Curry et al. 2020) for example build a science framework to support a decision-making process for large dam renewals and removals. The authors noted that the review and decision-making processes at these large scales are complex and having a science framework ensures there is a foundation to support successful and quicker integration and sharing of information among multiple sectors, decision-makers, and stakeholders, and adaptation of new information or social directions for the project. (Lima et al. 2021) carried out a multi-voiced multicriteria analysis that integrated the preferences of local researchers and decision makers in a process aimed at prioritizing watersheds that require the implementation of groundwater management instruments. The authors argued that the model is at its best when used as an aid in the decision-

making process and not as the only or final approach. In a related study, (Zolfaghary, Zakerinia, and Kazemi 2021) employed geographic information system (GIS) and multi criteria decision making (MCDM) in investigating the suitability of using urban treated wastewater as irrigation water. They concluded that due to the desirable effects of wastewater irrigation on crop yield, the improvement of criteria that had the highest effects on the suitability of using wastewater can play an effective role in reducing environmental and health hazards.

While many programmers have worked on the development of such a tool, only a few have implemented this tool in the water field specially on renovation and rehabilitation of water distribution networks. Oswald Marinoni (Marinoni 2004) described the implementation of an analytical hierarchy process in ArcGIS using the Visual Basic language to facilitate land use assessment. (Boroushaki and Malczewski 2008) focused on the integration of GIS and an extension of the analytical hierarchy process (AHP). They extended the work (Marinoni 2004) on the AHP method for spatial multicriteria decision analysis. As an improvement of the previous works on this field (Elhaj 2018) created a python tool to implement the analytical hierarchy process in ArcGIS. The Python programming language is actively used by many people, both in industry and academia, for a wide variety of purposes.

The main goal of this tool was to take data from the pipe layer and identify the sections that must be rehabilitated or renewed by using the Analytic Hierarchy Process (AHP) method without using any other calculating programs. The algorithm and the script used for creating this tool and verification of its results was also discussed.

III.2. Methodology

The research methodology of this chapter includes 3 phases, the algorithm phase, the AHP tool development phase and the application of the tool phase, Figure III.1 illustrates the 3 main phases of this work.

The algorithm phase showed the main instructions and operations used to run the tool, the AHP tool development phase illustrated how to create a tool and combining it with the AHP method with the use of python modules dedicated by ArcGIS, this phase also showed the script used for this tool. The final phase is the application of this tool in a study area to attempt to test and verify the results of the AHP tool.

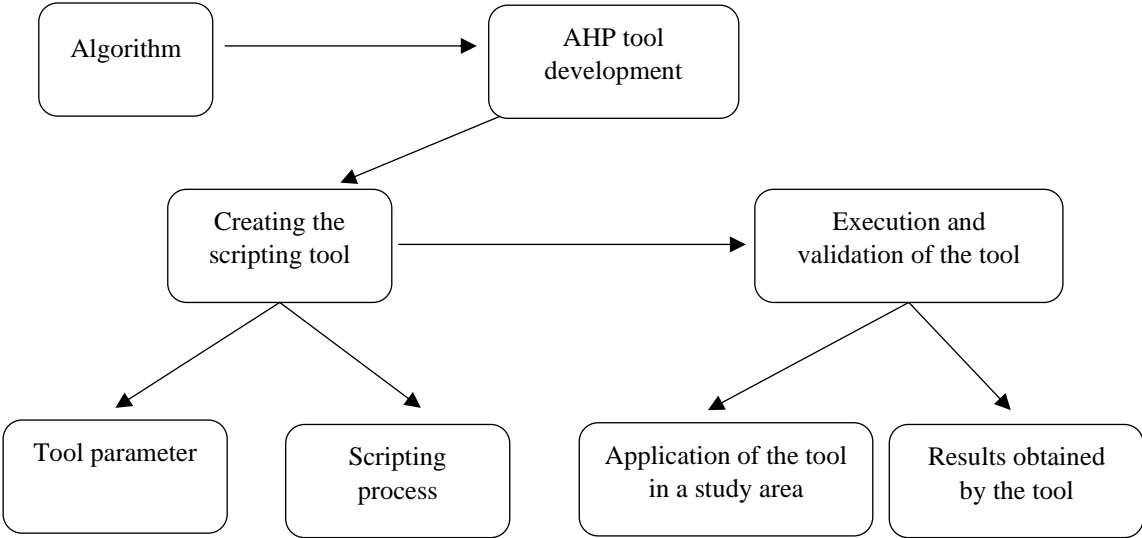


Figure III.1: The three phases in the development and application of a multicriteria decision making tool: algorithm, AHP tool development and application of the tool

III.3. Creation of the AHP python tool

The main goal of this tool is taking data from the pipe layer and calculate the emergency level by using the AHP method. As known this method is based on the binary comparison of several

criteria and must be represented in matrices of weights. The idea is to consider these matrices as tables because they are supported in ArcGIS and can be displayed on the table of contents.

The algorithm shown in Figure III.2 indicates the main instructions and operations used to run the tool:

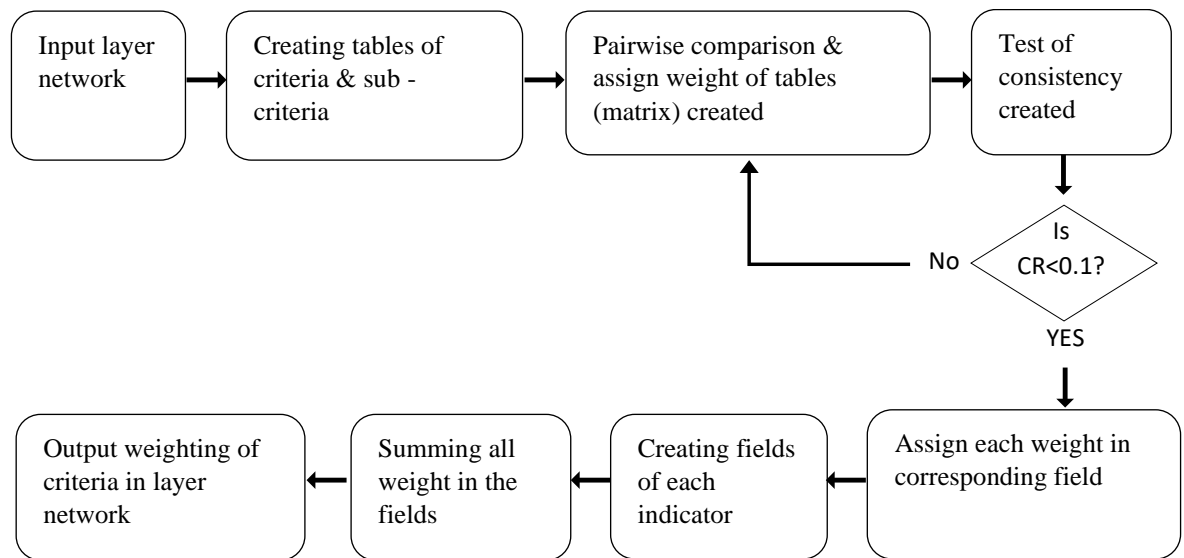


Figure III.2: The algorithm utilized to run the AHP tool in ArcGIS

III.3.1. Adding a script tool in ArcGIS

The first step of creating a tool is to add it by entering a name for the script tool, a label and optionally, a description for the script (see Figure III.3). This tool will act as the interface for users to execute the Python script. Secondly, an empty Python script must be created - `AHP_DrinkingSupply.py` - in the same folder as shown in Figure III.4. Serving as an initial template, this empty script sets the groundwork for the future incorporation of the Analytic Hierarchy Process (AHP) script.

III.3.2. Tool parameters

The tool needs parameters and must be set on the wizard panel to be called after that in the source code and executed as an input. The parameters are the link between the user and the program. Each parameter has a name which will be displayed in the tool dialog

box, a data type to indicate the parameter if it is a table, a layer, or a field and lastly has parameter properties as type if it is “required” or “optional”. This is employed if the parameter needs to use data from another parameter. It is a filter is utilized when the user wants to enter only certain values for a parameter. Multivalue is applied if the user wants to enter a list of values rather than just one value in a parameter.

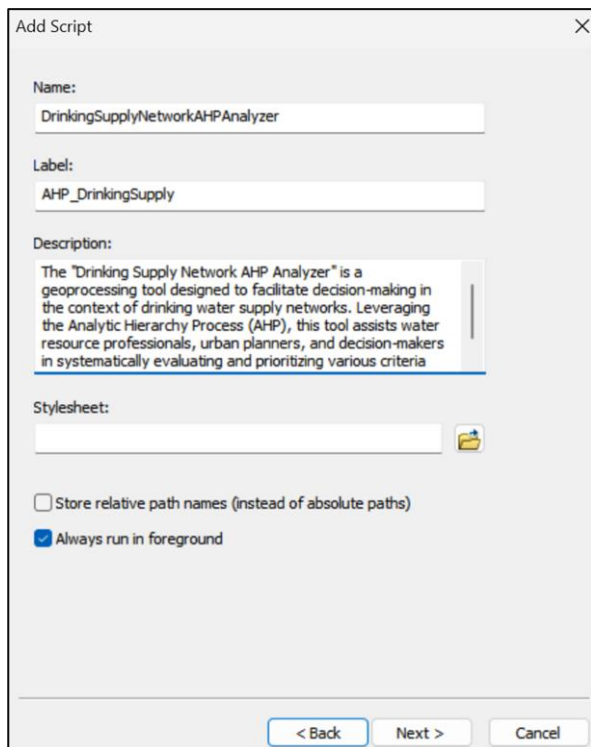


Figure III.3 : Name for the script tool, label and description for the script

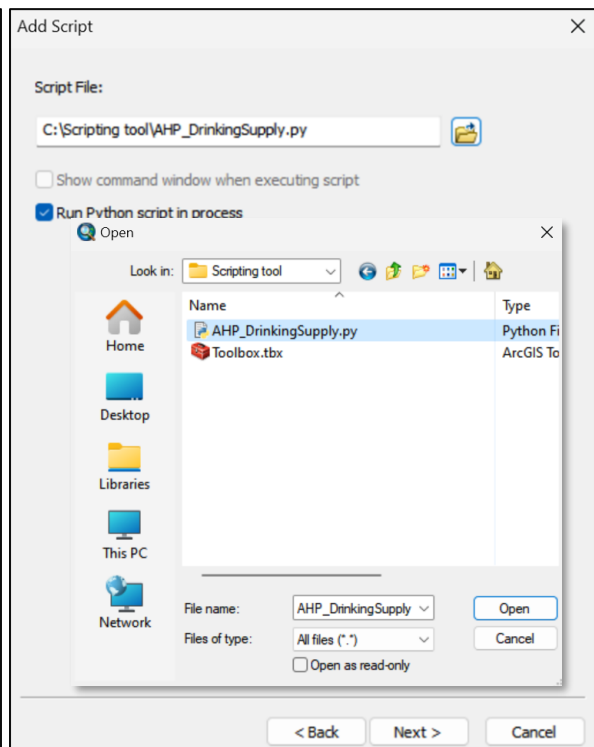


Figure III.4 : Linking the Python Script to the AHP Tool in the Toolbox

III.3.3. Creating the script tool

Five phases were created in the Python program to work with ArcGIS, the steps are given below:

The 1st phase was to create a table with the same columns and row names and creating a domain to use for ranking the criteria after asking the user to input the name of network layer and to select the fields so the program can take the name of each field and consider it as a criterion.

To create a table the function **CreateTable** was applied. The following Python script demonstrates how to use this function:

```
import arcpy

arcpy.env.workspace = "C:/folder"

out_path="C:/folder"

out_name = "pipe.dbf"

arcpy.CreateTable_management(out_path, out_name)
```

To create a table with the same columns and row names, the for loop is employed to iterate over the members of a sequence in order. This meant that the program would create fields each time in this table. The function **AddField** was used to add a field in the table which represented the name of the criteria. The following script demonstrates how this function was utilized:

```
for lyr in listlyr:

    arcpy.AddField_management(Tablepath,lyr,"DOUBLE")

    n=n+1
```

By designing the domain with **CreateDomain**, which is the scale proposed by Saaty (Saaty 1980), the user can make a pairwise comparison between the criteria in the table created by the first phase. The comparison is made using a scale to indicate which element is important to another element. The nine-point scale includes: [9, 8, 7, ..., 1/7, 1/8, 1/9] (Figure 2). Note that the domain is a dictionary in python language, to create a glossary for the scale of Saaty (Saaty 1980) , the following script was used:

```
#Create domaine

domName = "AHPdomaine"
```

```
arcpy.CreateDomain_management(GDBpath, domName, "domain_AHP",  
"DOUBLE", "CODED")
```

```
#Create domaine dictionary
```

```
domDict = {"0,5": "1/2", "0,333": "1/3", "0,25": "1/4", "0,20": "1/5", "0,1666": "1/6",  
"0,142857": "1/7", "0,125": "1/8", "0,11111": "1/9", "0,1": "1/10", "1": "1", "2": "2", "3":  
"3", "4": "4", "5": "5", "6": "6", "7": "7", "8": "8", "9": "9", "10": "10"}
```

The 2nd phase was to calculate the weight of each criterion in the table by creating a python program to calculate the sum of the columns of the table and then dividing each of the values in the column by the sum of the columns. The weight was obtained by calculating the average of each row.

To get access to the data of the table the function **Cursor** was applied to read and update attributes of the rows in this table. The following script demonstrates how to calculate the geometric mean of the rows:

```
#Calculate the geometric mean:  
  
with arcpy.da.UpdateCursor(fc, fieldNameList) as cursor:  
  
for row in cursor:  
  
    row[-1] = product(row[2:-1])** (1./len(row[2:-1]))  
  
    cursor.updateRow(row)
```

The third phase of the program involves adding indicator fields to the main layer, where the user's selected criteria and sub-criteria are weighted and the rows updated accordingly. This task was accomplished using three primary functions: **AddField**, **SelectLayerByAttribute**, and **CalculateField**. The below script serves as an example of how to utilize these functions.

```
arcpy.AddField_management(layer,field,"DOUBLE")
```

```
arcpy.SelectLayerByAttribute_management(layer, 'NEW_SELECTION',exp)
```

```
arcpy.CalculateField_management(layer,field,value,"PYTHON_9.3")
```

The 4th and the last phase were to calculate the sum of all fields added by the user so that the program consisted of calculating the sum of the columns selected. This value was divided by the max value of the sum to give the absolute weight of the indicators. The function **SearchCursor** was employed to read-only on a feature class or table. The script below demonstrates how to calculate and find the max value of the sum:

```
arcpy.AddField_management(layer,field,"DOUBLE")
```

```
arcpy.CalculateField_management(layer,field,value,"PYTHON_9.3")
```

```
arcpy.AddField_management(layer,"Absolute","DOUBLE")
```

```
with arcpy.da.SearchCursor(layer,field)as cursor:
```

```
    a= max(cursor)
```

```
    for i in a:
```

```
        i=float(i)
```

```
        value2='!'+field+'!'+ '/' +str(i)
```

```
arcpy.CalculateField_management(layer,"Absolute",value2,"PYTHON_9.3")
```

III.4. Conclusion

The Python-based AHP tool developed in this study leverages the capabilities of ArcGIS to update the decision-making process for identifying pipes that require rehabilitation or renewal in water distribution networks. The tool's algorithm follows a well-defined sequence of operations, including creating tables, defining criteria, calculating weights, and applying the

AHP method. The script, written in Python, consists of five distinct phases including the integration of various ArcGIS functions and modules, such as CreateTable, AddField, CreateDomain, UpdateCursor, SelectLayerByAttribute, CalculateField, and SearchCursor, contribute to the tool's efficiency and versatility.

CHAPTER IV:

Implementation and Validation of the Tool

IV.1. Introduction

A Python-based tool was created in the previous chapter to implement the Analytical Hierarchy Process (AHP) in the ArcGIS environment for decision-making in water distribution network management. The tool's algorithm and script were designed in the previous chapter to simplify the process of identifying pipes that need rehabilitation or renewal by considering multiple criteria and conducting pairwise comparisons based on Saaty's nine-point scale.

Although the development of the tool is a significant contribution to the field of water infrastructure management, it's essential to evaluate its practical application and verify the accuracy of its results. To accomplish this, we'll apply the AHP tool to a case study area, allowing for a comprehensive demonstration of its functionality and capabilities.

This chapter aims to provide a detailed walkthrough of the tool's application, illustrating the step-by-step process of data preparation, criteria selection, weight assignment, and decision analysis. By working with a real-world water distribution network, the tool's ability to handle complex scenarios and integrate various spatial and non-spatial factors will be thoroughly evaluated.

Furthermore, the results obtained from the AHP tool were analyzed and compared with existing condition assessments to validate the tool's decision-making capabilities. This process did not only showcase the tool's practical utility but also identify potential areas for improvement or future enhancements.

IV.2. Study Area

The developed AHP tool was applied to the water distribution network (WDN) of the southern urban agglomeration of Tlemcen, Algeria, encompassing the towns of Tlemcen, Chetouane, and Mansourah. This region, situated in the western part of Algeria, covers an area of

approximately 112 square kilometers, forming the Tlemcen inner basin (Chérifa Abdelbaki et al. 2019). The basin's boundaries are delineated by the Lalla Setti cliff to the south, Ain El Houtz hills to the north, Oum El Allou to the east, and the small volcanic cone mountains of Beni Mester to the west (Chérifa Abdelbaki et al. 2019).

The research site, located in the southern region of the urban agglomeration of Tlemcen, occupies an area of 3.4 square kilometers, as illustrated in Figure IV.1. The study area's topography is characterized by a rugged terrain and semi-rocky soil, featuring steep inclines with elevation differences ranging from 800 to 1100 meters (Berrezel, Abdelbaki, and Benabdelkrim 2022). The WDN of the study area exhibits a significant rate of water loss exceeding 50% due to various factors, including aging pipes, inadequate construction or repair practices, and insufficient maintenance and replacement of pipelines (Chérifa Abdelbaki et al. 2012). The water supply system lacks proper structural design, resulting from unplanned extensions made without adhering to basic design principles (Chérifa Abdelbaki et al. 2012). Several deficiencies have been identified in the network, such as frequent water supply interruptions, high levels of water loss due to leaks (60%), and a lack of attention to the aging and outdated piping infrastructure (Chérifa Abdelbaki et al. 2014). Consequently, the water networks in this region are facing severe management challenges..

IV.3. Data used

The database of the water distribution network (WDN) utilized in this research was acquired from multiple sources, including the works of (Chérifa Abdelbaki 2014; Berrezel, Abdelbaki, and Benabdelkrim 2022). The main data consisted of the water pipe network. The analyzed network (main pipes) spanned a length of 65 kilometers, comprising pipes with diameters ranging from 40 to 600 millimeters and constructed from various materials such as steel, galvanized steel, and high-density polyethylene (HDPE). The water distribution system

operated on a gravity-fed principle, utilizing 11 storage tanks with capacities ranging from 1500 to 2000 cubic meters, situated at altitudes between 800 and 1000 meters. The background map of the study area was obtained from Google Earth Pro and calibrated using the georeferencing tool available in ArcGIS software (Herbei et al. 2010).

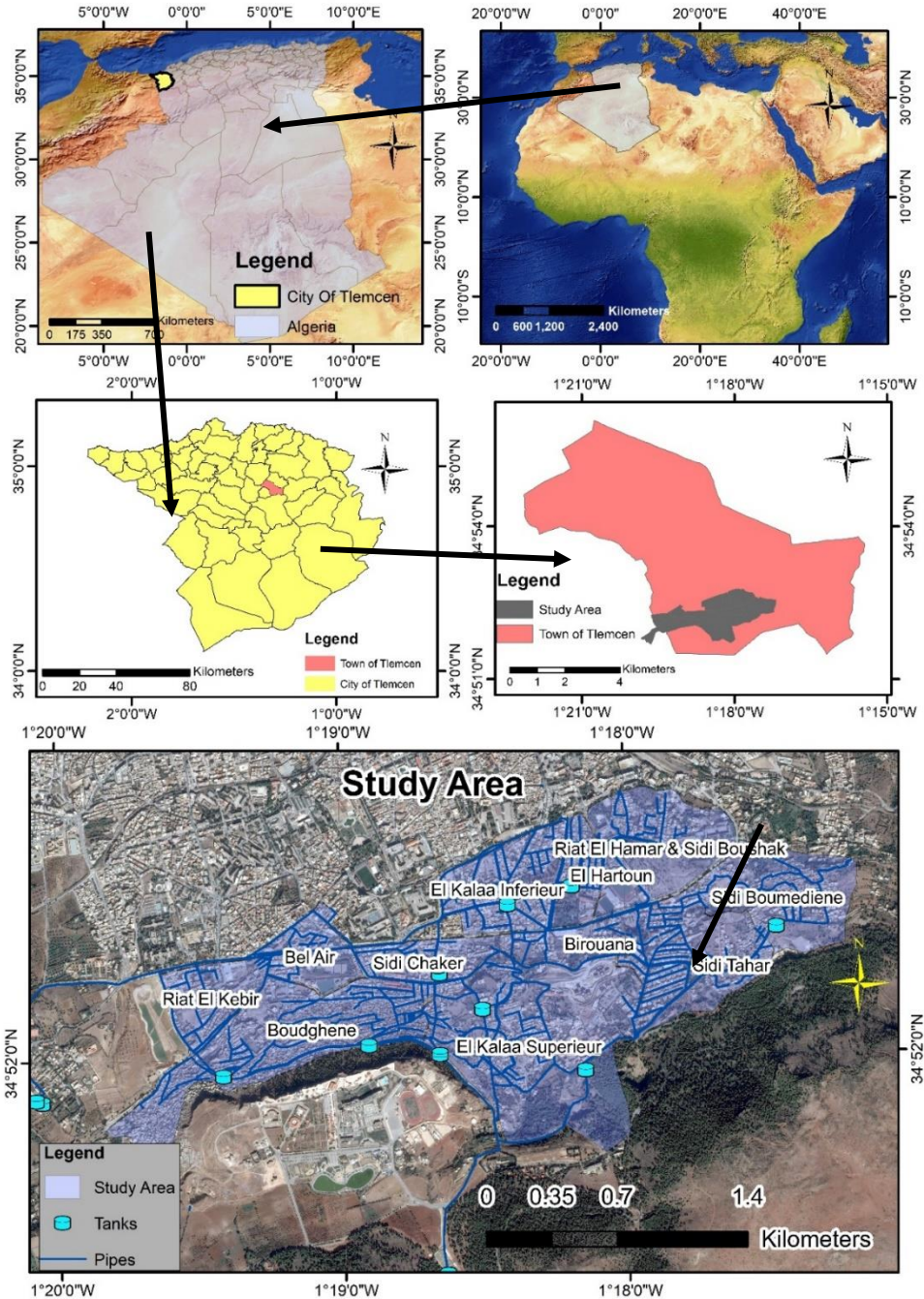


Figure IV.1: Location of the study area: Water distribution network of Southern part of the Tlemcen town urban cluster in Algeria.

IV.4. Navigating the Tool: A Practical Guide using the tool

The primary objective of this tool was to utilize data extracted from the pipe layer to determine sections requiring rehabilitation or renewal through the application of the Analytic Hierarchy Process (AHP) method, exclusively without relying on additional computational platforms, the validation of its results, were also elaborated upon.

To effectively employ the AHP tool for analyzing and prioritizing elements within a pipe network, it is essential to understand its operational procedures. This tool comprises five distinct sub-tools, each designed to facilitate specific aspects of the analysis process. Consequently, executing five scripts is necessary to yield the desired outcomes. The following guidelines detail the sequential steps required to navigate the AHP tool effectively:

- 1. Matrix of Criteria: The initial script, "Matrix of Criteria," serves as the foundation for the analysis process. It allows users to define and specify the criteria and options relevant to each level of the hierarchy. This step is pivotal in establishing the framework for subsequent evaluations as show in figure IV.2.

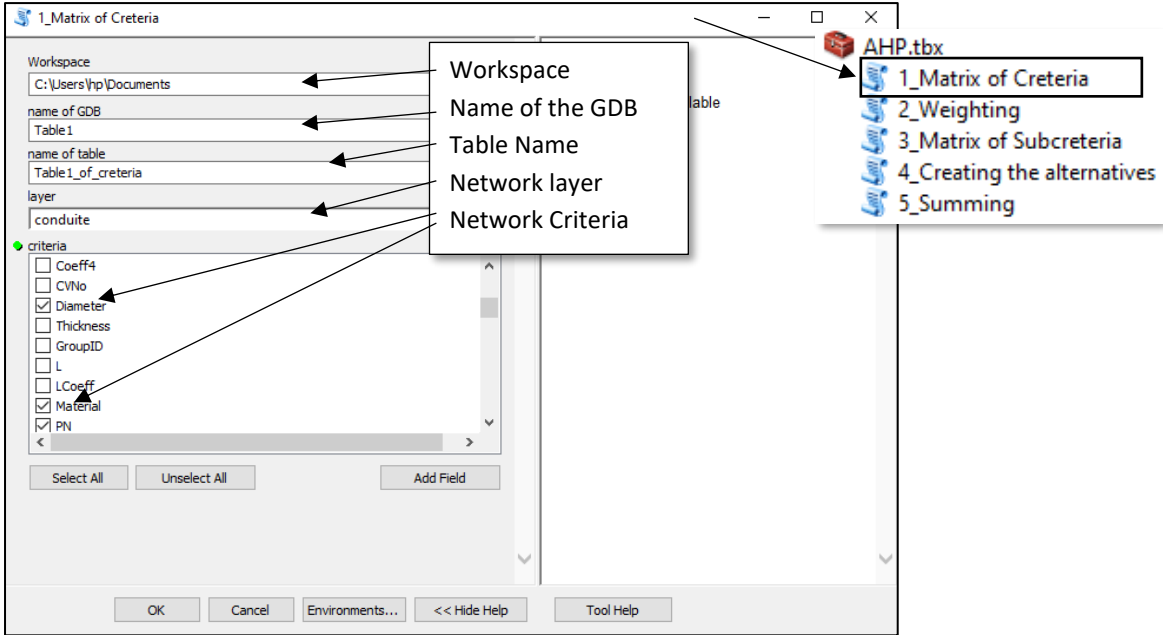


Figure IV.2: Creating the criteria table

The output of the first script, involves the creation of tables that reflect the structure of the binary comparison matrices (Figure IV.3). These tables feature identical column and row names corresponding to the criteria and indicators defined by the user. Subsequently, the tool utilizes these tables to facilitate binary comparisons and compute the weights associated with each criterion and indicator. This structured output streamlines the subsequent analytical processes, ensuring consistency and accuracy in the assessment of criteria importance and priority levels within the pipe network analysis framework.

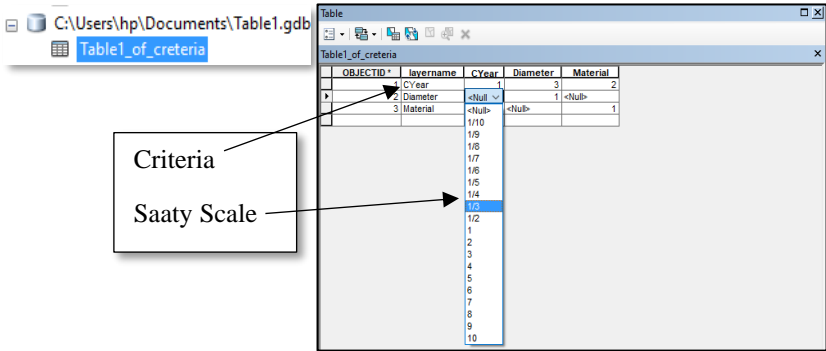


Figure IV.3: Pairwise comparison

2. In the second script, named "Weighting," (Figure IV.4) the user inserts the weights of the parent criteria, also known as "higher-level criteria." These are the criteria that have sub-criteria beneath them. Therefore, when assigning weights to the sub-criteria, it is essential to consider the weight of their parent criteria. The weighting tool automatically calculates the weight associated with each criterion based on the inputs provided by the user.

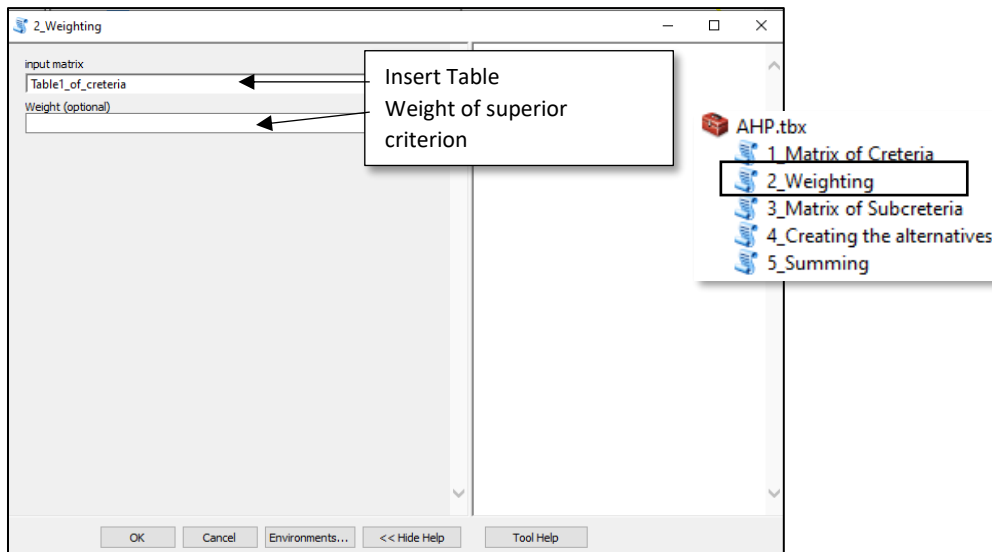


Figure IV.4: Judgment weight calculating

3. In the third script, known as the "Matrix of Subcriteria," users can generate a comprehensive table including indicators essential for assessing different alternatives within the pipe network (Figure IV.5). This script builds upon the criteria table established in the preceding step, allowing users to specify and weigh indicators crucial for the evaluation process.

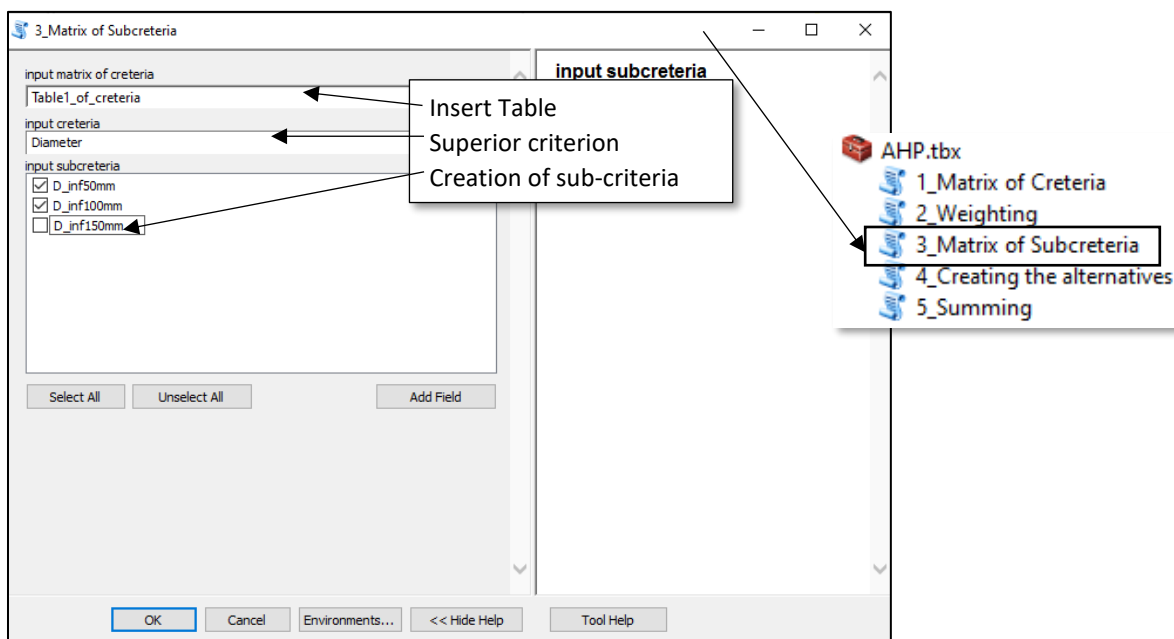


Figure IV.5: Creating the Sub-Criteria Table

- In the fourth script, referred to as "Creating the Alternatives," (Figure IV.6) the table of indicators generated in the previous step is utilized. This involves the creation of fields within the main layer of the pipe network dataset. Specifically, each field corresponds to the weight assigned to one sub-criterion. In our scenario, where we have 5 sub-criteria and 15 indicators, this process ensures that all relevant criteria and their associated weights are accurately represented within the dataset. Query Builder allows the selection of indicators and the creation of fields for the weight assignment of each section as shown in Figure IV.7.

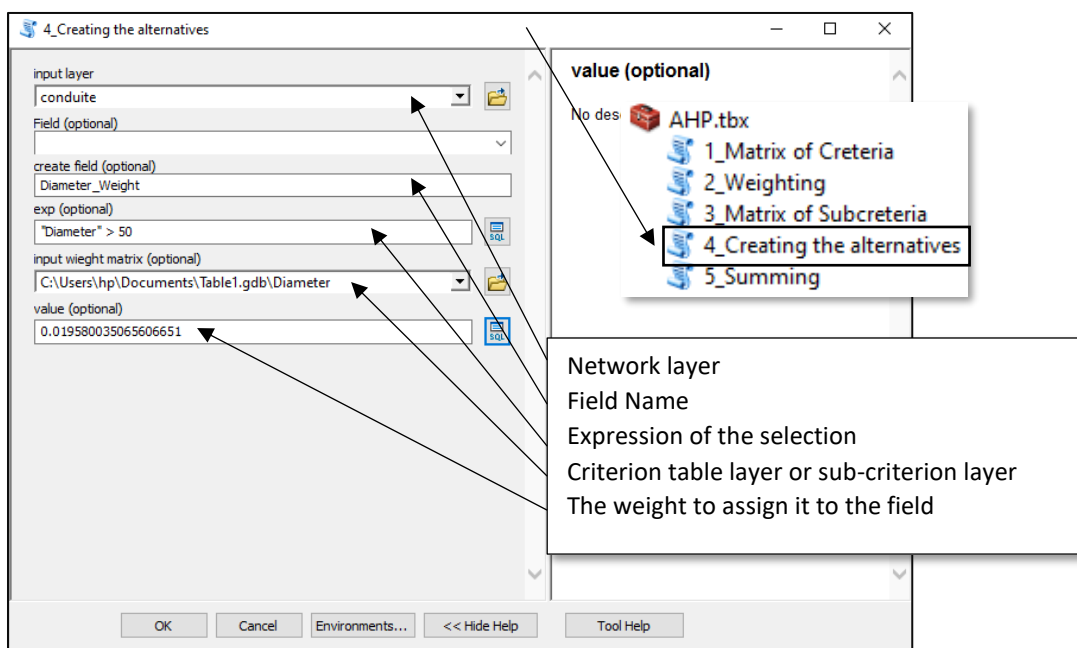


Figure IV.6 Creation of alternatives on the network layer

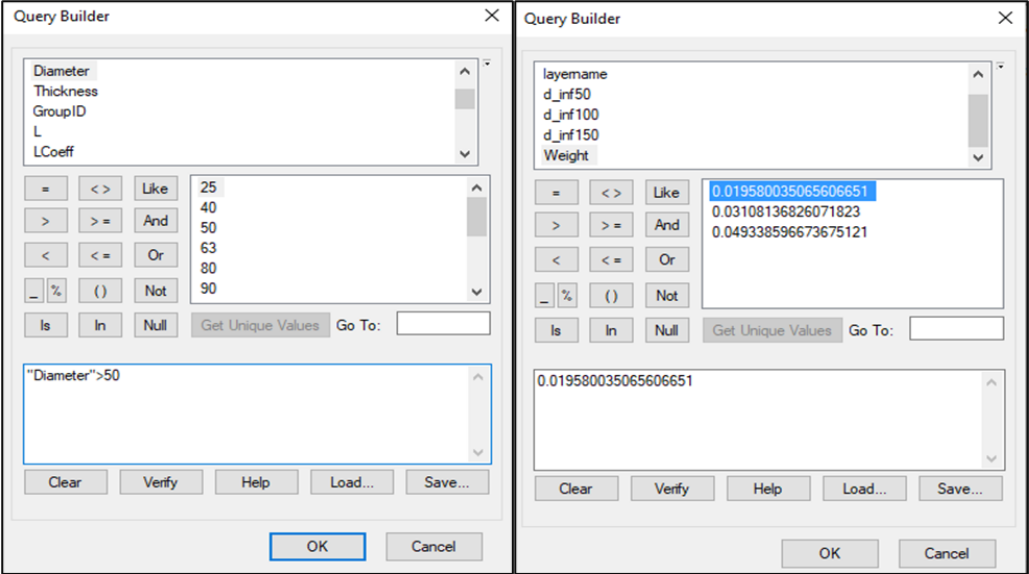


Figure IV.7: Expression of the selection and weight assignment for selected sections

- 5. The summing tool, integrated into the fifth script, facilitates the calculation of the total weight assigned to each pipe section. This is achieved by summing the values across the weight columns generated in the earlier steps. Figures IV.8 and IV.9 provide a visual guide on utilizing the tool to compute a new field that aggregates these weights. This final weight determination process ensures that each pipe section is appropriately evaluated based on the collective importance of its associated criteria and indicators.

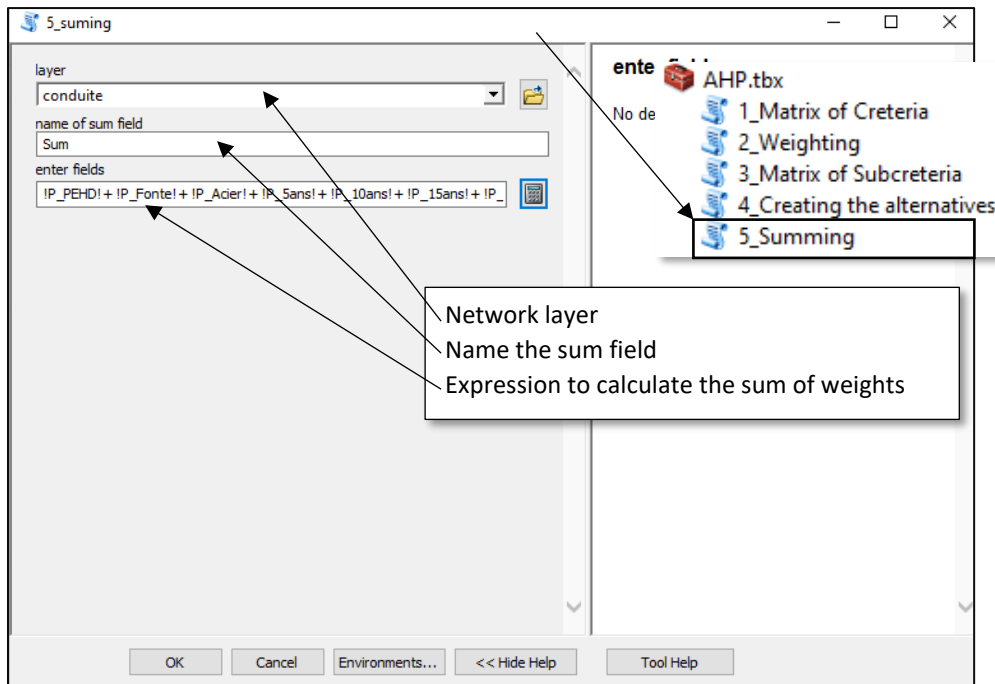


Figure IV.8: Calculation of the sum of weights

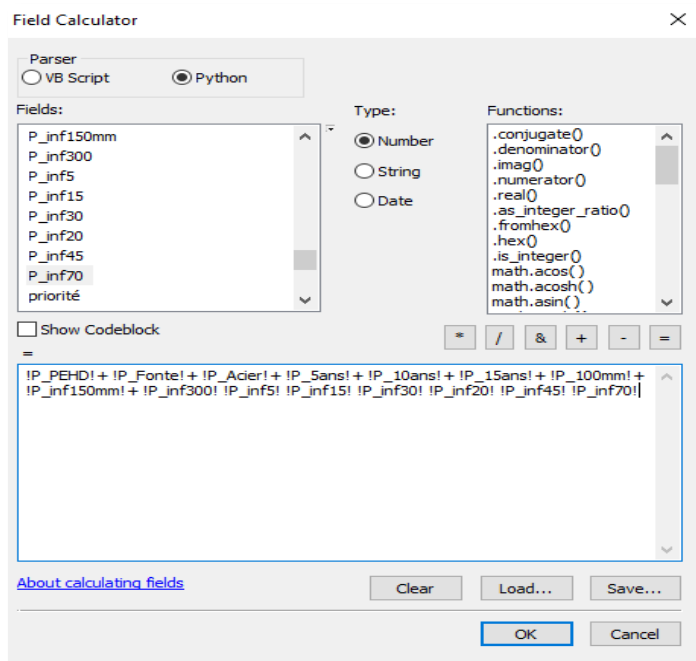


Figure IV.9: Field calculator

Once the final weights of each pipe section are calculated, the user can proceed to classify them based on their respective weights to prioritize maintenance actions or other decision-making processes pertaining to the pipe network. The proposed classification system categorizes the

sections into three classes: green for low priority (level 3), yellow for medium priority (level 2), and red for high priority (level 1). This systematic classification enables the identification of priority areas for maintenance actions and facilitates the classification of pipelines into immediate, intermediate, and long-range repair categories within the water distribution network.

IV.5. Geospatial Analysis for WDN Prioritization

The primary pipeline under examination is 65 kilometers long and has a diameter range of 40 to 600 mm, made of different materials such as cast iron, PEHD, and steel. The pipes have been classified based on their weight, which has allowed the network to be prioritized based on their level of emergency. Each pipe has been assigned an order, category, and color to reflect its emergency status. Pipes with higher weights are given higher priority status, with more urgent categories and more distinctive colors (such as red) as shown in Figure IV.10. Similarly, pipes with lower weights are assigned lower orders, less urgent categories, and less distinctive colors (such as green) to reflect their lower priority status.

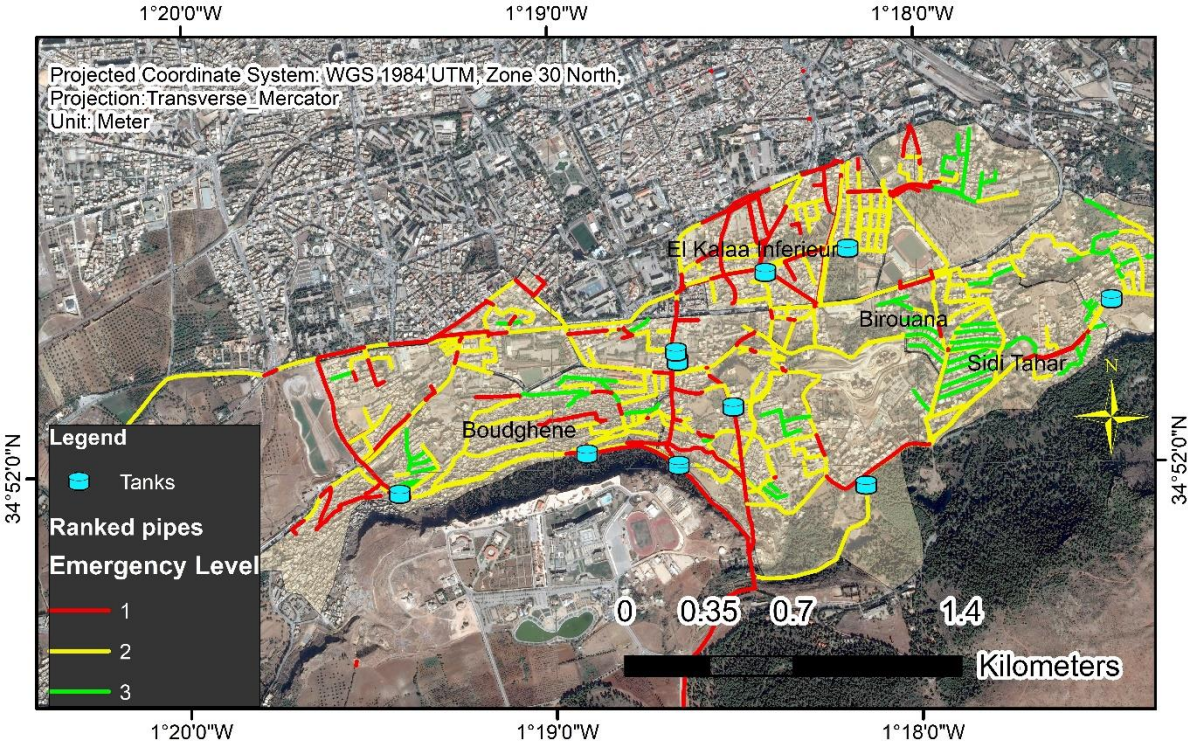


Figure IV.10: Ranked pipes using the AHP tool

In Figure IV.11, a detailed analysis is presented regarding the factors that play a role in determining when pipe renewal is necessary. The evaluation assigns weights to various indicators, with "Cast Iron" and "20 years" being assigned the highest values compared to other factors. This prioritization indicates that cast iron pipes that were installed two decades ago are the most likely pipes to require rehabilitation or replacement. This prioritization is based on two main factors. Firstly, cast iron pipes are known to be vulnerable to corrosion and wear and tear over time, which increases the risk of blockages and leaks (Tscheikner-Gratl et al. 2017). Secondly, pipes that have reached the 20-year mark are likely approaching the end of their expected lifespan, making them ideal candidates for preventative maintenance before major issues arise.

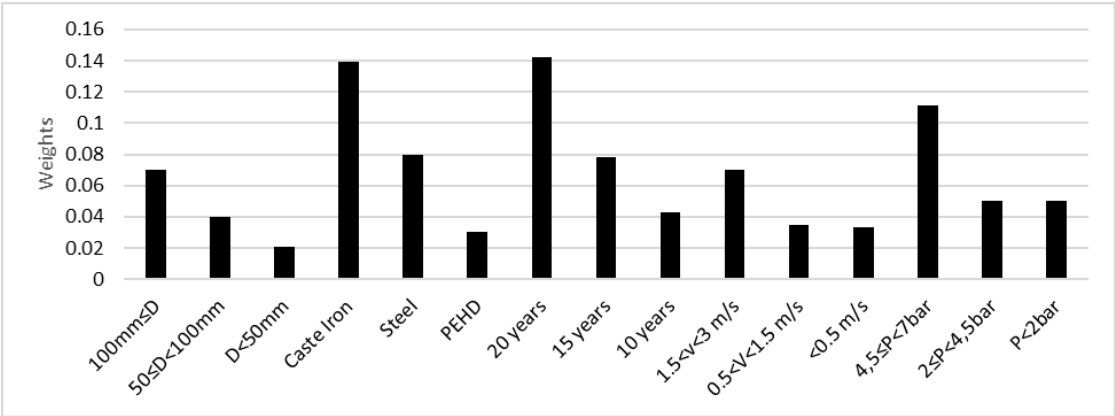


Figure IV.11: Ranked Indicators using AHP tool

This strategic approach ensures that resources are focused on the most critical areas of the pipe network, which maximizes efficiency and minimizes disruption. steel pipes experience more water losses compared to polyethylene pipes, which have fewer failures in the water distribution network. The results can also be impacted by the pressure criteria and the indicator " $4 < P < 7$ bar", as it is widely accepted that water pressure for domestic use should not exceed 4 bars (Aşchilean and Giurca 2018). If this value is exceeded, water leaks can occur (Abdelbaki et al. 2014).

According to the findings presented in Figure IV.12, it can be inferred that a significant proportion of the network, that is, 25%, is presently in a critical phase (level 1), thereby necessitating urgent rehabilitation measures. Moreover, it has been observed that 62% of the network is currently facing a medium degree of emergency (level 2), while the remaining 13% has been classified under the low level of emergency (level 3).

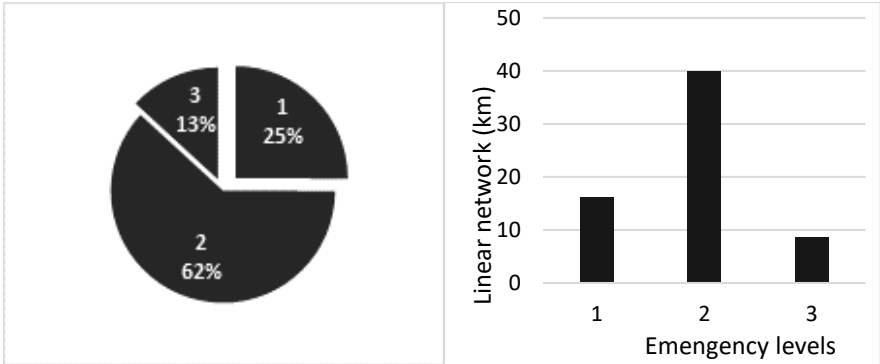


Figure IV.12: Weights of each emergency level obtained by the AHP Tool.

An effective way to analyze the distribution and importance of specific indicators on a network is by using ArcGIS to display their location on a map. For instance, the "material" criterion and its sub-criterion, the "PEHD" indicator, can be examined to understand its contribution to the overall prioritization of pipes. By displaying the distribution of this material on the network, decision-makers can determine its presence in high-priority areas and take informed decisions about rehabilitation and maintenance actions. This method helps decision-makers follow each indicator and observe its influence on the network, enabling them to classify network zones and select pipes with higher rehabilitation priorities. When sufficient network information is available, it is essential to choose effective criteria, including technical and non-technical criteria such as climate and special requirements.

Figure IV.13 illustrates this distribution, indicating a relatively low presence of PEHD pipes (3.5 km) in the high-priority areas. This spatial analysis aids decision-makers in strategically planning rehabilitation and maintenance efforts, considering both the relative weight and geographic context of specific indicators on the network.

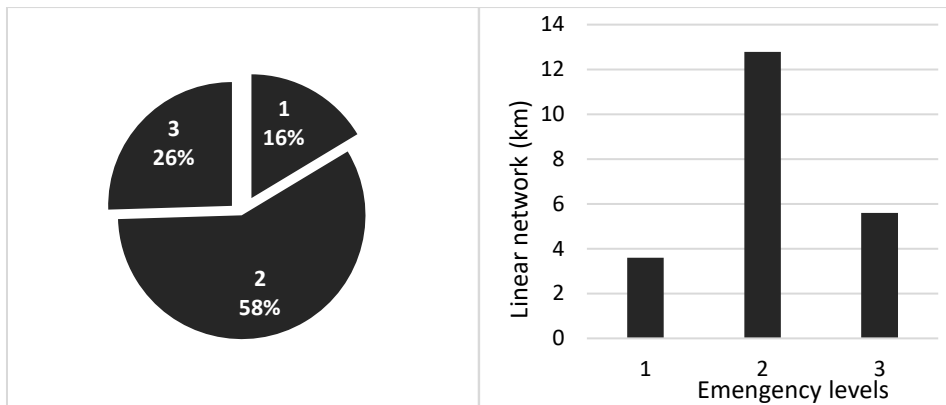


Figure IV.13 Linear network of PEHD pipes.

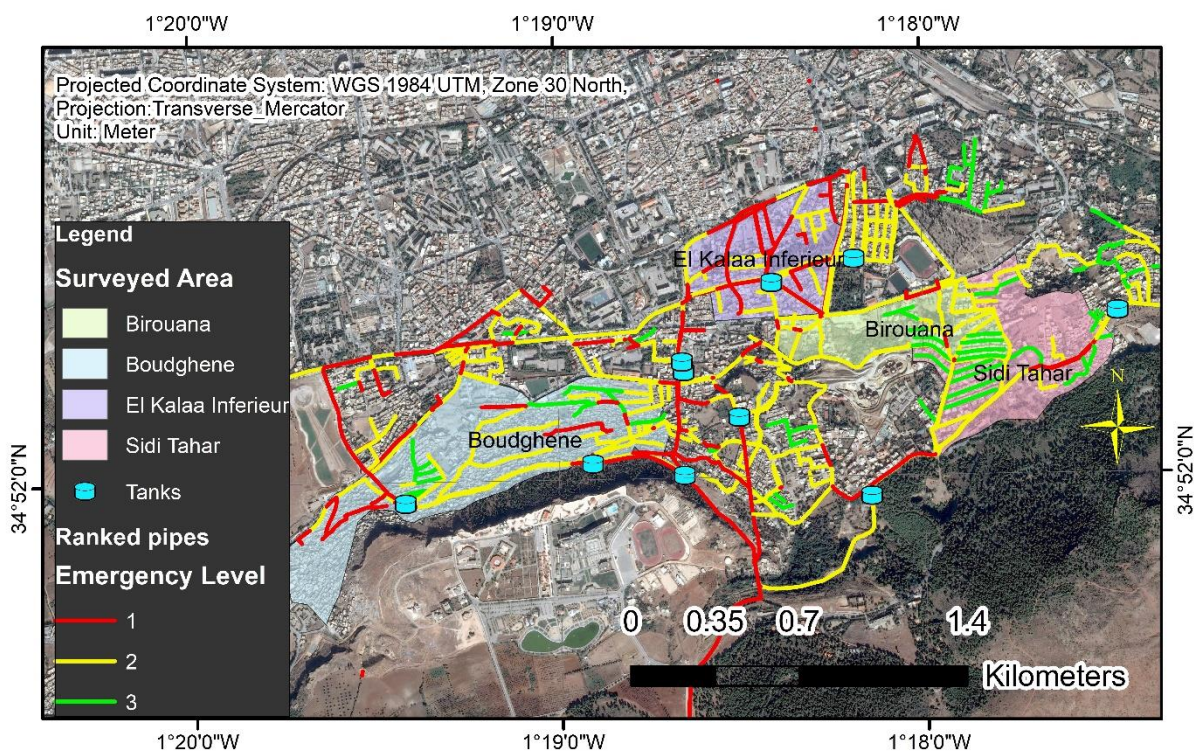


Figure IV.14: Spatial Distribution of Surveyed Regions

IV.6. Validation of the tool

The validation process is built upon the research of previous researchers (Abdelbaki et al. 2014; Abdelbaki et al. 2016; and Berrezel et al., 2022 and 2023). These researchers have looked into different aspects of drinking water network operations such as conducting surveys and

diagnosing issues arising from water supply disruptions. By incorporating the insights and findings from these studies, a more comprehensive and nuanced understanding of the emergency levels within the study area (Figure IV.14) was developed.

(Abdelbaki et al., 2014) utilized field surveys in their study, conducted in 2014, to validate and ensure the accuracy of their results with the actual ground conditions. This helped to increase the credibility and robustness of the study. The survey was designed to assess the quality of service provided to subscribers, which included evaluating the quality of repair work and customer complaints. To evaluate the satisfaction levels of customers with the current water supply service and to identify areas of improvement, both customer and manager surveys were conducted.

The conducted study involved surveying a total of 100 participants, consisting of 30 employees of Algérienne Des Eaux (ADE), the water company, and 70 subscribers residing in the urban area of Tlemcen. The satisfaction levels reported by the respondents in the surveyed regions, namely Birouana, Boudghene, El Kalaa Inferieure, and Sidi Tahar, varied.

According to the survey results in Figure IV.15, Birouana has a majority of respondents (50%) reporting moderate satisfaction, followed by good satisfaction (27%) and poor satisfaction (23%). Boudghene, on the other hand, has a higher percentage of moderate satisfaction (45%) with good satisfaction (25%) and poor satisfaction (30%). El Kalaa Inferieure experiences a majority of poor satisfaction (61%), lower levels of good satisfaction (24%), and moderate satisfaction (15%). Sidi Tahar stands out with the highest percentage of good satisfaction (40%), followed by moderate satisfaction (45%), and the lowest percentage of poor satisfaction (15%). It is noteworthy that the Analytical Hierarchy Process (AHP) rankings closely correspond to the levels of satisfaction reported in the survey for the majority of cases, thereby indicating a consistent pattern of prioritization.

We found that our classification of emergency levels matched 90% of the results obtained from the survey, indicating that our findings are valid. Additionally, the technical indicators presented in (Abdelbaki et al. 2014) study were crucial in validating our results. For example, the non-revenue water indicator in the survey revealed a high percentage of water losses, which corresponds to the high emergency level category areas we identified. Similarly, the customer complaints indicator showed a high number of complaints in certain areas, which was also consistent with our classification of high emergency-level areas. It's worth noting that we should provide more detailed information about our methodology in the relevant section.

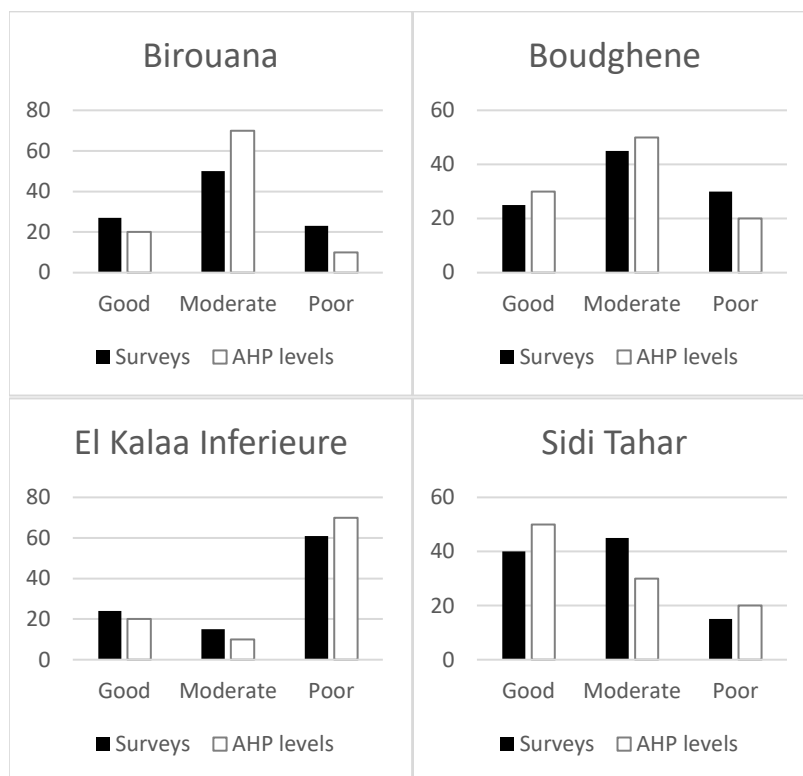


Figure IV.15: The validation outcome comparing the surveys with the AHP tool

IV.7. Conclusion

The application of the developed Python-based AHP tool in ArcGIS for decision-making in water distribution network management has demonstrated its practical utility and effectiveness.

The implementation of the tool in the case study area of the southern urban agglomeration of Tlemcen, Algeria, has provided valuable insights and validated the tool's capabilities.

The results of the study revealed that 25% of the analyzed network is in a critical state, necessitating immediate rehabilitation, while 62% exhibited a medium state of emergency, and 13% was found to be in a low state of emergency. The primary criteria that significantly influenced the prioritization of pipes for rehabilitation were material (26% of total weight), laying date (26% of total weight), and pressure (20% of total weight). Among the indicators, cast iron pipes (26% of total weight) and pipes with a laying date exceeding 20 years (26% of total weight) were assigned the highest weights, reflecting their criticality in the decision-making process.

The validation phase of the study played a crucial role in ensuring the accuracy and reliability of the obtained results. Field surveys confirmed the effectiveness of the GIS-based approach in identifying potential water infrastructure failures in the study area, further strengthening the credibility of the findings and reinforcing the tool's potential to guide water management decision-making processes in Tlemcen and other regions.

The developed tool offers a user-friendly interface that can be utilized by scientists, engineers, and water management professionals as a comprehensive guide for urban water management in Tlemcen and potentially other regions worldwide. This study represents a novel approach to the management of water distribution networks by seamlessly integrating GIS and multicriteria decision analysis (MCDA) techniques to prioritize rehabilitation and maintenance actions.

GENERAL CONCLUSION

General Conclusion

This study discusses the development of a novel method for decision-making to renovate and rehabilitate distribution water networks. To simplify the complexity of the system, a combination of decision support tools such as geographic information systems (GIS), multi-criteria analysis, and hydraulic simulation models were utilized. The method employs physical characteristics of pipes like diameter, materials, and laying date, along with the hydraulic structure of the network such as water velocity and pressure, to select relevant criteria. By applying the Analytic Hierarchy Process (AHP) method, dimensions, criteria, and indicators were classified, enabling the identification of priority sections for maintenance action based on emergency levels and color-coded categories, where level 3 is low priority, level 2 is medium priority, and level 1 is high priority for intervention in red color. The results, obtained from a case study in the East Arzew district, showed that 26% of the network is critical and requires immediate rehabilitation.

The Python-based AHP tool developed in this study leverages the capabilities of ArcGIS to streamline the decision-making process for identifying pipes that require rehabilitation or renewal in water distribution networks. The tool's algorithm follows a well-defined sequence of operations, including creating tables, defining criteria, calculating weights, and applying the AHP method. The script, written in Python, consists of five distinct phases and integrates various ArcGIS functions and modules, such as `CreateTable`, `AddField`, `CreateDomain`, `UpdateCursor`, `SelectLayerByAttribute`, `CalculateField`, and `SearchCursor`, contributing to the tool's efficiency and versatility.

The application of the developed Python-based AHP tool in ArcGIS for decision-making in water distribution network management has demonstrated its practical utility and effectiveness. The implementation of the tool in the case study area of the southern urban agglomeration of

Tlemcen, Algeria, has provided valuable insights and validated the tool's capabilities. The results revealed that 25% of the analyzed network in Tlemcen is in a critical state, necessitating immediate rehabilitation, while 62% exhibited a medium state of emergency, and 13% was found to be in a low state of emergency. The primary criteria that significantly influenced the prioritization of pipes for rehabilitation were material (26% of total weight), laying date (26% of total weight), and pressure (20% of total weight). Among the indicators, cast iron pipes (26% of total weight) and pipes with a laying date exceeding 20 years (26% of total weight) were assigned the highest weights, reflecting their criticality in the decision-making process.

The validation phase, involving field surveys, played a crucial role in ensuring the accuracy and reliability of the obtained results. It confirmed the effectiveness of the GIS-based approach in identifying potential water infrastructure failures in the study area, further strengthening the credibility of the findings and reinforcing the tool's potential to guide water management decision-making processes in Tlemcen and other regions. The developed tool offers a user-friendly interface that can be utilized by scientists, engineers, and water management professionals as a comprehensive guide for urban water management in Tlemcen and potentially other regions worldwide. This study represents a novel approach to the management of water distribution networks by seamlessly integrating GIS and multi-criteria decision analysis (MCDA) techniques to prioritize rehabilitation and maintenance actions.

REFERENCES

‘A Gentle Introduction to GIS — QGIS Documentation Documentation’. n.d. Accessed 26 January 2022. https://docs.qgis.org/3.16/en/docs/gentle_gis_introduction/index.html.

Abdelbaki, Chérifa. 2014. ‘Modélisation d’un réseau d’AEP et contribution à sa gestion à l’aide d’un SIG - Cas du Groupement Urbain de Tlemcen’. Thesis, Abou Bekr Belkaid. http://dspace.univ-tlemcen.dz/bitstream/112/7054/1/Doctorat_ABDELBAKI_Cherifa.pdf.

Abdelbaki, Chérifa, Mohamed Mouâd Benchaib, Salim Benziada, Hacène Mahmoudi, and Mattheus Goosen. 2017. ‘Management of a Water Distribution Network by Coupling GIS and Hydraulic Modeling: A Case Study of Chetouane in Algeria’. *Applied Water Science* 7 (3): 1561–67. <https://doi.org/10.1007/s13201-016-0416-1>.

Abdelbaki, Chérifa, Bénina Touaibia, Allal Mohamed Amine, and Kara Slimane Fadila. 2012. ‘Applied Systemic Approach to Water Supply Network the Case of an Urban Cluster of Tlemcen - Algeria’. *Procedia Engineering*, SWEE’11, 33 (January): 30–37. <https://doi.org/10.1016/j.proeng.2012.01.1173>.

Abdelbaki, Chérifa, Bénina Touaibia, Abdelhadi Ammari, Hacène Mahmoudi, and Mattheus Goosen. 2019. ‘Contribution of GIS and Hydraulic Modeling to the Management of Water Distribution Network’. In *Geospatial Challenges in the 21st Century*, edited by Kostis Koutsopoulos, Rafael de Miguel González, and Karl Donert, 125–50. Key Challenges in Geography. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-04750-4_7.

Abdelbaki, Chérifa, Bénina Touaibia, Hacène Mahmoudi, Sidi Mohamed Djelloul Smir, Mohamed Amine Allal, and Mattheus Goosen. 2014. ‘Efficiency and Performance of a Drinking Water Supply Network for an Urban Cluster at Tlemcen Algeria’. *Desalination and Water Treatment* 52 (10–12): 2165–73. <https://doi.org/10.1080/19443994.2013.870497>.

- Abokifa, Ahmed A., Y. Jeffrey Yang, Cynthia S. Lo, and Pratim Biswas. 2016. 'Water Quality Modeling in the Dead End Sections of Drinking Water Distribution Networks'. *Water Research* 89 (February): 107–17. <https://doi.org/10.1016/j.watres.2015.11.025>.
- Abrunhosa, Diana. 2015. 'Comparison Between A Sustainable And A Traditional Urban Drainage Solution With Mike Urban.' University of Porto.
- Ahmad, Ishtiyag, and Mukesh Kumar Verma. 2018. 'Application of Analytic Hierarchy Process in Water Resources Planning: A GIS Based Approach in the Identification of Suitable Site for Water Storage'. *Water Resources Management* 32 (15): 5093–5114. <https://doi.org/10.1007/s11269-018-2135-x>.
- Alrayess, Hesham. 2015. 'Performance Evaluation and Development of SDSS for Gaza City Water Network (Case Study The Northern Nasser Area)'. <https://doi.org/10.13140/RG.2.2.23920.35840>.
- Alves, Z., J. Muranho, T. Albuquerque, and A. Ferreira. 2014. 'Water Distribution Network's Modeling and Calibration. A Case Study Based on Scarce Inventory Data'. *Procedia Engineering*, 12th International Conference on Computing and Control for the Water Industry, CCWI2013, 70 (January): 31–40. <https://doi.org/10.1016/j.proeng.2014.02.005>.
- Alvisi, S., and M. Franchini. 2014. 'A Procedure for the Design of District Metered Areas in Water Distribution Systems'. *Procedia Engineering*, 12th International Conference on Computing and Control for the Water Industry, CCWI2013, 70 (January): 41–50. <https://doi.org/10.1016/j.proeng.2014.02.006>.
- AL-Washali, Taha, Saroj Sharma, Robert Lupoja, Fadhl AL-Nozaily, Mansour Haidera, and Maria Kennedy. 2020. 'Assessment of Water Losses in Distribution Networks: Methods, Applications, Uncertainties, and Implications in Intermittent Supply'.

- Resources, Conservation and Recycling* 152 (January): 104515.
<https://doi.org/10.1016/j.resconrec.2019.104515>.
- Amorocho-Daza, Henry, Sergio Cabrales, Raquel Santos, and Juan Saldarriaga. 2019. 'A New Multi-Criteria Decision Analysis Methodology for the Selection of New Water Supply Infrastructure'. *Water* 11 (4): 805. <https://doi.org/10.3390/w11040805>.
- Anagnostopoulos, K, Maria Gratziou, and A Vavatsikos. 2007. 'Using the Fuzzy Analytic Hierarchy Process for Selecting Wastewater Facilities at Prefecture Level'. *Eur. Water* 19 (January).
- Aronoff, Stan. 1989. 'Geographic Information Systems: A Management Perspective'. *Geocarto International* 4 (4): 58–58. <https://doi.org/10.1080/10106048909354237>.
- Așchilean, Ioan, Gheorghe Badea, Ioan Giurca, George Sebastian Naghiu, and Florin George Iloaie. 2017a. 'Choosing the Optimal Technology to Rehabilitate the Pipes in Water Distribution Systems Using the AHP Method'. *Energy Procedia* 112 (March): 19–26. <https://doi.org/10.1016/j.egypro.2017.03.1109>.
- . 2017b. 'Determining Priorities Concerning Water Distribution Network Rehabilitation'. *Energy Procedia, Sustainable Solutions for Energy and Environment, EENVIRO 2016, 26-28 October 2016, Bucharest, Romania*, 112 (March): 27–34. <https://doi.org/10.1016/j.egypro.2017.03.1055>.
- Așchilean, Ioan, and Ioan Giurca. 2018. 'Choosing a Water Distribution Pipe Rehabilitation Solution Using the Analytical Network Process Method'. *Water* 10 (4): 484. <https://doi.org/10.3390/w10040484>.
- Awe, O.M., S.T.A. Okolie, and O.S.I. Fayomi. 2019. 'Review of Water Distribution Systems Modelling and Performance Analysis Softwares'. *Journal of Physics: Conference Series* 1378 (2): 022067. <https://doi.org/10.1088/1742-6596/1378/2/022067>.

- Badri, Masood. 2001. 'A Combined AHP-GP Model for Quality Control Systems'. *International Journal of Production Economics* 72 (June): 27–40. [https://doi.org/10.1016/S0925-5273\(00\)00077-3](https://doi.org/10.1016/S0925-5273(00)00077-3).
- Barbeau, Benoit, Vincent Gauthier, Karine Julienne, and Annie Carrière. 2005. 'Dead-End Flushing of a Distribution System: Short and Long-Term Effects on Water Quality'. *Water Science & Technology Water Supply* 54 (June). <https://doi.org/10.2166/aqua.2005.0035>.
- Bender, Edward A. 1978. *An Introduction to Mathematical Modeling*. New York: Wiley.
- Benedini, Marcello, and George Tsakiris. 2013. 'Model Calibration and Verification'. In *Water Quality Modelling for Rivers and Streams*, by Marcello Benedini and George Tsakiris, 70:223–29. Water Science and Technology Library. Dordrecht: Springer Netherlands. https://doi.org/10.1007/978-94-007-5509-3_18.
- Berrezel, Yacine Abdelbaset, Chérifa Abdelbaki, Bouchrit Rouissat, Tarek Boumaaza, and Mourad Khaldoun. 'Decision Support System For The Management Of Water Distribution Networks A Case Study Of Tourville, Algeria'. *LARHYSS Journal* 20, no. 2 (10 June 2023): 93–110.
- Berrezel, Yacine Abdelbasset, Chérifa Abdelbaki, and Mohamed El Amine Benabdelkrim. 2022. 'Coupling of GIS and Hydraulic Modeling in Management of an Urban Water Distribution Network—A Case Study of Tlemcen (Algeria)'. In *Sustainable Energy-Water-Environment Nexus in Deserts*, edited by Essam Heggy, Veronica Bermudez, and Marc Vermeersch, 253–58. Advances in Science, Technology & Innovation. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-76081-6_30.
- Blindu, Igor. 2004. 'Outil d'aide au diagnostic du réseau d'eau potable pour la ville de Chisinau par analyse spatiale et temporelle des dysfonctionnements hydrauliques'. Phdthesis,

Ecole Nationale Supérieure des Mines de Saint-Etienne ; Université Jean Monnet - Saint-Etienne. <https://tel.archives-ouvertes.fr/tel-00779032>.

- Boroushaki, Soheil, and Jacek Malczewski. 2008. 'Implementing an Extension of the Analytical Hierarchy Process Using Ordered Weighted Averaging Operators with Fuzzy Quantifiers in ArcGIS'. *Computers & Geosciences* 34 (4): 399–410. <https://doi.org/10.1016/j.cageo.2007.04.003>.
- Carnero, María Carmen, and Andrés Gómez. 2018. 'Optimization of Maintenance in Production and Storage Systems for Domestic Water'. *Water Resources Management* 32 (1): 359–80. <https://doi.org/10.1007/s11269-017-1815-2>.
- Chabi, Nacira, Fouzia Houma Bachari, Nour El-Islam Bachari, and Abderrahmane Bouda. 2023. 'Oil Spill Vulnerable Areas in Arzew Gulf: A Study Case'. *SN Applied Sciences* 5 (6): 158. <https://doi.org/10.1007/s42452-023-05376-x>.
- Chang, Kang-Tsung. 2017. 'Geographic Information System'. In *International Encyclopedia of Geography: People, the Earth, Environment and Technology*, edited by Douglas Richardson, Noel Castree, Michael F. Goodchild, Audrey Kobayashi, Weidong Liu, and Richard A. Marston, 1–9. Oxford, UK: John Wiley & Sons, Ltd. <https://doi.org/10.1002/9781118786352.wbieg0152>.
- Cherifa, Abdelbaki, Mohamed Benchaib, S. Benziada, Hacene Mahmoudi, and Mattheus Goosen. 2016. 'Management of a Water Distribution Network by Coupling GIS and Hydraulic Modeling: A Case Study of Chetouane in Algeria'. *Applied Water Sciences* 7 (April). <https://doi.org/10.1007/s13201-016-0416-1>.
- Christodoulou, Symeon E., Michalis Fragiadakis, Agathoklis Agathokleous, and Savvas Xanthos. 2018. 'Chapter 1 - Introduction'. In *Urban Water Distribution Networks*, edited by Symeon E. Christodoulou, Michalis Fragiadakis, Agathoklis Agathokleous,

- and Savvas Xanthos, 1–20. Butterworth-Heinemann. <https://doi.org/10.1016/B978-0-12-813652-2.00001-3>.
- Crouch, Dora P. 1993. *Water Management in Ancient Greek Cities*. New York: Oxford University Press. <https://doi.org/10.1093/oso/9780195072808.001.0001>.
- Curry, R. Allen, Gordon Yamazaki, Tommi Linnansaari, Wendy Monk, Kurt M. Samways, Rebecca Dolson, Kelly R. Munkittrick, and Anthony Bielecki. 2020. ‘Large Dam Renewals and Removals—Part 1: Building a Science Framework to Support a Decision-Making Process’. *River Research and Applications* 36 (8): 1460–71. <https://doi.org/10.1002/rra.3680>.
- Dlamini, V. G. 2009. ‘Promoting Multiple Water Use Services Based on Integrated Water Resources Management: The Planning and Implementation’. In *Water Distribution Systems Analysis 2008*, 1–10. Kruger National Park, South Africa: American Society of Civil Engineers. [https://doi.org/10.1061/41024\(340\)7](https://doi.org/10.1061/41024(340)7).
- Dobesova, Zdena. 2011. ‘Programming Language Python for Data Processing’. In *2011 International Conference on Electrical and Control Engineering*, 4866–69. Yichang, China: IEEE. <https://doi.org/10.1109/ICECENG.2011.6057428>.
- Düzce, Hakan Murat. 2017. ‘CURRENT CLASSIFICATION OF MULTI CRITERIA DECISION ANALYSIS METHODS AND PUBLIC SECTOR IMPLEMENTATIONS’. In , 241–61.
- EL ABIDINE, Roukh ZINE, and Nadji ABDELMANSOUR. 2019. ‘Landslide Susceptibility Mapping Using Information Value and Frequency Ratio for the Arzew Sector (North-Western of Algeria)’. *Bulletin of the Mineral Research and Exploration* 160 (160): 197–211.
- El-Awar, Faraj, M. Makke, Rami Zurayk, and Rabi Mohtar. 2000. ‘A Hydro-Spatial Hierarchical Method For Siting Water Harvesting Reservoirs in Dry Areas’. *Applied*

- Engineering in Agriculture, ASAE* 16 (July): 395–404.
<https://doi.org/10.13031/2013.5223>.
- Elhaj, Khalid. 2018. ‘Creating a Python Toolbox to Implement the Analytical Hierarchy Process Method in ARCGIS’. <https://doi.org/10.13140/RG.2.2.35076.42883>.
- Escobar, F., G. Hunter, I. Bishop, and A. Zerger. 2008. ‘Introduction to GIS’. *Department of Geomatics, The University of Melbourne, Available Online at: Http://Www. Sli. Unimelb. Edu. Au/Gisweb/(Accessed 02 April 2008)*.
- Farina, Giulia, Enrico Creaco, and Marco Franchini. 2014. ‘Using EPANET for Modelling Water Distribution Systems with Users along the Pipes’. *Civil Engineering and Environmental Systems* 31 (1): 36–50. <https://doi.org/10.1080/10286608.2013.820279>.
- Fazal, Shahab. 2008. *GIS Basics*. New Age International.
- Fortier, Paul J., and Howard E. Michel. 2003. ‘8 - Simulation Analysis’. In *Computer Systems Performance Evaluation and Prediction*, edited by Paul J. Fortier and Howard E. Michel, 251–78. Burlington: Digital Press. <https://doi.org/10.1016/B978-155558260-9/50008-4>.
- Fujita, Masafumi, Yoshiyuki Ishiwatari, Iori Mishima, Norihiko Utsuno, and Takeshi Kato. 2014. ‘Effect of Ageing of Pipe and Lining Materials on Elemental Composition of Suspended Particles in a Water Distribution System’. *Water Resources Management* 28 (6): 1645–53. <https://doi.org/10.1007/s11269-014-0571-9>.
- GISGeography. 2015. ‘The Remarkable History of GIS’. GIS Geography. 12 October 2015. <https://gisgeography.com/history-of-gis/>.
- Golden, Bruce L., Edward A. Wasil, and Patrick T. Harker, eds. 1989. *The Analytic Hierarchy Process: Applications and Studies*. Berlin, Heidelberg: Springer Berlin Heidelberg. <https://doi.org/10.1007/978-3-642-50244-6>.

- Goodchild, Michael F. 2009. 'Geographic Information Systems and Science: Today and Tomorrow'. *Annals of GIS* 15 (1): 3–9. <https://doi.org/10.1080/19475680903250715>.
- . 2012. 'Geographic Information Systems'. In *Geographic Information Systems*, 341–45. University of California Press. <https://doi.org/10.1525/9780520951785-064>.
- Goodchild, Michael F., and Robert P. Haining. 2003. 'GIS and Spatial Data Analysis: Converging Perspectives'. *Papers in Regional Science* 83 (1): 363–85. <https://doi.org/10.1007/s10110-003-0190-y>.
- Greco, Salvatore, Matthias Ehrgott, and José Rui Figueira, eds. 2016. *Multiple Criteria Decision Analysis: State of the Art Surveys*. Vol. 233. International Series in Operations Research & Management Science. New York, NY: Springer New York. <https://doi.org/10.1007/978-1-4939-3094-4>.
- Greenberg, Joshua D., Miles G. Logsdon, and Jerry F. Franklin. 2002. 'Introduction to Geographic Information Systems (GIS)'. In *Learning Landscape Ecology: A Practical Guide to Concepts and Techniques*, edited by Sarah E. Gergel and Monica G. Turner, 17–31. New York, NY: Springer. https://doi.org/10.1007/0-387-21613-8_3.
- Guragai, B., T. Hashimoto, K. Oguma, and S. Takizawa. 2018. 'Data Logger-Based Measurement of Household Water Consumption and Micro-Component Analysis of an Intermittent Water Supply System'. *Journal of Cleaner Production* 197 (October): 1159–68. <https://doi.org/10.1016/j.jclepro.2018.06.198>.
- Herbei, Mihai Valentin, Valeria Ciolac, Adrian Şmuleac, Eleonora Nistor, and L. Ciolac. 2010. 'Georeferencing of Topographical Maps Using the Software ARCGIS'. *Research Journal of Agricultural Science* 42 (3): 595–606.
- Hountondji, B., and F. P. Codo. 2019. 'Design of a hydraulic model for the Monzougoudo water supply network in Benin'. *LARHYSS Journal P-ISSN 1112-3680 / E-ISSN 2521-9782*, no. 38 (June): 71–91.

- ‘How To: Use Scripting in ArcGIS Desktop to Run Custom Tools and Repetitive Geoprocessing Workflows and Tasks’. n.d. Accessed 29 January 2022. <https://support.esri.com/en/technical-article/000006921>.
- Huisman, Otto. 2009. *Principles of Geographic Information Systems An Introductory Textbook*. Editors Otto Huisman and Rolf A. de By. ITC. <http://ndl.ethernet.edu.et/handle/123456789/52841>.
- Ingeduld, Petr, Ajay Pradhan, Zdenek Svitak, and Ashok Terrai. 2008. ‘Modelling Intermittent Water Supply Systems with EPANET’. In *Water Distribution Systems Analysis Symposium 2006*, 1–8. Cincinnati, Ohio, United States: American Society of Civil Engineers. [https://doi.org/10.1061/40941\(247\)37](https://doi.org/10.1061/40941(247)37).
- ‘Introduction to Modeling and Simulation’. 1995. *JOHNS HOPKINS APL TECHNICAL DIGEST* 16 (1): 12.
- Jahan, Ali, Kevin L. Edwards, and Marjan Bahraminasab. 2016. ‘Multi-Criteria Decision-Making for Materials Selection’. In *Multi-Criteria Decision Analysis for Supporting the Selection of Engineering Materials in Product Design*, 63–80. Elsevier. <https://doi.org/10.1016/B978-0-08-100536-1.00004-7>.
- Kabir, Golam, Rehan Sadiq, and Solomon Tesfamariam. 2014. ‘A Review of Multi-Criteria Decision-Making Methods for Infrastructure Management’. *Structure and Infrastructure Engineering* 10 (9): 1176–1210. <https://doi.org/10.1080/15732479.2013.795978>.
- Kanakoudis, Vasilis, and Stavroula Tsitsifli. 2019. ‘Water Networks Management: New Perspectives’. *Water* 11 (2): 239. <https://doi.org/10.3390/w11020239>.
- Kara, Selami, I. Ethem Karadirek, Ayse Muhammetoglu, and Habib Muhammetoglu. 2016. ‘Hydraulic Modeling of a Water Distribution Network in a Tourism Area with Highly Varying Characteristics’. *Procedia Engineering*, International Conference on Efficient

- & Sustainable Water Systems Management toward Worth Living Development, 2nd EWaS 2016, 162 (January): 521–29. <https://doi.org/10.1016/j.proeng.2016.11.096>.
- Klingel, P., and J. Deuerlein. 2009. ‘Rehabilitation Strategy for Water Supply Systems in Developing Countries Case Study: IWRM Oasis Béni Abbès, Algeria’. In *Water Distribution Systems Analysis 2008*, 1–13. Kruger National Park, South Africa: American Society of Civil Engineers. [https://doi.org/10.1061/41024\(340\)14](https://doi.org/10.1061/41024(340)14).
- Knoerl, John J. 1991. ‘Mapping History Using Geographic Information Systems’. *The Public Historian* 13 (3): 97–108. <https://doi.org/10.2307/3378555>.
- Köksalan, Murat, Jyrki Wallenius, and Stanley Zionts. 2011. *Multiple Criteria Decision Making: From Early History to the 21st Century*. WORLD SCIENTIFIC. <https://doi.org/10.1142/8042>.
- . 2013. ‘An Early History of Multiple Criteria Decision Making: AN EARLY HISTORY OF MULTIPLE CRITERIA DECISION MAKING’. *Journal of Multi-Criteria Decision Analysis* 20 (1–2): 87–94. <https://doi.org/10.1002/mcda.1481>.
- Lima, María Lourdes, Agustina Barilari, Héctor E. Massone, and Mónica Pascual. 2021. ‘Incorporating Local Researchers’ and Decision Makers’ Preferences for Groundwater Resources Management in a Spatial Multi-Voiced Decision Model’. *Journal of Environmental Management* 302 (Pt A): 113954. <https://doi.org/10.1016/j.jenvman.2021.113954>.
- Maguire, David J. 1991. ‘An Overview and Definition of GIS’. *Geographical Information Systems: Principles and Applications* 1: 9–20.
- Majumder, Mrinmoy. 2015. ‘Multi Criteria Decision Making’. In *Impact of Urbanization on Water Shortage in Face of Climatic Aberrations*, by Mrinmoy Majumder, 35–47. SpringerBriefs in Water Science and Technology. Singapore: Springer Singapore. https://doi.org/10.1007/978-981-4560-73-3_2.

- Mala-Jetmarova, Helena, Andrew Barton, and A.M. Bagirov. 2015. 'A History of Water Distribution Systems and Their Optimisation'. *Water Science & Technology Water Supply* 15 (February): 224–35. <https://doi.org/10.2166/ws.2014.115>.
- Marinoni, Oswald. 2004. 'Implementation of the Analytical Hierarchy Process with VBA in ArcGIS'. *Computers & Geosciences* 30 (6): 637–46. <https://doi.org/10.1016/j.cageo.2004.03.010>.
- Marion, Glenn, Daniel Lawson, and Glenn Marion. 2008. 'An Introduction to Mathematical Modelling', 35.
- Mei, Xie, Renzo Rosso, G. Huang, and G. Nie. 1987. 'Application of Analytical Hierarchy Process to Water Resources Policy and Management in Beijing, China' 180 (January).
- Metelka, Tomáš. 2006. 'INTEGRATED URBAN WATER CYCLE MODELING'. In *Integrated Urban Water Resources Management*, edited by Petr Hlavinek, Tamara Kukharchyk, Jiri Marsalek, and Ivana Mahrikova, 51–58. NATO Security through Science Series. Dordrecht: Kluwer Academic Publishers. https://doi.org/10.1007/1-4020-4685-5_6.
- Mu, Enrique, and Milagros Pereyra-Rojas. 2017. 'Understanding the Analytic Hierarchy Process'. In *Practical Decision Making: An Introduction to the Analytic Hierarchy Process (AHP) Using Super Decisions V2*, edited by Enrique Mu and Milagros Pereyra-Rojas, 7–22. SpringerBriefs in Operations Research. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-33861-3_2.
- Munier, Nolberto, Eloy Hontoria, and Fernando Jiménez-Sáez. 2019. *Strategic Approach in Multi-Criteria Decision Making: A Practical Guide for Complex Scenarios*. Vol. 275. International Series in Operations Research & Management Science. Cham: Springer International Publishing. <https://doi.org/10.1007/978-3-030-02726-1>.

- Muralidhar, Krishnamurthy. 2003. 'Monte Carlo Simulation'. In *Encyclopedia of Information Systems*, edited by Hossein Bidgoli, 193–201. New York: Elsevier. <https://doi.org/10.1016/B0-12-227240-4/00114-3>.
- Mutoti, Grace, J. Dietz, Syed Imran, and James Taylor. 2007. 'Pilot-Scale Verification and Analysis of Iron Release Flux Model'. *Journal of Environmental Engineering* 133 (February). [https://doi.org/10.1061/\(ASCE\)0733-9372\(2007\)133:2\(173\)](https://doi.org/10.1061/(ASCE)0733-9372(2007)133:2(173)).
- National Research Council. 2006. *Drinking Water Distribution Systems: Assessing and Reducing Risks*. Washington, DC: The National Academies Press. <https://doi.org/10.17226/11728>.
- Pandey, P., R. Mishra, and R. K. Chauhan. 2022. 'Future Prospects in the Implementation of a Real-Time Smart Water Supply Management and Water Quality Monitoring System'. *LARHYSS Journal P-ISSN 1112-3680 / E-ISSN 2521-9782*, no. 51 (September): 237–52.
- Patel, K., and D. Mehta. 2022. 'Design of the Continuous Water Supply System Using Watergems Software: A Case Study of Surat City'. *LARHYSS Journal P-ISSN 1112-3680 / E-ISSN 2521-9782*, no. 50 (June): 125–36.
- Pérez-Pérez, E.J., F.R. López-Estrada, G. Valencia-Palomo, L. Torres, V. Puig, and J.D. Mina-Antonio. 2021. 'Leak Diagnosis in Pipelines Using a Combined Artificial Neural Network Approach'. *Control Engineering Practice* 107 (February): 104677. <https://doi.org/10.1016/j.conengprac.2020.104677>.
- Rura-Porterfield, Melissa, Duane Marble, and David Alvarez. 2014. 'In Memoriam: Roger Tomlinson – “The Father of GIS” and the Transition to Computerized Geographic Information.' *Photogrammetric Engineering and Remote Sensing* 80 (May): 400–401.
- Saaty, Thomas L. 1980. *The Analytic Hierarchy Process: Planning, Priority Setting, Resources Allocation*. McGraw, New York.

- . 1988. ‘What Is the Analytic Hierarchy Process?’ In *Mathematical Models for Decision Support*, edited by Gautam Mitra, Harvey J. Greenberg, Freerk A. Lootsma, Marcel J. Rijkaert, and Hans J. Zimmermann, 109–21. Berlin, Heidelberg: Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-83555-1_5.
- . 2001. ‘Fundamentals of the Analytic Hierarchy Process’. In *The Analytic Hierarchy Process in Natural Resource and Environmental Decision Making*, edited by Daniel L. Schmoldt, Jyrki Kangas, Guillermo A. Mendoza, and Mauno Pesonen, 15–35. *Managing Forest Ecosystems*. Dordrecht: Springer Netherlands. https://doi.org/10.1007/978-94-015-9799-9_2.
- . 2008. ‘Decision Making with the Analytic Hierarchy Process’. *International Journal of Services Sciences* 1 (1): 83. <https://doi.org/10.1504/IJSSCI.2008.017590>.
- Sebert, Louis. 1999. *Mapping a Northern Land: The Survey of Canada, 1947-1994*. Edited by Gerald McGrath and Louis M. Sebert. First Edition. Montreal ; Ithaca: McGill-Queen’s University Press.
- Şener, Şehnaz, Erhan Şener, Bilgehan Nas, and Remzi Karagüzel. 2010. ‘Combining AHP with GIS for Landfill Site Selection: A Case Study in the Lake Beyşehir Catchment Area (Konya, Turkey)’. *Waste Management* 30 (11): 2037–46. <https://doi.org/10.1016/j.wasman.2010.05.024>.
- Solutions, DTK Hydronet. 2019. ‘What Are District Metered Areas (DMA)?’ DTK Hydronet Solutio. 4 June 2019. <https://www.dtkhydronet.com/post/what-are-district-metered-areas-dma>.
- Sonaje, Nitin P, and Mandar G Joshi. 2015. ‘A REVIEW OF MODELING AND APPLICATION OF WATER DISTRIBUTION NETWORKS (WDN) SOFTWARES’ 3 (5): 5.

- Sorokine, Alexandre, and Kurt Ackermann. 2000. 'Scripting in GIS Applications: Experimental Standards-Based Framework for Perl'. In *Proceedings of the Eighth ACM International Symposium on Advances in Geographic Information Systems - GIS '00*, 102–7. Washington, D.C., United States: ACM Press. <https://doi.org/10.1145/355274.355289>.
- Tarigan, A P M, D Rahmad, R A Sembiring, and R Iskandar. 2018. 'An Application of the AHP in Water Resources Management: A Case Study on Urban Drainage Rehabilitation in Medan City'. *IOP Conference Series: Materials Science and Engineering* 309 (February): 012096. <https://doi.org/10.1088/1757-899X/309/1/012096>.
- 'The History of Geographic Information Systems (GIS) | BCS'. n.d. Accessed 20 November 2021. <https://www.bcs.org/articles-opinion-and-research/the-history-of-geographic-information-systems-gis/>.
- Tomlinson, R. F. 1974. 'Geographical Information Systems, Spatial Data Analysis and Decision Making in Government'. *Doctoral Thesis, University of London*. Doctoral, University of London. <https://discovery.ucl.ac.uk/id/eprint/1563584/>.
- Tomlinson, R.F., H.W. Calkins, and Duane Marble. 1976. *Computer Handling of Geographic Data: An Examination of Selected Geographic Information Systems*.
- Toms, Silas. 2015. *ArcPy and ArcGIS – Geospatial Analysis with Python*. Packt Publishing Ltd.
- Tscheikner-Gratl, Franz, Patrick Egger, Wolfgang Rauch, and Manfred Kleidorfer. 2017. 'Comparison of Multi-Criteria Decision Support Methods for Integrated Rehabilitation Prioritization'. *Water* 9 (2): 68. <https://doi.org/10.3390/w9020068>.
- Tsihrintzis, Vassilios, Rizwan Hamid, and Hector Fuentes. 1996. 'Use of Geographic Information Systems (GIS) in Water Resources: A Review'. *Water Resources Management* 10 (January): 251–77. <https://doi.org/10.1007/BF00508896>.
- 'Understanding and Managing Losses in Water Distribution Networks'. 2003. WaterWorld. 1 September 2003. <https://www.waterworld.com/drinking-water/infrastructure->

funding/article/16200323/understanding-and-managing-losses-in-water-distribution-networks.

- Vreeburg, J., and Joby Boxall. 2007. 'Discolouration in Potable Water Distribution Systems: A Review'. *Water Research* 41 (March): 519–29. <https://doi.org/10.1016/j.watres.2006.09.028>.
- Wang, Y. 2013. '24 - Seismic Risk Assessment of Water Supply Systems'. In *Handbook of Seismic Risk Analysis and Management of Civil Infrastructure Systems*, edited by S. Tesfamariam and K. Goda, 659–84. Woodhead Publishing Series in Civil and Structural Engineering. Woodhead Publishing. <https://doi.org/10.1533/9780857098986.4.659>.
- Yin, Chenggang, and Alison Mckay. 2018. 'Introduction to Modeling and Simulation Techniques'. In .
- Yoo, Do Guen, Ho Min Lee, Ali Sadollah, and Joong Hoon Kim. 2015. 'Optimal Pipe Size Design for Looped Irrigation Water Supply System Using Harmony Search: Saemangeum Project Area'. *The Scientific World Journal* 2015: 1–10. <https://doi.org/10.1155/2015/651763>.
- Zandbergen, Paul A. 2015. *Python Scripting for ArcGIS*. Esri Press.
- Zhang, Mingda, Peng Yue, and Xia Guo. 2014. 'GIScript: Towards an Interoperable Geospatial Scripting Language for GIS Programming'. In *2014 The Third International Conference on Agro-Geoinformatics*, 1–5. Beijing, China: IEEE. <https://doi.org/10.1109/Agro-Geoinformatics.2014.6910592>.
- Zhou, Weifeng, Yingxue Li, Juan Hou, Wei Fan, Liangqi Xu, and Weiping Xiao. 2019. 'Automated Cartography of Fisheries Oceanographic Atlas Using ArcPy Based on Global Time Series Grid Data of Marine Environment'. *IOP Conference Series: Earth and Environmental Science* 234 (March): 012023. <https://doi.org/10.1088/1755-1315/234/1/012023>.

Zolfaghary, Parvin, Mahdi Zakerinia, and Hossein Kazemi. 2021. 'A Model for the Use of Urban Treated Wastewater in Agriculture Using Multiple Criteria Decision Making (MCDM) and Geographic Information System (GIS)'. *Agricultural Water Management* 243 (January): 106490. <https://doi.org/10.1016/j.agwat.2020.106490>.

Zyoud, Shaher H., Hafez Shaheen, Subhi Samhan, Ayman Rabi, Firas Al-Wadi, and Daniela Fuchs-Hanusch. 2016. 'Utilizing Analytic Hierarchy Process (AHP) for Decision Making in Water Loss Management of Intermittent Water Supply Systems'. *Journal of Water, Sanitation and Hygiene for Development* 6 (4): 534–46. <https://doi.org/10.2166/washdev.2016.123>.