

ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

**INVESTIGATION OF MANAGED AQUIFER RECHARGE SITE
SUITABILITY THROUGH MULTI-TIERED DECISION MAKING
APPROACH**



Ph.D. THESIS

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Department of Civil Engineering

Hydraulics and Water Resources Engineering Programme

OCTOBER 2023

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**YÖNETİLEN AKİFER BESLEME SAHASI UYGUNLUĞUNUN ÇOK
KRİTERLİ KARAR VERME YAKLAŞIMI İLE İNCELENMESİ**

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To my parents, spouse, and Sohan.



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ABBREVIATIONS

AHP	: Analytic Hierarchy Process
ANP	: Analytic Network Process
DI	: DRASTIC Index
DSS	: Decision Support Systems
EDAS	: Evaluation based on Distance from Average Solution
FGD	: Focus Group Discussion
FIS	: Fuzzy Inference System
FL	: Fuzzy Logic
FR	: Frequency Ratio
GIS	: Geographical Information Systems
MAR	: Managed Aquifer Recharge
MCDA	: Multi-Criteria Decision Analysis
MSL	: MAR Suitability Index
PROMETHEE	: Preference Ranking Organization Method for Enrichment Evaluations
RWH	: Rainwater Harvesting
SAW	: Simple Additive Weighting
TOPSIS	: Technique for Order of Preference by Similarity to Ideal Solution
VIKOR:	: VlseKriterijumska Optimizacija I Kompromisno Resenje
VZR	: Vadose Zone Recharge
WLC	: Weighted Linear Combination
WOA	: Weighted Overlay Analysis



SYMBOLS

CR	: Consistency Ratio
RI	: Random Index
λ_{max}	: Maximum Eigenvalue
M_{gi}^j	: Triangular Fuzzy Numbers
l_{ij}, m_{ij}, u_{ij}	: Lower, Mean, and Upper width of the Fuzzy Equivalents
S_i	: Fuzzy Synthetic Extent
r_{ij}	: Normalized Evaluation Matrix
A^+	: Positive Ideal Solution
A^-	: Negative Ideal Solution
d_i^+	: Shortest Geometric Distance to the Positive Ideal Solution
d_i^-	: longest geometric distance to the negative ideal solution
CC_i	: Closeness Coefficient
A_{ij}	: Decision Matrix
Q_i	: VIKOR Index
f_i^+	: Best Value
f_i^-	: Worst Value



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INVESTIGATION OF MANAGED AQUIFER RECHARGE SITE SUITABILITY THROUGH MULTI-TIERED DECISION MAKING APPROACH

SUMMARY

Globally, groundwater resources encounter notable challenges encompassing issues of chemical contamination, depletion, anthropogenic activities, and seawater intrusion. These challenges are further exacerbated by the prevailing arid climatic conditions and rapid population growth, resulting in restricted recharge and substantial overdraft, respectively. Consequently, the implementation of sustainable measures becomes imperative to facilitate the efficacious and enduring stewardship of these invaluable resources. While diverse management strategies have been proposed and adopted worldwide over the years to contend with these threats, ranging from optimizing pumping rates to enhancing water use efficiency, managed aquifer recharge (MAR) stands out today as one of the most promising technological approaches for addressing the degradation of subsurface resources. MAR entails the injection of reclaimed water (such as stormwater and treated wastewater) into the aquifer via various recharge structures, either for subsequent retrieval during dry period or for environmental enhancement purposes.

Besides their acknowledged efficacy in replenishing stressed aquifers, MAR technologies are highly susceptible to instances of failure or suboptimal performance if not meticulously executed within appropriate sites. The process of identifying suitable locations for the construction of recharge facilities is notably intricate, owing to the multitude of decision parameters at play. This challenge is further compounded in countries where MAR remains a novice subject, thereby amplifying the complexity of the task. The exploration of MAR potential through the utilization of integrated geographic information system and multi-criteria decision analysis (GIS-MCDA) techniques is acknowledged within the research community as a valuable and insightful approach. Nonetheless, the MCDA-based decision frameworks proposed in the pertinent literature often lack robust mathematical underpinnings. Furthermore, while the mapping of MAR site suitability is commonly conducted at the watershed level, its implementation at the national and urban scales tends to be overlooked. Hence, besides providing an in-depth literature survey about the state of the art in GIS-MCDA based MAR sites suitability mapping, the studies encompassed within this thesis introduce novel and holistic contributions to the scholarly discourse, spanning both conceptual and methodological dimensions.

Within the scope of this thesis, robust and reliable multi-tiered decision making frameworks designed to evaluate the potential of MAR across diverse geographical scales, encompassing national, watershed, and city extend were proposed. Moreover, we introduced a coupled groundwater vulnerability and MAR potential mapping model for the sack of identifying promising regions with minimized vulnerability to contamination for MAR implementation. In the first study conducted in this thesis, a

robust approach that combines fuzzy analytical hierarchy process (AHP) and technique for order of preference by similarity to ideal solution (TOPSIS) to delineate suitable sites for MAR structures at a countrywide scale was proposed. The proposed model is applied to Djibouti, a hot, dry, and water-stressed country. A set of nine decision criteria were identified and a pairwise comparison survey was conducted to determine their relative importance. Additionally, the TOPSIS method was employed to integrate the decision layers and prioritize the study area. The results highlight the significance of rainfall, slope, and NDVI as the most influential decision parameters, while drainage density has the least impact. The suitability analysis reveals that 10.63%, 23.20%, and 31.06% of the country have very high, high, and moderate potential for MAR activities, respectively. Furthermore, an evaluation of viable MAR technologies within the nation is conducted based on the specific conditions prevailing in Djibouti.

At the watershed level, the second study within this thesis focuses on a significant MAR technology extensively employed in arid and semi-arid regions: rainwater harvesting (RWH). RWH offers a promising strategy to address the pervasive challenge of water scarcity in such regions. It involves capturing stormwater for domestic and agricultural use while contributing to aquifer replenishment. In this research, a hybrid approach is proposed, integrating fuzzy AHP and VlseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR) algorithms. This approach is implemented in the water-stressed southeastern basin of Djibouti. This study represents the pioneering endeavor to comprehensively assess RWH potential in Djibouti. Despite existing RWH practices in the country, their implementation often lacks robust scientific foundations, resulting in reduced effectiveness and operational vulnerabilities. A hierarchical structure with 12 decision parameters is formulated, organized into 3 dimensions: physical, environmental, and socio-economic. These dimensions are further divided into 4 specific criteria, establishing a comprehensive framework for addressing the complex issue. Notably, this research extends the incorporation of socio-economic parameters beyond constraint mapping, encompassing suitability analysis as well. Additionally, the application of the VIKOR algorithm for RWH mapping is unprecedented in the literature, marking a pioneering contribution. Findings highlight the significance of the environmental (47.67%) and physical (37.98%) dimensions, with the socio-economic cluster (14.35%) exhibiting lower importance in the fuzzy AHP analysis. Also, the suitability map reveals a substantial area, approximately 872.5 km², with moderate to very high suitability for various RWH structures like check dams, percolation tanks, and terracing.

Regarding the third study, the potential of drywells in an urban environment was investigated using multi-tiered decision approach. In fact, despite existing several MAR technologies, land availability for installation and limited municipal budget restrict their usage, especially in urbanized areas. Consequently, drywells emerge as a highly regarded solution for replenishing stressed shallow urban aquifers, primarily owing their reputation to their minimal land requirement and cost-effectiveness aligned with municipal budgets. Nevertheless, the widespread implementation of drywells is hampered by the absence of comprehensive guidelines and frameworks governing their siting. In this third research endeavor, a coupled fuzzy AHP and TOPSIS model is proposed to identify favorable zones for drywell construction in the urban city of Kayseri, Turkey—an area prone to declining water tables. It is noteworthy that this research represents the initial attempt in investigating the site suitability of drywells through an integrated GIS-MCDA technique. Based on an in-

depth literature survey and technical reports relevant decision criteria were selected and their relative weights were determined through the fuzzy AHP. The results indicated that hydraulic conductivity, depth to groundwater, soil texture, and land use/land cover were the most determining criteria with 33.9%, 17.8%, 11.2%, and 10.1% of weights, respectively. The validation of these criterion weights was conducted by comparing them with those from previous MAR suitability mapping efforts in relevant literature. Additionally, a sensitivity analysis was performed to underscore the robustness and stability of the findings under various degrees of fuzziness. Finally, the study area was divided into 54 sub-regions based on the road-network of the city and the TOPSIS was applied to prioritize the sub-regions to help identify promising areas for the vadose zone wells construction.

Concerning the fourth study in this thesis, a combined groundwater vulnerability and MAR sites suitability mapping model was introduced in the pertinent literature. Notably, while drywells stand out as a superior MAR technology in urban environments, the task of identifying appropriate locations with minimal susceptibility to contamination for drywell projects presents an intricate challenge. Hence, the present research proposes a framework encapsulating the combined assessment of groundwater vulnerability and MAR sites suitability analysis to pinpoint the most featured areas for installing drywells in Kayseri, Turkey. To extrapolate the vulnerable zones, not only the original DRASTIC but also its MCDA based modified variants were evaluated with regard to different hydrochemical parameters using the area under the receiver operating characteristic (ROC) curve (AUC). Besides, the fuzzy AHP rationale was adopted to signify the importance level of criteria and the robustness of the framework was highlighted with sensitivity analysis. In addition, the decision layers and the attained vulnerability layer were combined using the weighted overlay (WOA). The findings indicate that the DRASTIC-SWARA correlates well with the arsenic (AUC=0.856) and chloride (AUC=0.648) and was adopted as the vulnerability model. Groundwater quality parameters such as chloride and sodium adsorption ratio, as well as the vadose zone thickness, were found to be the most significant decision parameters with importance levels of 16.75%, 14.51%, and 15.73%, respectively. Overall, 28.24% of the study area was unsuitable for recharge activities with high to very high vulnerability, while the remaining part was further prioritized into low to high suitability classes for MAR application. The proposed framework offers valuable tool to decision makers for the delineation of favorable MAR sites with minimized susceptibility to contamination.

The decision frameworks proposed within this thesis empower policy-makers and stakeholders to efficiently discern and prioritize regions exhibiting promising MAR potential across various geographical scales. Particularly, the outcomes from the initial two investigations in this thesis hold primary relevance for Djibouti's water resources authorities, aimed at bolstering sustainable water resource management through MAR and RWH strategies in the country. Regarding the third study, it is believed that the proposed GIS-based hybrid MCDA framework in delineating sites favorable for drywells construction can be adopted by municipalities lacking guidelines and standards for siting drywells. Furthermore, it is anticipated that the integrated model presented in the final study of this thesis can facilitate the sustainable management of aquifers and contribute to the mitigation of water scarcity challenges in various global regions, all while minimizing the risk of MAR project failure due to the installation of recharge facilities in areas susceptible to groundwater contamination.



YÖNETİLEN AKİFER BESLEME SAHASI UYGUNLUĞUNUN ÇOK KRİTERLİ KARAR VERME YAKLAŞIMI İLE İNCELENMESİ

ÖZET

Küresel olarak, yeraltı suyu kaynakları kimyasal kirlenme, tükenme, antropojenik faaliyetler ve deniz suyu girişi konularını kapsayan önemli zorluklarla karşı karşıyadır. Bu zorluklar, hakim olan kurak iklim koşulları ve hızlı nüfus artışı ile daha da şiddetlenmekte ve sırasıyla kısıtlı yeniden besleme ve önemli ölçüde aşırı su çekimi ile sonuçlanmaktadır. Sonuç olarak, bu paha biçilmez kaynakların etkin ve kalıcı bir şekilde yönetilmesini kolaylaştırmak için sürdürülebilir önlemlerin uygulanması zorunlu hale gelmektedir. Bu tehditlerle mücadele etmek için yıllar boyunca dünya çapında pompalama oranlarının optimize edilmesinden su kullanım verimliliğinin artırılmasına kadar çeşitli yönetim stratejileri önerilmiş ve benimsenmiş olsa da, yönetilen akifer beslemesi (MAR) bugün yeraltı kaynaklarının bozulmasını ele almak için en umut verici teknolojik yaklaşımlardan biri olarak öne çıkmaktadır. MAR, kurak dönemlerde geri kazanım ya da çevresel iyileştirme amacıyla çeşitli besleme yapıları aracılığıyla akifere geri kazanılmış su (yağmur suyu ve arıtılmış atık su gibi) enjekte edilmesini gerektirir.

MAR teknolojileri, baskı altındaki akiferleri yenilemedeki kabul görmüş etkinliklerinin yanı sıra, uygun sahalarda titizlikle uygulanmadıkları takdirde başarısızlık veya optimum altı performans örneklerine karşı oldukça hassastır. Besleme tesislerinin inşası için uygun yerlerin belirlenmesi süreci, çok sayıda karar parametresinin devreye girmesi nedeniyle oldukça karmaşıktır. MAR'ın yeni bir konu olduğu ülkelerde bu zorluk daha da artmakta, dolayısıyla uygulamanın karmaşıklığı daha da artmaktadır. Entegre coğrafi bilgi sistemi ve çok kriterli karar analizi (GIS-MCDA) tekniklerinin kullanılması yoluyla MAR potansiyelinin araştırılması, araştırma camiasında değerli ve gerekli bir yaklaşım olarak kabul edilmektedir. Bununla birlikte, ilgili literatürde önerilen MCDA tabanlı karar çerçeveleri genellikle sağlam matematiksel temellerden yoksundur. Ayrıca, MAR sahasının uygunluğunun haritalanması genellikle havza düzeyinde gerçekleştirilirken, ulusal ve kentsel ölçeklerde uygulanması göz ardı edilme eğilimindedir. Bu nedenle, GIS-MCDA tabanlı MAR sahaları uygunluk haritalamasında son teknoloji hakkında derinlemesine bir literatür araştırması sunmanın yanı sıra, bu tez kapsamında yer alan çalışmalar, hem kavramsal hem de yöntemsel boyutları kapsayan bilimsel söyleme yeni ve bütünsel katkılar sunmaktadır.

Bu tez kapsamında, ulusal, havza ve şehir ölçeğini kapsayan çeşitli coğrafi ölçeklerde MAR potansiyelini değerlendirmek için tasarlanmış sağlam ve güvenilir çok katmanlı karar verme yaklaşımları önerilmiştir. Ayrıca, MAR uygulaması için kirlenmeye karşı hassasiyeti en aza indirilmiş umut vaat eden bölgelerin belirlenmesi amacıyla birleştirilmiş bir yeraltı suyu hassasiyeti ve MAR potansiyeli haritalama modeli tanıtılmıştır. Bu tez kapsamında yürütülen ilk çalışmada, ülke ölçeğinde MAR yapıları için uygun alanların belirlenmesi amacıyla bulanık analitik hiyerarşi süreci (AHP) ve

ideal çözüme benzerlik yoluyla tercih sıralaması tekniğini (TOPSIS) birleştiren sağlam bir yaklaşım önerilmiştir. Önerilen model, sıcak, kurak ve su sıkıntısı çeken bir ülke olan Cibuti'ye uygulanmıştır. Dokuz farklı karar kriteri belirlenmiş ve bunların göreceli önemini belirlemek için ikili karşılaştırma anketi yapılmıştır. Ayrıca, karar katmanlarını entegre etmek ve çalışma alanını önceliklendirmek için TOPSIS yöntemi kullanılmıştır. Sonuçlar, yağış, eğim ve yaprak alan endeksinin (NDVI) en etkili karar parametreleri olarak önemini vurgularken, drenaj yoğunluğu en az etkiye sahiptir. Uygunluk analizi, ülkenin %10,63'ünün, %23,20'sinin ve %31,06'sının MAR faaliyetleri için sırasıyla çok yüksek, yüksek ve orta potansiyele sahip olduğunu ortaya koymaktadır. Ayrıca, Cibuti'de geçerli olan özel koşullara dayalı olarak ülke içinde uygulanabilir MAR teknolojilerinin bir değerlendirmesi yapılmıştır.

Havza düzeyinde, bu tez kapsamındaki ikinci çalışma, kurak ve yarı kurak bölgelerde yaygın olarak kullanılan ve önemli MAR teknolojilerinden biri olan yağmur suyu hasadına (RWH) odaklanılmıştır. RWH, bu tür bölgelerdeki yaygın su kıtlığı sorununu ele almak için umut verici bir strateji sunmaktadır. Akiferlerin yenilenmesine katkıda bulunurken evsel ve tarımsal kullanım için yağmur suyunun tutulmasını içerir. Bu araştırmada, bulanık AHP ve Vlsekriterijumska Optimizacija I Kompromisno Resenje (VIKOR) algoritmalarını entegre eden hibrit bir yaklaşım önerilmektedir. Bu yaklaşım, Cibuti'nin su sıkıntısı çeken güneydoğu havzasında uygulanmıştır. Bu çalışma, Cibuti'deki RWH potansiyelini kapsamlı bir şekilde değerlendirmek için öncü bir çabayı temsil etmektedir. Ülkedeki mevcut RWH uygulamalarına rağmen, bunların uygulanması genellikle sağlam bilimsel temellerden yoksundur ve bu da etkinliğin azalmasına ve operasyonel kırılganlıklara neden olmaktadır. Fiziksel, çevresel ve sosyo-ekonomik olmak üzere 3 boyutta organize edilen 12 karar parametresine sahip hiyerarşik bir yapı formüle edilmiştir. Bu boyutlar ayrıca 4 spesifik kritere bölünerek karmaşık bir konunun ele alınması için kapsamlı bir çerçeve oluşturulmuştur. Özellikle, bu araştırma sosyo-ekonomik parametrelerin dahil edilmesini kısıt haritalamanın ötesine taşıyarak uygunluk analizini de kapsamaktadır. Ayrıca, RWH haritalaması için VIKOR algoritmasının uygulanması literatürde daha önce görülmemiş olup öncü bir katkıdır. Bulgular, çevresel (%47,67) ve fiziksel (%37,98) boyutların önemini vurgularken, sosyo-ekonomik kümenin (%14,35) bulanık AHP analizinde daha düşük bir öneme sahip olduğunu göstermektedir. Ayrıca, uygunluk haritası, kontrol barajları, perkolasyon tankları ve teraslama gibi çeşitli RWH yapıları için orta ila çok yüksek uygunluğa sahip yaklaşık 872,5 km²'lik önemli bir alanı ortaya koymaktadır.

Üçüncü çalışmada ise kuru kuyuların kentsel ortamdaki potansiyeli çok katmanlı karar yaklaşımı kullanılarak araştırılmıştır. Aslında, mevcut çeşitli MAR teknolojilerine rağmen, kurulum için arazi mevcudiyeti ve sınırlı belediye bütçesi, özellikle şehirleşmiş alanlarda kullanımlarını kısıtlamaktadır. Sonuç olarak, kuru kuyular, öncelikle minimum arazi gereksinimi ve belediye bütçeleriyle uyumlu maliyet etkinliği nedeniyle, baskı altındaki sıkı kentsel akiferlerin yenilenmesi için oldukça saygın bir çözüm olarak ortaya çıkmaktadır. Bununla birlikte, kuru kuyuların yaygın bir şekilde uygulanması, konumlarını düzenleyen kapsamlı kılavuzların ve çerçevelerin bulunmaması nedeniyle engellenmektedir. Bu üçüncü araştırma çalışmasında, yeraltı su seviyesinin düşme eğilimi gösterdiği Kayseri (Türkiye) kentinde kuru kuyu inşası için uygun bölgeleri belirlemek üzere birleşik bir bulanık AHP ve TOPSIS modeli önerilmektedir. Bu araştırmanın, entegre bir GIS-MCDA tekniği aracılığıyla kuru kuyuların saha uygunluğunun araştırılmasına yönelik ilk girişimi temsil etmesi dikkat çekicidir. Derinlemesine bir literatür araştırmasına ve

teknik raporlara dayanarak ilgili karar kriterleri seçilmiş ve bunların göreceli ağırlıkları bulanık AHP aracılığıyla belirlenmiştir. Sonuçlar, hidrolik iletkenlik, yeraltı suyu derinliği, toprak dokusu ve arazi kullanımı/arazi örtüsünün sırasıyla %33,9, %17,8, %11,2 ve %10,1 ağırlıklarla en belirleyici kriterler olduğunu göstermiştir. Bu kriter ağırlıklarının doğrulanması, ilgili literatürdeki önceki MAR uygunluk haritalama çalışmalarından elde edilenlerle karşılaştırılarak gerçekleştirilmiştir. Ayrıca, çeşitli bulanıklık dereceleri altında bulguların sağlamlığını ve istikrarını vurgulamak için bir duyarlılık analizi yapılmıştır. Son olarak, çalışma alanı şehrin yol ağına dayalı olarak 54 alt bölgeye ayrılmış ve vadoz bölge kuyularının inşası için umut verici alanların belirlenmesine yardımcı olmak üzere alt bölgelere öncelik vermek için TOPSIS uygulanmıştır.

Bu tezdeki dördüncü çalışma ile ilgili olarak, ilgili literatürde birleşik bir yeraltı suyu hassasiyeti ve MAR sahaları uygunluk haritalama modeli tanıtılmıştır. Özellikle, kuru kuyular kentsel ortamlarda üstün bir MAR teknolojisi olarak öne çıkarken, kuru kuyu projeleri için kirlenmeye en az duyarlı uygun yerleri belirleme görevi karmaşık bir zorluk teşkil etmektedir. Bu nedenle, bu araştırma, Kayseri'de kuru kuyu kurulumu için en özellikli alanları belirlemek amacıyla yeraltı suyu hassasiyeti ve MAR sahaları uygunluk analizinin birleşik değerlendirmesini kapsayan bir çerçeve önermektedir. Hassas bölgeleri tahmin etmek için, sadece orijinal DRASTIC değil, aynı zamanda MCDA tabanlı modifiye edilmiş varyantları da alıcı işletim karakteristiği (ROC) eğrisi (AUC) altındaki alan kullanılarak farklı hidrokimyasal parametreler açısından değerlendirilmiştir. Ayrıca, kriterlerin önem seviyesini belirtmek için bulanık AHP mantığı benimsenmiş ve duyarlılık analizi ile çerçevenin sağlamlığı vurgulanmıştır. Buna ek olarak, karar katmanları ve elde edilen hassasiyet katmanı ağırlıklı bindirme (WOA) kullanılarak birleştirilmiştir. Bulgular DRASTIC-SWARA'nın arsenik (AUC=0.856) ve klorür (AUC=0.648) ile iyi korelasyon gösterdiğini ve hassasiyet modeli olarak benimsendiğini ortaya koymaktadır. Klorür ve sodyum adsorpsiyon oranı gibi yeraltı suyu kalitesi parametrelerinin yanı sıra vadoz zon kalınlığı sırasıyla %16,75, %14,51 ve %15,73 önem düzeyleriyle en önemli karar parametreleri olarak bulunmuştur. Genel olarak, çalışma alanının %28,24'ü yüksek ila çok yüksek hassasiyete sahip şarj faaliyetleri için uygun değilken, kalan kısım MAR uygulaması için düşük ila yüksek uygunluk sınıflarına göre önceliklendirilmiştir. Önerilen yaklaşım, kirlenmeye karşı duyarlılığı en aza indirilmiş uygun MAR sahalarının belirlenmesi için karar vericilere değerli bir araç sunmaktadır.

Bu tezde önerilen karar çerçeveleri, politika yapıcılara ve paydaşlara çeşitli coğrafi ölçeklerde umut verici MAR potansiyeli sergileyen bölgeleri etkin bir şekilde ayırt etme ve önceliklendirme yetkisi vermektedir. Özellikle, bu tezdeki ilk iki araştırmanın sonuçları, ülkedeki MAR ve RWH stratejileri yoluyla sürdürülebilir su kaynakları yönetimini desteklemeyi amaçlayan Cibuti'nin su kaynakları yetkilileri için birincil öneme sahiptir. Üçüncü çalışma ile ilgili olarak, kuru kuyu inşası için uygun alanların belirlenmesinde önerilen GIS tabanlı hibrit MCDA çerçevesinin, kuru kuyuların oturtulması için kılavuz ve standartlardan yoksun belediyeler tarafından benimsenebileceğine inanılmaktadır. Ayrıca, bu tezin son çalışmasında sunulan entegre modelin, akiferlerin sürdürülebilir yönetimini kolaylaştırabileceği ve çeşitli küresel bölgelerdeki su kıtlığı sorunlarının azaltılmasına katkıda bulunabileceği ve aynı zamanda yeraltı suyu kirliliğine duyarlı alanlarda şarj tesislerinin kurulması nedeniyle MAR projesinin başarısız olma riskini en aza indirebileceği öngörülmektedir.



1. INTRODUCTION

1.1 Motivation

The existing research recognizes that the global population is projected to experience a significant increase in the forthcoming years, with the majority of individuals expected to reside in urbanized areas (Lall et al., 2020). This substantial growth in population engenders significant challenges to fresh water resources, underscoring the imperative for the implementation of long-term water sustainability practices to ensure the protection of water resources (Bekele et al., 2018; Dillon et al., 2019). Despite elaborative management and acknowledgement of surface waters (e.g., rivers, streams, lakes, etc.), the sustainability of groundwater does not seem to have the same success (Howard, 2015). Associatively, groundwater resources have been subject to severe challenges, including chemical contamination, depletion, anthropogenic activities, and seawater intrusion (Ahmed & Altunkaynak, 2020; Lall et al., 2020; Vigna, 2022) in recent decades. In addition to impacting the availability of subsurface resources, these challenges also have a detrimental effect on the quality of groundwater resources, rendering them less suitable for human consumption and irrigation.

Different groundwater management strategies were proposed to mitigate the threads faced by subsurface resources ranging from pumping rates optimization, water use efficiency measures, and groundwater governance frameworks (Frija et al., 2014; Lall et al., 2020). However, managed aquifer recharge (MAR), formerly named artificial recharge (Bouwer, 2002), is one of the rewarding alternative technologies that can not only deal with the threats jeopardizing the amount of available groundwater resources but also enhance groundwater recharge. Therefore, MAR has been applied as a mechanism to replenish stressed aquifers, limit seawater intrusions, scale down land subsidence, and store excess water during the wet season (Bachtouli & Comte, 2019; Papadopoulos et al., 2022; Shi et al., 2016; Wendt et al., 2021), as well as being a sustainable urban water management technology (Page et al., 2018). The International Association of Hydrogeologists Commission on Managing Aquifer Recharge (IAH

Commission on MAR, 2019) defined MAR as "*the purposeful recharge of water to aquifers for subsequent recovery or environmental benefit*". According to Dillon et al. (2019), MAR implementations cover many technologies popularly applied to recover overtaxed groundwater systems (Figure 1.1). Bouwer (2002) also provided the simplest classification of artificial recharge systems by dividing them into three main groups, i.e., surface infiltration, vadose zone recharge (VZR), and direct injection, where water is directly introduced to the aquifer through deep wells.

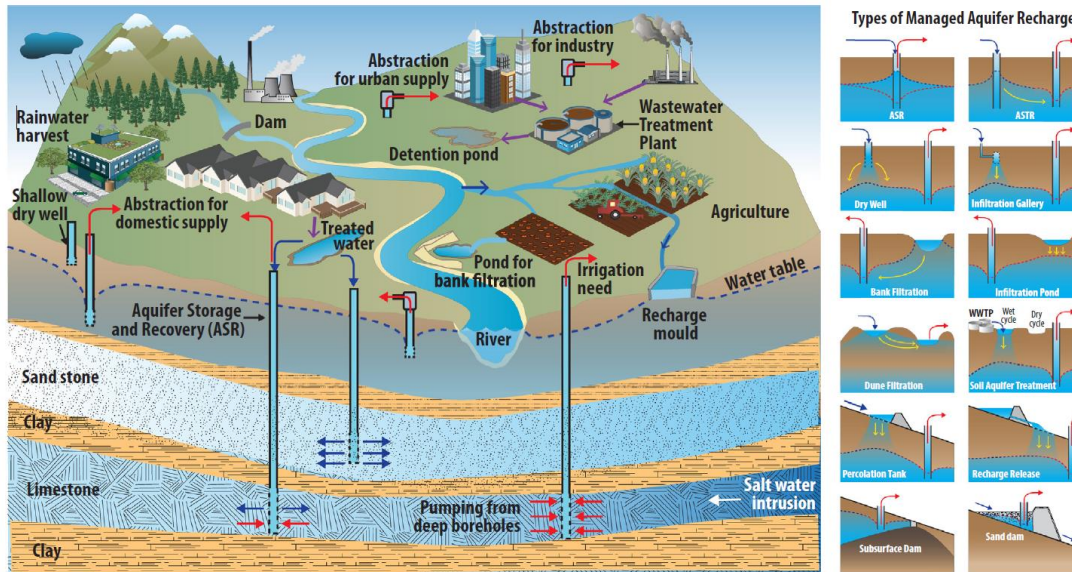


Figure 1.1 : Illustrative depictions of varied managed aquifer recharge (MAR) technologies (source: Alam et al. (2021)).

An example of a widely embraced MAR technology in arid and semi-arid regions is rainwater harvesting (RWH). RWH involves the collection and storage of storm runoff to augment the water supply for domestic and agricultural purposes, while also replenishing local aquifers (Ammar et al., 2016). Infiltration basins serve as another effective method of MAR, relying on the infiltration process whereby water is spread over wide areas using basins, dams, and channels to recharge an aquifer (Alam et al., 2021; Papadopoulos et al., 2022). In cases where confined layers are present, deep injection wells are commonly used to convey water to the aquifer system (Brown et al., 2005). To date, Aquifer Storage and Recovery (ASR) and Aquifer Storage Transfer and Recovery (ASTR) represent the prevailing deep injection MAR technologies that are being actively employed. On the other hand, vadose zone wells (i.e., drywells) offer advantages over other MAR techniques in recharging shallow urban aquifers due to their minimal land requirement and cost-effectiveness (Edwards et al., 2016; Händel

et al., 2016; Sasidharan et al., 2021). In general, Bouwer (Bouwer, 2002) asserts that the utilization of MAR systems offers numerous advantages compared to traditional water storage methods such as large dams. Artificial recharge of underground water via the MAR technology not only minimizes water loss due to evaporation but also enables a smaller spatial footprint requirement and enhanced long-term storage capacity with lower costs (Dillon et al., 2019).

The primary objective of the MAR projects is to inject as much reclaimed water into the system as possible. However, in addition to the physical parameters, the appropriate MAR technology for a particular project should be determined by considering the potential benefits and drawbacks. For instance, one of the challenges encountered in surface infiltration techniques is that they may lead to a loss of reclaimed water through evaporation due to their storage mechanisms (Edwards et.al. 2016). Also, they require permeable surfaces and consequent land availability making them less suited to urbanized environments. Despite these drawbacks, surface infiltration technologies offer the greatest capacity for attenuating contaminants, as opposed to deep injection systems which cause limited attenuation of pollutants implying water treatment before recharging, and thereby, inevitable additional costs. The VZR structures can be regarded as useful tools for urbanized areas, since the VZRs can be implemented with limited land impact and in impermeable areas while providing a certain level of contaminant attenuation in the vadose zone.

On the one hand, there are several benefits regarding the implementation of the MAR techniques to deal with the over-extracting of groundwater resources as addressed above. On the other hand, one of the major challenges during the design stage of a MAR project is to locate suitable sites due to the large number of factors affecting the site suitability of the MAR. Consequently, the research community has developed several approaches to tackle the corresponding issue. For example, Anbazhagan & Ramasamy (1997) utilized geophysical methods (particularly resistivity surveys) to identify appropriate sites for artificial recharge. Similarly, Christy & Lakshmanan (2017) employed electrical resistivity and ground penetrating radar methods to delineate feasible locations for MAR structures in Chennai, India, aiming to address saltwater intrusion. Brown et al. (2016), conversely, proposed a statistical analysis-based methodology to determine suitable sites for Aquifer Storage and Recovery (ASR) projects. In a different vein, Zaidi et al. (2015), Tiwari et al. (2017), and

Ahirwar et al. (2020) utilized an integrated geographic information system (GIS) and remote sensing methods to pinpoint promising regions for MAR activities. Nevertheless, the application of coupled GIS and multi-criteria decision analysis (GIS-MCDA) techniques can be regarded as one of the most embraced approaches in delineating sites favorable for MAR applications, recently. Hence, the ability of the GIS in storing and processing spatial data (L. K. Singh et al., 2017) and the robustness of MCDA methods in resolving multi-tiered decision-making problems (Malczewski & Rinner, 2015) make their integration rewarding alternative in identifying regions promising for MAR implementation.

Currently, the GIS-multi criteria decision analysis (GIS-MCDA) is widely regarded as the most promising and emerging alternative for identifying suitable sites for the implementation of MAR techniques (Sallwey, Bonilla Valverde, et al., 2019). The conflicts that arise from the presence of multi-disciplinary decision makers, particularly when defining the relative importance of decision criteria in MAR projects, can render traditional Decision Support Systems (DSS) and GIS techniques ineffective (Rahman et al., 2012). Therefore, the integration of GIS and MCDA rationale, which warrants rewarding approaches to resolve multi-tiered decision-making processes (Ekmekcioğlu et al., 2021), can yield more pragmatic outcomes that take both the spatial pattern of the decision alternatives and the value judgment of experts into account (Malczewski, 2006).

Nonetheless, certain limitations persist within the relevant body of literature. To begin with, on a spatial dimension, the evaluation of MAR potential has predominantly occurred at the scale of watersheds. However, it is imperative to emphasize the significance of examining MAR potential at a countrywide and city levels, particularly in regions where MAR is a novice concept (i.e. Horn of Africa, Turkey). Secondly, the contemporary MCDA based decision frameworks utilized to assess the potential of MAR often adhere to conventional paradigms, exhibiting a dearth of sophisticated mathematical foundations. Moreover, although pertinent literature covers extensive efforts that were devoted regarding the MCDA methodologies for some variants of the MAR techniques, such as surface infiltration and direct injection, little attention has paid concerning the VZR systems, notably drywells. Lastly, while the GIS-MCDA assessment for identifying suitable sites for MAR implementation have demonstrated effectiveness, it fails short in identifying vulnerable regions of the aquifer. Thus, it is

worth noting that the need to direct recharge efforts towards areas with the high suitability and low likelihood of vulnerability to contamination has still not been adequately addressed.

1.2 Objectives and Structure of the Thesis

The overarching goals of this thesis encompass the development of robust and reliable multi-tiered decision frameworks designed to delineate sites suitable for MAR structures on a national, watershed, and urban level. Moreover, the integration of groundwater vulnerability and MAR sites suitability models is another objective of the present thesis. The specific objectives of the thesis can be succinctly encapsulated in the ensuing manner:

- Conducting a comprehensive assessment of MAR potential mapping within the water-stressed nation of Djibouti on a national scale, alongside an exploration of the feasible MAR technologies in the country.
- Identifying regions with significant potential for rainwater harvesting (RWH), a prevalent MAR technique in arid and semi-arid zones, on a watershed scale, while concurrently integrating socio-economic parameters into the decision-making framework.
- Initiating the delineation of regions promising to the implementation of drywells within an urbanized context, achieved through a holistic multi-tiered decision framework, aimed at mitigating their limitations arising from the absence of adequate guidelines and standards governing the deployment of drywells in numerous countries.
- Integrating the DRASTIC model within the MAR potential mapping decision framework in order to prioritize the study area in terms of suitability while at the same time delineating the vulnerable zones of the aquifer.

Regarding the structure of the thesis, it can be outlined as follows:

Chapter 1 The first chapter provides a short description about the topic, the objectives and organization of the thesis, along with a comprehensive

review of the literature pertaining to the mapping of MAR potential as well as RWH site suitability mapping.

- Chapter 2 The MCDA algorithms used in this thesis are described in this chapter notably the fuzzy analytic hierarchy process (AHP), the technique for order of preference by similarity to ideal solution (TOPSIS), and the VlseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR) algorithms.
- Chapter 3 The third chapter encompasses the identification of favorable regions for the implementation of MAR practices within the hot dry country of Djibouti, spanning a nationwide scope. This assessment is carried out through the utilization of a hybrid approach that combines the fuzzy AHP with the TOPSIS method. Furthermore, an evaluation of the viable MAR technologies applicable within the country is undertaken, facilitated by the utilization of the web-based INOWAS platform.
- Chapter 4 The subsequent section, Chapter Four, contains the assessment of RWH potential on the southeastern basin of Djibouti as a means to mitigate water scarcity and water table decline. In contrast to the often adopted conventional MCDA methods, a coupled fuzzy AHP-VIKOR decision framework was proposed here to generate RWH maps, while considering physical, environmental, and socio-economic dimensions. Moreover, the practical application of the proposed framework is demonstrated, thereby offering valuable insights to both policymakers and decision-makers.
- Chapter 5 Drywells have proven their effectiveness and benefits compared to most MAR technologies in recharging shallow urban aquifers throughout the years, yet they are handicapped by the nonexistence of proper guidelines and standards regarding their implementation in most countries. Within the fifth chapter, an initial step was taken to introduce a multi-tiered decision framework aimed at identifying suitable locations for the construction of drywells. This framework was subsequently applied in the urban city of Kayseri.

Chapter 6 In chapter 6, an integrated groundwater vulnerability and MAR sites suitability mapping framework was introduced and implemented within the urban city of Kayseri. This approach pursued a dual objective: initially, vulnerable regions of the aquifer were identified using the DRASTIC model, effectively segregating them for subsequent evaluation, while concurrently, the remaining portions of the aquifer were subjected to a refined prioritization based on their MAR suitability, using a coupled fuzzy AHP and weighted overlay approach.

Chapter 7 Lastly, the final chapter of our thesis encompasses the provision of a succinct overview of the concluding remarks, followed by recommendations directed towards the research community. These recommendations pertain to the enhancement of the robustness of MAR mapping efforts in subsequent endeavors.

1.3 Literature Review

1.3.1 General review of GIS-MCDA based MAR opportunities mapping

To meet the groundwater resources induced challenges, several MAR tools have been developed by the research society. Stefan and Ansems (2018) established a MAR inventory portal (<http://marportal.un-igrac.org/>) by compiling and interpreting a total of 1200 MAR case studies from 63 countries. In this vein, one can access the relevant information, including site name, location, the operation year, MAR type, influent water source used for recharge, and the reference of each project, through the corresponding portal. The INOWAS research group also developed a different database (<https://inowas.com/tools/t04-database-for-gis-mcda/>) regarding the GIS-based MAR suitability mapping studies where details on MAR type, water source, criteria, and decision rule method considered in each study can be retrieved (Sallwey, Schlick, et al., 2019). Yet, these databases are not constantly updated and contain limited knowledge regarding the most recent GIS-MCDA-based MAR suitability mapping studies. Thus, the current research introduces a review of the recent attempts regarding the utilization of state-of-the-art technologies in MAR opportunities mapping (Table 1.1).

The methodologies for conducting MAR suitability mapping in the literature are quite varied, as noted by Sallwey et al. (2019). However, recent studies have shown widespread acceptance of the procedure proposed by Rahman et al. (2012). This procedure consists of four key decision steps (Figure 1.2), which are as follows:

(i) *Problem statement*: The initial step involves providing a general overview of the study area, clearly defining the purpose of the artificial recharge, and outlining the recharge techniques intended to address the identified problem.

(ii) *Constraint mapping*: The second step involves identifying and eliminating infeasible areas that may negatively impact the potential effectiveness of MAR before proceeding with the suitability assessment.

(iii) *Suitability mapping*: The third step involves identifying relevant decision criteria, determining the significance level of each criterion, and integrating the thematic layers of various parameters to create a suitability map that prioritizes the study area.

(iv) *Sensitivity analysis*: The final step involves conducting a sensitivity analysis to evaluate and assess the robustness and reliability of the decision analysis framework.

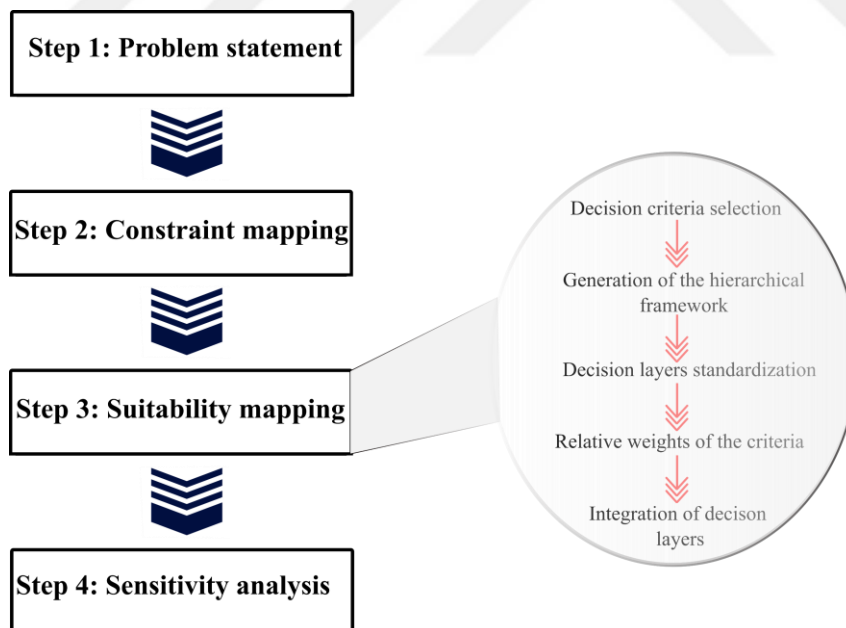


Figure 1.2 : MAR potential mapping procedure (adopted from Rahman et al. (2012)).

In the pertinent literature, water table decline and water scarcity are the principal reason for artificial recharge requirement in the vast majority of the existing studies

(Fuentes & Vervoort, 2020; Hussaini et al., 2021; Kamangar et al., 2019; Kharazi et al., 2019; Papadopoulos et al., 2022; Tahvili et al., 2021; Zhang et al., 2019). For instance, Aju et al. (2021) conducted an integrated GIS-MCDA approach and investigated the sites suitable to implement MAR structures for recharging the groundwater in the Vamanapuram River Basin (VRB), South India, that fall in the semi-critical category in terms of water scarcity and water table decline. In a similar vein, Zhang et al. (2019) explored viable sites for MAR interventions in the West Coast region of South Africa as a strategic response to the prevailing water scarcity challenge in the focalized area in their study. Moreover, Elewa et al. (2021) similarly explored the potential of MAR, particularly in the context of RWH technology, within the Wadi Watir basin located in the Sinai Peninsula of Egypt. This investigation was conducted as a proactive measure for mitigating the prevailing water crisis in the region. However, it is important to note that the motivations for MAR interventions in the scholarly discourse extend beyond the aforementioned factors. MAR sites suitability mapping studies further addressed other problems and/or reasons such as salinization (Kazakis, 2018), fluoride contamination (M. Arshad et al., 2022), groundwater sustainability (Phankamolsil et al., 2022) and emergency scenario (Soliman et al., 2022).

The constraint mapping phase is an important step in identifying suitable areas for artificial recharge, during which areas that are not suitable for recharge are eliminated for further consideration before starting the suitability mapping task. Sallwey et al. (2019) reported from 63 studies applying GIS-MCDA methods for MAR suitability mapping that 48% of them used constraint mapping as a tool to screen out infeasible regions. To exemplify, Nasiri et al. (2013) four layers including slope ($> 8\%$), geomorphology (rocky outcrops), alluvium thickness ($< 10\text{m}$) and land use (river bed and irrigated farming) were taken into account to determine the unfeasible areas. Ajjur and Mogheir (2020) present a demonstrative case wherein zones designated for recreational purposes, earmarked for tourism development, airports, built-up areas, nature reserves, and coastal areas were excluded from the suitability mapping process. Similarly, Soliman et al. (2022), adopted parameters such as surface slope, land use/land cover, unsaturated thickness, and distance from the pollution sources as constraint factors. In Figure 1.3, we provide a comprehensive compilation of the criteria employed in the existing literature to facilitate the process of site screening.

Nevertheless, criteria including slope, land use/land cover, geological characteristics, and distance from residential areas prominently emerge as widely adopted constraints in the identification of suitable sites for the implementation of MAR initiatives.

Furthermore, the criteria selected and decision rules applied for the suitability mapping phase show a significant diversity even when the considered MAR technology is the same. In line, Russo et al. (2015) highlighted that there is a lack of standard criteria set in MAR suitability mapping. For instance, Tahvili et al. (2021) and Chowdhury & Paul (2021) both investigated sites favorable for rainwater harvesting. On the one hand, Tahvili et al. (2021) found *water quality, groundwater drops, percentage of vegetation, average of annual rainfall, soil depth, soil permeability, soil texture, and electrical conductivity of soil* were among the most effective criteria for rainwater harvesting site delineation. On the other hand, *runoff, soil, slope, lineament density, drainage density, land use/landcover, distance from road, and distance from river* were the most driving factors in MAR suitability assessments concerning the study conducted by Chowdhury & Paul (2021). Yet, data availability and accessibility as well as the definition of the problem play a determinant role in the identification of the criteria set used in MAR studies (Bonilla Valverde, 2018; Rahman et al., 2012).

In another respect, Sallwey et al. (2019) reviewed the GIS-based MAR studies (available in the INOWAS database) and revealed that weighted linear combination (WLC), AHP, fuzzy logic (FL), decision tree, and PROMETHEE are the commonly applied techniques to locate the sites favorable for the MAR projects. For instance, Sandoval and Tiburan (2019) used the analytical hierarchy process (AHP) technique along the GIS to delineate sites suitable for MAR structures to address the groundwater depletion in Mount Makiling Forest Reserve, Philippines. Aju et al. (2021) similarly adopted the AHP to identify possible sites to construct recharge facilities to tackle water scarcity in the Vamanapuram River Basin (VRB), South India. They found that rainwater infiltration pits and injection wells are suitable for the western and north-central zones of the basin, while percolation ponds and pond-cum injection wells were deemed appropriate for the central regions. Soliman et al. (2022) employed the AHP to identify feasible MAR sites for emergency scenarios for Nuweiba alluvial aquifer, Sinai, Egypt. However, in recent years, other MCDA tools (such as fuzzy AHP, ANP, TOPSIS, EDAS, and SAW) were also employed in the MAR opportunities mapping as shown in Table 1.1. For instance, Kamangar et al. (2019) used ANP and AHP for

criteria weight assignment and TOPSIS method to overlay thematic layers, while Kharazi et al. (2019) applied different MCDA methods (such as AHP, TOPSIS, and EDAS) for prioritizing the sites suitable for underground dams in the Semnan plain, Iran. Furthermore, Hussaini et al. (2021) generated different MAR suitability maps based on three techniques, i.e., FL, AHP, and ANP. They found that the ANP-based map was more accurate and reliable compared to the maps generated through its counterparts. This result can inherently be associated with the fact that the AHP method disregards the interrelationship among criteria, while the ANP method takes the interrelationships into account during the construction of hierarchical representations (Ekmekcioğlu, Koc, & Özger, 2022). In addition, further attempts incorporated the fuzzy set theory introduced by Zadeh (1965) to minimize the uncertainties that exist in the complex decision-making mechanisms. Such that, Chowdhury and Paul (2021) delineated suitable sites for rainwater harvesting structures (i.e., ponds and pans, percolation tank, check dam, and nala-bunds) by the fuzzy AHP technique for criteria weight assessments and fuzzy gamma operator for combining the involved parameters. Similarly, Papadopoulos et al. (2022) applied the fuzzy AHP and FIS for the assignment of the weights considered and the delineation of the sites auspicious for infiltration basins, respectively.

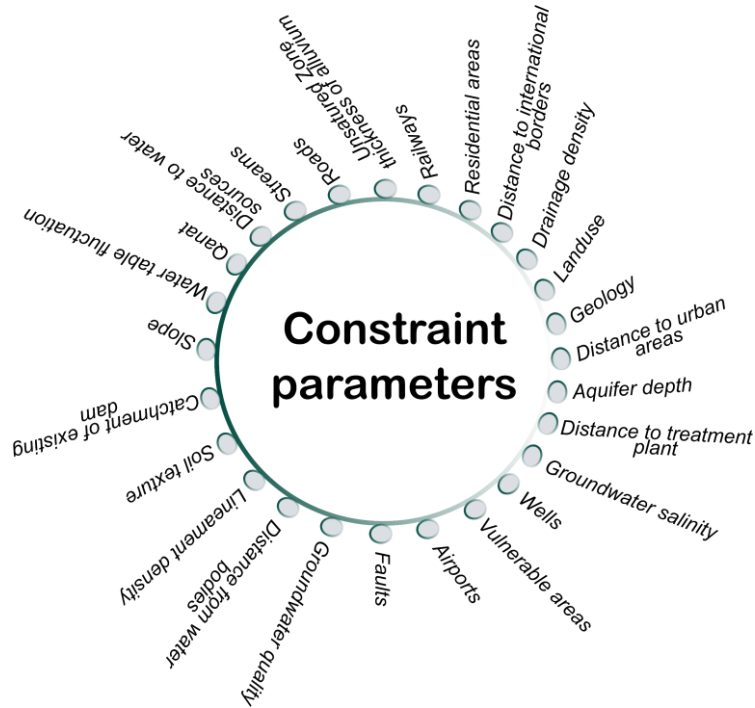


Figure 1.3 : List of constraint parameters adopted so far in MAR sites suitability mapping studies.

Table 1.1 : List of recent GIS-MCDA based studies on MAR site suitability mapping.

Reference	Country	Problem	Considered MAR technique	No. of decision criteria	Decision rule	Sensitivity
Ghazavi et al. (2018)	Iran	Water scarcity	Injection wells	5	FL	No
Kazakis (2018)	Greece	Aquifer salinization	Riverbank infiltration and infiltration bonds	10	AHP	Yes
Zhang et al. (2019)	South Africa	Water scarcity	Infiltration ponds	12	AHP and WLC	No
Sandoval & Tiburan (2019)	Philippines	Groundwater depletion	Injection wells	10	AHP	No
Kharazi et al. (2019)	Iran	Water scarcity	Underground dams	16	AHP, TOPSIS and EDAS	No
Kamangar et al. (2019)	Iran	Water table decline	N/A	10	ANP, AHP and TOPSIS	No
Fuentes & Vervoort (2020)	Australia	Water table decline	N/A	9	AHP	Yes
Shadmehri Toosi et al. (2020)	Iran	N/A	Ponds and pans, check dams, percolation tanks, nala-bunds, terracing, and gully plugs	6	AHP and WLC	No
Chowdhury & Paul (2021)	India	Drought	Rainwater harvesting	8	Fuzzy AHP and fuzzy gamma operator	No
Rajasekhar et al. (2021)	India	Water table decline	N/A	8	FL, AHP and FR	No
Aju et al. (2021)	India	Water scarcity	Injection wells, percolation ponds, rainwater pits and pond-cum injection wells	9	AHP	No
Tahvili et al. (2021)	Iran	Water scarcity	Rainwater harvesting	8	TOPSIS	No
Hussaini et al. (2021)	Afghanistan	Water table decline	N/A	7	FL, ANP and AHP	No
Papadopoulos et al. (2022)	Greece	Excess water storage	Infiltration basins	9	Fuzzy AHP and FIS	No
Soliman et al. (2022)	Egypt	Emergency scenario	Infiltration pond, controlled flooding, percolation pond, recharge releases, open wells and shafts, percolation tanks	6	AHP	Yes
Arshad et al. (2022)	India	Fluoride contamination	N/A	7	AHP	No
Phankamolsil et al. (2022)	Thailand	Groundwater sustainability	Injection wells	5	SAW	No

Notes: AHP: analytic hierarchy process; TOPSIS: technique for order of preference by similarity to ideal solution; WLC: weighted linear combination; EDAS: evaluation based on distance from average solution; SAW: simple additive weighting; FL: fuzzy logic; FIS: fuzzy inference system; FR: frequency ratio

1.3.2 Overview of GIS-MCDA based RWH potential mapping studies

In regions classified as arid or semi-arid, rainfed agriculture is the predominant method of farming. However, these regions face significant challenges due to severe aridity and irregular temporal and spatial rainfall distribution, leading to limited water availability for crop and livestock production, as well as other environmental stressors (i.e. saltwater intrusion) that affect groundwater resources (Ammar et al., 2016). In order to address water scarcity and ensure sustainable management of water resources amidst changing environmental conditions, RWH combined with artificial recharge has been identified as one of the most effective water management techniques in the 21st century (Singh et al., 2017). Hence, the identification of suitable areas for constructing RWH structures holds significant importance for planners and managers in order to optimize water availability and land productivity, and address the challenges of water scarcity and environmental issues in arid and semi-arid regions (Ezzeldin et al., 2022; Singh et al., 2017). The application of coupled GIS-MCDA as a means to generate RWH site suitability maps has gained momentum in recent years with dozens of case studies around the world (Figure 1.4).

However, refining the list of decision criteria and identifying relevant decision parameters remains one of the most challenging aspects of MCDA problems. Over the years, the nature and size of criteria involved in RWH mapping have undergone significant changes. Initially, a set of physical criteria to delineate sites suitable for RWH was proposed by the Integrated Mission for Sustainable Development (IMSD) (IMSD, 1995), as noted by Chowdhury and Paul (2021). Slope, soil, drainage, and land use were the criteria proposed by the IMSD guideline (Bulcock & Jewitt, 2013). These criteria were used by Singh et al. (2009) and Chowdary et al. (2009) to identify sites suitable for RWH facilities in the Soankhad watershed, Punjab, and for Mayurakshi watershed, India, respectively. From another facet, Oweis et al. (1998) incorporated the initial criteria set including the environmental and socio-economic parameters such as rainfall and crop characteristics in order to identify favorable sites for RWH implementation at a pilot study area in central Syria. However, the guideline proposed by the Food and Agriculture Organization of the United Nations

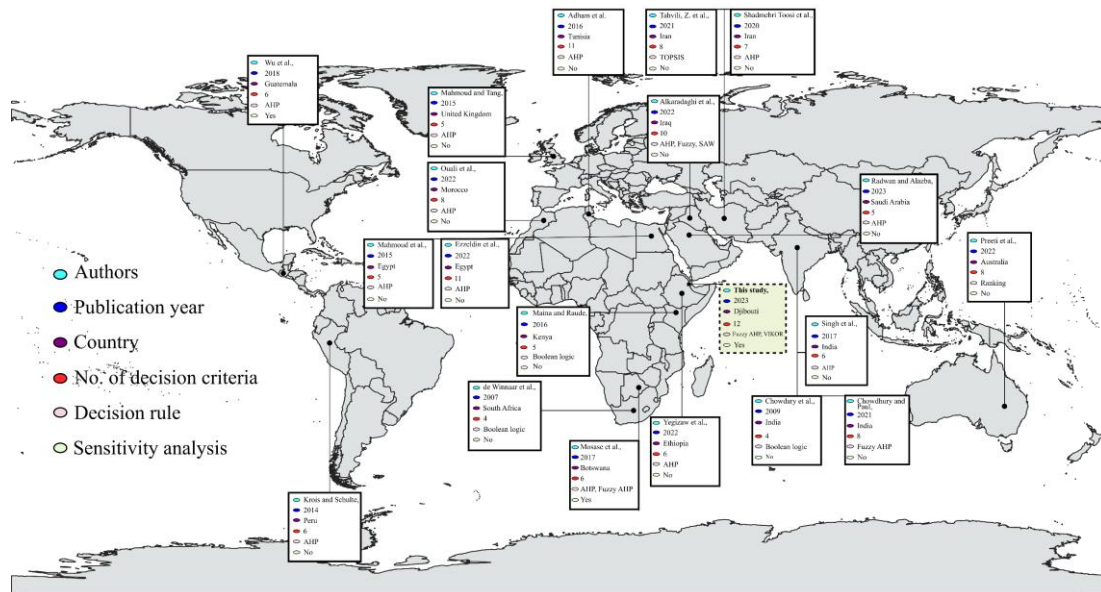


Figure 1.4 : Spatial distribution of the GIS-MCDA based RWH mapping studies.

(FAO, 2003) (i.e. slope, soil texture, soil depth, land use), environmental (i.e. rainfall, runoff depth) and socio-economic factors (i.e. crop characteristics, population density, population experience with RWH, accessibility and related cost) (Ammar et al., 2016; Bulcock & Jewitt, 2013). Mati et al. (2006) adopted to some extent the FAO guideline by mapping the potential of RWH in Africa on both the continental and country levels with respect to ten different countries, i.e., Botswana, Ethiopia, Kenya, Malawi, Mozambique, Rwanda, Tanzania, Uganda, Zambia, and Zimbabwe. Rainfall, topography, soils, land use, population density, and streams network were the principal decision criteria used for prioritizing RWH in their project. However, it should be noted that while the physical and environmental criteria utilized in the relevant literature demonstrate consistency, the same cannot be said for the socio-economic parameters. For instance, Yegizaw et al. (2022) and Ezzeldin et al. (2022) incorporated both distance to settlements and roads as socio-economic criteria into their analysis, while Harka et al. (2020) and Wu et al. (2018) took the proximity to agricultural parcels into account without the evaluation of distance to roads. On the other hand, Chowdhury and Paul (2021) judged distance from roads and distance from rivers as important criteria to consider in the RWH site selection. More importantly, a significant number of the literature omit socio-economic parameters from the decision criteria although adopting the FAO guideline (Grum et al., 2016; Krois & Schulte,

2014; Kumar & Jhariya, 2017; Mahmoud et al., 2015; Maina & Raude, 2016; Mosase et al., 2017; Rajasekhar et al., 2020; Singh et al., 2017; Tahvili et al., 2021).

Figure 1.4 provides an overview of previous studies that have utilized GIS-MCDA tools for mapping RWH potential. The figure includes information such as the authors, publication year, country of study, number of decision criteria considered, application of sensitivity analysis, and, notably, the specific MCDA technique used in each study. One can see, that the AHP technique is one of the most adopted MCDA methods in RWH suitability mapping with 11 out of the 15 reviewed studies in this paper using it as a decision rule technique. The aforementioned observation reinforces the conclusions drawn by Sallwey et al. (2019) who noted a substantial rise in the utilization of AHP in MAR site suitability mapping since 2013. The authors attributed this success to the robustness of AHP in decision-making, its systematic procedure that considers all aspects of the problem statement, and its ability to offer a structured approach to problem-solving. Notwithstanding the benefits of using the AHP method, certain studies have highlighted its potential drawback, i.e., its limited ability to capture the intrinsic vagueness of human decision-making processes (Mouhoumed et al., 2023). In this vein, Mosase et al. (2017) conducted a study to evaluate the effectiveness of incorporating fuzzy logic in assessing the suitability of RWH sites in the semi-arid South East District of Botswana by comparing the traditional AHP with its fuzzified version. They concluded that the fuzzy AHP outperforms conventional AHP in accounting for uncertainties associated with decision-making by integrating AHP, fuzzy logic, alpha cut, and Lambda functions. Similarly, Chowdhury and Paul (2021) dealing with the identification of sites suitable for RWH structures (such as ponds and pans, percolation tanks, check dams, and nala-bunds) for the Kandi subdivision of the Murshidabad district of India adopted the fuzzy AHP in conjunction with the fuzzy gamma operator technique for decision criteria assessment and integration of the thematic layers, respectively. Also, other MCDA techniques have been introduced in the literature recently. For instance, Tahvili et al. (2021) employed the technique for order of preference by similarity to ideal solution (TOPSIS) in locating areas favorable for RWH to address water scarcity in the Anarak watershed, Iran. Meanwhile, Alkaradaghi et al. (2022) used the simple additive weighting (SAW) method along with AHP and fuzzy logic to identify optimum sites for RWH in the Qaradagh basin, Iraq.



2. METHODOLOGY

2.1 GIS Weighted Overlay Analysis

The weighted overlay analysis (WOA) combining multiple thematic raster layers into a single layer is one of the commonly adopted spatial GIS tools. The WOA takes both the pre-defined criteria weights pertaining to different spatial layers and their actual values into account to evaluate the combined impacts of the thematic layers for producing overall results. Compared to the weighted sum tool that is another knowledge-based empirical raster processing method (Khatun et al., 2022), the WOA possesses a greater degree of as it allows not only facilitating the standardization of input factors through conversion to a user-defined scale (Ahmad et al., 2022) but also enabling the specification of benefit factors and cost factors for which higher values indicate more and less suitability, respectively.

The WOA have extensively been used in a wide range of purposes, such as groundwater potential zoning (Kayal et al., 2022), identifying artificial groundwater recharge zones (Aju et al., 2021; Kaliraj et al., 2015; Sandoval & Tiburan, 2019), groundwater quality mapping (Ben Brahim et al., 2022), etc. The current research utilized the WOA rationale via the WhiteboxTools (Lindsay, 2014) for QGIS to conduct the assessments regarding the MAR suitability areas. The calculation procedure of the WOA can be expressed as follows:

$$MSL = \sum_{i=1}^n R_i \times W_i \quad (2.1)$$

where MSL is the MAR suitability index, while R_i and W_i denote the raster layer and the weight of i^{th} criteria, respectively.

2.2 MCDA Rationale

The MCDA is a technique used in complex decision-making processes. MCDA methods are generally employed to evaluate alternative options by considering multiple criteria or objectives, and rather than providing an ideal solution, they enable

extracting the compromised solution (Campello et al., 2022). Within MCDA rationale, the first step involves identifying the criteria considered in the decision-making process, which represent the metrics used to evaluate the alternatives. Subsequently, weighting is applied to assign importance degrees to the identified criteria, reflecting their relative significance. Following that, each alternative is subjected to performance evaluation based on the pre-defined criteria involving objective evaluation of the alternatives' performance. Finally, by utilizing the corresponding outcomes, an aggregation method is employed to determine the overall performance of the alternatives aiding to rank the alternatives and identify the optimum solution(s). MCDA is applied in various domains, including businesses (Yalcin et al., 2022), public policies (Anastasiadou & Gavanis, 2023), environmental management (Koc et al., 2021), and healthcare (Zhao & Zhou, 2023) projects. Different techniques and tools are available within the MCDA framework, including AHP, analytic network process (ANP), TOPSIS, and preference ranking organization method for enrichment evaluations (PROMETHEE). However, the choice of technique depends on the specific characteristics of the decision problem, the available data, and the preferences of the decision-makers. Overall, MCDA provides a structured and systematic approach to decision-making, enabling stakeholders to consider multiple criteria and objectives in a comprehensive manner. It supports more informed and rational decision-making, especially in complex situations where there are trade-offs and conflicting preferences among different criteria.

2.2.1 Fuzzy analytic hierarchy process

The Analytical Hierarchy Process (AHP), introduced by Saaty (Saaty, 1977), is frequently employed to construct a hierarchical framework that captures intricate problem structures, aligning with the subjective assessments of experts. This methodological framework enables a detailed and granular analysis of complex problems, allowing for the incorporation of subjective judgments from experts while maintaining a scientific rigor. The AHP employs a systematic and rigorous approach to hierarchically structure a problem, beginning with a primary goal and progressively delving into criteria, sub-criteria, and subsequent levels, ultimately encompassing a comprehensive set of alternatives (Saaty, 1990). This hierarchical representation offers experts a comprehensive understanding of the intricate relationships inherent in the context, enabling a holistic view of the problem. Furthermore, it aids in evaluating the

comparability of elements at the same level, allowing for meaningful comparisons and assessments (Liu et al., 2020). Subsequently, elements are subjected to pairwise comparisons on a 9-level scale to derive their relative weights, facilitating the quantification of their respective importance in the decision-making process. Although the primary objective of AHP is to incorporate expert knowledge, the classical AHP method falls short in addressing the non-numeric uncertainties inherent in human thinking processes. Consequently, for the resolution of such problems, the implementation of fuzzy AHP provides a more robust solution. The fuzzy AHP method integrates the principles of fuzzy sets, initially introduced by Zadeh (1965), to address the intricate and ambiguous nature of the environment and experts' preferences. Fuzzy AHP tackles the challenges posed by the vagueness and imprecision in decision-making by allowing for fuzzy linguistic assessments and the representation of uncertainties through fuzzy numbers. By capturing and quantifying the inherent ambiguity, fuzzy AHP offers a more reliable and comprehensive approach to handle complex problems and supports more informed decision-making processes. When decision-makers evaluate criteria and alternatives, they can utilize natural language expressions alongside precise numerical values. Therefore, the fuzzy AHP method closely resembles human thinking and perceptions. As a result, it has been consistently employed by numerous researchers across various fields (Goodarzi et al., 2023; Ma et al., 2022; Mallick et al., 2019).

In the initial step of utilizing fuzzy AHP, the decision hierarchy structure is established by incorporating all the criteria, including primary criteria, sub-criteria, goals, and alternatives. To determine the order, each pair of items is compared using a nine-point significance scale. The steps of the fuzzy AHP approach are commonly arranged in the following manner:

1. After the hierarchical structure is revealed, decision-makers construct binary comparison matrices in accordance with their perspectives. These matrices encompass the relative evaluations and favored choices among the components at each level of the hierarchy. Following the acquirement of necessary information from the expert group (linguistic variables based on a typical 1-9 Likert scale), triangular fuzzy AHP rationale was applied to the decisions of the respondents (Figure 2.1). Although some other techniques (e.g., interval membership, trapezoidal membership, etc.) have been introduced in the pertinent literature for fuzzifying the decision variables, this research adopted triangular fuzzy membership due to its commonly applied feature and practicality. In addition, triangular fuzzy membership ensures the most likely, smallest possible, and largest possible variants of the respondents' judgments. Thus, l_{ij} , m_{ij} and u_{ij} indicating the lower, mean, and upper width of the pairwise judgments of the experts for criterion i compared to the criterion j , respectively, are determined (Table 2.1).

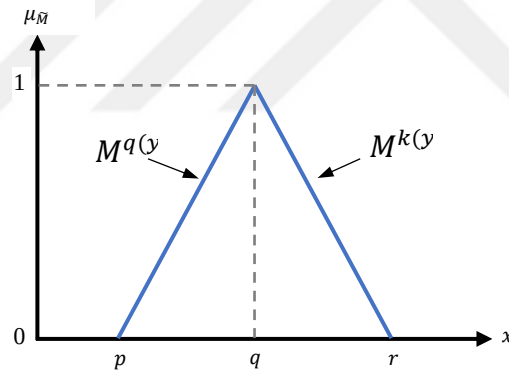


Figure 2.1 : Representation of triangular fuzzy membership

2. In the fuzzy AHP approach, an additional step is implemented to verify the consistency of experts' pairwise comparisons. This is achieved by calculating the consistency ratio (CR), where CR values exceeding 0.1 indicate inconsistent judgments made by respondents, while CR values below the threshold indicate a more consistent set of expert preferences. The following expression can be utilized to determine the CR values, thus assessing the level of consistency in the decision-making process.

$$CR = \frac{\frac{\lambda_{max} - n}{n - 1}}{RI} \quad (2.2)$$

where λ_{max} and n denote the maximum eigenvalue of the matrix and the number of criteria in the matrix, respectively. In addition, RI is the random index, which was introduced by Saaty (2004), grounding on the size of the matrix (Table 2.2).

Table 2.1 : Linguistic scales and triangular fuzzy reciprocals of AHP and Fuzzy AHP.

Linguistic variables	AHP		Fuzzy AHP	
	Importance	Value for reciprocals	Triangular fuzzy numbers (l_{ij}, m_{ij}, u_{ij})	Triangular fuzzy reciprocals $(1/u_{ij}, 1/m_{ij}, 1/l_{ij})$
Equally important	1	(1/1)	(1,1,1)	(1,1,1)
Intermediate value	2	(1/2)	(1,2,3)	(1/3,1/2,1)
Moderately important	3	(1/3)	(2,3,4)	(1/4,1/3,1/2)
Intermediate value	4	(1/4)	(3,4,5)	(1/5,1/4,1/3)
Important	5	(1/5)	(4,5,6)	(1/6,1/5,1/4)
Intermediate value	6	(1/6)	(5,6,7)	(1/7,1/6,1/5)
Very important	7	(1/7)	(6,7,8)	(1/8,1/7,1/6)
Intermediate value	8	(1/8)	(7,8,9)	(1/9,1/8,1/7)
Extremely important	9	(1/9)	(9,9,9)	(1/9,1/9,1/9)

Table 2.2 : Random index.

N	1	2	3	4	5	6	7	8	9	10
Random Index	0	0	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49

3. In this step, the fuzzy equivalents of each linguistic variable are calculated. Equation 2.3 outlines the method for determining the lower (l_{ijk}), mean (m_{ijk}), and upper (u_{ijk}) width of the fuzzy equivalents using the triangular membership function.

$$l_{ij} = \left(\prod_{k=1}^K l_{ijk} \right)^{1/K} ; m_{ij} = \left(\prod_{k=1}^K m_{ijk} \right)^{1/K} ; u_{ij} = \left(\prod_{k=1}^K u_{ijk} \right)^{1/K} \quad (2.3)$$

in which K is the total number of respondents.

4. Chang's extent analysis suggests considering each object to employ extent analysis for specific goals. Hence, fuzzy quantities are attained via crisp mathematical notations. In Chang's extent analysis, $X = \{x_1, x_2, x_3, \dots, x_n\}$ is a set of objects and $U = \{u_1, u_2, u_3, \dots, u_m\}$ is a set of goals. The value of the fuzzy synthetic extent based on the object i is computed through equation 2.4:

$$S_i = \sum_{j=1}^m M_{gi}^j \times \left[\sum_{j=1}^n \sum_{j=1}^m M_{gi}^j \right]^{-1} \quad (2.4)$$

where M_{gi}^j denotes the triangular fuzzy numbers. In addition, the possibility degree is computed with the fuzzy synthetic extent value. Where $M_1 = (l_1, m_1, u_1)$ and $M_2 = (l_2, m_2, u_2)$ are two triangular fuzzy numbers, the possibility degree of $M_2 = (l_2, m_2, u_2) \geq M_1 = (l_1, m_1, u_1)$ is defined by equation 2.5:

$$V(M_2 \geq M_1) = \text{htg}(M_1 \cap M_2) = \begin{cases} 1 & \text{if } m_2 \geq m_1 \\ 0 & \text{if } l_1 \geq u_2 \\ \frac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)} & \text{otherwise} \end{cases} \quad (2.5)$$

Following the calculation of the possibility degree for convex fuzzy numbers, the weight vector is computed and the normalized weight vectors (W) indicating the finalized decisions of the respondents are identified:

$$W = (d(A_1), d(A_2), \dots, d(A_n))^T \quad (2.6)$$

2.2.2 Technique for order of preference by similarity to ideal solution

The TOPSIS method is a well-established decision-making technique that has been widely used in various fields. According to Hwang and Yoon (1981), TOPSIS is based on the concept of ranking alternatives by their relative proximity to the ideal solution. On the one hand, the positive ideal solution represents the alternative that maximizes benefit criteria and minimizes cost criteria. On the other hand, the negative ideal solution minimizes benefit criteria and maximizes cost criteria. The selection of the most suitable alternative is performed based on its proximity to the positive ideal solution and distance from the negative ideal solution. The TOPSIS method provides a systematic approach to decision-making, considering multiple criteria simultaneously. Overall, the TOPSIS method has proven to be effective in evaluating and ranking alternatives, and its application has been documented in numerous scientific studies (Albulescu et al., 2022; Chen, 2019; Nguyen et al., 2020).

The TOPSIS essentially contains six steps:

1. **Defining the Decision Matrix:** A decision matrix is formulated, encompassing all available alternatives along with their corresponding performance values on various criteria. The decision matrix is typically represented as an $m \times n$ matrix, where m is the number of alternatives and n is the number of criteria. The decision matrix according to the TOPSIS method is shown Equation 2.7.

$$A_{ij} = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \dots & a_{mn} \end{bmatrix} \quad (2.7)$$

2. **Normalizing the Decision Matrix:** The decision matrix is normalized to eliminate any scale differences among the criteria. This step ensures that all criteria are given equal weightage in the decision-making process. Various normalization methods can be used, such as min-max normalization or vector normalization. The normalization of the decision matrix can be calculated through the formula depicted in Equation 2.8.

$$r_{ij} = \frac{a_{ij}}{\sqrt{\sum_{k=1}^m a_{kj}^2}} \quad (i = 1, 2, \dots, m; j = 1, 2, \dots, n) \quad (2.8)$$

3. **Assigning Weights to the Criteria:** The relative importance or weights of the criteria is determined. The weights reflect the significance of each criterion in the decision-making process. The determination of weights can be subjective, based on expert judgment, or derived using mathematical techniques like Analytic Hierarchy Process (AHP) or Entropy Weight Method. At this stage, the weighted decision matrix is obtained by multiplying the data in the normalized decision matrix, obtained in the second step of the TOPSIS method, with the weight values determined through the previously conducted weighting method. The sum of the data obtained from the weighting method must be equal to 1.
4. **Determining the Positive and Negative Ideal Solutions:** The positive ideal solution and the negative ideal solution are identified based on the maximum and minimum values, respectively, for each criterion. The positive ideal solution represents the alternative that achieves the maximum benefit and the

minimum cost, while the negative ideal solution represents the alternative that minimizes the benefit and maximizes the cost. The TOPSIS method assumes that each criterion exhibits a monotonically increasing or decreasing trend. To determine the ideal solution set, the maximum value of the column in the weighted decision matrix is selected. If the criterion is cost-oriented or in a minimization direction, the smallest criterion is chosen. The relevant formula for the ideal solution set is shown in Equation 2.9.

$$A^+ = \{(maxv_{ij}|j \in J), (minv_{ij}|j \in J')\} \quad (2.9)$$

In the negative ideal solution set, the smallest values of the data in the columns containing criterion values in the weighted decision matrix will be examined. The formula for the negative ideal solution set is shown in Equation 2.10.

$$A^- = \{(minv_{ij}|j \in J), (maxv_{ij}|j \in J')\} \quad (2.10)$$

5. Calculating the Euclidean Distances: The Euclidean distance between each alternative and the positive and negative ideal solutions is calculated. The Euclidean distance represents the overall proximity or distance of each alternative to the ideal solutions in the multi-dimensional criteria space. As a result of this process, the deviation values for the alternatives are defined as the shortest geometric distance to the positive ideal solution (d_i^+) and longest geometric distance to the negative ideal solution (d_i^-) measures. The formulas for ideal separation and negative ideal separation are shown in Equation 2.11-12.

$$d_i^+ = \sqrt{\sum_{j=1}^n (v_{ij} - v_j^+)^2} \quad (2.11)$$

$$d_i^- = \sqrt{\sum_{j=1}^n (v_{ij} - v_j^-)^2} \quad (2.12)$$

6. Calculating the Proximity to the Ideal Solutions: The relative proximity of each alternative to the positive and negative ideal solutions is determined. This can be done by calculating the relative closeness coefficient, which is the ratio of

the distance from the negative ideal solution to the sum of the distances from the positive and negative ideal solutions. The calculation of the relative closeness to the ideal solution is shown in Equation 2.13.

$$CC_i = \frac{d_i^-}{d_i^- + d_i^+} \quad (2.13)$$

The obtained CC_i value takes a value in the range of $0 \leq CC_i \leq 1$. $CC_i = 1$ indicates the absolute proximity of the alternative to the ideal solution, while $CC_i = 0$ indicates the absolute proximity of the alternative to the negative ideal solution. The ranking of alternatives is determined by sorting the obtained CC_i values in descending order, indicating their level of importance.

2.2.3 VlseKriterijumska optimizacija i kompromisno resenje

Opricovic (1998) first introduced the VIKOR (VlseKriterijumska Optimizacija I Kompromisno Resenje) algorithm to deal with multi-tiered decision-making tasks encompassing various conflicting and qualitative criteria. The VIKOR technique mainly focuses on the prioritization and/or selection of alternatives based on subjective decisions of the experts attained through surveys. Similar to other MCDM practices, within a VIKOR application, compromise solution is sought; however, the main rationale is to find to the corresponding solution based on the closest distance to the ideal solution (Opricovic & Tzeng, 2004). Although this concept is similar to the approach embraced in the TOPSIS algorithm which is another widely employed MCDM-based prioritization (alternative ranking) method, the VIKOR additionally takes the relative importance of distance to the positive and negative ideal solutions into account according to Opricovic and Tzeng (2007). The VIKOR technique comprises the following 6 steps:

1. The decision matrix is formed with respect to n criteria and m alternatives as follows:

$$A_{ij} = \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{pmatrix} \quad (2.14)$$

2. The best (f_i^+) and worst (f_i^-) values are determined to signify whether the purposeful effect of each criterion is cost or benefit:

$$\begin{aligned} f_j^+ &= \begin{cases} \left(\max_i x_{ij} \right) & \text{if } j - \text{th function represent a benefit} \\ \left(\min_i x_{ij} \right) & \text{if } j - \text{th function represent a cost} \end{cases} \\ f_i^- &= \begin{cases} \left(\min_i x_{ij} \right) & \text{if } j - \text{th function represent a benefit} \\ \left(\max_i x_{ij} \right) & \text{if } j - \text{th function represent a cost} \end{cases} \end{aligned} \quad (2.15)$$

3. Linear normalization is performed and the decision matrix is transformed to normalize matrix (R) containing n criteria and m alternatives. To accomplish this aim, the components of the normalized matrix (r_{ij}) are determined as follows:

$$r_{ij} = \frac{f_i^+ - x_{ij}}{f_i^+ - f_i^-} \quad (2.16)$$

where $i = 1, 2, \dots, m$ and $j = 1, 2, \dots, n$.

$$R_{ij} = \begin{pmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{pmatrix} \quad (2.17)$$

4. The weighted normalized decision matrix is obtained by multiplying r_{ij} and w_j :

$$V_{ij} = \begin{pmatrix} v_{11} & v_{12} & \cdots & v_{1n} \\ v_{21} & v_{22} & \cdots & v_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ v_{m1} & v_{m2} & \cdots & v_{mn} \end{pmatrix} \quad (2.18)$$

5. The separation values are computed to be used in determining the VIKOR index values:

$$S'_i = \sum_{j=1}^n V_{ij} \quad ; \quad R_j = \max_j V_{ij} \quad (2.19)$$

6. Finally, the VIKOR index (Q_i) values are calculated to rank the alternatives. To determine the VIKOR index, maximum and minimum of separation values are first identified as follows:

$$S^+ = \min_i S'_i \quad ; \quad S^- = \max_i S'_i \quad (2.20)$$

$$R^+ = \min_i R_i \quad ; \quad R^- = \max_i R_i \quad (2.21)$$

and then,

$$Q_i = \frac{q \cdot (S'_i - S^+)}{S^- - S^+} + \frac{(1 - q) \cdot (R_i - R^+)}{R^- - R^+} \quad (2.22)$$

in which, q is a weight for the strategy of maximum group utility, while $(1 - q)$ refers to the weight of individual regret. The alternative with the lowest Q_i Sort value is the most preferred compromise solution positioning on the upper side of the descending order, while for the highest Q_i sort value vice versa.



3. IDENTIFICATION OF FAVORABLE REGIONS FOR MAR IMPLEMENTATION IN DJIBOUTI AT A COUNTRY SCALE¹

3.1 Framework Description

The present research aimed to establish a robust decision framework encompassing the adoption of different MCDA techniques. Hence, a thorough literature survey was conducted at first, leading to the extraction of decision criteria that influence determining the MAR (non-) suitable regions. To quantitatively evaluate the corresponding decision criteria, this study introduced the fuzzy AHP algorithm with the triangular fuzzy membership function. It is important to note that, along with dealing with interpersonal uncertainty handled by the adoption of fuzzy set theory, the reliability of the subjective judgments of the experts and the stability of the entire criteria weighting process were ensured with the consistency ratio checks and sensitivity analysis, respectively. Given the necessity to mimic the real-world conditions in such analysis to extrapolate the results that can potentially be applied in focalized regions, this research further integrated the criteria weights with the current values of the decision criteria within the TOPSIS analysis in order to designate the MAR suitable regions in Djibouti. The research steps considered in this study are depicted in Figure 3.1.

3.2 Characteristics of the Study Area

Djibouti, situated in the Horn of Africa, is the smallest country in the region with a land area of approximately 23,200 km² (Figure 3.2). The country has a current estimated population of one million and shares terrestrial borders with Eritrea,

¹ This chapter is based on the paper “Mouhoumed, R. M., Ekmekcioğlu, Ö., Başakın, E. E., & Özger, M. (2023). Integrated Fuzzy AHP-TOPSIS Model for Assessing Managed Aquifer Recharge Potential in a Hot Dry Region: A Case Study of Djibouti at a Country Scale. *Water*, 15(14), 2534. <https://doi.org/10.3390/w15142534>”.

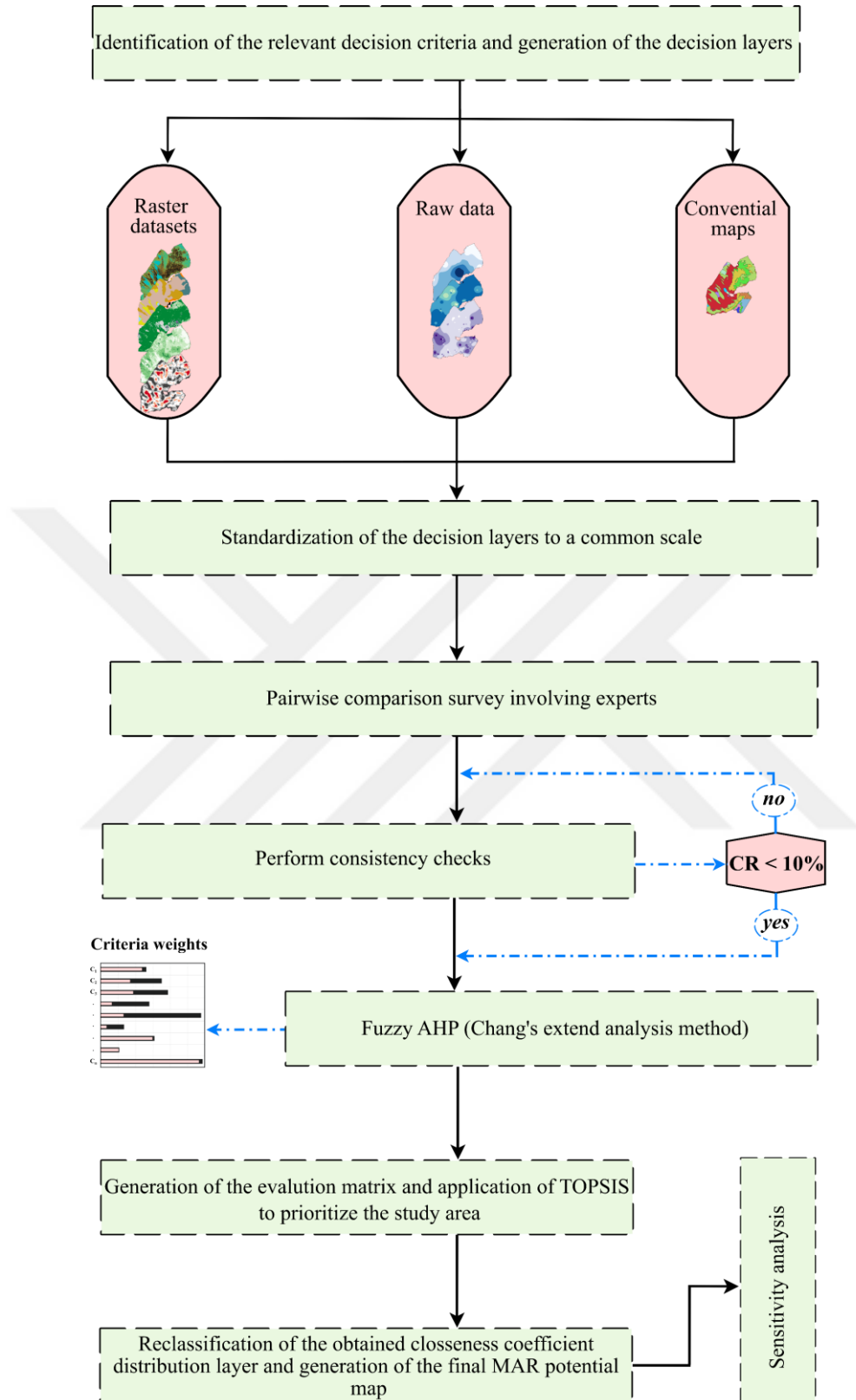


Figure 3.1 : Flow of the research steps.

Ethiopia, and Somalia as well as maritime borders with Yemen. The climate of Djibouti is characterized by hot and arid conditions, with an annual mean rainfall of 150 mm and temperatures ranging from 20 °C to 30 °C in winter (October to April) and 30 °C to 45 °C in summer (May to September) (Dabar et al., 2021). In Djibouti, the principal groundwater reserves consist of fractured volcanic aquifers, primarily represented by three geological formations: the Dalha basalts, the Stratoid basalts, and the Mabla rhyolites (Awaleh et al., 2017; Jalludin & Razack, 2004). These geological formations serve as the main sources of groundwater supply, characterized by their fractured nature and high permeability, allowing for substantial quantities of groundwater to be extracted. Furthermore, sedimentary aquifers with a transmissivity between 5.6×10^{-6} and $1.3 \times 10^{-3} \text{ m}^2/\text{s}$ (Awaleh et al., 2017) are present along some watersheds and the eastern coastal part of the focalized region.

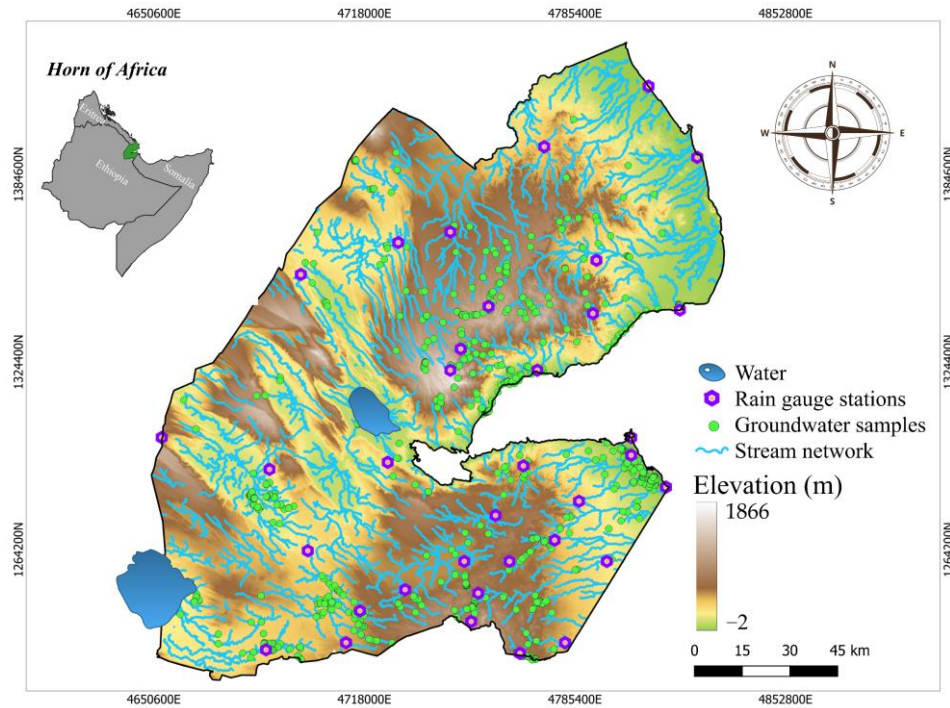


Figure 3.2 : Study area.

The water demand of the country heavily relies on groundwater due to the absence of permanent surface water resources. This overdependence has led to the widespread use of abstraction wells without proper planning or sustainable management practices (MAEPE-RH, 2015). Consequently, this excessive groundwater extraction coupled with reduced recharge rates due to climate variability poses substantial challenges to the subsurface resources (i.e., depletion, contamination, saltwater intrusion). In light of the corresponding challenging circumstances, investigating the feasibility of MAR

in Djibouti assumes great importance as it presents a viable solution to mitigate water shortage and achieve long-term sustainability.

3.3 Data Source and Layers Processing

Utilizing an extensive review of existing literature and consulting with experts in the field, a comprehensive analysis resulted in the identification of nine pertinent parameters for delineating regions suitable for MAR activities. These selected criteria were subsequently categorized into three primary clusters, each encompassing three criteria, in order to establish an improved hierarchical framework (Table 3.1). The surface cluster consists of the slope, soil texture, and curve number, while the rainfall, normalized difference vegetation index (NDVI), and drainage density were incorporated into the decision framework under the umbrella of the environmental cluster. Lastly, the subsurface cluster comprises depth to groundwater, geology, and groundwater quality (specifically the electrical conductivity in this investigation). Additionally, a concise description of the influence of each criterion in the MAR potential mapping decision framework can also be found in Table 3.1.

The generation of a spatial thematic layer for each factor involved in the decision framework represents an important step in MAR mapping. In line with, a raster layer was generated for each criterion based on various data sources. For instance, slope and drainage density maps (depicted in Figures 3.3a and 3.3f, respectively) were derived from the ALOS World 3D (AW3D) digital elevation model with a 5m resolution (NTT DATA Corp, 2016). The available slope analysis tools in QGIS were used to generate the slope layer of the focalized region in percent, while, the drainage density raster layer was obtained by applying the line density interpolation algorithm. Soil texture was obtained from the Harmonized World Soil Database version 2.0 (HWSD v2.0) (FAO & IIASA, 2023) and the resulting map is given in Figure 3.3b. The curve number map (Figure 3.3c) of the focalized region was clipped from the global curve number (GCN250) dataset provided by Jaafar and Ahmad (Jaafar & Ahmad, 2019). The GCN250 dataset has a resolution of 250m and can be downloaded in raster format. To establish the rainfall distribution throughout the country, the average annual rainfall of various stations was acquired from Dabar et al. (Dabar et al., 2022) and the precipitation raster layer (Figure 3.3d) was generated using the inverse distance

Table 3.1 : List of selected decision criteria, accompanied by their corresponding descriptions, along with the ratings assigned to the criteria classes.

Clusters	Criteria	ID	Classes	Rating	Source Reference
Surface	Slope ^a (%)	S	0-2	5	AW3D (NTT DATA Corp, 2016)
			2.-5	4	
			5.-10	3	
			10.-25	2	
			> 25	1	
	Soil texture ^b	ST	Eutric Fluvisols (FLeu)	5	HWSD v2.0 (FAO & IIASA, 2023)
			Petric Gypsisols (GYp)	4	
			Eutric Leptosols (LPeu)	2	
			Lithic Leptosols (LPli)	2	
			Haptic Solonchaks (SCh)	1	
	Curve number ^c	CN	75-85	5	Jaafar and Ahmad (Jaafar & Ahmad, 2019)
			67-75	4	
			62-67	3	
			55-62	2	
			40-55	1	
Environment	Rainfall ^d (mm)	R _i	153-220	5	Dabar et al. (Dabar et al., 2022)
			134-153	4	
			118-134	3	
			95-118	2	
			43-95	1	
	Normalized difference vegetation index ^e	NDVI	0-10-0.24	5	Sentinel 2 (European Space Agency, 2015)
			0.05-0.10	4	
			0.02-0.05	3	
			0-0.02	1	

Table 3.1 (continued): List of selected decision criteria, accompanied by their corresponding descriptions, along with the ratings assigned to the criteria classes.

Clusters	Criteria	ID	Classes	Rating	Source Reference
Subsurface	Drainage density ^f (km/km ²)	DD	0-4.13	5	AW3D (NTT DATA Corp, 2016)
			4.13-7.10	4	
			7.10-10.17	3	
			10.17-14.12	2	
			14.12-24.47	1	
	Depth to groundwater ^g (m)	DG	0.7-13	1	MAEPE-RH
			13-21	5	
			21-35	3	
			35-67	2	
			> 67	1	
	Geology ^h	G	Sedimentary formations	5	MAEPE-RH (MAEPE-RH, 2015)
			Recent basalt (1 Ma- actual)	3	
			Stratoid basalt (3.4-1 Ma)	2	
			Golf basalt (3.4-1 Ma)	2	
			Somali basalt (9-3.4 Ma)	2	
			Dalha basalt (9-3.4 Ma)	2	
			Adolei basalt (25Ma)	2	
			Stratoid rhyolite	1	
			Mabla rhyolite	1	
			Cretaceous-Jurassic base	1	
	Groundwater quality ⁱ (μS/cm)	EC	200-1000	5	MAEPE-RH
			1000-2100	4	
			2100-2600	3	
			2600-3700	2	
			> 3700	1	

Notes: ^a Slope serves as a highly utilized decision criterion in the context of MAR mapping due to its significant influence on the convergence and divergence of runoff water, ultimately affecting the infiltration capacity (Bonilla Valverde et al., 2016). ^b Rajasekhar et al. (Rajasekhar et al., 2020) noted that soil type plays a critical role in regulating both infiltration rates and the potential generation of runoff. Specifically, soils with a high clay content tend to display diminished infiltration rates and increased runoff, whereas soils with a high sand content tend to exhibit enhanced infiltration rates and reduced runoff. ^c As a dimensionless index that characterizes the soil's ability to absorb water, the curve number can be used to indirectly estimate the volume of runoff that could be harvested in a particular area for MAR usage (Ahani Amineh et al., 2017). ^d Rainfall plays a pivotal role in MAR mapping since rainwater represents the main source of water for MAR projects worldwide (Sallwey, Schlick, et al., 2019). ^e According to Ansems et al. (Ansems et al., 2015) high NDVI regions could be an indicative of the temporal availability of water, thereby the potential to reclaim large volumes of water. ^f Drainage density is inversely proportional to permeability such that areas with high drainage density hints the presence of low permeable rock, whereas low drainage density suggests the presence of more permeable rock. (M. Arshad et al., 2022). ^g The depth of the groundwater influences the feasibility of the MAR project as well as the recharge rates (Zaidi et al., 2015). ^h The rock type prevalent in a given region plays a vital role in governing the movement and distribution of groundwater (Selvarani et al., 2017). ⁱ Injecting reclaimed water in a poor groundwater quality region could jeopardize the MAR benefit, thereby it is important to include in the decision framework groundwater quality parameters (Ahani Amineh et al., 2017).

weighting (IDW) interpolation method. Regarding the calculation of the NDVI illustrated in Figure 3.3e, Sentinel 2 imagery was employed and the following formula was applied:

$$NDVI = \frac{NIR - RED}{NIR + RED} \quad (3.1)$$

where, NIR and RED represent the near-infrared and red bands, respectively. The acquisition of Sentinel imagery from Google Earth Engine and the necessary computations to obtain the NDVI were performed using the Geemap python package (Q. Wu, 2020). The geological representation of the country was digitized from a technical report (MAEPE-RH, 2015), while the layers depicting depth to groundwater and electrical conductivity were generated using the IDW interpolation based on raw data obtained from the Ministry of Agriculture, Water, Fisheries and Livestock, in charge of Fishery Resources (MAEPE-RH) of Djibouti. Hence, Figures 3.3g, 3.3h, and 3.3i illustrate the depth to groundwater, geology, and electrical conductivity maps, respectively. It is important to highlight that all geoprocessing tasks in this research were conducted using QGIS 3.28 (QGIS Development Team, 2022).

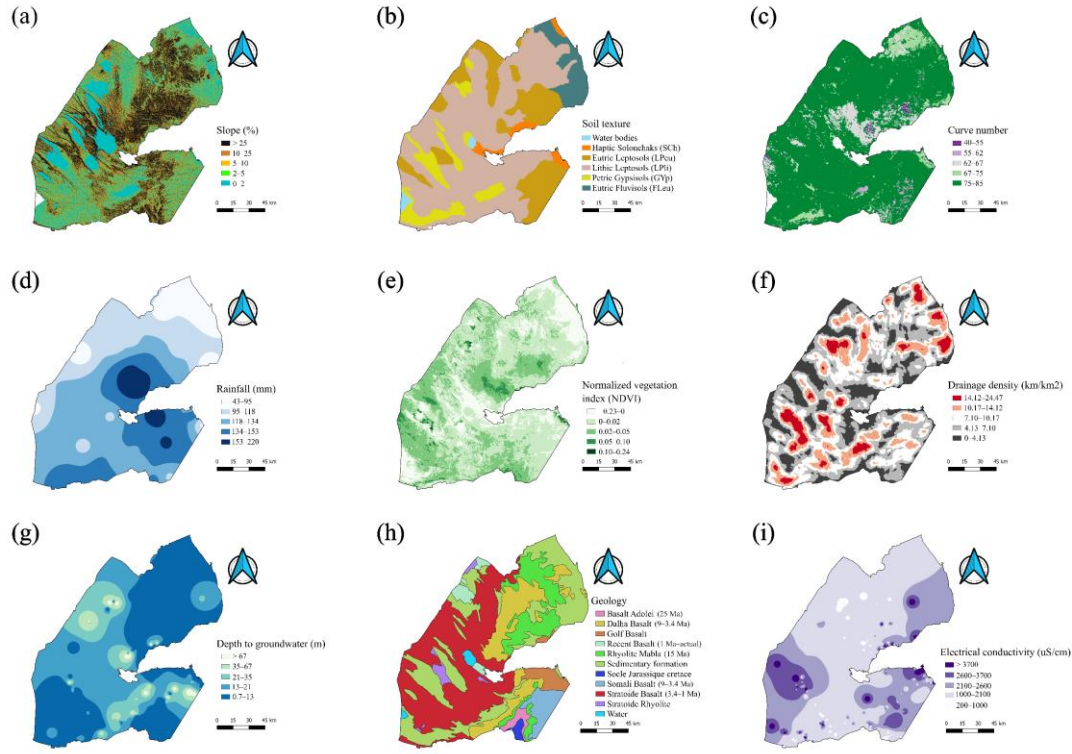


Figure 3.3 : Thematic maps of the relevant decision criteria for MAR potential mapping: (a) slope, (b) soil texture, (c) curve number, (d) rainfall, (e) normalized difference vegetation index, (f) drainage density, (g) depth to groundwater, (h) geology, and (i) electrical conductivity.

During this stage, the need for standardizing the decision layers becomes imperative due to their diverse nature in this study. Existing literature encompasses various standardization techniques, including fuzzy membership functions, stepwise functions, AHP, and the utilization of rates/scores for feature classes (Aju et al., 2021; Bonilla Valverde et al., 2016; Fuentes & Vervoort, 2020; Ghazavi et al., 2018b; Hussaini et al., 2021; Shadmehri Toosi et al., 2020; Zhang et al., 2019). Consequently, this study employed the rating technique to reduce the complexity of the proposed framework, whereby a scale of 5 was assigned to cells exhibiting high suitability for MAR potential, while a rating of 1 was attributed to the least suitable cells (Table 3.1).

3.4 Decision Criteria Weighting

This research has explored the role of different criteria in assessing the MAR mapping based on three dimensions, i.e., surface, environment, and subsurface. The fuzzy AHP technique was employed not only to reveal the contribution of each dimension but also

to demonstrate the impact of nine different criteria on the MAR suitability assessments. Hence, the present study utilized the outcomes of the judgments of the expert group (Table 3.2) to compute the weights of both main clusters and the corresponding criteria. To ensure the reliability of the obtained results, consistency ratios were initially investigated. It is especially worth mentioning that attaining CR values smaller than 10% indicates that the decision framework is consistent and further computations including the criteria weighting can be pursued. Figure 3.4 quite reveals that all the experts were found consistent in pairwise comparisons. In qualitative assessments, the experts may confuse about their results due to the complex nature of the pairwise comparison matrix leading to inconsistent evaluations. However, this research refined the list of criteria (3 x 3) and the main clusters (1 x 3), and the experts yielded consistent results in the first round of the surveys.

Table 3.2 : Profile of the experts attended the pairwise comparisons.

ID	Sector	Job description	Background	Experience (years)
Expert 1	Academia	Professor	Civil and Environmental Engineering	16
Expert 2	Academia	Associate Professor	Environmental Engineering	11
Expert 3	Municipality	Head of Department	Civil Engineering (PhD)	20
Expert 4	Municipality	Planning Engineer	Architecture (MSc)	6
Expert 5	Water administration	Unit Manager	Civil Engineering	8
Expert 6	Water administration	Technical Office Engineer	Geological Engineering (MSc)	5
Expert 7	Private sector	General Manager	Environmental Engineering (MSc)	15
Expert 8	Private sector	Modelling and Design Engineer	Geological Engineering	6

Table 3.3 highlights that, among the three main clusters, environment dimension (with a weight of 48.85%) has determined as the most significant, followed by the surface (30.36%) and subsurface (20.79%) dimensions, respectively. Table 3.3 also includes the local and global weights of the criteria considered. Accordingly, among the surface cluster, the slope was the most determinant criterion as it gained the highest weight with 43.92%, while curve number and soil texture followed the slope with 31.27% and 24.81%. In addition, the rainfall criterion (62.80%) outperformed the NDVI (24.33%) and drainage density (12.86%) with respect to the criteria weights calculated through the fuzzy AHP. The local criteria weights regarding the subsurface dimension depict that there was a more homogenous distribution within the considered three criteria,

i.e., groundwater quality (37.27%), geology (33.41%), and depth to groundwater (29.32%), indicating that each criterion has no distinctive impact on the determination of suitable MAR sites.

Furthermore, global weights, which directly indicate the contribution of each criterion to the final suitability assessment of the focalized region, were also presented in Table 3.3. According to the results obtained, rainfall having a global weight of 30.68% outperformed its counterparts. In addition, rainfall was followed by the slope (with a global weight of 13.33%) and NDVI (with a global weight of 11.89%). On the other hand, among nine decision criteria, the fuzzy AHP assessments underestimated the role of depth to groundwater, drainage density, and geology as the lowest weights were assigned to the corresponding factors.

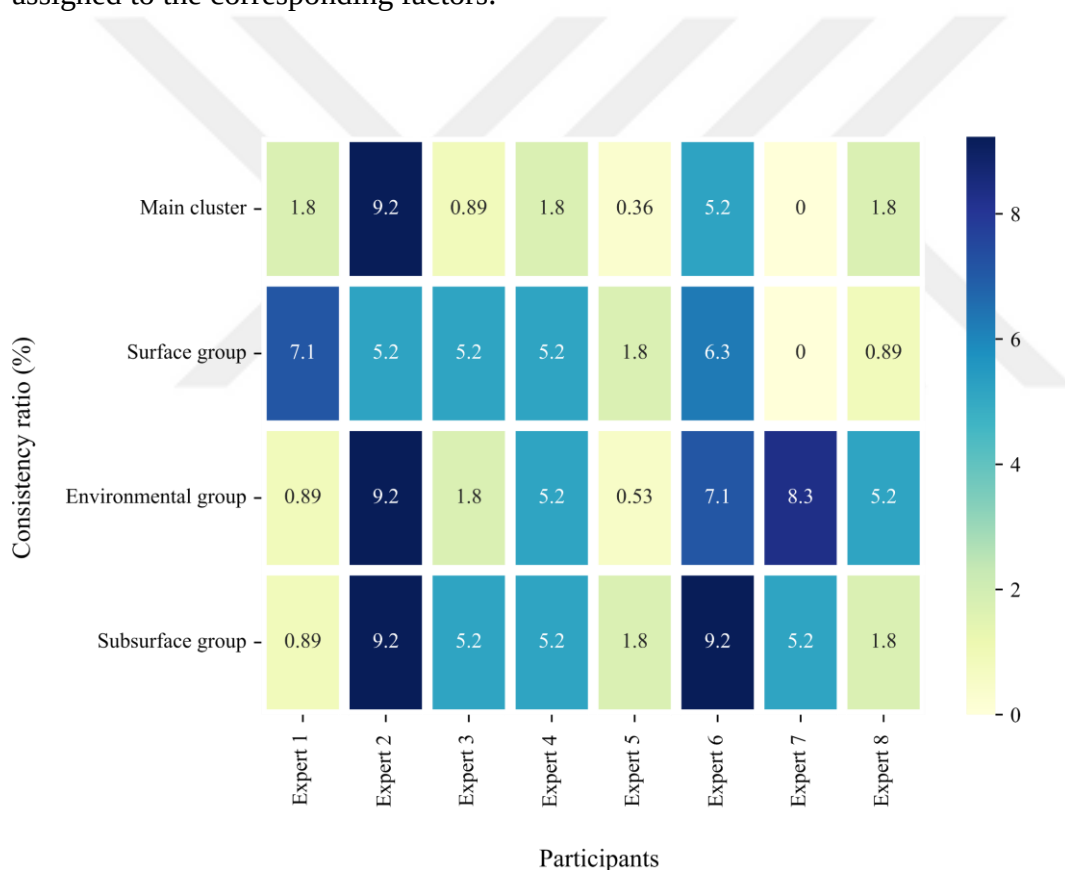


Figure 3.4 : Consistency ratios of the experts attended the pairwise comparisons questionnaire.

Table 3.3 : Decision criteria weights and their respective ranking.

Cluster	Weight	Criteria	Criteria Weight		Rank	
			local	global	local	global
Surface	30.36%	Slope	43.92%	13.33%	1	2
		Soil texture	24.81%	7.53%	3	6
		Curve number	31.27%	9.50%	2	4
Environment	48.85%	Rainfall	62.80%	30.68%	1	1
		NDVI	24.33%	11.89%	2	3
		Drainage density	12.86%	6.28%	3	8
Subsurface	20.79%	Depth to groundwater	29.32%	6.10%	3	9
		Geology	33.41%	6.95%	2	7
		Groundwater quality (EC)	37.27%	7.75%	1	5

In this study, the sensitivity analysis with respect to different fuzziness degrees was implemented to ensure the stability of the attained results as well as underscore the transparency of the criteria weighting attempts. Hence, in addition to dealing with interpersonal uncertainty by utilizing the fuzzy AHP rationale (Koc et al., 2023), the robustness of the criteria assessments is ensured via the sensitivity analysis conducted through different fuzziness degrees (i.e., 1.2, 1.4, 1.6, 1.8, and 2.0). The corresponding manner was embraced due to its previous implementations (Ekmekcioğlu, Koc, Dabanli, et al., 2022). Fuzziness degrees capture the level of ambiguity or uncertainty associated with the linguistic judgments or criteria weights in AHP. Sensitivity analysis helps understand the impact of variations in fuzziness degrees on the final results, enabling better management and interpretation of uncertainty (Figure 3.5). Such that, the most significant aspect in assessing the sensitivity plot is focusing on the variations of the criteria importance orders. The figure exhibits that, with regard to the alterations in fuzziness degrees, the fuzzy AHP results yielded consistent outcomes as there is no considerable variation in criteria rankings. Therefore, one can conclude that the factors having a significant impact on model outcomes account for similar importance considering various fuzziness degrees. The level of confidence/agreement in the decision process is ensured with the sensitivity analysis and it is highlighted that the quality of the experts' preferences is aligned with the consistent decision context (Figure 3.5).

In this study, an additional sensitivity analysis approach was conducted. To accomplish this aim, the weights of the criteria were shifted each other and the obtained results were compared in accordance with the baseline scenario (i.e., originally attained criteria weights) with respect to the root mean square error (RMSE) computations (Table 3.4). The results showed that the vast majority of the scenarios yielded considerably lower RMSE values, except once R_1 (i.e., rainfall) is changed

with its counterparts. The corresponding results can be explained by the fact that the rainfall was originally overestimated by the experts illustrating its high influence on the final MAR suitability decision.

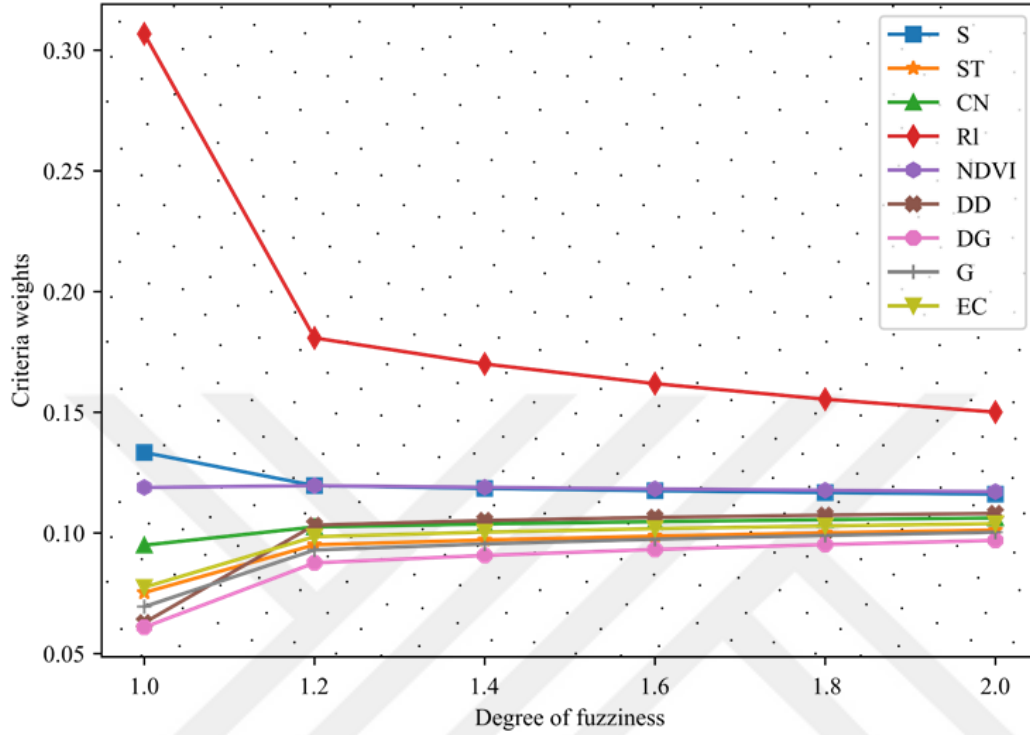


Figure 3.5 : Sensitivity analysis with respect to different fuzziness degrees.

Table 3.4 : Sensitivity analysis results based on shifting criteria weights.

Scenario ID	Shifting	RMSE	Scenario ID	Shifting	RMSE	Scenario ID	Shifting	RMSE
Scenario 1	S-ST	0.0209	Scenario 13	ST-DG	0.0062	Scenario 25	R _i -G	0.1932
Scenario 2	S-CN	0.0259	Scenario 14	ST-G	0.0014	Scenario 26	R _i -EC	0.1519
Scenario 3	S-R _i	0.1416	Scenario 15	ST-EC	0.0008	Scenario 27	NDVI-DD	0.0242
Scenario 4	S-NDVI	0.0075	Scenario 16	CN-R _i	0.2059	Scenario 28	NDVI-DG	0.0327
Scenario 5	S-DD	0.0366	Scenario 17	CN-NDVI	0.0190	Scenario 29	NDVI-G	0.0213
Scenario 6	S-DG	0.0384	Scenario 18	CN-DD	0.0130	Scenario 30	NDVI-EC	0.0182
Scenario 7	S-G	0.0239	Scenario 19	CN-DG	0.0095	Scenario 31	DD-DG	0.0005
Scenario 8	S-EC	0.0246	Scenario 20	CN-G	0.0154	Scenario 32	DD-G	0.0028
Scenario 9	ST-CN	0.0126	Scenario 21	CN-EC	0.0067	Scenario 33	DD-EC	0.0037
Scenario 10	ST-R _i	0.1687	Scenario 22	R _i -NDVI	0.1234	Scenario 34	DG-G	0.0036
Scenario 11	ST-NDVI	0.0141	Scenario 23	R _i -DD	0.1633	Scenario 35	DG-EC	0.0046
Scenario 12	ST-DD	0.0049	Scenario 24	R _i -DG	0.1938	Scenario 36	G-EC	0.0030

3.5 MAR Potential Mapping

The current research analyzed the suitability of MAR potential in Djibouti using the TOPSIS approach. To accomplish this aim, the criteria weights attained through the fuzzy AHP analysis were integrated with the actual values of the corresponding criteria in the field, and then, subjected to the TOPSIS algorithm aiding to explore the prioritization of suitable regions. Figure 3.6 encompasses two different sub-figures, in which (a) the first represents the map generated based on the closeness coefficients, whereas (b) the latter provides the reclassification of the suitability assessments based on the closeness coefficients using Jenks natural break method. In addition, the higher the closeness coefficient, the higher the suitability of the MAR implementation. Hence, one can conclude that the north and west parts of the country (with orange and red colors) are less suitable compared to other regions (Figure 3.6a). Contrarily, middle- and south-east parts of the country mainly covering the vicinity of the Gulf of Tadjourah are more suitable for MAR applications. In addition to the west part of the country, south Djibouti posed very high suitability to the MAR implementations (Figure 3.6b). The corresponding results can further be explained by the decision criteria; such that high suitable parts are significantly correlated to the high rainfall values (Figure 3.3d) which was found as the most determinant decision criterion.

Furthermore, Figure 3.7 illustrates the distribution of the different suitability clusters based on the corresponding regions' surface areas. According to the figure, one can conclude that nearly one-third of the country is moderately suitable for the MAR implementation. Likewise, one-third of the country is suitable (high and very high suitability) to the corresponding sustainable solutions, whereas the remaining parts are not (low and very low suitability). The attained results, on the one hand, showed that approximately 16.38% of the country demonstrates very high suitability to the MAR implementation, in which these regions are mainly located in the middle and south parts. On the other hand, nearly 15.76% of the entire country that is mainly located in the north-eastern part, which implies very low suitability to MAR solutions.

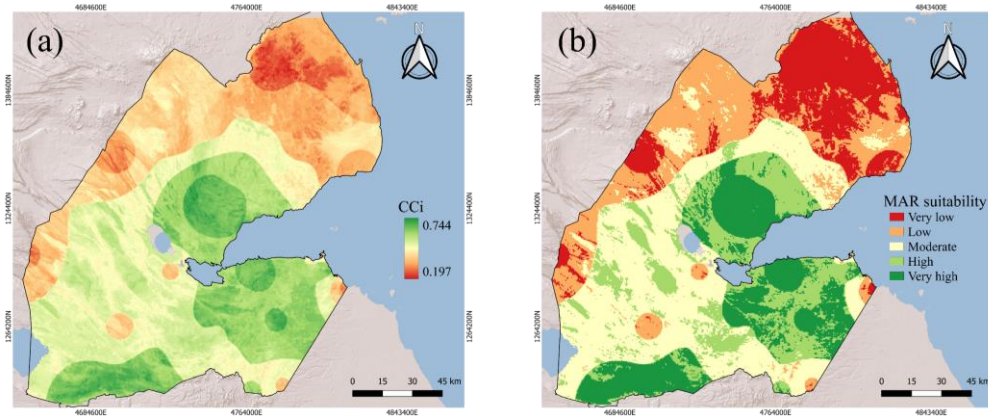


Figure 3.6 : MAR suitability potential of Djibouti based on the integrated fuzzy AHP-TOPSIS approach: (a) the closeness coefficients (CCi) distributions, and (b) the reclassified version of it.

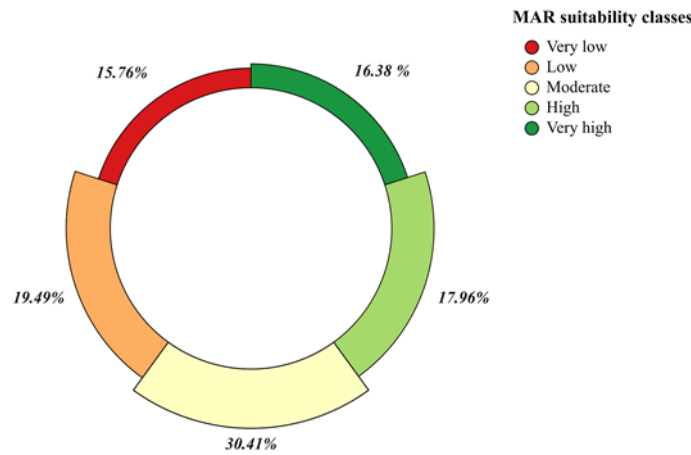


Figure 3.7 : Percentage distributions of the different suitability classes in terms of surface area.

3.6 Assessment of the Feasible MAR Technologies in Djibouti

MAR potential maps serve as effective tools for evaluating the artificial recharge feasibility of large areas. However, one limitation of such broad-scale MAR assessments is their inability to provide insights into the feasibility of specific MAR technologies within a focused region. For instance, in the case of Djibouti, where permanent rivers are absent, bank filtration technology is deemed unfeasible. Fortunately, several tools have been developed to enhance the practicality of MAR and address the complexities associated with its implementation. Among these tools, the web-based INOWAS platform stands out, providing a diverse array of functionalities aimed at facilitating MAR initiatives (such as groundwater flow/transport numerical and analytical simulation models, MAR databases, data-driven tool, etc). Specifically, tool no.6 within the platform enables the selection of

appropriate MAR techniques based on specific characteristics and conditions of the area of interest, including factors such as the availability of water sources and other pertinent considerations. Notably, the development of this tool by the INOWAS research group is based on extensive investigations encompassing several hundred MAR studies conducted worldwide (INOWAS, 2018). Therefore, the data-driven tool was used to assess the type of MAR techniques feasible in Djibouti and the result was depicted in Figure 3.8. The findings revealed that Aquifer Storage and Recovery (ASR) and Aquifer Storage Transfer and Recovery (ASTR) technologies could be adopted to store reclaimed water in the aquifer for future recovery or for addressing environmental concerns such as saltwater intrusion. These techniques could potentially utilize the treated water from the wastewater treatment plant in Douda having a daily capacity of treating 2000 m³ of water (ONEAD, 2023), and from the Ambouli dam storing a considerable amount of water that can be diverted for MAR activities alongside its flood mitigation purpose. Additionally, surface spreading techniques (such as infiltration ponds, ditches, and furrows, as well as barriers and bunds, etc.) requiring rainwater as target sources were found to be feasible for recharging local aquifers. Furthermore, drywells and flooding MAR techniques show promise in recharging shallow aquifers in the country, aiming to achieve groundwater sustainability and address recurring droughts.

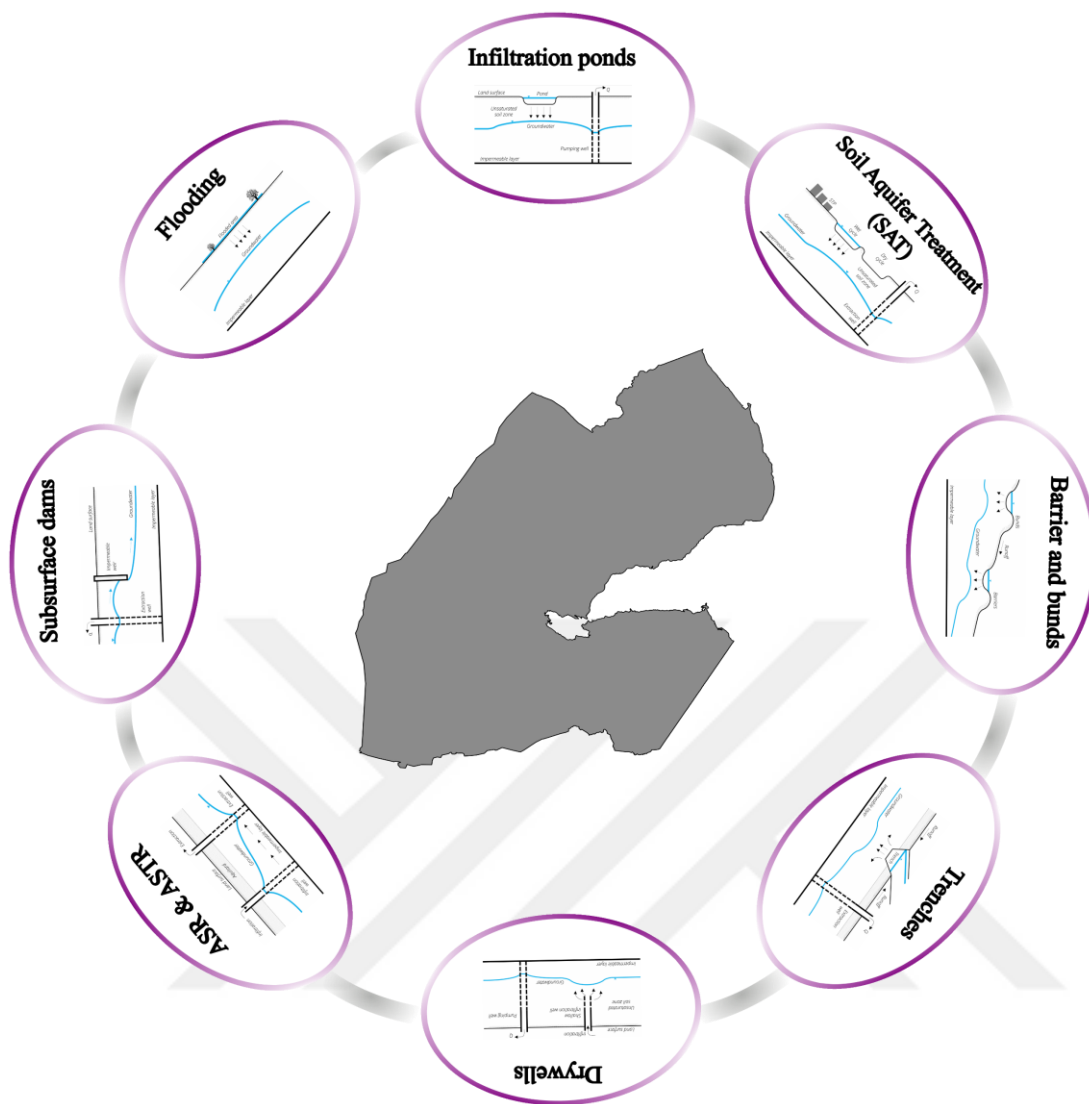


Figure 3.8 : Graphical representation of the feasible MAR techniques in Djibouti.

4. EVALUATION OF RAINWATER HARVESTING POTENTIAL IN ARID REGIONS: A CASE STUDY OF THE SOUTHEASTERN BASIN OF DJIBOUTI

4.1 Description of the Focalized Basin and Problem Statement

Djibouti, classified as one of the smallest African nations in terms of both population and land coverage, has a population size of one million and a surface area spanning 23,200 km². The focus of this study is the southeastern basin of Djibouti, comprising six distinct watersheds, namely Ambouli, Deydey weyn, Barisle, Ambado, Douda, and Damerjog. Collectively, these watersheds encompass an area of 1,358 km², which includes the capital city of Djibouti, approximately half of the Holhol administration district, and the eastern part of Arta (Figure 4.1). The climate prevailing in Djibouti is typified by its hot and arid nature, featuring an annual average rainfall of approximately 150 mm. Temperatures exhibit a range between 20 °C and 30 °C during the winter months spanning from October to April, while summer temperatures soar from 30 °C to 45 °C between May and September (Dabar et al., 2021). Geologically, the country's subsurface is primarily composed of fractured volcanic rocks, such as the Dalha and Stratoid basalts, along with the presence of Mabla rhyolites (Awaleh et al., 2017; Jalludin & Razack, 2004). However, the study area is predominantly characterized by the Dalha, Somali, and Golf basalts, along with the occurrence of sedimentary formations and the Mabla rhyolites in smaller portions of the investigated basin.

The absence of permanent surface water resources in the Republic of Djibouti has compelled the population to depend entirely on the country's groundwater resources. Consequently, the dependency on groundwater has led to an uneven distribution of abstraction wells and a lack of adequate planning and sustainable management practices across the country. The primary objective of well implementation has been solely to meet the water demand, without considering long-term sustainability (MAEPE-RH, 2015). Additionally, simulation models assessing drought trends indicate a substantial inclination towards aridity in the country, specifically in the

eastern coastal area, with over 80% of the occurrences of extreme and severe dryness taking place between 2007 and 2017 (Dabar et al., 2022). As a result, the combination of excessive groundwater extraction and progressively arid climatic conditions has led to considerable depletion in specific regions, as well as the intrusion of saltwater into coastal aquifers nationwide. Given these circumstances, the investigation of RWH potential in Djibouti assumes critical importance, as it offers a promising long-term solution to alleviate water scarcity and address salinization issues by stabilizing the saltwater-freshwater interface through artificial recharge. Thus, this study proposes an integrated fuzzy AHP-VIKOR framework to delineates sites suitable for RWH structures in Djibouti. Additionally, although some countries have notable histories in RWH practices, such as India, Iran, and Egypt, the topic is still not well covered in the Horn of Africa region, despite being one of the most affected areas by water scarcity and climate variability. The proposed decision framework steps are depicted in Figure 4.2.

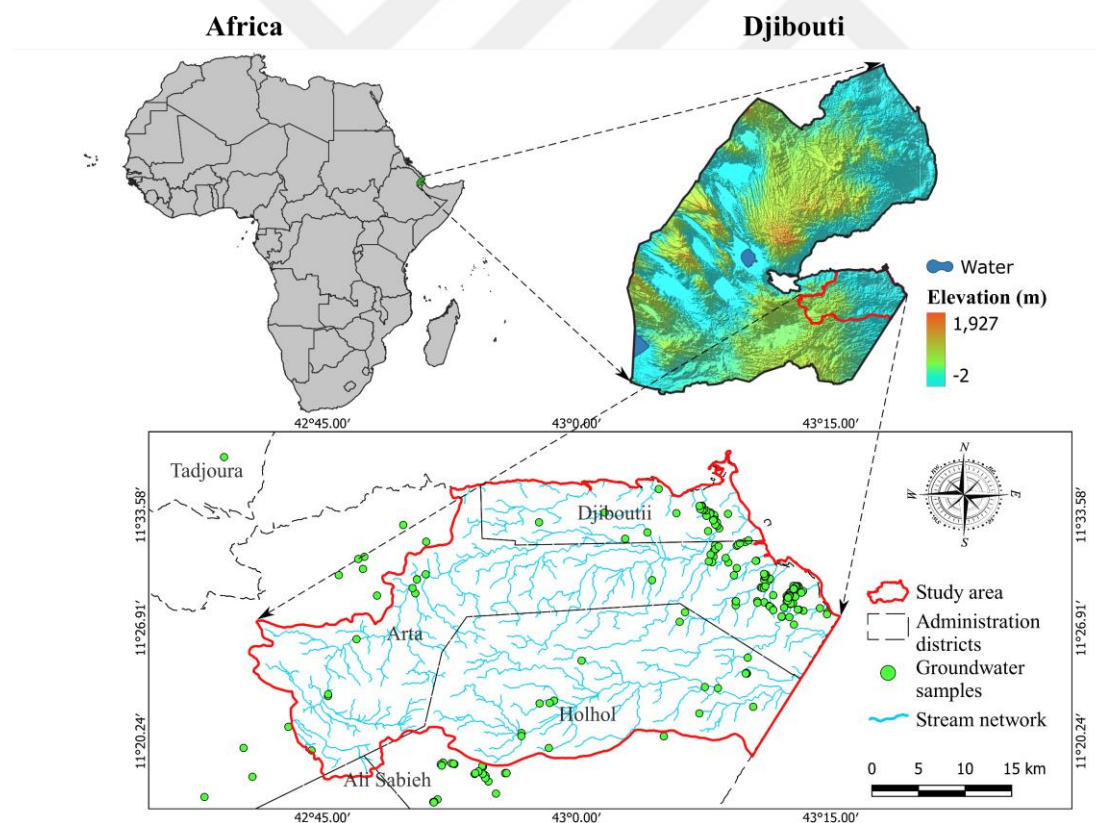


Figure 4.1 : Djibouti southeastern watershed.

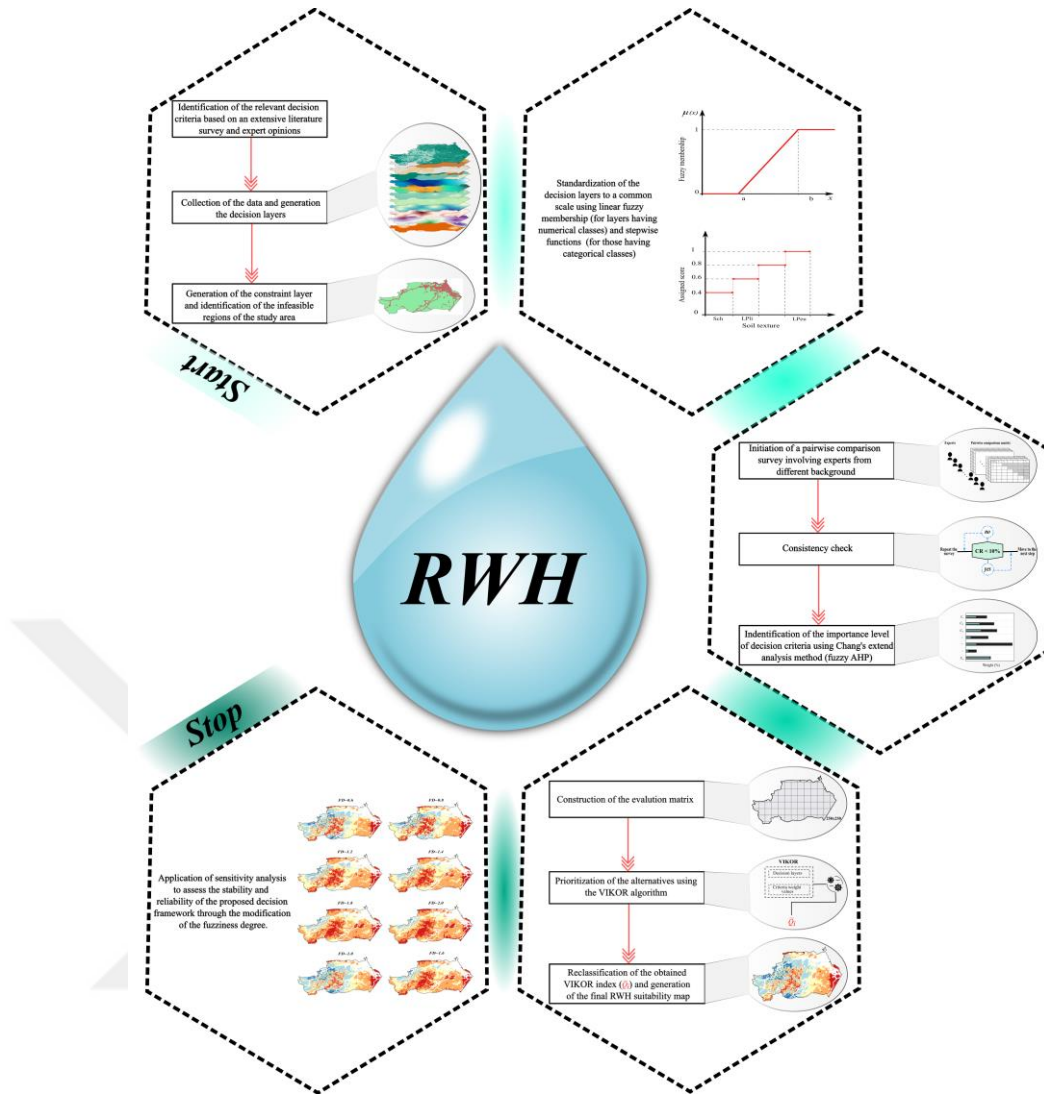


Figure 4.2 : Flowchart showcasing the proposed decision framework for RWH potential mapping.

4.2 Constraint Mapping

Screening out infeasible regions prior to the suitability mapping process constitutes a crucial stage in MAR opportunities mapping, following the problem definition phase that involves the explicit delineation of the objectives of the artificial recharge and the identification of the MAR methods to be utilized. In the pertinent literature, various factors have been adopted as constraint parameters for the identification of unsuitable areas. However, Sallwey et al. (2019) have pointed out that these factors are highly dependent on the objective of the study and the MAR technology being considered. In this vein, in RWH potential mapping studies socio-economic parameters are generally adopted as constraint parameters to eliminate unsuitable areas for further consideration (Al-shabeeb, 2016; Alene et al., 2022; Ezzeldin et al., 2022; Maina & Raude, 2016;

Shadmehri Toosi et al., 2020; Yegizaw et al., 2022). To generate the constraint layer for this study, four parameters, namely distance to built-up areas, distance to roads, distance to agricultural parcels, and distance to wells were adopted as described in Table 4.1. These parameters were carefully chosen based on a thorough review of the existing literature in the topic, and considering their potential negative impacts on RWH structure sitting. For instance, constructing RWH structures in built-up areas may raise safety concerns such as flooding and may also result in potential conflict with urban expansion (Shadmehri Toosi et al., 2020). Similarly, maintaining a safe distance from the road network is essential to avoid future conflicts between road development and constructed structures (Al-Adamat et al., 2010). About wells, the requirement comes from the necessity of erecting RWH structures at a distance sufficient enough from production wells to permit adequate travel time to the infiltrated water (Shadmehri Toosi et al., 2020). Concerning agricultural parcels, they need to be excluded since they are valuable economic and environmental resources to protect from any disturbance related to any RWH activities (Al-Adamat et al., 2010; Baban & Wan-Yusof, 2003; Shadmehri Toosi et al., 2020). Therefore, using the proximity raster distance tool in QGIS 3.28 an individual layer was generated for each parameter and reclassified using boolean logic by assigning a score of 0 and 1 to restricted and feasible areas, respectively. Table 1 presents the reclassification scheme and the corresponding score assigned to each parameter. Finally, the individual layers were combined to create the constraint layer, as illustrated in Figure 4.3. This process enabled the identification of areas that were unsuitable for RWH structures and helped to ensure that only feasible locations were considered in the site suitability analysis.

Table 4.1 : Parameters adopted to screen out infeasible regions for RWH implementation.

Parameter	Class	Rating	References
Distance to built-up areas (m)	> 250	1	Al-shabeeb (2016); Shadmehri Toosi et al. (2020); Ezzeldin et al. (2022); Maina and Raude (2016); Yegizaw et al. (2022); Alene et al. (2022); Jha et al. (2014); Al-Adamat et al. (2010); Matomela et al. (2020)
	≤ 250	0	
Distance to roads/railways (m)	> 250	1	Al-shabeeb (2016); Shadmehri Toosi et al. (2020); Ezzeldin et al. (2022); Yegizaw et al. (2022); Alene et al. (2022); Al-Adamat et al. (2010); Matomela et al. (2020)
	≤ 250	0	
Distance to agricultural parcels (m)	> 250	1	Al-shabeeb (2016); Shadmehri Toosi et al. (2020)
	≤ 250	0	
Distance to wells (m)	> 500	1	Al-shabeeb (2016); Shadmehri Toosi et al. (2020); Al-Adamat et al. (2010)
	≤ 500	0	
	≤ 500	0	

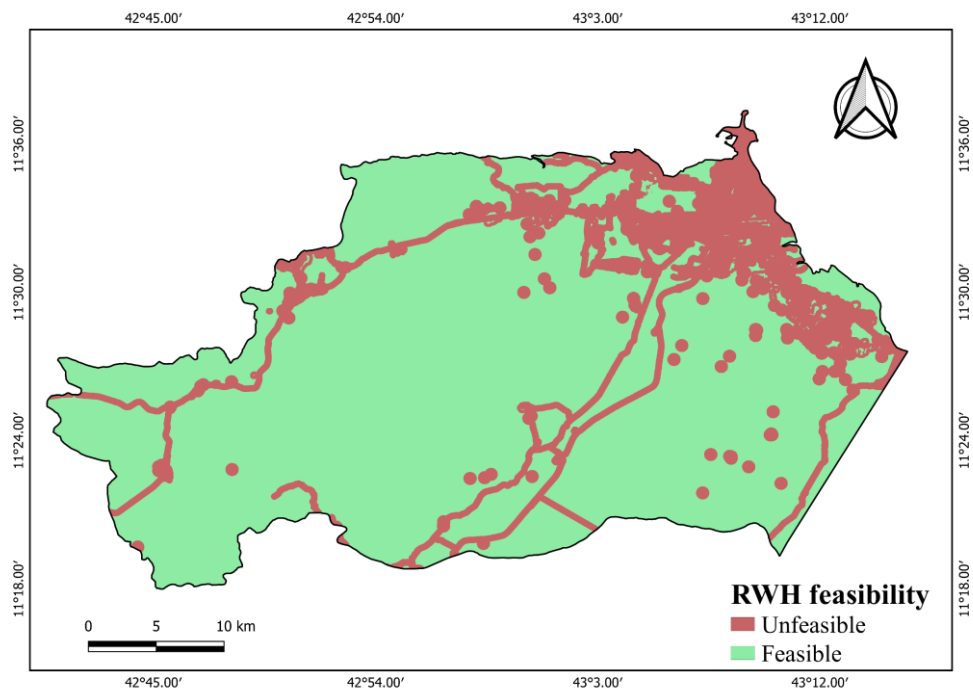


Figure 4.3 : Boolean logic-based constraint map.

4.3 Decision Criteria Descriptions and Layers Generation

Based on an in-depth literature survey a total of 12 decision criteria were identified as relevant to locate promising regions for RWH facilities implementation. These criteria were refined and organized into three main clusters: physical (slope, soil texture, land use/land cover, watershed size), environmental (rainfall, runoff, electrical conductivity, normalized difference vegetation index), and socio-economic (proximity

to settlements, distance to roads, proximity to agricultural parcels, agricultural parcels density) each comprising of four criteria in order for constructing a better hierarchical representation as presented in Figure 4.4. Following a brief description of the relevance of each parameter used in this study and the data source used for their generation allowing a comprehensive understanding of the layers used in the analysis and increasing the transparency of the research process.

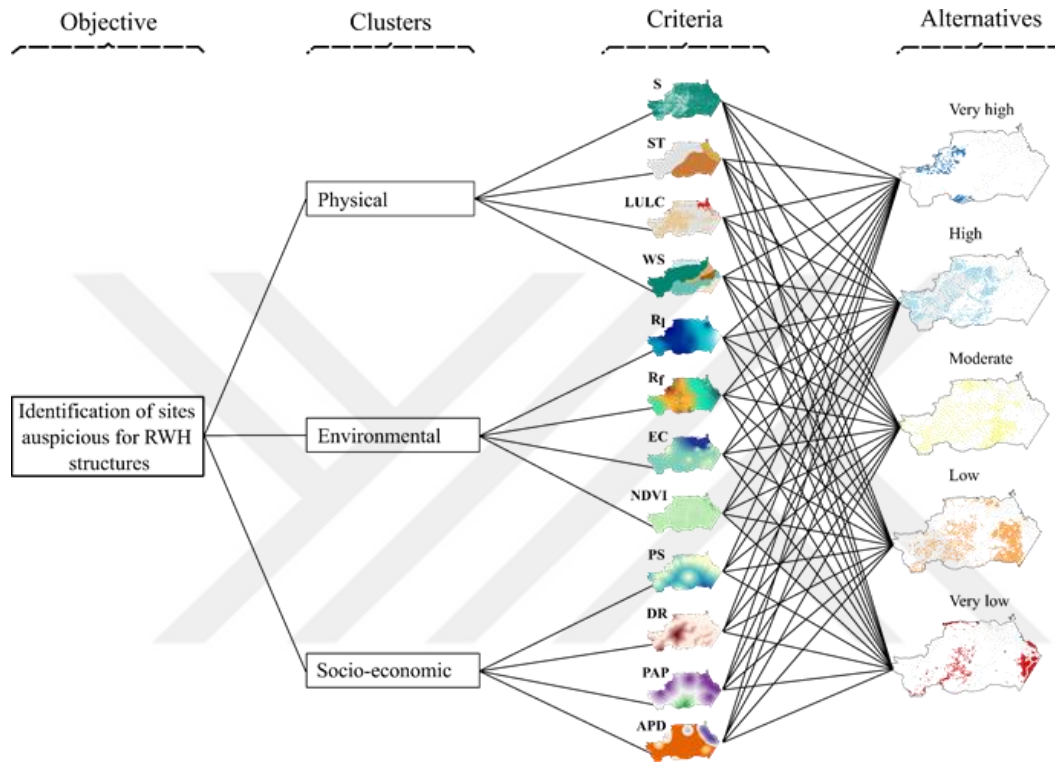


Figure 4.4 : Hierarchical framework of the study.

- **Physical criteria group**

Slope– is a commonly utilized factor in rainwater harvesting (RWH) opportunity mapping, as noted by Ammar et al. (2016). This popularity is due to the fact that slope plays a critical role in controlling the convergence and divergence of surface runoff, which is closely linked to the infiltration capacity of the soil (Ahmadi et al., 2017; Mouhoumed et al., 2023). In particular, areas with gentle slopes are known to exhibit higher infiltration rates compared to those with steeper slopes. Consequently, the inclusion of slope in RWH sites suitability mapping can assist in identifying locations with greater potential for infiltration and thereby the potential to alleviate the water level of the local aquifer as well. The ALOS World 3D (AW3D) digital elevation model with 5m resolution (NTT DATA Corp, 2016) was used to derive the slope of the study area and the corresponding map was made available in Figure 4.5a.

Soil texture– is an important factor in RWH since it has a significant influence on the ability of the soil to infiltrate large volume of water as well as its control on the volume of runoff that can be generated (Alene et al., 2022; Alkaradaghi et al., 2022). For example, soils with high clay content tend to exhibit low infiltration and high runoff rates, while soils with high sand content tend to exhibit high infiltration rates and low runoff rates, as noted by Rajasekhar et al. (2020). For this study, the Harmonized World Soil Database version 2.0 (FAO & IIASA, 2023) was utilized to extract the soil texture data for the region of interest. The data was obtained at a resolution of approximately 1km and the resulting map is displayed in Figure 4.5b.

Watershed size– the surface area of a watershed is a crucial parameter that significantly affects the runoff process. Larger basins have the potential to produce a greater volume of runoff water for reclamation compared to smaller watersheds (Elewa et al., 2021; Ezzeldin et al., 2022). The study area comprises six watersheds of varying sizes, with the Ambouli basin being the largest, covering an area of 643.24 km². The Deydey Weyn (329 km²), Ambada (114.74 km²), and Barisle (110.73 km²) follow in the 2nd, 3rd, and 4th places, respectively, while the Dameerjoog basin is the smallest and least favorable for RWH (Figure 4.5c).

Land use/land cover (LULC)– represents another critical physical criterion for the identification of suitable sites for RWH. LULC has a direct impact on the volume of runoff that can be harvested within a given area, as well as being an essential parameter in the selection of appropriate water harvesting techniques for specific locations (Harka et al., 2020; Waghaye et al., 2023). According to Jha et al. (2014), for instance, agricultural LULC classes are considered more appropriate for farm ponds, whereas degraded forest areas are favorable for percolation tanks. In this study, the LULC layer was extracted from Sentinel-2 imagery, with a spatial resolution of 10 meters (Karra et al., 2021), and subsequently pre-processed (Figure 4.5d).

- **Environmental criteria group**

Rainfall– has all its importance in RWH potential assessment since stormwater runoff represents the only source of reclaimed water. Therefore, the presence of adequate rainfall is a fundamental prerequisite for the successful implementation and operation of RWH systems (Ammar et al., 2016). The average annual precipitation data from various meteorological measuring stations in the study area were acquired from Dabar et al. (2022) and used to generate a point vector. Then, the inverse distance weighting

(IDW) method was used to interpolate the precipitation point data, which resulted in the production of a rainfall map for the focalized region (Figure 4.5e).

Runoff– used as often as rainfall, runoff depth is a dominant decision parameter in locating promising sites for RWH structures. The parameter provides an indication of the amount of rainwater that can be potentially captured in a given area (Ezzeldin et al., 2022; Matomela et al., 2020). To compute the runoff depth numerous studies in the pertinent literature have adopted the Soil Conservation Service Curve Number (SCS-CN) method, due to its simplicity and stability (Jha et al., 2014). In line with, this study utilized the SCS-CN to generate the runoff map by applying the following equation:

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)} \quad (4.1)$$

where Q is the runoff depth, P is the precipitation, and S is the potential maximum retention after runoff begins. The value of S was determined using the following equation:

$$S = 254 \left(\frac{100}{CN} - 1 \right) \quad (4.2)$$

where CN represents the curve number, which was obtained from the global curve number (GCN250) dataset with a resolution of 250m (Jaafar & Ahmad, 2019).

Electrical conductivity– in RWH projects where the objective is not only to harvest rainwater but also to recharge the local aquifer by extending the infiltration time, having knowledge about the quality of the pre-existing water in the aquifer is crucial for maximizing the benefits of the recharged water. In this research, electrical conductivity (EC) was utilized as an indicator of groundwater quality in the study area, which is known to face serious saltwater intrusion. EC, which is an indicator of the level of dissolved salts in water was mapped using 107 samples measurements obtained from the database of the Ministry of Agriculture, Water, Fisheries and Livestock (MAEPE-RH, 2015) of Djibouti and interpolated by means of IDW (Figure 4.5g).

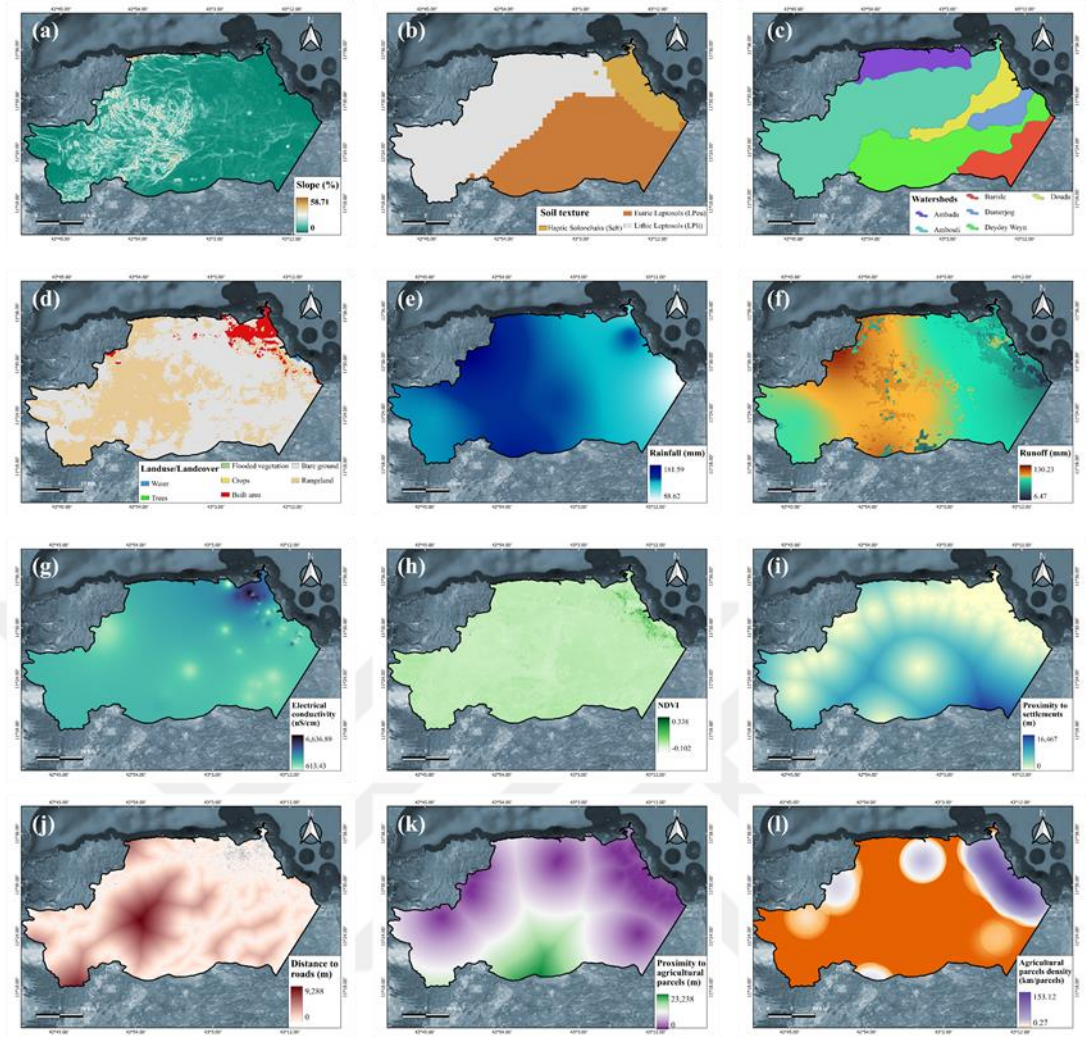


Figure 4.5 : enerated decision layers for the identification of areas suitable for RWH structures: (a) slope, (b) soil texture, (c) watershed size, (d) land use/land cover, (e) rainfall, (f) runoff, (g) electrical conductivity, (h) normalized difference vegetation index, (i) proximity to settlements, (j) distance to roads, (k) proximity to agricultural parcels, (l) agricultural parcels density.

Normalized difference vegetation index (NDVI)– the parameter provides insight about the density and health of vegetation in a given area. Moreover, as outlined by Ansems et al. (2015), the NDVI can be employed to identify areas that are susceptible to frequent flooding, with elevated NDVI values indicating seasonal flooding and the potential to yield significant volumes of water for MAR initiatives. To calculate NDVI, Sentinel 2 images were utilized in this study, and the following equation was employed:

$$NDVI = \frac{NIR - RED}{NIR + RED} \quad (4.3)$$

Here, NIR and RED denote the near-infrared and red bands, respectively.

- **Socio-economic criteria group**

Proximity to settlements– the distances of RWH structures to human settlements is crucial for both safety and transportation cost management reasons. Although it is mandatory to ensure a safe distance from settlements, it is also desirable to minimize transportation costs by not placing them too far away. Both de Winnaar et al. (2007) and Khan et al. (2022) have emphasized the importance of this aspect. In this study, the proximity raster distance tool from QGIS 3.28 (QGIS Development Team, 2022) was utilized to create a proximity to settlements layer, which was visualized through the corresponding map presented in Figure 4.5i.

Distance to agricultural parcels– in line with the objective of meeting the agricultural water demand in arid and semi-arid regions, it is advisable to construct RWH structures in close proximity to farmlands, as is the case with settlements (R. S. Wu et al., 2018). The agricultural parcels in the focalized region were digitized and the proximity raster distance tool was employed to generate a map depicting the distance to these parcels. The resulting map can be found in Figure 4.5k.

Distance to roads– mostly adopted as a restriction parameter it's also recognized to influence the success of RWH projects. This is because constructed structures need to be easily accessible for the local communities and not too far from practical roads to facilitate periodic maintenance, which is crucial for the good operation and longevity of the facilities (Ezzeldin et al., 2022). To determine the distance to roads layer (Figure 4.j), the road network of the study area was obtained from OpenStreetMap (OSM) using the OSM downloader plugin in QGIS and then rasterized before applying the proximity raster distance algorithm.

Agricultural parcels density– although a novel parameter in the literature and overlooked by the research community, this study included the corresponding criterion to see its impact on the mapping of RWH potential. Directing RWH efforts towards areas with a high density of agricultural parcels has the potential to increase the success and benefits of such projects, as well as the number of people who could potentially benefit from them. A density map of the digitized agricultural parcels was generated in the present research (Figure 4.5l).

4.4 Thematic Layers Standardization Techniques

The nature of the different decision criteria involved in RWH mapping makes the normalization of the thematic layers in a common scale an imperative step in the decision analysis. In the topic, the application of scores/rates to the layer classes is one of the most commonly used standardization approach (Adham et al., 2016; Alkaradaghi et al., 2022; Ezzeldin et al., 2022; Krois & Schulte, 2014; Maina & Raude, 2016; Shadmehri Toosi et al., 2020; Singh et al., 2017; Yegizaw et al., 2022). Nevertheless, in this paper, we have adopted a hybrid approach for standardizing the layers, using fuzzy membership functions for numerical parameters (i.e. slope, rainfall, and proximity to settlements) and step-wise functions for categorical variables such as soil texture and land use/land cover (Figure 4.6). The resulting maps derived from the applied functions display a range of values between 1 and 0, whereby cells with the greatest potential for RWH receive a value of 1, whereas those deemed the least suitable receive a value of 0. With regards to the linear fuzzy membership function, it is characterized by the following definition:

$$\mu(x) = \begin{cases} 0 & x \leq a \\ \frac{x-a}{b-a} & \text{if } a < x < b \\ 1 & x \geq b \end{cases} \quad (4.4)$$

Where a and b are the low (no membership) and high (full membership) bound, respectively. Table 4.2 presents the input values assigned to the linear function for each decision parameter. These values were determined based on a comprehensive literature survey and expert opinions.

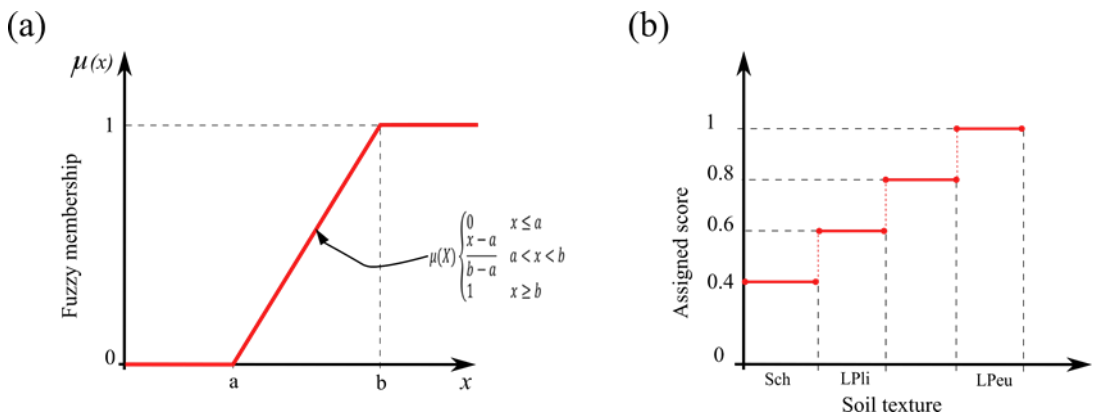


Figure 4.6 : Graphical representation of the (a) linear fuzzy membership and (b) step-wise (i.e. soil texture) functions.

Table 4.2 : List of utilized criteria in the analysis and the standardization function adopted to standardize thematic layers.

Clusters	Criteria	ID	Standardization function	Membership bound		References
				Low	High	
Physical	Slope (%)	S	DLFM	20	0	Alkaradaghi et al. (2022); Rajasekhar et al.(2020); Harka et al. (2020); Wu et al. (2018); Singh et al. (2021); Kumar and Jhariya (2017); Elewa et al. (2021); Singh et al. (2017); Farooq et al. (2022); Preeti et al. (2022); Alene et al. (2022); Khan et al. (2022); Maina and Raude (2016); Farooq et al. (2022); Vema et al. (2019); Yegizaw et al. (2022); Ouali et al. (2022); Mahmoud et al. (2015); Krois and Schulte (2014); Waghaye et al. (2023); Roy et al. (2022); Radwan and Alazba (2023); Gavhane et al. (2023); Chowdhury and Paul (2021); Shadmehri Toosi et al. (2020); Ezzeldin et al. (2022); Al-shabeeb (2016); Matomela et al. (2020); Chimdessa et al. (2022)
	Soil texture	ST	SW	-	-	
	Watersheds size (km ²)	WS	ILFM	0	640	
	Land use/Land cover	LULC	SW	-	-	
						Ezzeldin et al. (2022); Patil et al. (2022); Elewa et al. (2021); Patil et al. (2022); Maina and Raude (2016); Farooq et al. (2022); Yegizaw et al. (2022); Alkaradaghi et al. (2022); Mahmoud et al. (2015); Krois and Schulte (2014); Kumar and Jhariya (2017); Preeti et al. (2022); Alene et al. (2022); Roy et al. (2022); Khan et al. (2022); Harka et al. (2020); Wu et al. (2018); Radwan and Alazba (2023); Gavhane et al. (2023); Chowdhury and Paul (2021); Shadmehri Toosi et al. (2020); Ezzeldin et al. (2022); Chimdessa et al. (2022)

Table 4.2 (continued): List of utilized criteria in the analysis and the standardization function adopted to standardize thematic layers.

Clusters	Criteria	ID	Standardization function	Membership bound		References
				Low	High	
Environmental	Rainfall (mm)	R _i	ILFM	100	180	Adham et al. (2016); Patil et al. (2022); Yegizaw et al. (2022); Alkaradaghi et al. (2022); Krois and Schulte (2014); Mahmoud et al. (2015); Kumar and Jhariya (2017); Preeti et al. (2022); Ouali et al. (2022) (R. S. Wu et al., 2018); Radwan and Alazba (2023); Tahvili et al. (2021); Shadmehri Toosi et al. (2020); Al-shabeeb (2016); Chimdessa et al. (2022)
	Runoff (mm)	R _f	ILFM	17	120	de Winnaar et al. (2007); Patil et al. (2022); Farooq et al. (2022); Vema et al. (2019); Mahmoud et al. (2015); Krois and Schulte (2014); Roy et al. (2022); Waghaye et al. (2023); Alene et al. (2022); Khan et al. (2022); Ouali et al. (2022); Harka et al. (2020); Wu et al. (2018); Radwan and Alazba (2023); Gavhane et al. (2023); Ezzeldin et al. (2022); Chimdessa et al. (2022)
	Electrical conductivity (μS/cm)	EC	DLFM	3000	1000	Ahani Amineh et al. (2017)
Socio-economic	NDVI	NDVI	ILFM	0	0.5	Tahvili et al. (2021); Ansems et al. (2015); Rawat et al. (2023)
	Proximity to settlements (m)	PS	DLFM	10000	250	de Winnaar et al. (2007); Adham et al. (2016); Yegizaw et al. (2022); Alkaradaghi et al. (2022); Khan et al. (2022); Harka et al. (2020); Ezzeldin et al. (2022)
	Distance to roads (m)	DR	DLFM	5000	250	Yegizaw et al. (2022); Preeti et al. (2022); Khan et al. (2022); Wu et al. (2018); Chowdhury and Paul (2021); Ezzeldin et al. (2022); Matomela et al. (2020)
	Proximity to agricultural parcels (m)	PAP	DLFM	10000	250	de Winnaar et al. (2007); Harka et al. (2020); Wu et al. (2018)
	Agricultural parcels density (km/parcels)	APD	ILFM	0	150	-

DLFM: decreasing linear fuzzy membership function; ILFM: increasing linear fuzzy membership function; SW: step-wise function

4.5 Results of the Fuzzy AHP Analysis

This study assessed the potential of RWH in the south eastern basin of Djibouti using twelve decision criteria based on three dimensions, i.e., physical, environmental and socio-economic. To determine the relative importance of each decision parameter, the fuzzy AHP method was employed, supported by a pairwise comparison survey (the structure of the pairwise questionnaire can be seen in Table A.1-A.4). It is worth highlighting that the MCDA approach heavily relies on expert judgments, making the participants of the survey a significant source of uncertainty within the decision framework. Likely, the AHP method enables the assessment of the consistency of expert responses by calculating the CR value. The profile of the experts who took part in the pairwise questionnaire is illustrated in Table A.5. In this research, the consistency of the responses given in each pairwise matrix (consisting of 4 sub-criteria in physical cluster, 4 sub-criteria in environment cluster, 4 sub-criteria in socio-economic cluster, and 4 main corresponding clusters) was calculated and the obtained results are given Figure 4.7. It can be observed that all obtained CR values are below 10%, indicating a consistent decision framework. Consequently, further computations, including criteria weighting, can be confidently carried.

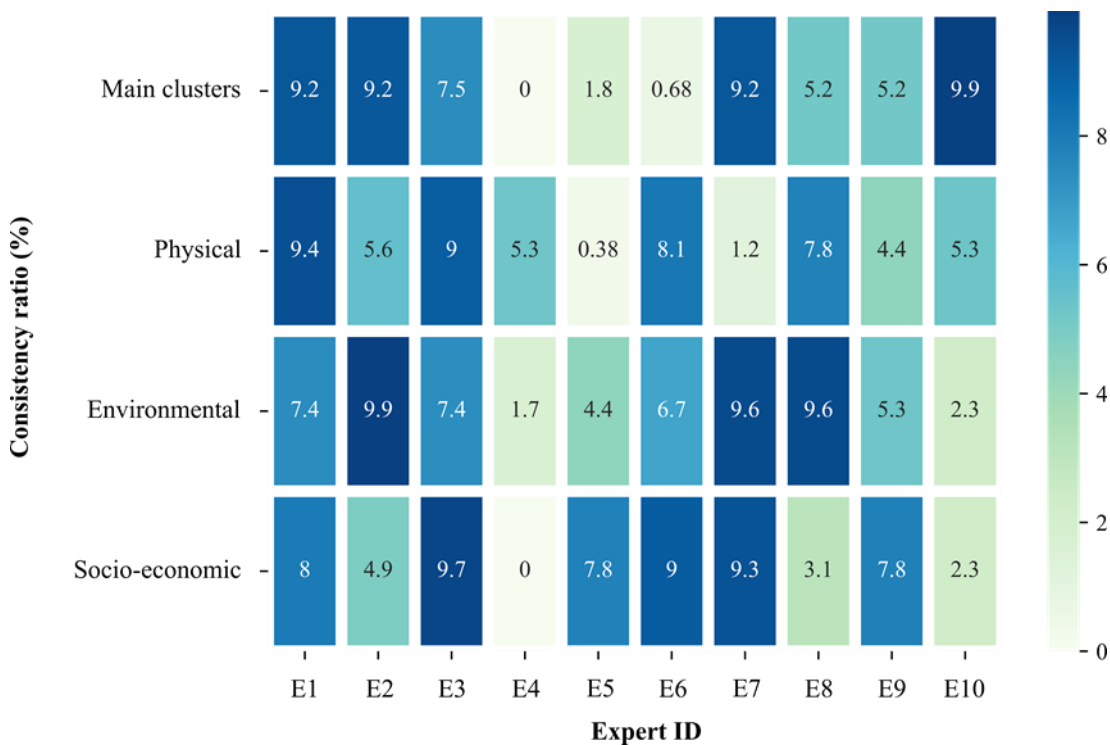


Figure 4.7 : Experts' pairwise comparison survey consistency ratios.

Table 4.3 presents the outcomes of the decision criteria weighting process conducted using the fuzzy AHP algorithm. The table illustrates the obtained weights for the main clusters and their corresponding criteria. Consequently, the environment dimension emerged as the most significant, exhibiting a weight of 47.67% compared to its counterpart. The physical cluster followed in second place, with a weight of 37.98%, while the socio-economic dimension ranked 3rd, with a significance level of 14.35%. Furthermore, Table 4.3 provides the local weights of the decision parameters within their respective cluster groupings. In the physical cluster, slope and watershed size were assigned the highest weights, amounting to 50.36% and 26.19%, respectively. While LULC and soil texture ranked 3rd and 4th with weights of 16.03% and 7.42%, respectively. Regarding the environment dimension, rainfall (49.37), runoff (31.04%) and electrical conductivity (11.29%) completed the podium in the 1st, 2nd, and 3rd place, respectively, whereas NDVI was deemed the least significant in this group. Within the socio-economic cluster, the proximity to agricultural parcels criterion had the highest local weight of 32.60%, closely followed by the proximity to settlements and agricultural parcels density criteria with importance levels of 29.27% and 27.69%, respectively. However, the distance to roads parameter was considerably underestimated by the pairwise questionnaire participants, as it obtained a weight of 10.44% within this set.

Table 4.3 : Relative weights and ranks of decision criteria obtained through the fuzzy AHP analysis.

Cluster	Weight	Criteria	Criteria weight		Rank	
			local	global	local	global
Physical	37.98%	Slope	50.36%	19.13%	1	2
		Land use/Land cover	16.03%	6.09%	3	5
		Soil texture	7.42%	2.82%	4	11
		Watershed size	26.19%	9.95%	2	4
Environment	47.67%	Rainfall	49.37%	23.53%	1	1
		Runoff	31.04%	14.79%	2	3
		Electrical conductivity	11.29%	5.38%	3	6
		NDVI	8.30%	3.96%	4	10
Socio-economic	14.35%	Proximity to settlements	29.27%	4.20%	2	8
		Distances to roads	10.44%	1.50%	4	12
		Proximity to agricultural parcels	32.60%	4.68%	1	7
		Agricultural parcels density	27.69%	3.97%	3	9

Also, Table 4.3 presents the global weights, which illustrate the overall level of importance of each decision parameter within the RHW potential mapping decision framework. Based on the obtained results, rainfall, slope, runoff, and watershed size

emerge as the most significant factors, with global weights of 23.53%, 19.13%, 14.79%, and 9.95% respectively. Interestingly, although NDVI is part of the environment cluster, which carries the highest weights, it received a weight that is nearly equivalent to the agricultural parcels density criterion, positioning it among the least weighted criteria. Nevertheless, it is worth noting that the distance to roads (1.50%) is identified as the least important criterion in the weighting process, ranking 12th. It is closely preceded by soil texture (2.82%) in the 11th place and NDVI (3.96%) in the 10th place.

4.6 RWH Potential Mapping

The prioritization and calculation of the suitability degree of distinct zones within a specific focalized region represent the cornerstone in RWH potential mapping research. In the current study, the VIKOR algorithm was adopted to calculate the suitability index ($\tilde{Q}_i$) and thereby generate the final RWH potential map. To construct the evaluation matrix, which is the most fundamental aspect of the algorithm, certain steps were undertaken. To begin, a rectangular grid layer with a spatial resolution of 250m by 250m was created. It is worth noting that infeasible regions had already been identified and excluded (Figure 4.3), using boolean logic based on the constraint parameters mentioned earlier (Table 4.1), thus confining the analysis to feasible regions only (representing 79.56% of the studied basin). Subsequently, the zonal statistics tool was applied to calculate the average value for each pixel in the grid layer, by taking the twelve decision layers as input raster layers. In the current analysis, the process yielded an evaluation matrix comprising 18,191 rows and 12 columns.

In order to enhance the depth of the analysis, the VIKOR index was computed individually for the distinct clusters (Figure 4.8a, b, c) as well as for the overall dimensions (Figure 4.9). The results unveil notable variations in the suitability pattern across the different dimensions. For instance, when considering the physical dimension, areas in the center and north of the basin demonstrate high $\tilde{Q}_i$ (close to 1), indicating lower suitability for RWH activities. This can primarily be attributed to the presence of steep slopes in these regions. Conversely, the western and eastern sections of the Ambouli sub-watershed, along with most parts of the Deydey-Weyn sub-watershed except its northwestern region, exhibit low $\tilde{Q}_i$ values, indicating higher potential for RWH (Figure 4.8a). This could be attributed to the larger surface area of

these two sub-watersheds compared to their counterparts, with the Ambouli and Deydey-Weyn ranking as the first and second largest in terms of surface area, respectively. Regarding the environment dimension (Figure 4.8b), the basin center shows $\tilde{Q}_i$ values tending towards 0, indicating an enhanced potential for RWH implementation. This can be attributed to the significant amount of rainfall received in these regions, as well as their favorable conditions for generating notable surface runoff. It is important to note that the electrical conductivity and NDVI layers have limited impact on suitability, as indicated by their significance levels in the fuzzy AHP analysis. On the other hand, within the socio-economic criteria group (Figure 4.8c), the central region of the basin demonstrates large $\tilde{Q}_i$ values, signifying poor potential for constructing RWH structures. This is due to the low density of agricultural parcels in these zones and their considerable distance from both agricultural parcels and settlements. The eastern portion of the basin, however, display promising potential (low $\tilde{Q}_i$) for RWH, owing to the presence of extensive agricultural activities and the availability of urban settlements in this part of the study area.

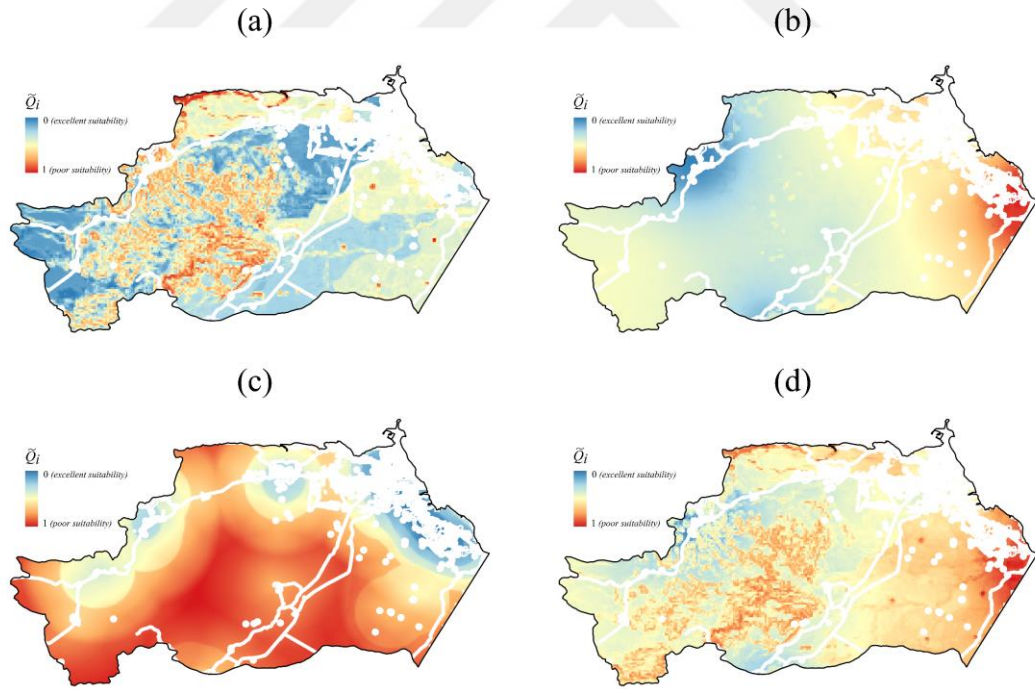


Figure 4.8 : RWH potential analysis based on the individual and overall clusters. (a) Physical, (b) Environment, (c) Socio-economic, and (d) Overall.

Figure 4.8d presents the comprehensive assessment of RWH potential by integrating all relevant criteria dimensions, namely physical, environmental, and socio-economic, within the scope of this research. The resulting overall $\tilde{Q}_i$ distribution map was

subsequently reclassified into five suitability classes using the Jenks natural break method, as depicted in Figure 4.9. According to the final RWH potential map (Figure 4.9), the findings indicate that the southeastern part of the basin exhibits very low and low suitability for RWH implementation. Conversely, the northwestern part is predominantly characterized by very high and high suitability categories. Furthermore, in terms of surface area, it is observed that 10.83% and 24.92% of the feasible region of the basin demonstrate very low and low suitability potential for RWH. Conversely, 6.39% and 29.02% of the feasible regions exhibit very high and high suitability, respectively, while approximately 28.84% of the analyzed region demonstrates moderate suitability for RWH implementation.

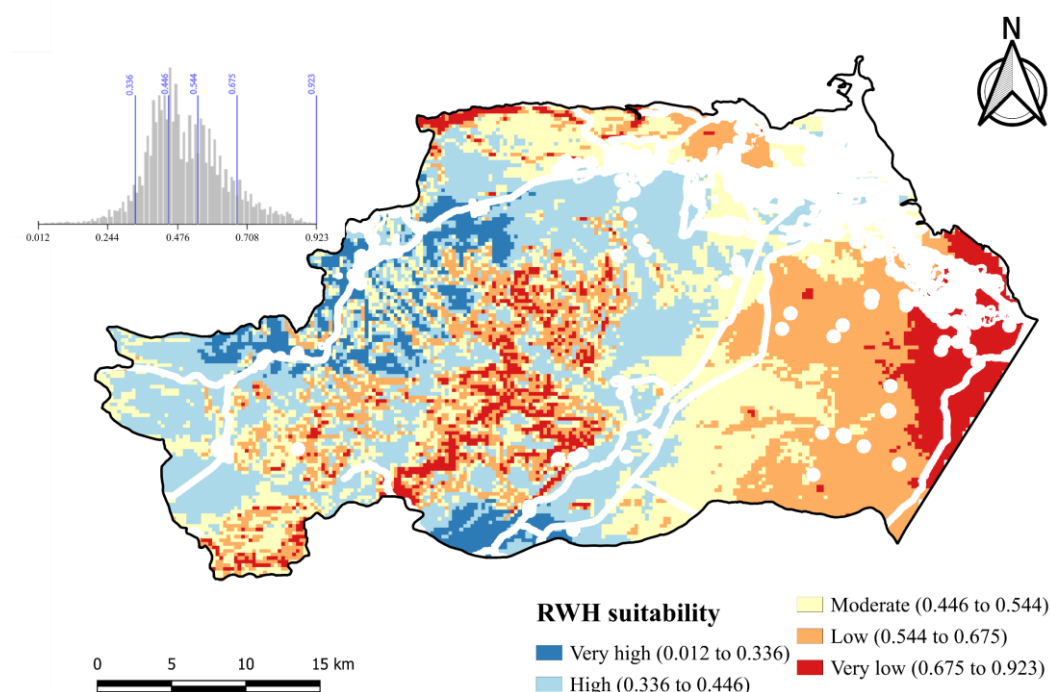


Figure 4.9 : RWH potential map of the study area obtained through the proposed decision framework.

4.7 Sensitivity Analysis

This study also aimed to assess the robustness and reliability of the proposed decision framework through the application of sensitivity analysis, which plays a critical role in evaluating the stability and transparency of proposed models. In this research, sensitivity analysis was performed by modifying the fuzziness degrees (FD) within the fuzzy AHP algorithm. The original fuzziness degree ($FD=1.0$) served as the baseline

scenario, and to examine the sensitivity of the results, seven additional scenarios were generated by incrementally changing the FD values by 0.2. These scenarios included FD values of 0.6, 0.8, 1.2, 1.4, 1.6, 1.8, and 2.0. The purpose of introducing these variations in FD was to observe potential changes in the ranking of criteria under different levels of fuzziness. The findings of the sensitivity analysis, which are presented in Table 4.4, illustrate the variations in criteria weights and overall ranking based on different FD values. Interestingly, it is evident that the four most weighted decision criteria consistently maintained their initial ranking across all scenarios. Moreover, for $FD=1.2$ and 1.4 the ranking stays the same to the baseline for the first five significant criteria, while, for $FD > 1.4$, there is no variation in the ranking for the first seven significant criteria.

Beyond the evaluation of criteria ranking variations, the current study also investigated the influence of FD adjustments on the suitability pattern. Figure 4.10 and 4.11 depict the RWH potential maps generated based on the FD scenarios and the Pearson correlation coefficients attained based on the VIKOR index values pertaining to computation cells in each scenario, respectively. The results demonstrate slight changes in the suitability pattern across all scenarios. Still, it is important to note that the basin center and southeastern regions stay the least suitable for RWH activities, while, the northwestern is largely dominated by very high, high, and moderate suitability classes in all scenarios, yielding results similar to the baseline scenario (Figure 11). In addition, there are no significant discrepancies in the VIKOR index values among the FD scenarios with regard to the correlation coefficients depicted in Figure 12. While, once the difference between the fuzziness degrees (for example $FD: 1.0$ and $FD: 2.0$), variations are observed in the correlations as expected, there are still high correlations (i.e., with a minimum of 0.8) concerning the entire region of focus. Overall, this research included the sensitivity analysis to enhance the transparency of the proposed hybrid MCDM scheme and ensured its stability and robustness as no major changes were observed in both the decision criteria ranking and suitability pattern.

Table 4.4 : Weights and ranks of the decision criteria reached through the variation of the fuzziness degree.

Criteria	Fuzziness degree															
	0.6		0.8		1.0		1.2		1.4		1.6		1.8		2.0	
	w	r	w	r	w	r	w	r	w	r	w	r	w	r	w	r
S	0.2135	2	0.1574	2	0.1913	2	0.1244	2	0.1175	2	0.1123	2	0.1082	2	0.1048	2
LULC	0.0529	6	0.0677	6	0.0609	5	0.0756	5	0.0772	5	0.0784	5	0.0793	5	0.0801	5
ST	0.0063	12	0.0418	11	0.0282	11	0.0612	11	0.0650	11	0.0678	11	0.0701	11	0.0720	11
WS	0.0979	4	0.0929	4	0.0995	4	0.0894	4	0.0887	4	0.0881	4	0.0875	4	0.0871	4
R _l	0.2510	1	0.1783	1	0.2353	1	0.1363	1	0.1277	1	0.1212	1	0.1161	1	0.1119	1
R _f	0.1407	3	0.1190	3	0.1479	3	0.1050	3	0.1019	3	0.0996	3	0.0977	3	0.0961	3
EC	0.0336	9	0.0611	9	0.0538	6	0.0734	7	0.0754	7	0.0769	6	0.0780	6	0.0789	6
NDVI	0.0200	11	0.0538	10	0.0396	10	0.0696	9	0.0723	9	0.0743	8	0.0758	8	0.0771	8
PS	0.0528	7	0.0629	7	0.0420	8	0.0706	8	0.0725	8	0.0738	9	0.0749	9	0.0758	9
DR	0.0217	10	0.0359	12	0.0150	12	0.0506	12	0.0547	12	0.0580	12	0.0608	12	0.0632	12
PAP	0.0588	5	0.0682	5	0.0468	7	0.0745	6	0.0758	6	0.0768	7	0.0775	7	0.0781	7
APD	0.0508	8	0.0612	8	0.0397	9	0.0694	10	0.0713	10	0.0728	10	0.0740	10	0.0750	10

Notes: “w”: weights; “r”: ranking; Bold number in the ranking columns indicates a change of the criteria rank compared to the baseline scenario (FD:1.0)

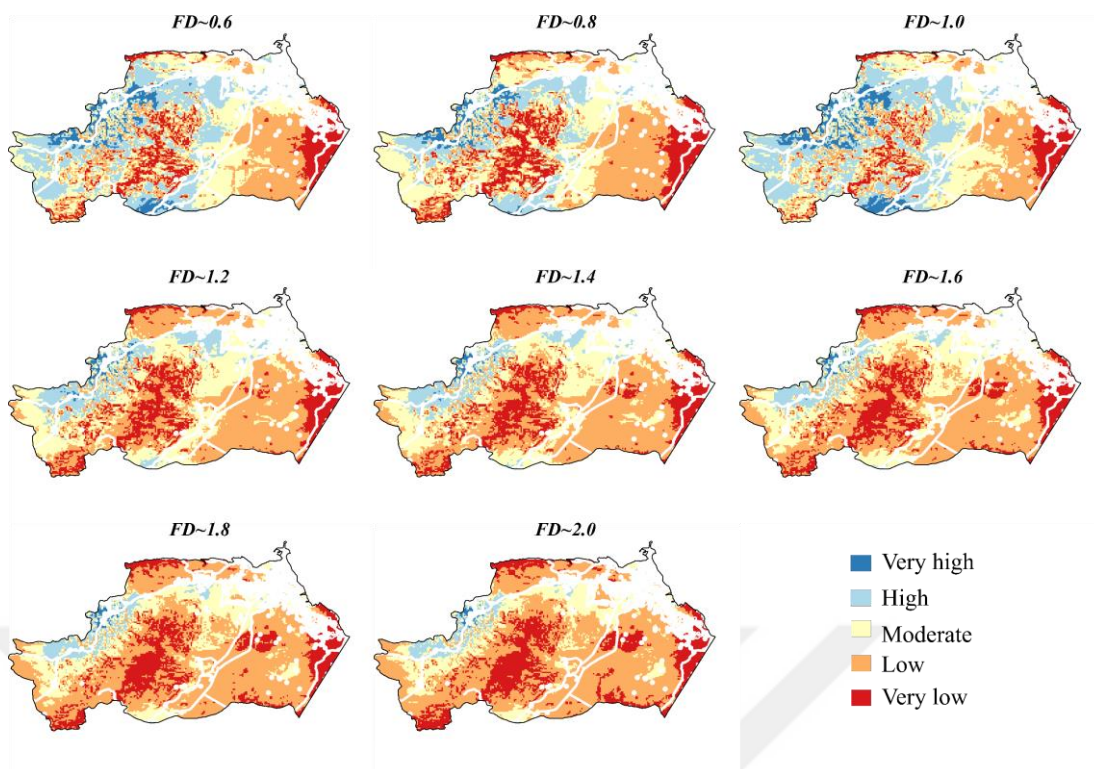


Figure 4.10 : RWH potential maps generated through the variations of the fuzziness degree (FD).

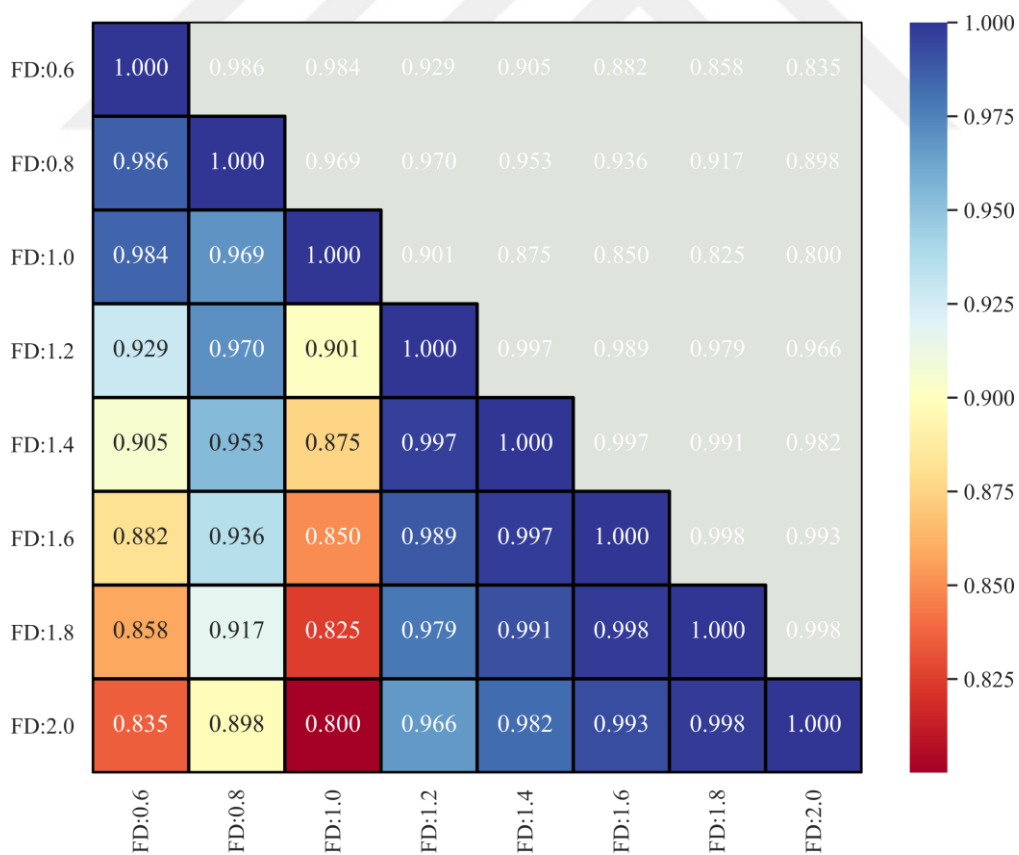


Figure 4.11 : Pearson correlation calculated for the different RWH suitability maps generated through different fuzziness degrees.

4.8 Comparison of the Obtained Criteria Weights with those Adopted in the Pertinent Literature

Due to the fact that the GIS-MCDA rational heavily relies on the subjective judgments of the experts taking parts in the pairwise questionnaire, the decision criteria weighting phase represents one of the most significant aspect of the model and a primary source of uncertainty (Malczewski & Rinner, 2015). This significance also holds true in the context of RWH potential mapping, where the attained levels of significance often lack strong correlations between different studies and are often dictated by the profile of the pairwise survey participants. Interestingly, most studies in this field overlook providing detailed descriptions of the experts involved in the pairwise survey, despite the potential benefits of doing so. Such information could significantly enhance the transparency of proposed models and offer valuable insights to fellow researchers. Nevertheless, in addition to sensitivity analysis, it is imperative to compare the obtained weights with those reported in the literature. Such comparative analysis aids in identifying any discrepancies or potential biases in the weight assignment process and contributes to the overall credibility of the proposed decision framework. Thus, in this research we assessed the weights adopted in relevant studies in the topic and compared it to our study as presented in the box plot given in Figure 4.12. Notably, certain decision criteria are commonly employed in RWH mapping, such as slope, rainfall, land use/land cover, and soil texture. However, it is worth mentioning that some parameters adopted in our study exhibit rarity or novelty in the pertinent literature. As a result, we were unable to include certain criteria, such as electrical conductivity, proximity to agricultural parcels, and agricultural parcels, in the comparative analysis.

According to Figure 4.12, among the 23 studies evaluated in this weight comparison attempt the quasi totality of them include slope in their decision framework, while LULC is the second most used appearing in 16 of them. This finding corroborates the results reported by Sallwey et al. (2019), who also observed a higher frequency of usage for these two criteria compared to their counterparts in the relevant literature. Nonetheless, differences are noticeable between the two criteria sets, particularly in their interquartile range (IQR). It can be seen that LULC has a much lower IQR (7.5%) compared to slope that display a much larger IQR (17.5%). For both the importance levels assigned to them in our study are within their respective IQR and closely

coincide with the median of their respective set. Regarding soil texture, it emerges as the third most frequently employed criterion, appearing in 15 of the studies. Despite displaying a similar IQR to LULC, the weight assigned to soil texture in our study roughly coincides with the minimum value. This is in contrast to Mahmoud et al. (2015), which assigned an outlier weight of 36% to soil texture, indicating a substantial deviation from the norm in the set. Our study, along with the findings of Rajasekhar et al. (2020), assigned a weight of approximately 3% to soil texture, reflecting a significantly lower value compared to the median of the set (15%). This low significance level could be attributed to the fact that soil texture was clustered together with slope, LULC, and watershed size, and the experts in our pairwise survey considered these criteria to be much more important than soil texture. As for runoff, it emerges as the fourth most frequently employed criterion and exhibits the largest IQR, with a notable difference of 48% between the highest (Waghaye et al., 2023) and lowest (Chimdessa et al., 2022) assigned weights within the set. In our study, the weight assigned to runoff aligns with the first quartile. Conversely, the weight attributed to rainfall in our study perfectly coincides with the median weight of the corresponding set. Furthermore, considering the criteria of watershed size, proximity to settlements, distance to roads, and NDVI, although they are sparingly applied in RWH potential mapping, the weights obtained in our research closely aligned with the median weight in their respective sets.

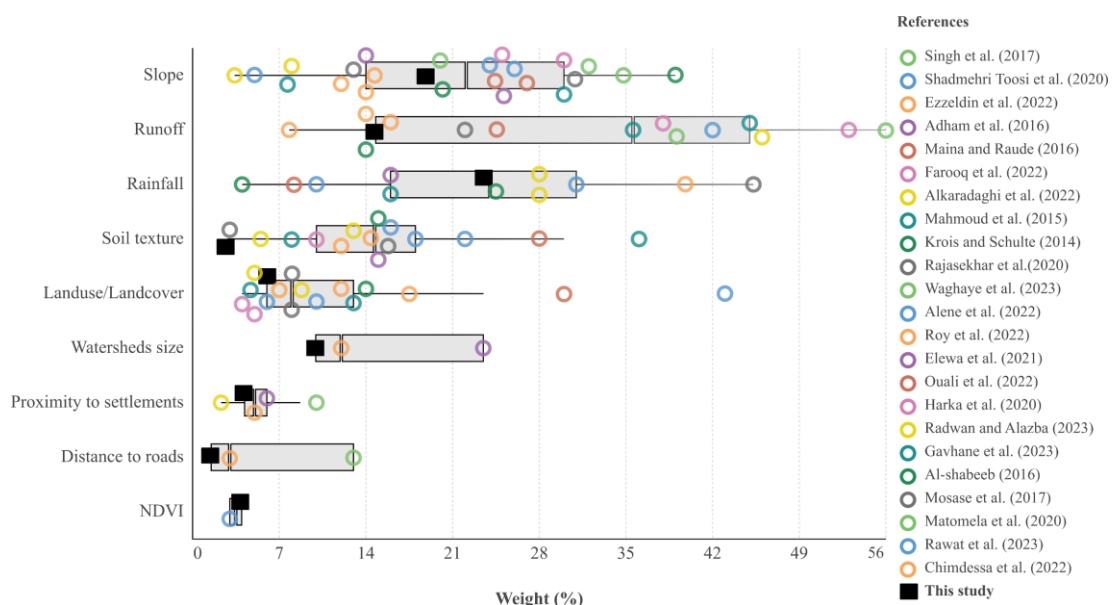


Figure 4.12 : A comparative overview of obtained criteria weights in relation to relevant RWH potential mapping studies.

As a whole, the weights assigned to the decision criteria in the present research shows limited discrepancies and strongly align with the findings introduced in the pertinent literature. Although minor distinctions could be observed, one should take the size of the utilized decision parameters in this study. Moreover, it is important to acknowledge that MCDM methods, heavily rely on the subjective judgments of experts. Consequently, the importance levels of the criteria may exhibit variations when compared to those reported in the existing literature (Mouhoumed et al., 2023). The diverse perspectives and individual interpretations of experts can contribute to such discrepancies, underscoring the inherent subjectivity in MCDM processes. Thus, we recognize the significance of disclosing the background and expertise of the involved experts in RWH potential mapping studies.

4.9 Assessment of the RWH Strategies in the Focalized Region and Practical Utilization of the Proposed Framework

The ever-increasing climate variability has given rise to a remarkable phenomenon where some of the driest regions on Earth are now facing concurrent occurrences of flash floods and droughts (Yin et al., 2023). This unprecedented situation has drawn attention to the urgent need for sustainable water management strategies. One promising approach to tackle this dual challenge is through the implementation of RWH structures. By capturing and storing rainwater when it is abundant, this practice serves as a vital requirement to alleviate water scarcity during dry spells as well as a means to recharge local aquifers. Moreover, it offers the additional benefit of flood mitigation during heavy rainfall events. Its implementation holds significant potential to enhance water availability and resilience in the face of increasingly unpredictable weather patterns. Consequently, the research community recognizes the pivotal role of identifying promising regions for the installation of RWH structures, particularly in areas grappling with extreme climate variability, such as the Horn of Africa.

The present study focuses on assessing the potential of RWH in the southeastern basin of Djibouti, an area that accommodates more than 60% of the country's total population. The investigation identifies suitable areas for RWH activities within this region, serving as a fundamental basis for subsequent on-site evaluations and pilot projects. These on-site investigations will play a pivotal role in determining the most suitable RWH technology to be implemented in different parts of the watershed.

Despite RWH not being a novice topic in this water-stressed country and having been practiced for several decades, certain limitations persist, particularly concerning the types of RWH strategies employed thus far. Notably, according to a report by Cheurfa et al. (2017) on the elaboration of a national strategy for the participatory management of hydraulic structures in Djibouti, it was found that underground cisterns (mostly cemented) and infiltration ponds are the only two RWH techniques that have been adopted in the country. Furthermore, their findings reveal that a total of 38 ponds and 108 cisterns are distributed across the nation, with less than ten of these structures located within the focused region of this study. Despite the presence of these structures, it is essential to acknowledge their state of degradation and vulnerability to anthropogenic contaminations due to poor protection and maintenance (Cheurfa et al., 2017). This highlights the pressing need for more robust RWH practices in the country. The limited number of existing RWH structures in the region underscores the overall lack of emphasis placed on stormwater harvesting despite its potential benefits for water security and groundwater recharge enhancement in Djibouti.

While the proposed framework yielded robust and reliable results, a comprehensive discussion is warranted regarding the selection of RWH techniques to be potentially adopted in the identified promising areas. It is crucial to consider the overall characteristics of the different parts of the basin when deciding on the application of a specific RWH technology in each area. In this regard, it is imperative to not only rely on the already practiced techniques such as cisterns and ponds within the region but also to explore and evaluate other viable RWH structures that might be better suited for certain locations. For instance, the implementation of check dams, which are efficient RWH structures constructed over small streams, could prove advantageous in areas characterized by gentle slopes ($< 15\%$) and fine soil texture (Singh et al., 2017). Regions identified as having very high and high RWH suitability in the western portion of the study area, as well as the central part of the Deydey Weyn sub-watershed (Figure 4c), may present favorable conditions for the installation of check dams. Another effective technology to be considered for inclusion in the RWH inventory of the country is percolation tanks. While they are cost effective and ideally suited for flat terrains ($< 5\%$) (Ezzeldin et al., 2022), they have proven to be highly effective in recharging fractured aquifers and can play a crucial role in mitigating saltwater intrusion—an issue posing a significant threat to the country's subsurface resources.

Furthermore, terracing technology, which involves the excavation of soil from lower elevations and its deposition in upper levels to form bunds along contours, presents an alternative solution for regions with steep slopes and unstable soils (Shadmehri Toosi et al., 2020). However, it is important to note that terracing requires considerable financial resources for construction and regular maintenance. Nevertheless, if properly maintained, terracing can enhance infiltration and effectively control soil erosion.

Overall, an additional but hypothetically generated flow presented in Figure 4.13 illustrates the practical utilization of such an established framework regarding the execution of effective decisions in RWH attempts. Associatively, the first step covers the identification of whether the focalized region is feasible to implement an RWH structure. As expected, one should disregard RWH strategies for unfeasible areas reflecting that attempts should further be oriented towards different approaches for enhancing the presence of reclaimed water in the region of interest. Additionally, for feasible regions warranting the instrumental role of RWH structures, a decision-making scheme should be constituted concerning divergent criteria under the umbrella of various aspects, particularly based upon the major dimensions of the sustainability concept, with respect to not only the availability but also the accessibility of the relevant data. Further, the prioritization of the feasible parts of the focalized region is ensured by the incorporation of the outcomes of criteria weighting process into the actual values found in the decision layers. The corresponding step yielding the entirety of suitability analysis opens a road for starting from the high and very high suitable areas. The professionals diligently chosen among the stakeholders are then assigned to the field investigations to determine the appropriate RWH structure for regions posing high and very high suitability. Following the detection of certain RWH types as well as their applications in the field, the outcomes attained should be continuously monitored and the contributions of the installed structures (e.g., check dams, percolation tanks, terracing, etc.) should be recorded. A final step is sought to explore the impacts of proposed actions on the region to constitute a fertile for the re-operation of formed framework. Overall, the continuous improvements are satisfied based on the lesson-learned from achieved through a careful review of the findings and similar steps should be followed until procuring the maximized benefits.

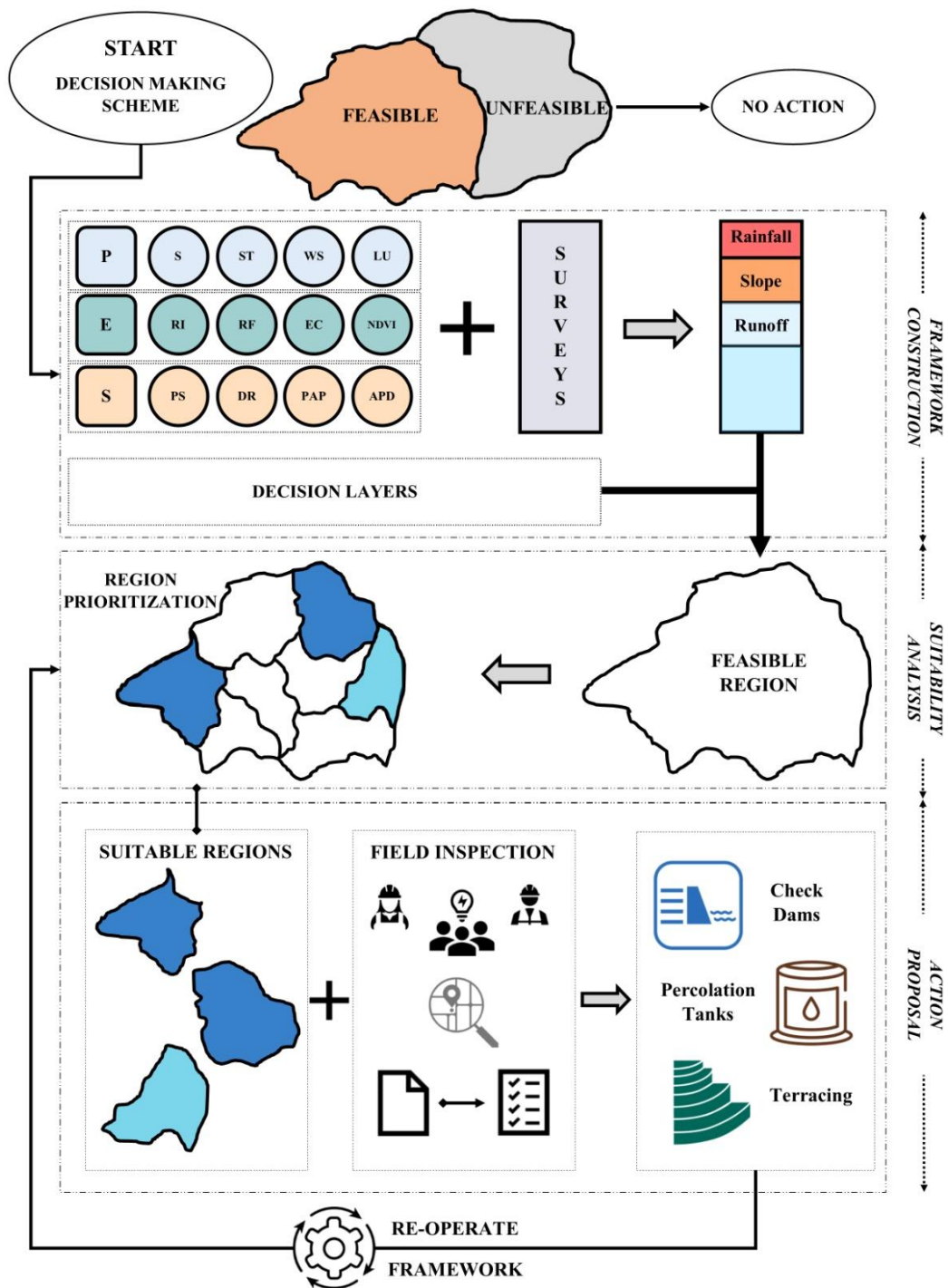


Figure 4.13 : The use of the proposed framework in practical applications.



5. ARTIFICIAL GROUNDWATER RECHARGE THROUGH DRYWELLS: DELINEATION OF PROMISING REGIONS (CITY LEVEL)²

5.1 Drywells Background and Description of the Proposed Decision Framework

The recharge method selected for a project depends not only on the site conditions and the infiltration performance of the selected MAR structure but also on its benefits and drawbacks. For instance, surface infiltration techniques, such as in-channel (dams placed across streams) and off-channel systems (i.e., infiltration basins) offers the highest contaminants attenuation performances in all MAR technologies but requires permeable and large surface areas (Bouwer, 2002). Due to pavements restricting permeability and urbanization that limits the land availability, surface infiltration techniques are less suitable in urbanized areas (Edwards et al., 2016). However, vadose zone recharge (VZR) techniques (especially drywells), which are small diameter shallow wells that end before reaching the water table, offer a promising solution for densely urbanized environments since they have negligible land impact, lead to minimal evapotranspiration losses, and can be installed in impermeable areas with limited financial resources (Edwards et al., 2016; Händel et al., 2016; Sasidharan et al., 2018).

Many scholars have highlighted the viability and efficiency of using small diameter shallow wells for conveying reclaimed water to the aquifer compared to infiltration basins which has been one of the mostly adopted artificial recharge mechanisms across the globe, recently. For instance, a comparison was performed by Händel et al. (2014) between the infiltration performances of drywells and surface basins using divergent numerical simulations under conditions that are commonly faced in field settings. The findings of the corresponding study indicated that a 10m by 6m infiltration basins and a group of 1.5 small diameter (~5cm) shallow wells produced similar recharge rates.

² This chapter is based on the paper “Mouhoumed, R. M., Ekmekcioglu, O., & Ozger, M. (2023). A hybrid MCDA approach for delineating sites suitable for artificial groundwater recharge using drywells. *Journal of Hydrology*, 620. <https://doi.org/https://doi.org/10.1016/j.jhydrol.2023.129387>”.

Likewise, Sasidharan et al. (2021) compared these two systems by further considering subsurface heterogeneity with the commercial HYDRUS (2D/3D) software and discovered that five drywells produce a higher infiltration rate than a 70m diameter circular basin. Although drywells are well-regarded by the scientific community, the VZR mechanisms have been impeded by the potential risk of groundwater contamination due to the discharge of polluted stormwater runoff directly into the subsurface soil, circumventing the surface soil and near-surface sediment (Edwards et al., 2016). Despite being extensively adopted in the US for several decades to alleviate stressed aquifers, there have been no reported instances of groundwater contamination linked to drywells (Brian, 2018). Additionally, proper siting and periodic maintenance of drywells was recommended by Edwards et al. (2016) in dealing with most contaminants found in urban stormwater, while contemporary drywell designs often incorporate pretreatment or sedimentation chambers (Edwards et al., 2022; Lock et al., 2017).

The present research contains a step-wise approach to delineate and prioritize the sub-regions within Kayseri city concerning their suitability for the implementation of drywells. This methodology involves several distinct steps, encompassing (1) retrieving essential criteria that affect drywells site suitability, (2) assessment of the importance of the refined criteria list based on the fuzzy AHP approach, and (3) the identification of the suitable areas in accordance with the TOPSIS technique (Figure 5.1). **In the first step**, the relevant criteria were identified by means of the literature survey encompassing both the research articles and the reports. Accordingly, 9 relevant criteria were selected to pin down sites favorable for VZR drywells. This step also includes generating raster layers to be used in the suitability analysis. All the GIS applications were performed with open-source QGIS software (QGIS Development Team, 2022). After GIS-based processing, thematic layers were standardized and the ranking of the layers was attained as a result of the focus group discussion (FGD) session involving experts from divergent backgrounds. **The second phase** of the process consists of conducting the AHP surveys. A 9-by-9 questionnaire was performed with each expert and the consistencies of the experts were checked. It is important to note that the experts failing to meet the consistency threshold (i.e., less than 10%) were repeated (two rounds at maximum) until ensuring an acceptable consistency ratio (CR). **The third step** covers determining the clusters and criteria

weights using Chang's extend analysis (within the fuzzy AHP) method by replacing the crisp scales given by experts in the AHP survey with their equivalent triangular fuzzy numbers (TFN) along with the TOPSIS implementation for prioritizing the alternative sites suitable for drywells in the Kayseri plain.

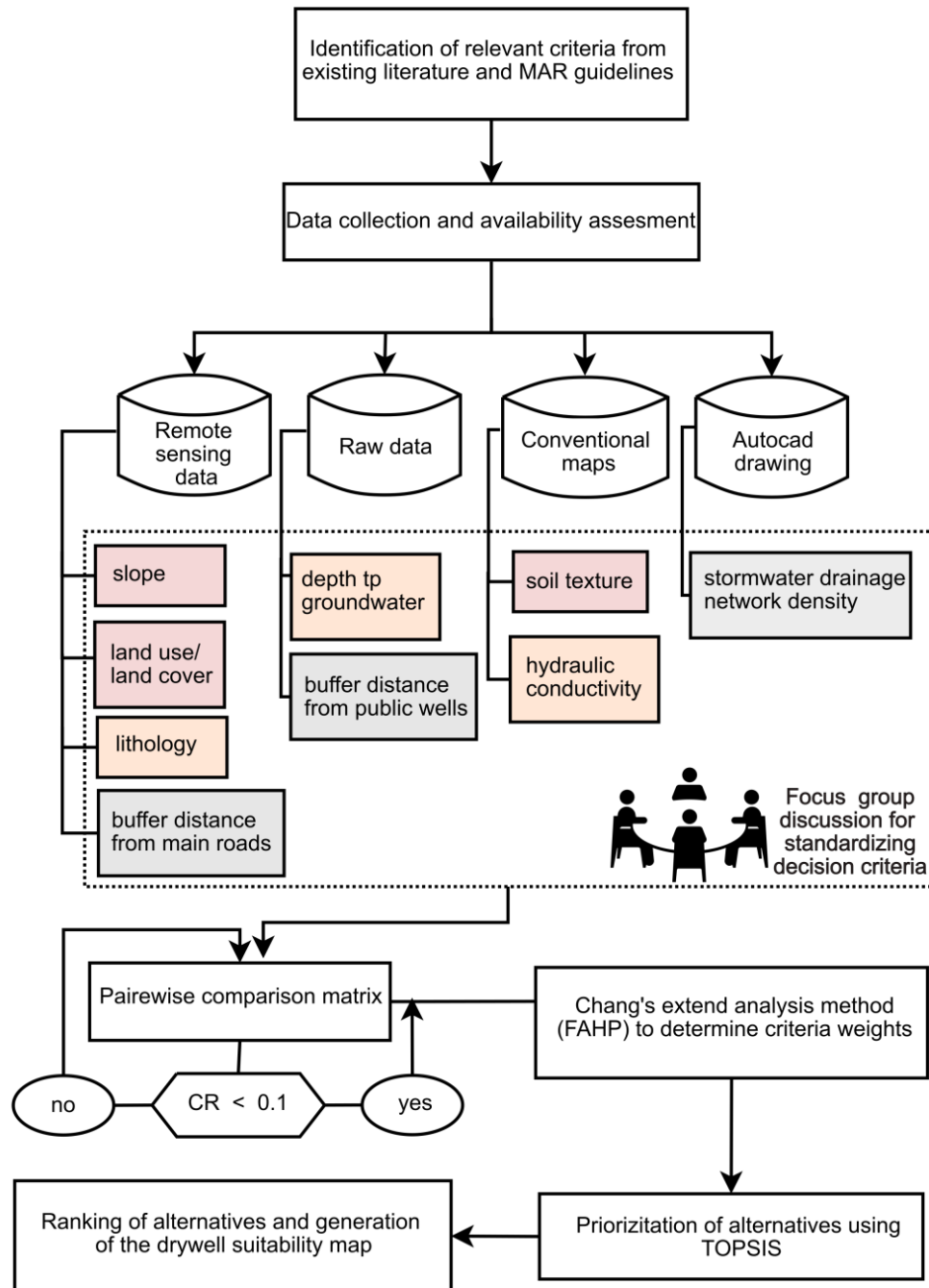


Figure 5.1 : Flowchart of the decision framework.

5.2 Study Area (Kayseri city)

Kayseri is among the most populated cities in Turkey with more than one million residents and is located in Central Anatolia. The study zone covers 218.53 km² in total

within the boundaries of Kayseri province including the districts of Melikgazi (in large part) and Kocasinan (small part in the north) (Figure 5.2). The climate of the city reflects the cold semi-arid climatic characteristics with nearly a hundred rainy days over a year and an average snow day of 36 (Turkish State Meteorology Service, 2022). In addition, the highest temperature reaches 38°C on hot days (especially during July and August), while the lowest temperatures are observed between -6°C and -2°C in winter (Değirmenci et al., 2008). The lithology of the study area is predominated by alluvium deposits and pyroclastic rocks; however, units such as basalt, andesite, sandstone, and agglomerate also exist.

The Kayseri plain contains two aquifer systems that are separated by an impermeable or semi-permeable layer (mainly andesite and basalt). As snowfall falls on the higher elevations of Erciyes mountain (3917 m) located in the vicinity of the focused region, it recharges the lower pressurized volcanic aquifer, which is the main aquifer, whereas rainfall in the plain contributes negligibly. It is estimated that groundwater flows from the south and southeast to the north and northwest of the region, with a velocity of 15-20 cm/day (Değirmenci et al., 2011a). Moreover, on top of it, there is a shallow alluvial aquifer with a much lower yield due to its thickness and extension, which constitutes a secondary aquifer (Yazıcı et al., 2015). Direct infiltration from precipitation in the plain mainly recharges this unconfined aquifer. Overall, the hydraulic conductivity values measured in the alluvial aquifer in the study area vary between 1.1×10^{-5} and 6.4×10^{-4} m/s.

The water demand of the city is majorly contingent upon the groundwater sources. The records attained in 2010 illustrated that the municipality supply nearly 60 billion m³ of water for domestic purposes annually (Değirmenci, Tezcan, et al., 2011) and recent evidence addresses the unavertable increase in water consumption over the last decade. The huge amount of the water demand is satisfied by the pressurized lower aquifer that has a consequent yield with water of high quality (Nuray Ates et al., 2021) and from a spring with a discharge of 300 l/s (Değirmenci, Ekmekçi, et al., 2011). Urbanization on the plain considerably downscales the natural recharge of the upper aquifer and rough usage of groundwater resources for irrigation purposes currently causing a decline in the water table. Therefore, current conditions point out that more water is expected to be abstracted from the lower aquifer to meet irrigation demand if the

shallow aquifer is depleted in the future, a scenario that could lead to irreversible outcomes.

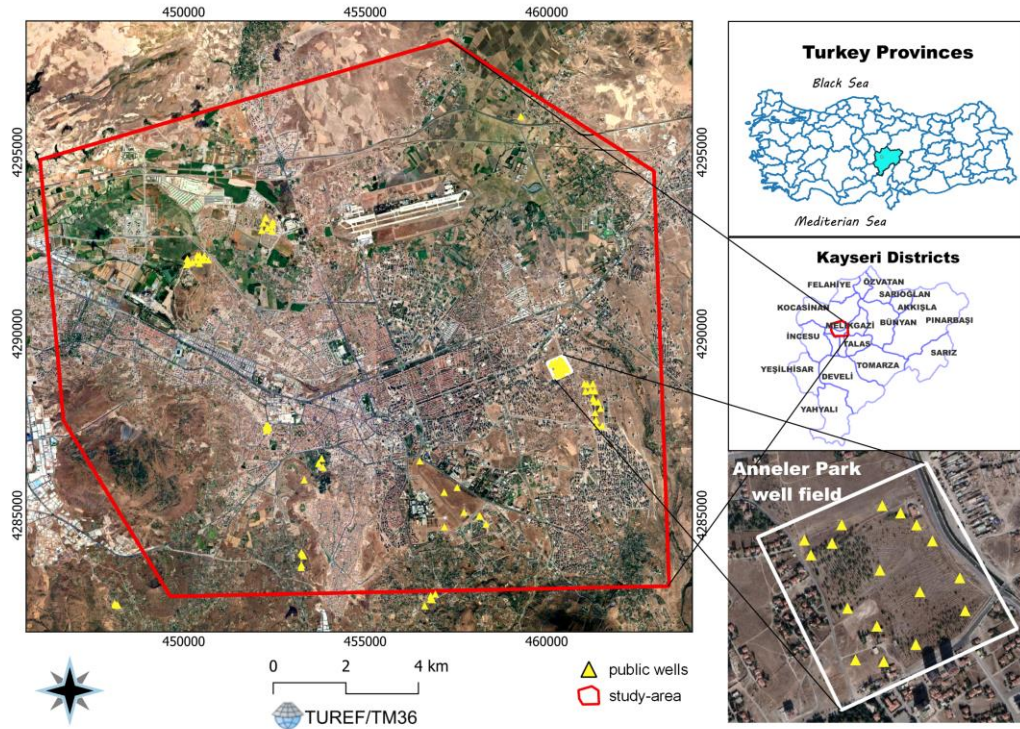


Figure 5.2 : Study area (Kayseri city).

5.3 Descriptions of the Utilized Layers

The selection of relevant criteria for the drywell site suitability analysis was performed based on peer-reviewed studies (Edwards et al., 2016) and national guidelines (Geosyntec consultants, 2020; Portland.gov, 2016; US Environmental Protection Agency, 1999) that dealt with the MAR technology. Table B.1 presents a brief summary of the thematic layers utilized for the mapping purpose including the sources, corresponding datasets, format of the data, and their references. The current research included three different factors impacting the assessment of site suitability of drywells based on three main clusters, i.e., surface, economy/protection, and aquifer. Thus, *slope*, *land use/land cover*, and *soil texture* criteria were considered within the “surface cluster” (Figure 5.3). Also, *stormwater drainage network density*, *buffer distance from public wells*, and *buffer distance from main roads* were taken into account within the “economy/protection cluster”, while *depth to groundwater*, *lithology*, and *hydraulic conductivity* were used in assessing the “aquifer cluster”. Below, brief descriptions of each criterion as well as their relations with the MAR site suitability are provided.

a) Slope- is one of the most widely used decision criteria in GIS-MCDA based MAR studies. The reason for the common adoption of the slope criterion is not only related to the availability and free access of a large number of DEM data with lower resolution in recent years but also it controls the convergence and divergence of water, which is affiliated with the infiltration capacity (Ahmadi et al., 2017; Ekmekcioğlu & Koc, 2022). In this regard, mild slopes have higher infiltration rates compared to steep slopes (A. Chowdhury et al., 2010). In addition, well clogging due to the suspended sediments existing in the stormwater is one of the major concerns in drywells projects and is encountered by soil erosions that occur in regions having higher slopes.

b) Land use/Land cover- contributes to the accurate prediction of the contaminant types in urban zones surrounding drywells sites and their effects on the aquifers (Edwards et al., 2016). There are a number of studies illustrating the impact of land use on stormwater runoff in terms of pollutant discharges (ARBSWRP, 2018; US Environmental Protection Agency, 1999). Different types of pollutants can be found in different land use classes, for instance, commercial and industrial areas are known to contain pollutants such as heavy metals, bacteria, oil and grease, semi-volatile organic compounds (SVOCs), volatile organic compounds (VOCs), and total dissolved solids (TDS). The major contaminants detected in stormwater samples collected from residential areas are bacteria, heavy metals, oil and grease, and TDS (ARBSWRP, 2018). This study categorized the LULC criterion into five classes, i.e., 1. forest and seminatural areas; 2. arable lands, permanent crops, pastures, and heterogeneous agricultural areas; 3. urban fabric, green urban areas, sports and leisure facilities; 4. industrial, commercial and transport units; 5. mine, dump, and construction sites (Figure 5.3b).

c) Soil texture- is another widely included factor in MAR suitability assessments and is closely related to the ability of the soil to infiltrate large volumes of surface water into the sub-surface (M. Arshad et al., 2022; Tahvili et al., 2021). Sites having coarse-grained (e.g. sand) materials have high infiltration capacity with a relatively lower potential to attenuate contaminants. In contrast, soils containing higher clay yield promising performance in contaminant filtering, whereas they have poor infiltration performance. Therefore, great attention needs to be paid to account for the soil texture factor and providing a balance between infiltration performance and contaminants

filtration ability of the vadose zone is essential for sitting drywells. The soil texture map of the study area is available in Figure 5.3c.

d) Stormwater drainage network density- could have a significant impact on the site selection since the stormwater is generally regarded as the main water source in drywell projects. Hence, the closer the installation of the drywells to the existing infrastructure, the lower the need for financial resources in recharging the systems from the stormwater drainage networks. Some scholars indeed considered similar parameters by including in their model the distance between water supply sources and MAR site but they generally refer to the distance to waste treatment plants (Ahmadi et al., 2017; Brown et al., 2005; Gdoura et al., 2015; Kallali et al., 2007; Tsangaratos et al., 2017). In this context, a density map of the stormwater drainage network of the city was generated and reclassified into five classes in the present work (Figure 5.3d).

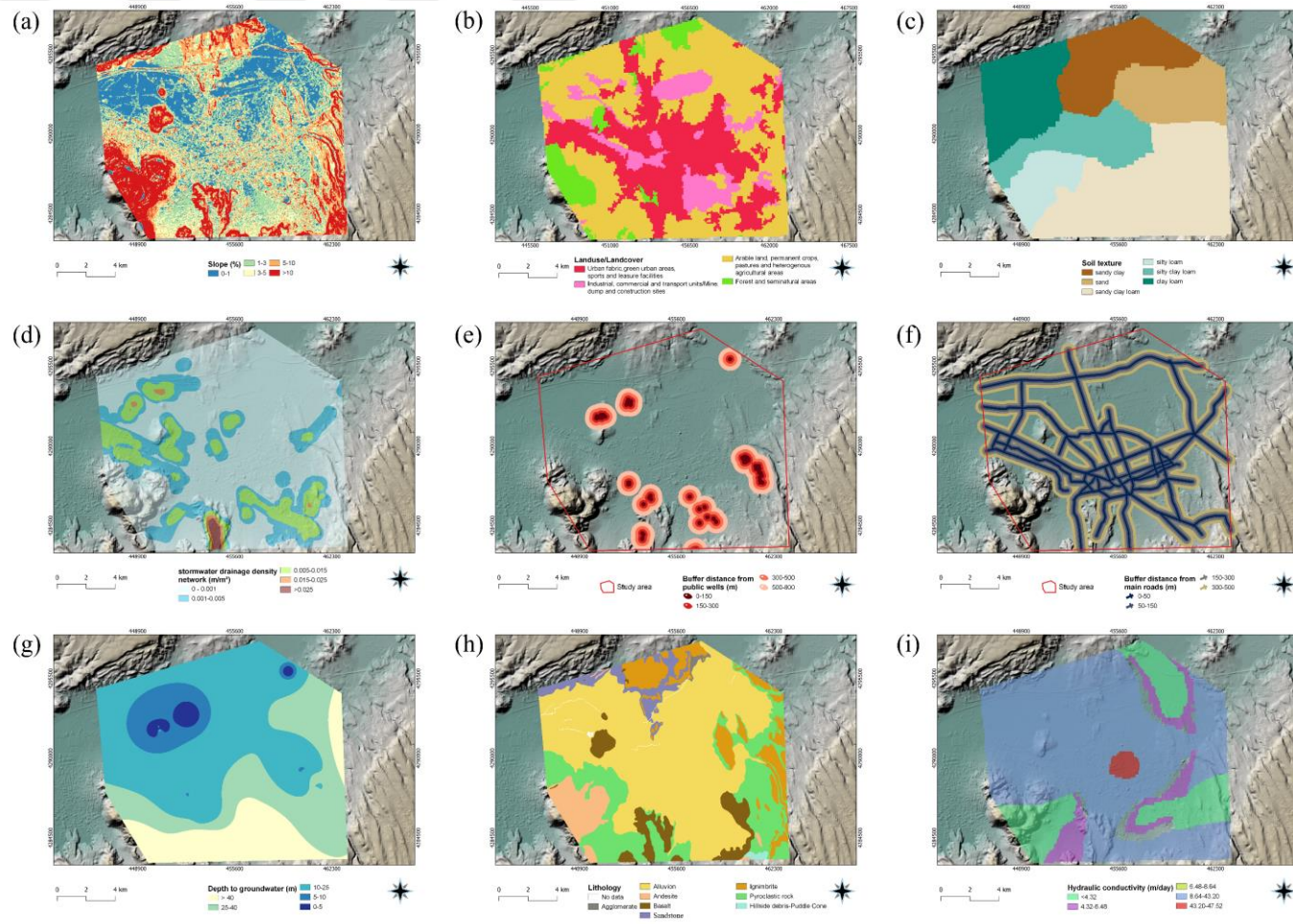
e) Buffer distance from public wells- was included in the proposed framework as the theories on the origin of the drywells highlight that vadose zone wells need to be away from public wells at a certain distance in order to provide a sufficient time of travel (Geosyntec consultants, 2020). To exemplify, there is a mandatory separation distance between drywells and public supply wells in the United States where the applications of drywells are widely embraced. However, it is especially worth mentioning that the corresponding threshold distance may vary according to the states' mandates (Lock et al., 2017); such that satisfying a horizontal distance of 60 m away from drinking wells at minimum in Illinois, while providing at least 150 m is essential in Oregon. The generated map regarding buffer distance from public wells criterion is provided in Figure 5.3e.

f) Buffer distance from main roads- is among the significant drivers of the MAR implementations, especially considering the stormwater runoff contamination due to the applied sodium chloride (i.e., salt) on roads and highways as a de-icing agent. Existing body knowledge recognized that the corresponding practice results in considerable harm to the surrounding environment, notably to surface and subsurface resources by contaminating the aquifer and surface water resources (Snodgrass et al., 2017). In addition to the salt application, Von Gunten et al. (2020) reported that heavy metals penetrating from asphalt concrete that was found near roads and highways could have a detrimental impact on groundwater and nearby soil. Therefore, a multi

buffer distance from main roads spatial layer was generated for the focalized region (Figure 5.3f).

g) Depth to groundwater- is regarded as another crucial factor in drywells' applications as suggested by many state guidelines and standards in the U.S. Typically, drywells are designed to be 1-2 m diameter wells ending before reaching the water table. Hence, similar to the horizontal distances mentioned in the earlier factors, a vertical separation distance between the bottom of the drywell and the seasonal high-water table is essential in constituting effective MAR techniques. The need for the corresponding vertical distance comes from the fact that the system benefits from the vadose zone as a contaminant attenuation mechanism in reducing the risk of pollution. Here, the geologic conditions of the regions drive the required vertical distance, and hence, likewise, the buffer distance from the public wells, different threshold values were determined by divergent states of the U.S (Lock et al., 2017). The minimum vertical distance that is required to be satisfied across the U.S. is determined to be between 3 to 8 m based on the American River Basin Stormwater Resource Plan (2018). However, for instance, in some regions (e.g., Riverside County, Los Angeles County, Arizona, etc.), the mandatory vertical distance between the drywell bottom and the water table is specified as 3 m (ADEQ, 2018; Cities and County of Riverside, 2012; County of Los Angeles, 2009). The map produced for depth to groundwater criterion in the studied region is provided in Figure 5.3g.

h) Lithology- describes the physical characteristics of the rock that composes the geological formation as well as its mineral content, grain size, and packing (Freeze and Cherry, 1979). The movement and occurrence of groundwater are closely related to the rock type of the region (Selvam et al., 2016; Selvarani et al., 2017). Thus, having detailed information on the geological formations of the region is of utmost importance for attaining maximum benefit from artificial recharge. The lithology map of the study area was obtained from the geology dataset of Kayseri province. Here, the plain is mostly dominated by alluvium deposits and pyroclastic rocks covering 54% and 20% of the study region, respectively. In addition, north and north-west cover the sandstone formation, while volcanic rocks (such as ignimbrite, andesite, and basalt) accounting for 21% of the total formation are also available in the focalized region (Figure 5.3h).



i) Hydraulic conductivity- is among the most important physical parameters of the aquifers (Altunkaynak & Şen, 2011) and vital components in assessing MAR projects. The reason for it can be explained by the fact that some physical properties (such as the transmissivity, hydraulic conductivity, and storage coefficient) can be used to assess the volume of water that could be injected into the groundwater system. Ahani Amineh et al. (2017) addressed that aquifer characteristics are relevant indicators to estimate the capacity of the system to not only store but also recover the water. Therefore, in the current research, the hydraulic conductivity of the shallow aquifer obtained from Değirmenci et al (2011) was incorporated into the criteria set and reclassified into five classes (Figure 5.3i).

5.4 Determination of the Criteria Importance Levels

In GIS-MCDA models, one of the most challenging tasks is to refine the list of influential criteria and to determine the importance of each decision variable as these techniques highly depend on experts' judgments. Thus, the consistency of each respondent for each pairwise matrix was determined via the CR values at first (Table 5.1) in order to ensure the stability and legitimacy of the attained outcomes.

Table 5.1 highlights that all the experts involved in the AHP questionnaire were consistent as the CR values are under the threshold value of 10%. In addition, Figure 5.4 is presented to illustrate the results of the fuzzy AHP analysis containing the significance level of each criteria for the site suitability mapping task (further details pertaining to the standardization of the decision layer classes are available for reference in Table B.2.). The findings indicate that the “aquifer” was assigned as the most determining cluster with a weight of 0.578 followed by the “surface” and “economy/protection” clusters having weights of 0.289 and 0.133, respectively. Among the “aquifer” cluster, hydraulic conductivity had the highest importance (0.586 in terms of local weight) which also outperformed all other criteria with a global weight of 0.339 (Figure 5.4). In addition, Figure 5.4 quite reveals that the depth to groundwater was the second most important criterion among both the “aquifer” cluster and all criteria set with local and global weights of 0.309 and 0.178, respectively. The acquired outcomes further highlighted the role of soil texture (0.112) and LULC (0.101) criteria that were placed in the 3rd and 4th order of importance within the overall assessments. What is striking about the results is that despite the weight of the

“aquifer” cluster being considerably higher than the other two clusters, the lithology criterion has one of the lowest weights (0.061) according to the overall comparison scheme. This result underlines the limited contribution of lithological variations in the site suitability analysis of the MAR implementations. Accordingly, buffer distance from main roads and stormwater drainage network density were the least two effective criteria receiving the lowest global weights of 0.018 and 0.037, respectively, for drywell sitting (Figure 5.4).

Table 5.1 : Consistency ratios of the experts attended the survey.

Experts	Main clusters	Surface (S, LULC, ST)	Economy/Protection (SDND, BDPW, BDMR)	Aquifer (DG, L, HC)
E1	4.65%	7.47%	9.42%	1.58%
E2	0.00%	4.63%	3.34%	0.79%
E3	6.23%	9.46%	9.42%	0.79%
E4	6.39%	6.42%	9.42%	0.00%
E5	9.42%	9.37%	4.65%	0.79%
E6	0.32%	1.58%	4.63%	4.65%
E7	0.00%	8.24%	0.00%	0.00%
E8	6.25%	8.27%	9.42%	9.37%
E9	2.13%	6.39%	7.47%	1.58%
E10	0.00%	2.51%	6.39%	4.64%

This study further examined the sensitivities of the employed criteria to the fuzzy degrees in order for underpinning the stability and robustness of the fuzzy AHP decision framework and its corresponding outcomes. For this reason, different fuzziness degrees, namely 1.2, 1.4, 1.6, 1.8, and 2.0, were taken into account and the alterations in the criteria weights were deduced. The same fuzzy AHP procedures were performed by considering the additional fuzziness degrees, in which Figure 5.5 exhibits the change in criteria weights based on the employed degree of fuzziness values. Figure 5.5 quite reveals that the proposed fuzzy AHP scheme yielded stable results as no change was observed in the rankings of decision criteria.

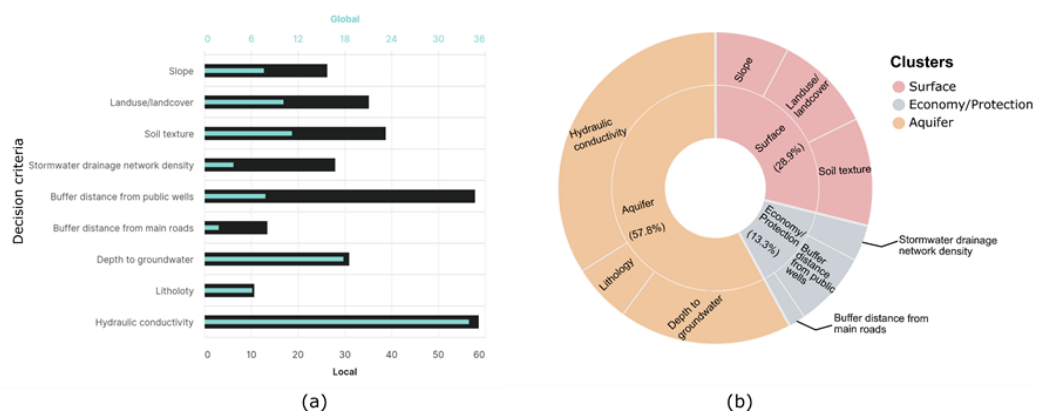


Figure 5.4 : Aggregate local and global weights of criteria.

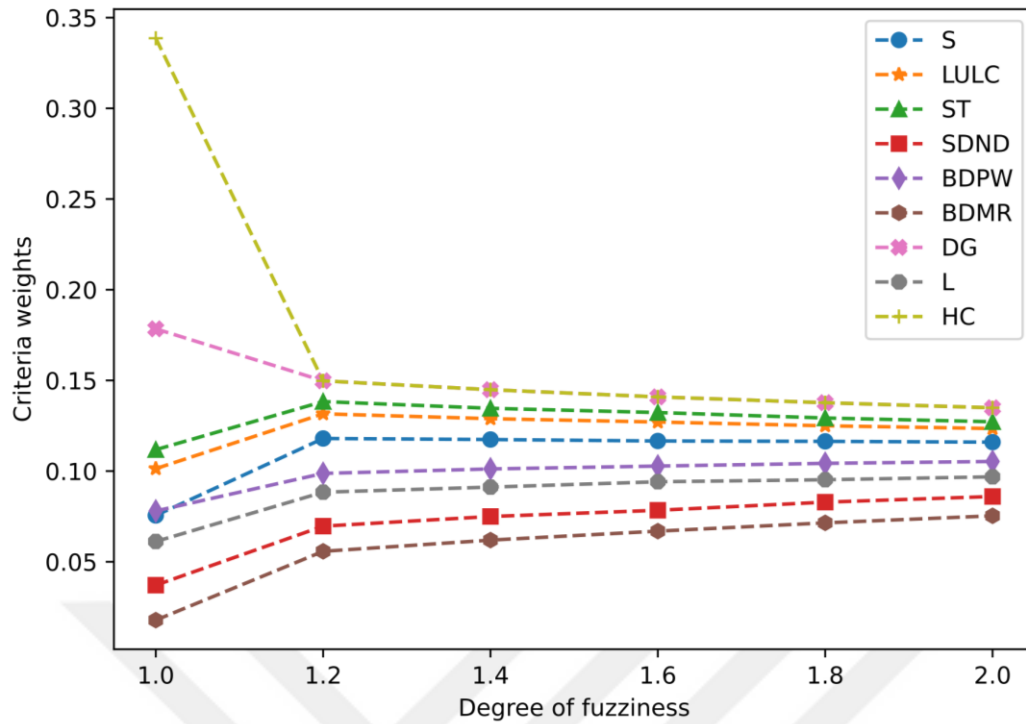


Figure 5.5 : Sensitivity analysis with respect to different fuzziness degrees.

5.5 Identification of Zones Auspicious for Drywells

The site suitability assessments were performed through partitioning the study area into smaller areas accounting for a total of 54 sub-regions based on the main roads network of the city. To accomplish this aim, the TOPSIS algorithm was used and the alternative distances from positive and negative ideal solutions were calculated for surface, economy/protection, aquifer, and overall clusters separately. The closeness coefficient values and the corresponding ranks of regions regarding site suitability were also determined (Table 4.2). Based on the Jenks natural break method, closeness coefficients were classified into five classes, i.e., very high, high, moderate, low, and very low. The results were then mapped for the different criteria group (Figure 5.6) as well as the overall suitability (Figure 5.7).

Table 5.2 : Closeness coefficients and corresponding ranks of the regions.

Regions	Surface		Economy/Protection		Aquifer		Overall Suitability	
	CCi	Rank	CCi	Rank	CCi	Rank	CCi	Rank
Region1	0.4358	37	0.8075	1	0.6914	26	0.6347	25
Region2	0.4565	35	0.4064	23	0.6807	31	0.6203	34
Region3	0.5215	29	0.3773	30	0.8458	1	0.7304	4
Region4	0.3558	47	0.3772	31	0.5648	46	0.4959	47
Region5	0.4818	34	0.6725	4	0.6773	33	0.6306	29
Region6	0.7084	4	0.3941	25	0.7972	11	0.7555	1
Region7	0.5649	20	0.442	19	0.6599	37	0.6311	28
Region8	0.3356	48	0.4809	11	0.6967	23	0.5961	41
Region9	0.3665	44	0.7047	3	0.6771	34	0.6108	37
Region10	0.3621	45	0.306	44	0.8014	7	0.6611	12
Region11	0.2987	51	0.4223	20	0.7628	14	0.6281	31
Region12	0.4244	38	0.3078	41	0.8014	7	0.6782	9
Region13	0.3866	43	0.7551	2	0.6962	24	0.6282	30
Region14	0.5469	26	0.39	26	0.767	13	0.6939	8
Region15	0.5129	32	0.421	21	0.6807	32	0.6326	27
Region16	0.4212	39	0.4589	14	0.6008	44	0.5599	46
Region17	0.5702	17	0.3026	47	0.7032	19	0.6593	13
Region18	0.3198	50	0.3609	33	0.6535	39	0.5602	45
Region19	0.506	33	0.4451	18	0.6728	35	0.6184	35
Region20	0.8419	1	0.3699	32	0.6218	42	0.6589	14
Region21	0.5781	16	0.6099	5	0.8248	4	0.7495	2
Region22	0.5885	11	0.3953	24	0.6842	30	0.656	15
Region23	0.5203	30	0.3073	42	0.8014	10	0.7036	7
Region24	0.3255	49	0.3333	34	0.7924	12	0.6397	24
Region25	0.5468	27	0.5846	7	0.6233	41	0.6062	39
Region26	0.3876	42	0.4925	10	0.6904	27	0.5982	40
Region27	0.7208	3	0.3067	43	0.2228	53	0.3446	52
Region28	0.2774	54	0.319	36	0.8422	2	0.6399	23
Region29	0.3565	46	0.3081	40	0.7295	15	0.6238	33
Region30	0.5659	19	0.3087	39	0.6968	21	0.6549	18
Region31	0.2913	52	0.3265	35	0.8297	3	0.6438	22
Region32	0.6169	8	0.4068	22	0.2983	51	0.3838	51
Region33	0.6464	6	0.4543	15	0.3588	49	0.41	49
Region34	0.3975	41	0.4502	17	0.619	43	0.5728	43
Region35	0.2867	53	0.4521	16	0.697	20	0.58	42
Region36	0.5851	14	0.2532	53	0.7195	17	0.6729	11
Region37	0.5633	21	0.3124	38	0.7056	18	0.6552	16
Region38	0.5566	25	0.3022	50	0.6962	25	0.6518	19
Region39	0.5329	28	0.5643	8	0.2835	52	0.3422	53
Region40	0.5688	18	0.3028	46	0.6968	21	0.6549	17
Region41	0.5144	31	0.5591	9	0.3577	50	0.3893	50
Region42	0.5618	22	0.3877	28	0.686	29	0.6518	20
Region43	0.5869	12	0.3025	48	0.7266	16	0.6775	10
Region44	0.5585	23	0.3028	45	0.8014	7	0.7128	6
Region45	0.5795	15	0.3023	49	0.6649	36	0.6329	26
Region46	0.4363	36	0.4799	12	0.6872	28	0.6273	32

Table 5.2 (continued): Closeness coefficients and corresponding ranks of the regions.

Regions	Surface		Economy/Protection		Aquifer		Overall Suitability	
	CCi	Rank	CCi	Rank	CCi	Rank	CCi	Rank
Region47	0.5577	24	0.6038	6	0.8073	5	0.7342	3
Region48	0.6054	9	0.0239	54	0.629	40	0.6081	38
Region49	0.5855	13	0.3178	37	0.8071	6	0.7292	5
Region50	0.3986	40	0.2783	51	0.1651	54	0.2483	54
Region51	0.7885	2	0.3849	29	0.5705	45	0.6116	36
Region52	0.5936	10	0.2568	52	0.4049	48	0.4446	48
Region53	0.628	7	0.4699	13	0.6566	38	0.6449	21
Region54	0.6636	5	0.3883	27	0.5483	47	0.5673	44

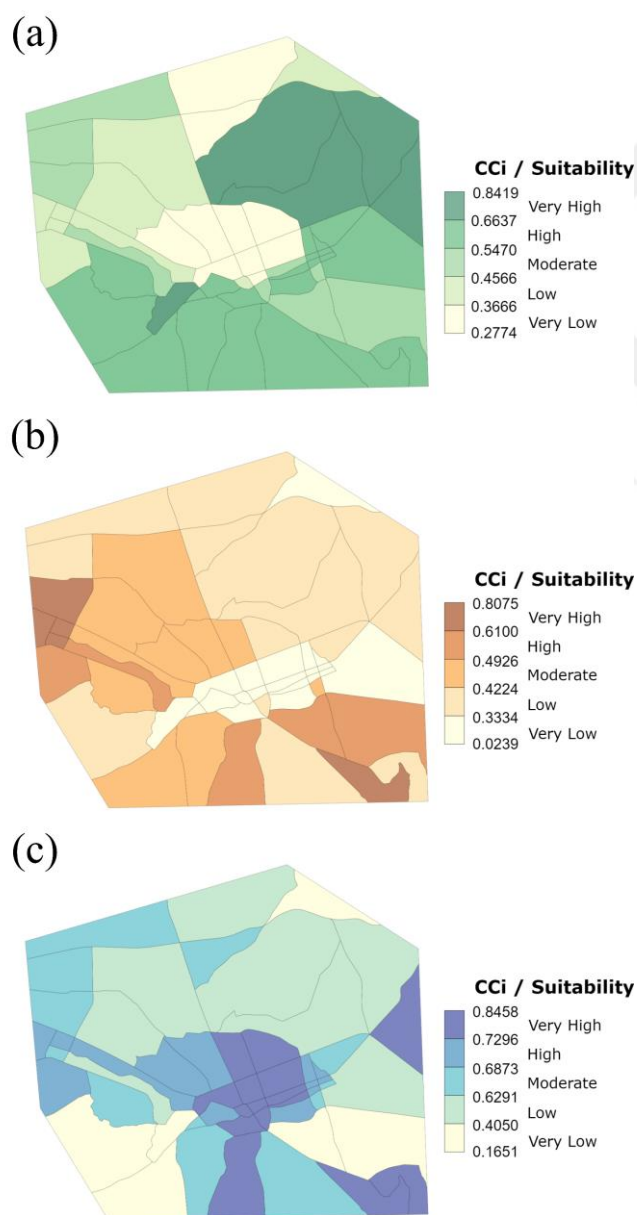


Figure 5.6 : Site suitability analysis based on different criteria group. (a) Surface, (b) Economy/Protection, (c) Aquifer.

The hybrid fuzzy AHP-TOPSIS analysis suggests that regions suitable for drywells implementation vary according to different clusters. For instance, depending on surface criteria, regions located in the southern, southwestern (sub-regions 27, 32, 33, and 53) and northeastern (sub-regions 6, 20, 51, and 54) part of the study area (Figure 5.6a) have high and very high suitability for artificial recharge through drywells. This could not only be explained by the presence of sand and silt loam soil texture classes, but also by the availability of nearly flat terrain and the absence of the least ranked LULC classes such as industrial, commercial, and transport units in the corresponding regions. However, the northern and northeastern (sub-regions 2, 4, 6, 18, 20, 51, and 54) areas of the city have moderate suitability with regard to criteria pertaining to the economy/protection cluster (i.e., SDND, BDPW, and BDMR) (Figure 5.6b), and this could be linked to the inexistence or presence of low stormwater drainage network in those sub-regions. Additionally, regions in the center (sub-regions 10, 12, 27, 28, 29, 30, 31, 36, 37, 44, and 49) received low closeness coefficient values and were deemed less suitable related to the existence of the dense road networks that could lead to groundwater pollution and the limited runoff drainage networks. It is also especially noteworthy to mention that drainage networks are currently available in those regions since they are mostly located in the city center. However, these regions have combined wastewater/stormwater drainage systems which makes suitability assessments challenging. Hence, evidence suggests that treatment would be required if water drained from such systems is used for recharge and draining water from combined sewers lead to a significant amount of costs causing prejudice to the economically friendly reputation of drywells (Portland.gov, 2016). Contrary to the abovementioned clusters, the most favorable regions are concentrated in the city center (sub-regions 3, 10, 11, 12, 23, 24, 28, 29, 44, and 49) in terms of the aquifer criteria group (Figure 5.6c). The relatively higher closeness coefficient values can be explained by the existence of high hydraulic conductivity porous media and deep-water table level in the corresponding zones.

In addition to the cluster-specific analysis, Figure 5.7 is provided to illustrate the overall suitability containing the integrated assessment of the overall criteria. According to the final results, sub-regions 6, 21, 47, 3, and 49 were found as the five most suitable zones that were classified as very high suitability to the artificial recharge through the drywells. Strong evidence can further be seen regarding the moderately

suitable sub-regions that are mostly located in the northwestern and central parts of the study area. On the other hand, the least ranked, and consequently, very low suitability regions for drywell construction are located in the southwestern (sub-regions 27, 33, and 32) and southeastern (sub-regions 41 and 39) of the area studied. The reason behind their low rank based on the overall assessment is that the corresponding sub-regions reflect considerably low values in the aquifer cluster that was found as the most influential cluster according to the fuzzy AHP analysis. To exemplify, sub-region 33 ranked at 6th, 15th, 49th and 49th according to the surface, economy/protection, aquifer, and overall criteria group, respectively. Nevertheless, this conclusion does not imply that the two other clusters are trivial compared to the “aquifer” cluster; such that sub-regions 6 and 20 had relatively high rankings with regard to the overall evaluations, despite they had considerably low rankings in terms of the “aquifer” cluster.

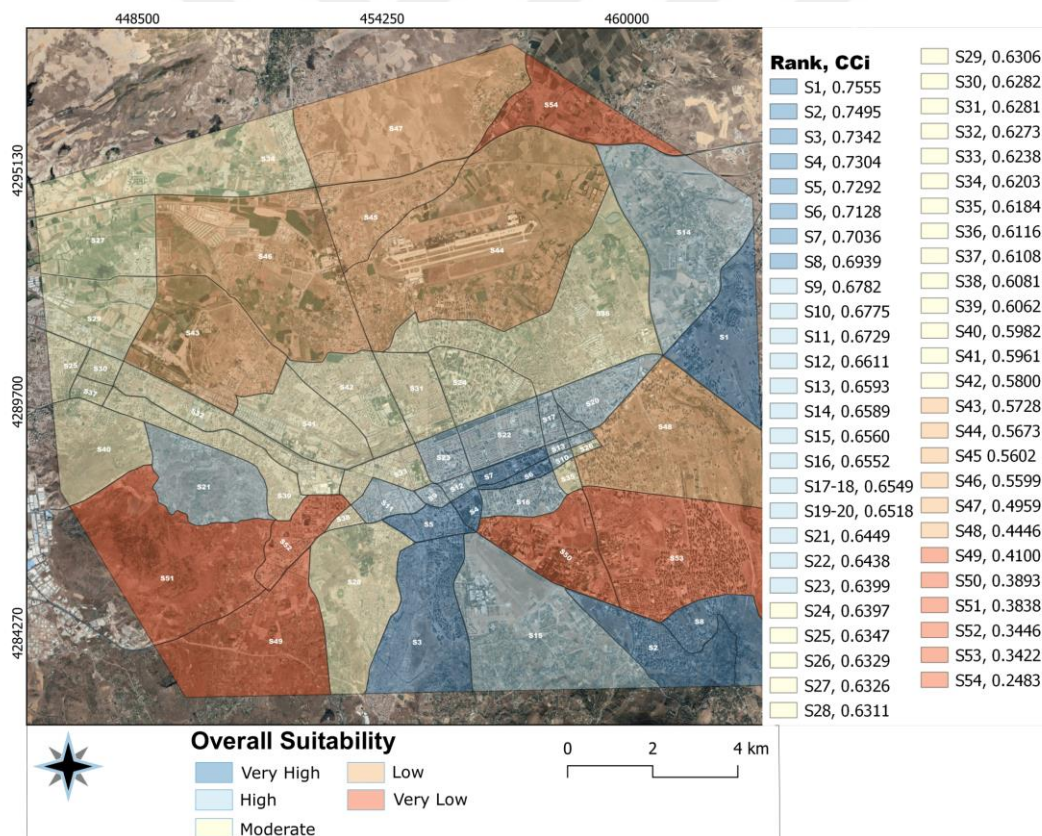


Figure 5.7 : Overall drywells suitability map using hybrid fuzzy AHP-TOPSIS approach.

5.6 Assessment of the Criteria Weights

The importance level of criteria in suitability mapping with regard to MAR implementations is closely related to the MAR technology considered and the type of the aquifer, i.e., confined or unconfined (Sallwey, Bonilla Valverde, et al., 2019). Therefore, on the one hand, where deep injection (DIs) structures (i.e., aquifer storage and recovery) are considered for MAR to recharge a confined aquifer, subsurface criteria or aquifer-related parameters are favored in weight assessments. On the other hand, in studies dealing with surface infiltration (SIs) techniques (e.g., surface spreading, in-channel modification, etc.), surface criteria acquire much importance compared to their counterparts. In this regard, we compared the weights obtained from the fuzzy AHP method with the weights applied in the SIs (Figure 5.8a) and DIs (Figure 5.8b) literature groups. Even though some of the criteria adopted in this paper show rareness in the existing literature, they were compared to the weights assigned to similar parameters in order to ensure a fair and comprehensive datum line. For instance, although the stormwater drainage network density was reported in none of the MAR suitability mapping studies, it reflects similarity to some other criteria, such as distance to wastewater treatment plant, distance from hydrographic network and source water availability (Anane et al., 2008; LaHaye et al., 2021; Papadopoulos et al., 2022; Rahman et al., 2013; Tsangaratos et al., 2017). Hence, they were re-grouped under the umbrella of “proximity to water sources” for comparison purposes (Figure 5.8) and the same approach was embraced for other criteria, such as the buffer distance from main road (Chezgi et al., 2016; Kazakis, 2018) and hydraulic conductivity (Gibson & Campana, 2018; Nasiri et al., 2013; Rahimi et al., 2014; A. Singh et al., 2013) being under “road network density” and “transmissivity/hydraulic conductivity” umbrellas, respectively.

Concerning the SIs literature group, the slope is one of the most utilized criteria in the existing studies and has weights with an interquartile range of (IQR) of 11.6% and a median of 12.8% (Figure 5.8a). In addition, a considerable amount of studies in the SIs group also used land use/land cover and soil texture. Here, the weights assigned to those two criteria in our study significantly coincide with the median of the respective sets. What is further important regarding the comparisons that the road network density criterion has the lowest IQR (representing the being least considered criteria) based on the existing literature, and accordingly, it had the lowest weight according to our

results. However, a significant difference can be observed regarding the hydraulic conductivity criterion as the weight computed for this factor in our assessments is the largest even compared to the study that gave the highest importance to hydraulic conductivity. This can be explained by the fact that some authors have assigned significantly greater values to the weights of other criteria. Mahmoud et al. (2014), for instance, assigned an influence of 42.6% to the soil texture criterion, while the median in that set is 13.1%. Likewise, Bonilla Valverde et al. (2016) allocated an importance level of 43.0% to the geology factor, and thus, gets the title of the study having the highest weighted criterion in the considered literature.

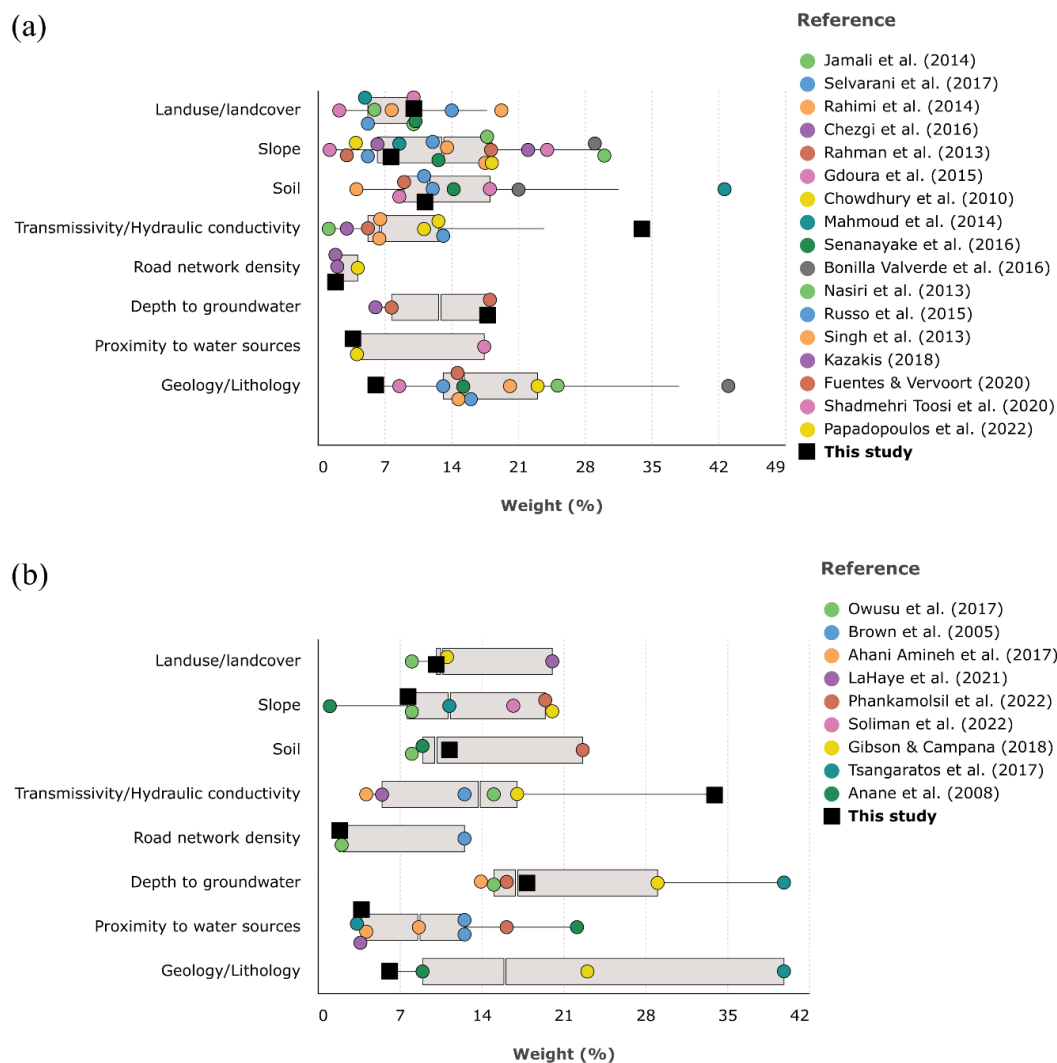


Figure 5.8 : Comparison of obtained criteria weights with existing MAR studies considering (a) surface infiltration and (b) deep injection technologies.

Based on the studies regarding the DIs literature group, the slope is used in two third of the reported literature in that group; however, it dropped to the second place

surpassing the proximity to water sources criterion. Depth to groundwater was among the least used criterion for SIs studies with only 3 applications over 17 studies, but in the DIs, five of the reported nine studies took the corresponding criterion into account (Figure 5.8b). Similar to the SIs group, the weight assigned to the hydraulic conductivity in our study represents the highest value for the DIs set. Nevertheless, Tsangaratos et al. (2017) assigned much larger weights than the hydraulic conductivity to the depth to groundwater and lithology criteria by giving them an equal weight of 39.8%. Furthermore, the weights obtained for land use/land cover, soil texture, and depth to groundwater criteria based on our study match with the median of the respective set, which illustrates that most of the outcomes of the current research accord with the earlier observations performed in the literature.

Overall, the major outcomes of the present research strongly corroborate the findings introduced in the pertinent literature. Although some distinctions can be observed, one should take the variability of the working principles of the adopted methodologies and the considered criteria into account in site suitability assessments. It is also worth noting that the characteristics of the focalized regions, the objectives of the study, and the fact that the MCDM methods heavily rely on the subjective judgments of the experts may lead to variations in the importance levels of the criteria within the relevant literature.



6. COUPLED GROUNDWATER VULNERABILITY AND MAR SITES SUITABILITY ASSESSMENT

6.1 Short Depiction of the Integrated Model

In this study, we aimed to integrate the evaluation of groundwater vulnerability with the MAR sites suitability assessment. In fact, implementing the recharge structures in vulnerable zones may diminish the potential benefits and result in long-term negative impacts on groundwater quality. Hence, installation of the MAR structures in vulnerable zones may further necessitate water treatment, making the MAR project inefficient and costly. This is due to the possibility of recovered water requiring treatment prior to use for drinking or irrigation, with associated expenses and time requirements. Therefore, careful consideration of groundwater vulnerability is of paramount importance when selecting the optimal location for MAR structures in order to avoid the corresponding negative impacts and ensure the long-term viability and sustainability of the MAR project (A. Arshad et al., 2020). Given all these facets, the current research aimed to present a framework combining the assessment of MAR site suitability and the DRASTIC method (Aller et al., 1987) that is a commonly employed technique for mapping groundwater vulnerability (Patel et al., 2022). The framework utilized in this study, detailing the tasks assigned to each decision step, is presented in Figure 6.1.

The proposed model was adopted in the urban city of Kayseri (see Figure 5.2). As mentioned in subsection 5.2, the subsurface resources of the city are prone to pronounced water table declines, particularly the shallow unconfined aquifer that is mainly used for agricultural purposes. Nevertheless, an effective method for replenishing the shallow aquifer in the Kayseri region would be recharging it with stormwater runoff, which is an abundant source of water that could be reclaimed using shallow wells. Drywells are now one of the popular methods for stormwater management and aquifer recharge, and accordingly, numerous studies have explored their implementation recently (Sasidharan et al., 2018). Moreover, modern drywells such as the MaxWell Plus systems comes with dual pre-treatment chambers that pre-

treats stormwater twice for constituent removal prior to infiltration (TorrentResources, 2014), guaranteeing that the water being recharged into the aquifer is free of pollutants and other contaminants or at least with minimal concentration. Hence, in this research, the goal is to identify promising areas for constructing drywell structures in the city of Kayseri, using GIS-MCDA techniques.

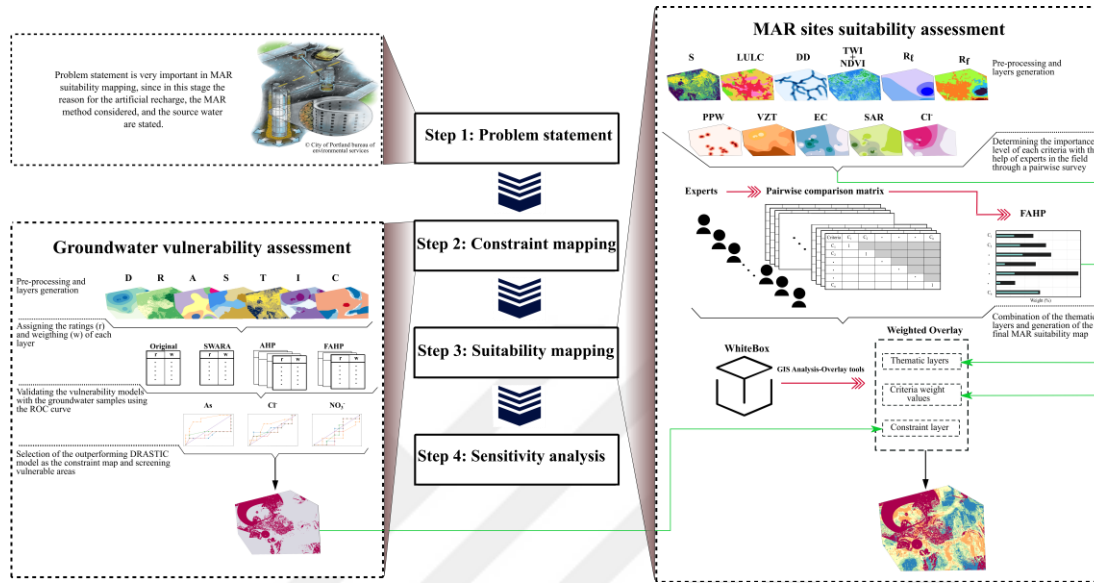


Figure 6.1 : The framework proposed to integrate the DRASTIC model and the MAR sites delineation assessment.

6.2 Site Screening and the DRASTIC Model Parameters

Attaining information regarding the potential vulnerability of an area can be challenging in the absence of groundwater vulnerability model utilizations. Therefore, the DRASTIC method was incorporated into this research as a constraint mapping tool to identify and eliminate highly vulnerable areas before acknowledging the suitability mapping attempts. The DRASTIC method is a widely recognized technique that combines and evaluates the intrinsic vulnerability of an aquifer through the examination of its physical and hydrogeological characteristics using an overlay and index approach (Aller et al., 1987). The corresponding model has extensively been used over the past years, globally, as a groundwater pollution assessment tool (de León-Gómez et al., 2021; Hasan et al., 2019; Khosravi et al., 2018; Soyaslan, 2020). The acronym “DRASTIC” stands for the seven hydrogeological factors, called depth to water (D), net recharge (R), aquifer media (A), soil media (S), topography (T), impact of the vadose zone (I), and hydraulic conductivity (C) (Figure 3b). In order to

determine vulnerability mapping, the DRASTIC index (DI) is calculated as the weighted sum overlay of the factors listed above, as shown in the equation below:

$$DI = D_r D_w + R_r R_w + A_r A_w + S_r S_w + T_r T_w + I_r I_w + C_r C_w \quad (6.1)$$

where “*r*” and “*w*” denote the ratings and weights, respectively, that are assigned to each individual factor.

The *depth to water table* is a crucial factor in evaluating intrinsic vulnerability as it relates to accessibility and potential contamination of groundwater. It also influences the duration of contact between contaminants and surrounding materials, as well as the potential for attenuation (Aller et al., 1987). Greater depth to water table provides longer travel times for contaminants making them undergo attenuation. The corresponding layer was obtained from the water table measurements from 76 wells in the Kayseri plain and interpolated using the inverse distance weighting (IDW) as shown in Figure 6.2a.

Net recharge refers to the quantity of rainwater that infiltrates into the ground and reaches the groundwater table (Patel et al., 2022). Recharge water, therefore, facilitates the transport of solid or liquid contaminants to the water table. Accordingly, regions with higher precipitation rates are more vulnerable to potential contamination potential compared those characterizing lower precipitation regimes. The net recharge of the study area was obtained through the Piscopo (2001) method (Figure 6.2b). The following equation is used to derive the net recharge layer:

$$net\ Recharge = Slope\ (\%) + Rainfall + Soil\ permeability \quad (6.2)$$

where slope was obtained from the Copernicus global digital surface model (Copernicus DSM GLO), provided by the European Space Agency and Sinergise (2021). The average rainfall was estimated and interpolated from the recording rain gauge stations located within the region. The soil permeability was obtained from the soil texture map used by Değirmenci et al. (2011a) in their research.

The *aquifer medium*, which refers to the geologic material that comprises an aquifer, plays a crucial role in determining the flow system and path length of groundwater within the aquifer (Aller et al., 1987). These factors are important in assessing the time available for various attenuation processes to occur, such as sorption, reactivity, and

dispersion (Piscopo, 2001). In the present study, the aquifer media layer was generated from 12 well logs data provided by the general directorate of water and sewerage administration of Kayseri municipality. The corresponding map is presented in Figure 6.2c.

The *soil media* denoting the type of soil that overlies the aquifer also regarded as another important component of the DRASTIC approach as it is used in determining the rate at which contaminants migrate into the aquifer from the soil. Different soil types have varying infiltration rates that have significant impact on the transport of contaminants into the aquifer. For instance, soil with a high clay content may exhibit lower permeability, which could impede the migration of contaminants in comparison to soils encompassing coarse-grained textures, such as sand or gravel (Umar et al., 2022). In this study, a soil texture map of the study area was obtained from Değirmenci et al. (2011a) and digitized to further aid in the assessment of groundwater vulnerability (Figure 6.2d).

The *topography* of an area influences the slope of the land surface, and thereby affects the fate of contaminants by either facilitating rapid runoff or prolonged period, enabling the infiltration (Aller et al., 1987). Therefore, areas with lower slope tend to have a greater potential for pollutants to percolate through the soil and reach the water table compared to steeper regions. The slope of the study area was determined from the Copernicus DSM GLO with 30m resolution using the OpenTopography DEM downloader plugin (European Space Agency & Sinergise, 2021) in QGIS and the corresponding map is presented in Figure 6.2e.

The *vadose zone*, also known as the saturated zone, refers to the subsurface above the water table. The attenuation potential of the vadose zone is highly influenced by the soil characteristics; such that factors such as the grain size of soil and the depth of the water table have a significant impact on the protective capacity of this zone. Areas with coarse soil and shallow water tables tend to be more vulnerable to pollutants, while those with finer soil and deeper water tables have lower vulnerability (Hussain et al., 2017). In this paper, the impact of the vadose zone layer was also determined through the Piscopo (2001) approach by using the following equation:

$$\text{Impact of the vadose zone} = \text{Soil permeability} + DTWT \quad (6.3)$$

where *DTWT* refers to the depth to water table.

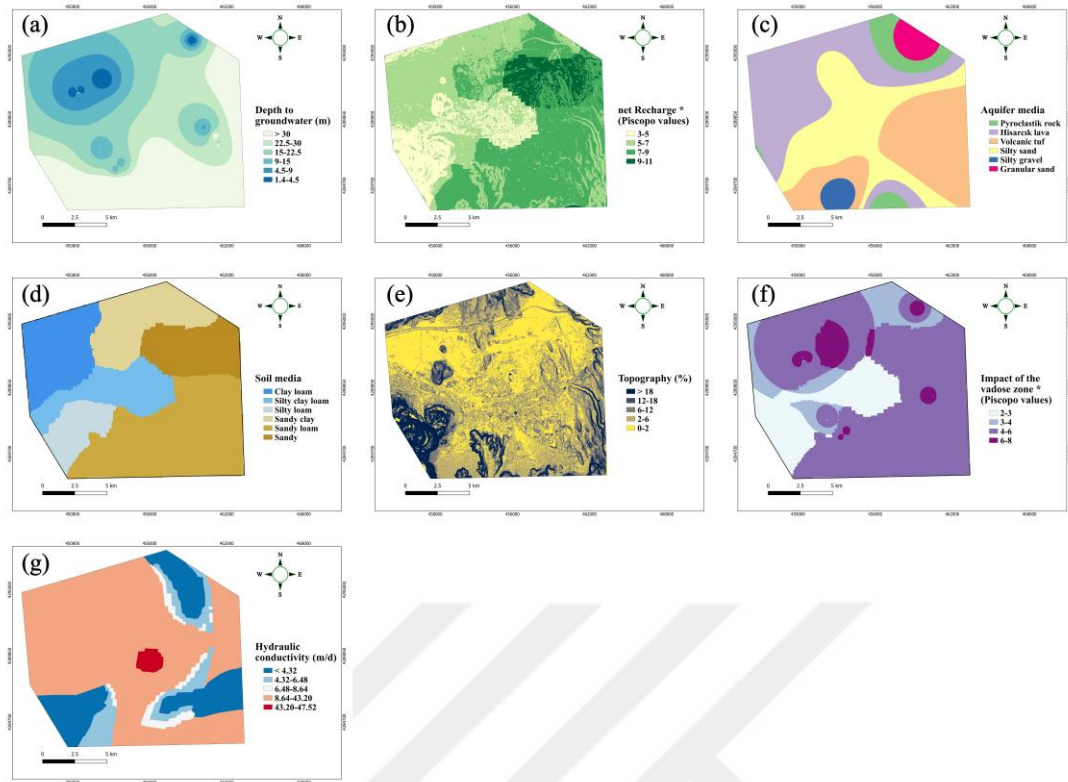


Figure 6.2 : Thematic layers of the DRASTIC model. (a) depth to water table, (b) net recharge, (c) aquifer media, (d) soil media, (e) topography, (f) impact of the vadose zone, and (g) hydraulic conductivity.

The *hydraulic conductivity* is a fundamental parameter characterizing the ability of the subsurface materials to transmit water, and it plays a pivotal role in determining the flow dynamics of contaminants within the aquifer (Karan et al., 2018). Areas with higher hydraulic conductivity are more susceptible to increased transportation of pollutants, resulting in escalated vulnerability to groundwater contamination. The hydraulic conductivity layer was obtained from the study conducted by Değirmenci et al. (2011a) and digitized as shown in Figure 6.2g.

In this study, in addition to the original DRASTIC model proposed by Aller et al. (1987), various modified vulnerability assessment models proposed in the relevant literature were also taken into consideration in order to manifest a comprehensive understanding. Several theories on the origin of DRASTIC approach have been proposed to improve its performance by modifying its ratings and weights, leading to a more precise vulnerability assessment (Patel et al., 2022). Therefore, the weights and ratings adopted in three modified MCDA based DRASTIC models, namely the AHP, fuzzy AHP, and the Stepwise Weight Assessment Ratio Analysis (SWARA), were retrieved from the existing literature in order to obtain a rigorous vulnerability map.

The ratings and weights assigned in those studies were grouped, averaged, and normalized, and the outcomes of this process are presented in Table 6.1.

6.3 Preparation of the MAR Sites Suitability Decision Layers

The suitability mapping phase constitutes a pivotal aspect of the assessment of potential MAR sites. This process involves the collection of relevant decision factors that may impact the suitability of an area for the MAR implementation, and the allocation of weights to each criterion based on its relative significance in determining appropriate locations for the MAR construction. This study identified 11 decision criteria (i.e. *slope, land use/land cover, drainage density, potential occurrence of shallow groundwater, rainfall, runoff, proximity to public wells, vadose zone thickness, electrical conductivity, sodium absorption ratio, and chloride*) through an extensive literature review encompassing research articles and technical reports regarding drywells, which is the MAR technology considered. The refined list of criteria were grouped into four main clusters: *surface, hydrometeorology, groundwater protection, and quality* in order for constructing a better hierarchical representation. Subsequently, a pairwise comparison survey was conducted involving experts from diverse backgrounds, and the fuzzy AHP method was employed to determine the criteria weights.

Sallwey et al. (2019) addressed that the *slope* is one of the most used criterion in MAR sites suitability mapping. The slope of the land surface plays a crucial role in the convergence and divergence of water, affiliating with the infiltration capacity of the soil (Ahmadi et al., 2017). Furthermore, clogging in drywells caused by suspended sediments in stormwater is a significant issue that arises from soil erosion in regions with steep slopes. In this research, the map produced for the soil layer was derived from the Copernicus DSM GLO dataset and further preprocessed using QGIS as presented in Figure 6.4a.

Land use/land cover (LULC) is another critical parameter in the assessment of sites favorable for VZR structures. LULC is of paramount importance in the accurate prediction of different stormwater pollutant types that pose divergence with regard to different land use types surrounding drywell sites and having drastic impacts on the aquifers. To accurately predict the presence of specific stormwater contaminants and their impact on the local groundwater system, it is crucial to gather comprehensive

information about the land use type in the vicinity of the drywell site (Edwards et al., 2016). The CORINE land cover (CLC) dataset (Büttner et al., 2017) was used to generate the LULC layer and the corresponding map is presented in Figure 6.4b.

Drainage Density (DD) is described as the proportion between the total length of all stream segments within the specified region of interest and the surface area (M. Arshad et al., 2022). This factor exhibits an inverse relationship with permeability, meaning the lower DD in a region the higher the permeability, resulting in increased infiltration and reduced surface runoff. Conversely, regions with high DD are more susceptible to not only erosions but also low infiltration rates and significant surface runoff. The DD map of the study area is displayed in Figure 6.4c.

The extend of the shallow aquifer in the Kayseri plain remains uncertain due to limited investigations and sparse documentation, highlighting the need for further research to determine its distribution and characteristics. Hence, to ensure the success of the recharge process, it is of utmost significance to implement drywells within the boundaries of the alluvial aquifer. To address this, a layer called the *potential occurrence of shallow aquifer (POSA)* was generated by combining the topography wetness index (TWI) and the normalized difference vegetation index (NDVI). Areas with high TWI and high NDVI could be used as an indicative of the presence of shallow groundwater (Ansems et al., 2015). It is worth mentioning that this research adopted the fuzzy linear membership functions to standardize the TWI and NDVI layers (as presented in Figure 6.3), and the sum overlay tool was used to generate the POSA layer (Figure 6.4d).

Rainfall (R_i) is another crucial parameter in the assessment of sites suitable for MAR technologies, as the variations in rainfall intensity regulate the hydrologic processes such as runoff, stream flow, and overland flow (Kaliraj et al., 2015). It is, therefore, the rainfall associates with the drywell projects, especially where the primary source of water is the stormwater runoff. Thus, average annual rainfall series were obtained from different meteorological measurement stations in not only Kayseri but also the regions located in its vicinity. Based on the acquired rainfall values, the finalized rainfall map was produced (Figure 6.4e) by means of the inverse distance weighted (IDW) as it is one of the commonly applied and accurate interpolation technique (Gong et al., 2014).

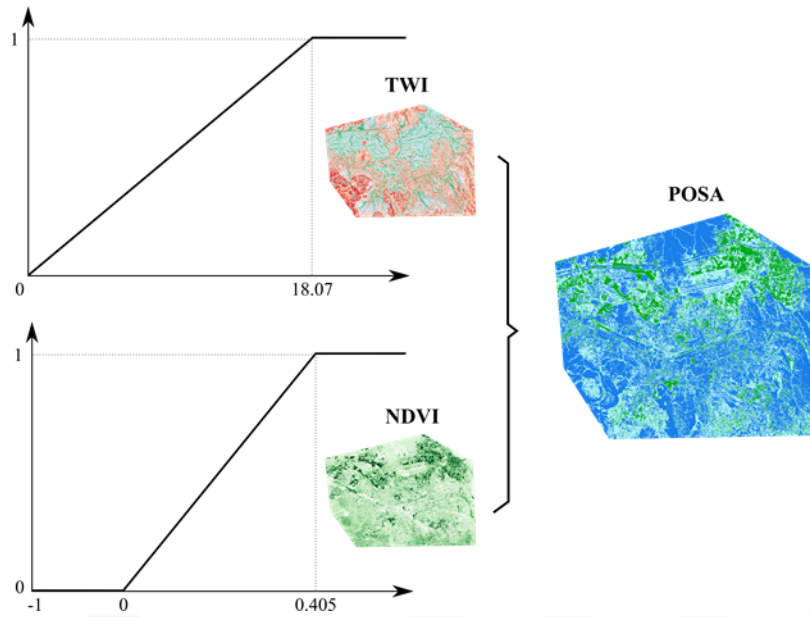


Figure 6.3 : Linear fuzzy membership functions adopted for the TWI and NDVI layers to obtain the POSA layer.

In addition to their usefulness for recharging stressed aquifers, drywells serve as effective low impact development (LID) strategies to mitigate surface runoff. Areas experiencing higher levels of runoff are prioritized for the installation of VZR structures (Ghazavi et al., 2018b). In this research, the *runoff* map was determined using the Curve number method, pioneered by U.S. Soil Conservation Service (SCS), through Equation 4.1.

The guidelines regarding the installation of drywells highlight that the drywell designs necessitates locating at a sufficient distance from production wells to permit adequate travel time to the recharged water (Geosyntec consultants, 2020). In the U.S., where the use of drywells is prevalent, there is a legally mandated separation distance between drywells and public supply wells. However, it is noteworthy that this threshold distance may vary based on the mandates of each state (Lock et al., 2017). For instance, a minimum horizontal distance of 60 meters from drinking wells is required in Illinois, while a distance of at least 150 meters is mandatory in Oregon (Geosyntec Consultants, 2018). In this research, a *proximity to public wells (PPW)* map (Figure 6.4g) was derived by taking the point coordinates of production wells using the proximity (raster distance) tool in QGIS.

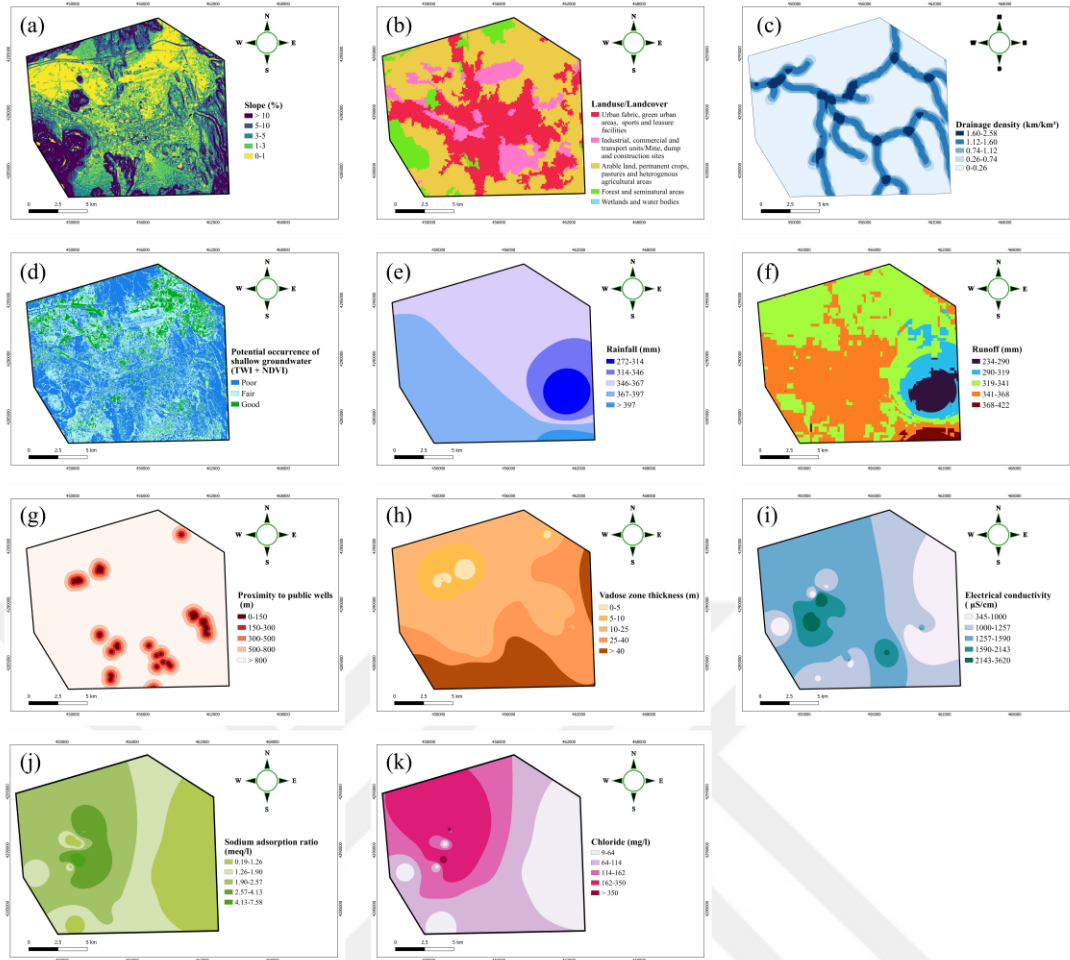


Figure 6.4 : Thematic layers generated for the suitability mapping assessment. (a) slope, (b) land use/land cover, (c) drainage density, (d) POSA, (e) rainfall, (f) runoff, (g) proximity to public wells, (h) vadose zone thickness, (i) electrical conductivity, (j) sodium adsorption ratio, and (k) chloride.

Likewise, guidelines governing the installation of drywells mandate a minimum separation distance between the drywells and the seasonal high water table (ADEQ, 2018; Cities and County of Riverside, 2012; County of Los Angeles, 2009; Lock et al., 2017), owing to the potential advantages conferred by a thick vadose zone in mitigating pollutants. The *thickness of the vadose zone* acts as a natural filter that retains pollutants within the zone and inhibits their migration into the underlying aquifer. Figure 6.4h illustrates the map of the vadose zone thickness.

The injection of reclaimed water in an area with compromised groundwater quality could jeopardize the recharged water, and thereby undermine the benefits of recharging or necessitate additional treatment prior to reuse (Ahani Amineh et al., 2017). Thus, assessing the quality of pre-existing water in the aquifer is imperative for successful MAR implementations. To address this issue, the current study aimed to

evaluate the groundwater quality in the Kayseri alluvial aquifer by using three key parameters, i.e., electrical conductivity (EC), chloride (Cl^-), and sodium adsorption ratio (SAR). Here, EC indicates the salinity and mineral content of water in terms of the ability to conduct electrical current. Insight on the water's origin and contamination level in groundwater can be determined through Cl^- concentration. The SAR parameter is used to evaluate the ratio of sodium concentration (Na^+) in one specimen to the total concentration of calcium (Ca^{2+}) and magnesium (Mg^{2+}) and is a crucial factor in determining the suitability of the water for irrigation activities (Sattari & Feizi, 2020). The following formula is used to calculate SAR:

$$SAR = \frac{Na^+}{\sqrt{\frac{1}{2} (Ca^{2+} + Mg^{2+})}} \quad (6.4)$$

where the concentrations of Na^+ , Ca^{2+} and Mg^{2+} are expressed in milliequivalents per liter. The corresponding hydrochemical parameters were obtained from the study conducted by Değirmenci et al. (2011a) and the IDW interpolation technique was performed to generate their maps as shown in Figure 6.4i,j,k, respectively.

6.4 Results of the DRASTIC Model

The implementation of recharge structures in areas prone to pollution could have adverse impact on the success of MAR projects. Hence, the delineation and exclusion of the vulnerable regions within the aquifer is of utmost importance. In this study, the DRASTIC method was used as a constraint tool to generate a groundwater vulnerability map. Previous researches have suggested that modifying the scores and weights of the conventional DRASTIC model can result in a robust correlation with certain hydrochemical parameters, such as nitrate (Balaji et al., 2021; Barzegar et al., 2019; Kazakis & Voudouris, 2015). Accordingly, this paper presents a comparison of the vulnerability maps generated through the original DRASTIC and three modified DRASTIC models that are based on three MCDA approaches, namely AHP, fuzzy AHP, and SWARA.

Table 6.1 illustrates the scores and weights employed in the investigated vulnerability models. In terms of ratings, the models seem to exhibit a level of importance consistent with that of the conventional DRASTIC model for the criteria ranges except the

SWARA model. The DRASTIC-SWARA model, as proposed by Torkashvand et al. (2021), exhibits differences in the ratings assigned to the classes of the D, R, and T layers compared to those of other models. Furthermore, significant variations in the weights assigned to the DRASTIC parameters can be observed across the different models. To exemplify, based on the DRASTIC-original D, I, and R are the most significant parameters with weights of 5, 5, and 4, respectively. In the DRASTIC-SWARA layers R, D, and S represents the main determinant with 0.351, 0.342, and 0.104. Based on the DRASTIC-AHP D, R, and I complete the podium with 0.236, 0.235, and 0.208, respectively. In reference to the DRASTIC-fuzzy AHP model, Table 5 reveals that I, D, and S are the predominant factors with values of 0.223, 0.207, and 0.161, respectively.

Vulnerability maps were generated based on the various DRASTIC models considered in this study and presented in Figure 6.5. The maps were reclassified into five classes: very low, low, moderate, high, and very high. The DRASTIC-original model revealed that a relatively small portion of the study area (5%) was categorized as having a very high vulnerability to groundwater contamination. Furthermore, 28% of the region exhibited high vulnerability, while 41% of the area showed moderate vulnerability. The low and very low vulnerability zones are mainly situated in the central and western parts of the city (Figure 6.5a). However, regarding the DRASTIC-SWARA, the low and very low vulnerability areas are more concentrated in the eastern part, with much greater surface coverage for both classes in a way that regions characterized by low and very low vulnerability cover 18% and 30% of the study region, respectively (Figure 6.5b). In contrast to the traditional DRASTIC, the high vulnerability zones have shifted to the north western and center parts of the focalized region. It is further worth noting that the DRASTIC-original, AHP and fuzzy AHP models (Figure 6.5a,c,d) displayed similarities in the obtained vulnerability pattern with only proportions of vulnerability classes varying. Nevertheless, the DRASTIC-AHP was the one giving the highest vulnerable regions (high to very high classes) among all considered models with around 45% of the study area unsuitable for MAR activities. Conversely, the SWARA vulnerability map has the largest suitable regions (very low to moderate classes) with nearly two-third of the focalized region fit to host MAR structures.

Table 6.1 :Ratings and weights used for the original DRASTIC, DRASTIC-SWARA, DRASTIC-AHP, and the DRASTIC-fuzzyAHP.

Layer	Range source	DRASTIC-original	DRASTIC-SWARA		DRASTIC-AHP			DRASTIC-fuzzy AHP					
		[1]		[2]		[3]	[4]	[5]	[6]		[7]	[8]	[9]
		rating		weight	rating		weight	rating		weight	rating		weight
Depth to water table (m)	1.4-4.5	9		5	0.112		0.342	0.381		0.236	1.862		0.207
	4.5-9.0	7			0.197			0.232			1.448		
	9.0-15.0	5			0.242			0.154			1.034		
	15-22.5	3			0.181			0.097			0.621		
	22.5-30	2			0.130			0.071			0.414		
	> 30	1			0.139			0.063			0.207		
* net Recharge	9.0-11.0	8		4	0.145		0.351	0.519		0.235	0.712		0.089
	7.0-9.0	5			0.163			0.268			0.445		
	5.0-7.0	3			0.280			0.136			0.267		
	3.0-5.0	1			0.412			0.077			0.089		
Aquifer media	Granular sand	8		3	0.339		0.075	0.525		0.090	1.094		0.137
	Silty gravel	6			0.257			0.211			0.820		
	Silty sand	5			0.202			0.118			0.684		
	Volcanic tuf	4			0.202			0.057			0.547		
	Hisarcık lava	3			0.000			0.063			0.410		
	Pyroclastic rock	2			0.000			0.025			0.273		
Soil media	Sandy	9		2	0.268		0.104	0.276		0.095	1.449		0.161
	Sandy loam	7			0.206			0.218			1.127		
	Sandy clay	6			0.172			0.250			0.966		
	Silty loam	5			0.142			0.150			0.805		
	Silty clay loam	3			0.107			0.054			0.483		
	Clay loam	2			0.105			0.052			0.322		
Topography (%)	0-2	10		1	0.212		0.004	0.418		0.032	0.525		0.053
	2.0-6.0	9			0.194			0.274			0.473		
	6.0-12.0	5			0.193			0.168			0.263		
	12.0-18.0	3			0.193			0.082			0.158		
	> 18	1			0.208			0.058			0.053		

Table 6.1 (continued): Ratings and weights used for the original DRASTIC, DRASTIC-SWARA, DRASTIC-AHP, and the DRASTIC-fuzzy AHP.

Layer	Range source	DRASTIC-original	DRASTIC-SWARA		DRASTIC-AHP			DRASTIC-fuzzy AHP					
		[1]		[2]		[3]	[4]	[5]	[6]		[7]	[8]	[9]
		rating		weight	rating		weight	rating		weight	rating		weight
* Impact of the vadose zone	6.0-8.0	8		5	0.545		0.051	0.495		0.208	1.784		0.223
	4.0-6	5			0.455			0.239			1.115		
	3.0-4	3			0.000			0.174			0.669		
	2.0-3	1			0.000			0.092			0.223		
hydraulic Conductivity (m/day)	43.20-47.52	8		3	0.360		0.071	0.435		0.104	1.055		0.132
	8.64-43.20	6			0.283			0.256			0.791		
	6.48-8.64	4			0.179			0.143			0.527		
	4.32-6.48	3			0.179			0.096			0.396		
	< 4.32	2			0.000			0.070			0.264		

Notes: * Layers generated by using the Piscopo method; [1] Aller et al. (1987); [2] Torkashvand et al. (2021); [3] Jhariya et al. (2019); [4] Bera et al. (2022); [5] Umar et al. (2022); [6] Karan et al. (2018); [7] Jesiya and Gopinath (2019); [8] Goodarzi et al. (2022); [9] Sresto et al. (2022).

Furthermore, validation is an important procedure in groundwater vulnerability mapping as it enables the assessment of the accuracy and reliability of the proposed models (A. Kumar & Pramod Krishna, 2020). In the validation of DRASTIC models, the correlation between the determined vulnerability index and the NO_3^- has long been adopted as a means of verification, assuming that the absence of nitrate characterizes the initial state of the aquifer. However, Hamza et al. (2015) argued that the validations that rely solely on NO_3^- concentration are inadequate and proposed the inclusion of data regarding other hydrochemical parameters in order for ensuring the robustness of the analysis. Consequently, recent studies have considered using multi-pollutants found in the groundwater to validate their models. Karan et al. (2018), for instance, used sulfate (SO_4^{2-}) and iron (Fe) concentrations as validation parameters. Momejian et al. (2019) employed total dissolved solids (TDS) and Cl^- to compare the accuracy of two different vulnerability indexes. Hasan et al. (2019) used the concentrations of three hydrochemical parameters, i.e., NO_3^- , EC, and chromium (Cr), for validating their models. In a similar vein, Yu et al. (2022) adopted the same number of parameters, including NO_3^- , Mg^{2+} , and chemical oxygen demand (COD), to validate the accuracy and compare the proposed DRASTIC models. In line with these studies, the present research selected NO_3^- , As and Cl^- to compare the output maps generated by the original and modified DRASTIC models and determined the superior approach. The results, shown in Figure 6.6, depict the ROC curves and calculated AUC values for the various vulnerability indexes in relation to NO_3^- , As and Cl^- concentrations. Although the DRASTIC-AHP outperformed its counterparts with an AUC of 0.454 with regards to the NO_3^- concentration, based on the obtained AUC values (Figure 6.6c), any model yielded satisfactory performance with no significant relationship with NO_3^- . Referring to the Cl^- (Figure 6.6b), the DRASTIC-SWARA produced the highest correlation with 0.648 followed by the DRASTIC-original, DRASTIC-AHP and DRASTIC-fuzzy AHP with AUC values of 0.549, 0.499, and 0.478, respectively. Given As (Figure 6.6a), likewise the comparisons made according to the Cl^- , the DRASTIC-SWARA surpassed other vulnerability models with an AUC of 0.856. Overall, based on the AUC classification proposed by Yesilnacar and Kadir (2005), the DRASTIC-SWARA showed superior performance compared to the others, with demonstrating average and very good performance category according to the Cl^- and As, respectively. As a result, the DRASTIC-SWARA was selected to generate the constraint map, and therefore, used to spot vulnerable zones in the aquifer.

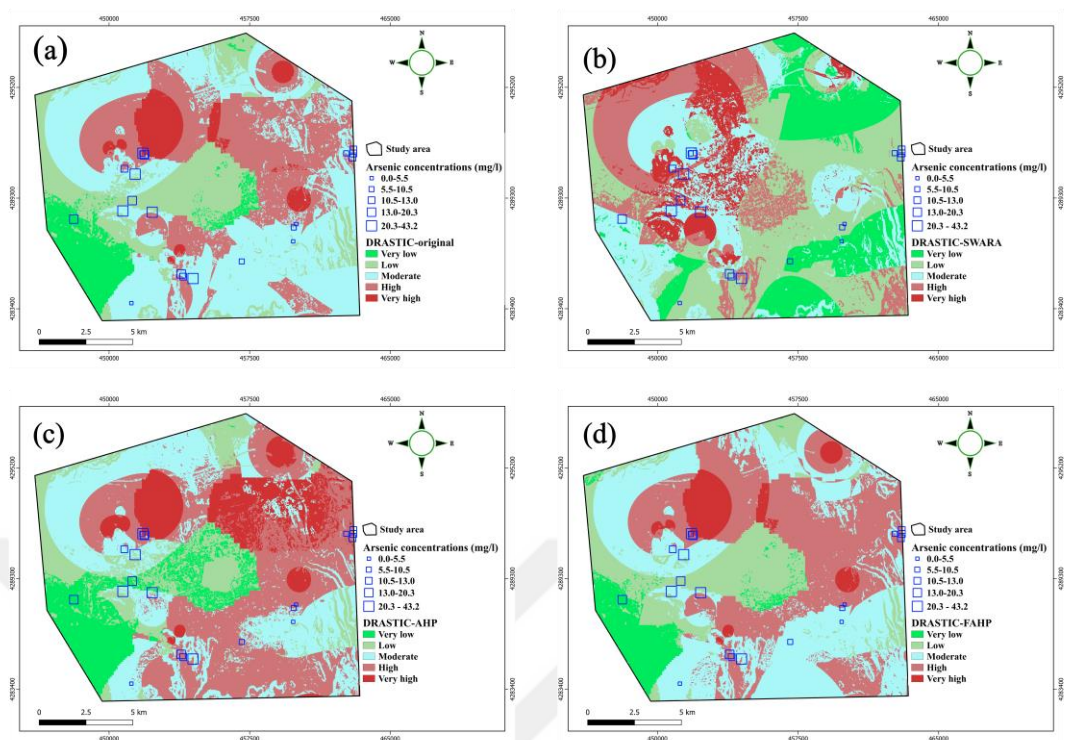


Figure 6.5 : Vulnerability maps derived based on the (a) original DRASTIC, (b) DRASTIC-SWARA, (c) DRASTIC-AHP, and (d) DRASTIC-fuzzy AHP.

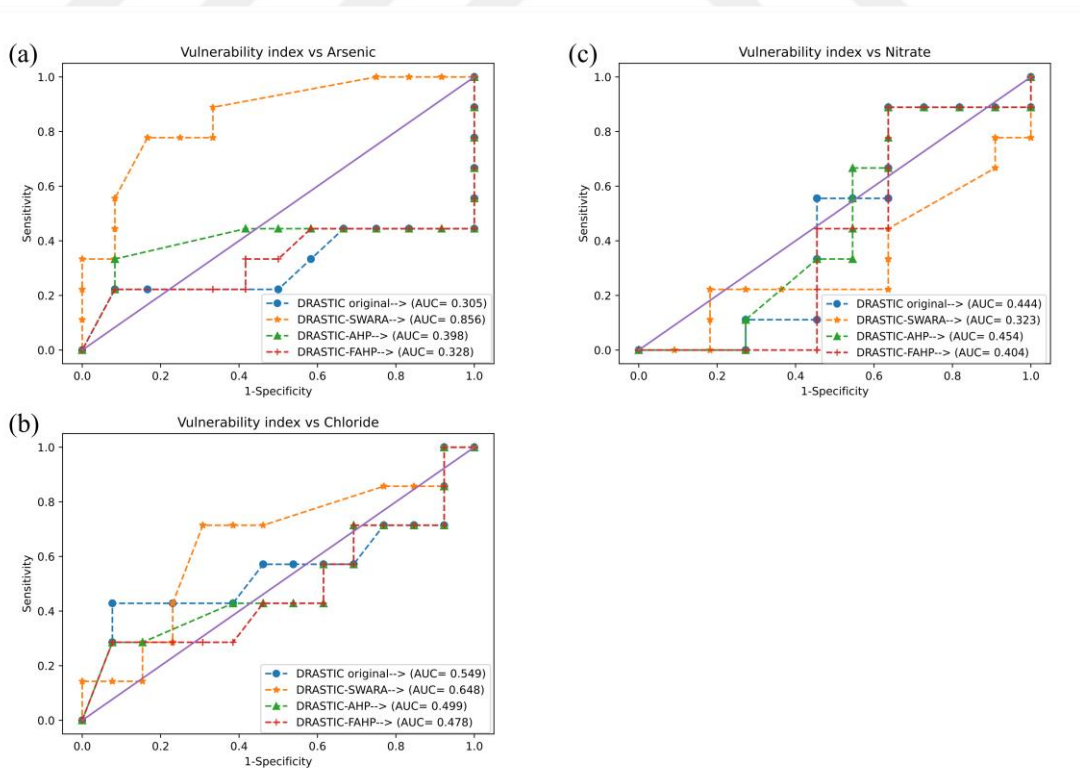


Figure 6.6 : ROC curves and obtained AUC scores of the DRASTIC models based on different hydrochemical indicators (As, Cl⁻, and NO₃⁻).

6.5 Results of the Fuzzy AHP Analysis

This research identified the relative importance of the clusters and the corresponding sub-criteria based on the fuzzy AHP analysis. However, as one of the most significant aspects of the GIS-MCDA approaches is to explore the weights of criteria considered and the fact that the MCDA rationale directly rely on the preferences of the experts who performed the pairwise comparison surveys (Malczewski & Rinner, 2015), it is essential to ensure the consistency of the judgements of the survey participants. In this regard, the CR values for each expert and every pairwise comparison made by them were measured to verify the reliability of the analysis. The heat map presented in Figure 6.7 illustrates the distributions of the weights as well as the maximum CR value reached by the different participants. As can be seen from the figure that all the experts who attended the pairwise comparison surveys provided consistent preferences since the CR values obtained for each expert were found below the threshold of 10%. Hence, the obtained maximum CR values illustrates the validity and consistency of the conducted pairwise surveys.

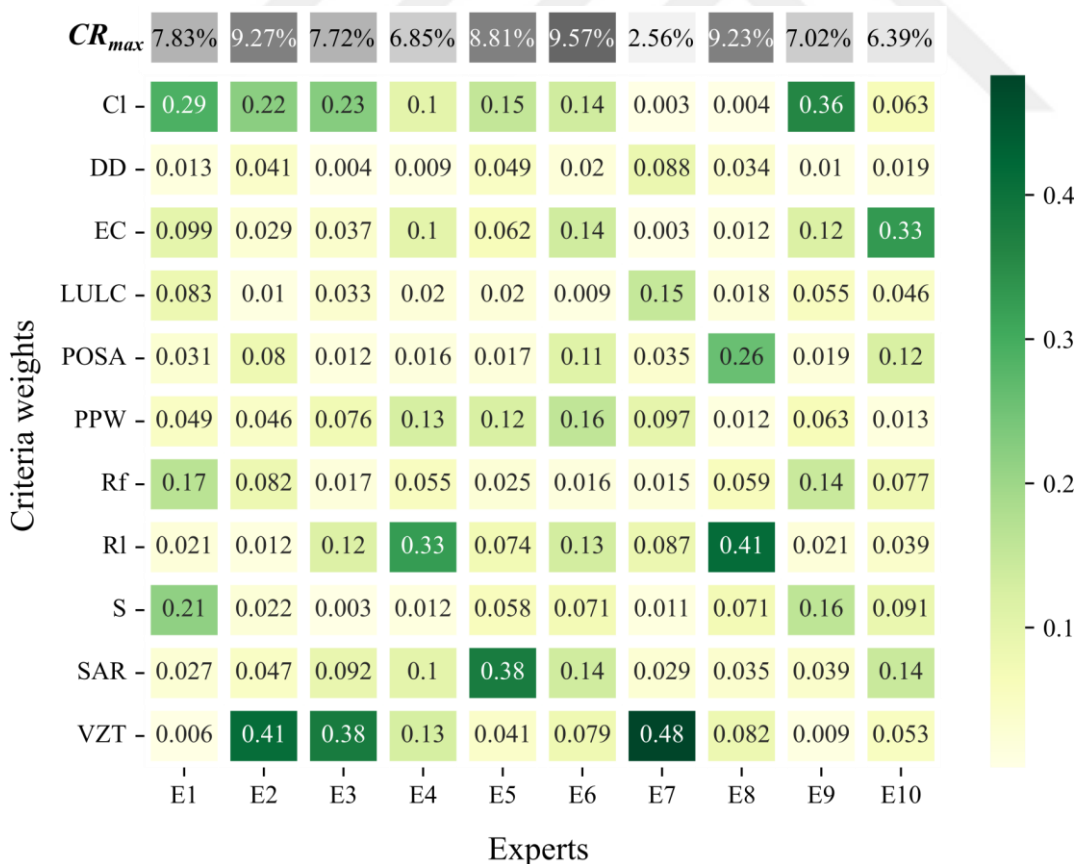


Figure 6.7 : Heat map of the criteria weights and the maximum CR values obtained through different participants.

Table 6.2 shows the global weights determined by the fuzzy AHP for the main clusters and each criterion. It was found that the groundwater quality cluster had the highest weight with 37.4%, followed by the surface and groundwater protection cluster with 25.2% and 19.4%, respectively. On the other hand, the hydrometeorology cluster was deemed to be the least important with a weight of 17.9%. Regarding the surface criteria group, the POSA was identified as the most influential parameter, with a global weight of 9.46%, while R_i and VZT ranked first in the hydrometeorology and groundwater protection clusters, respectively. Despite this, Cl^- was found as the most significant criterion in the overall assessments, followed by VZT, SAR, R_i , and POSA, respectively. This result further supports the findings of Fuentes and Vervoort (2020) and Rahman et al. (2013) who both gave large significance level to groundwater quality parameters. Also, one notable observation is that despite the groundwater quality having a significantly higher weight than the other three clusters, the EC criterion demonstrated the least contribution (6.15%) to the overall comparisons, succeeded by PPW and DD. The corresponding finding also corroborates to the pertinent literature, which has similarly assigned a low level of importance to EC in the delineation of sites suitable for the MAR implementation (Hussaini et al., 2021; Malekmohammadi et al., 2012; Sandoval & Tiburan, 2019).

The assessments based on the suitability mapping of MAR techniques are widely conducted approach to assess the potential of artificial recharge projects to address the challenges faced by aquifers in a particular region. However, the lack of field measurements or locating successful MAR projects in many countries poses a challenge to model validation in these studies (Sallwey, Bonilla Valverde, et al., 2019). Although some researchers have attempted to validate their decision frameworks indirectly by examining hydrochemical parameters, water table fluctuations, or numerical models (M. Arshad et al., 2022; Fuentes & Vervoort, 2020; Russo et al., 2015; Tiwari et al., 2017; Zhang et al., 2019), such endeavors are relatively infrequent. Consequently, the majority of scholars suggest the consistency checks and sensitivity analysis as sufficient tools for assessing the robustness of the proposed GIS-MCDA framework for MAR mapping (Kazakis, 2018; Rahman et al., 2013). This is because the weighting process, which is often subjective and highly depends on human judgments, constitutes the primary source of uncertainty in such frameworks.

Table 6.2 : Weights determined for each decision parameter through the fuzzy AHP analysis and the ratings assigned to criteria classes.

Clusters	Weight	Criteria	ID	Weight	Classes	Ratings	Global weight
Surface	25.2%	Slope (%)	S	6.61%	0-1	5	0.42
					1-3	4	0.33
					3-5	3	0.25
					5-10	2	0.17
					> 10	1	0.08
		Land use/Land cover	LULC	7.13%	Forest and seminatural areas	5	0.28
					Arable land, permanent crops, pastures and heterogenous agricultural areas	4	0.22
					Urban fabric, green urban areas, sports and leisure facilities	3	0.17
					Industrial, commercial and transport units	2	0.11
					Mine, dump and construction sites	1	0.06
		Drainage density (km/km ²)	DD	2.04%	0-0.38	5	0.10
					0.38-1.04	4	0.08
					1.04-1.73	3	0.06
					1.73-2.58	2	0.04
					2.58-4.46	1	0.02
		Potential occurrence of shallow groundwater (TWI+NDVI)	POSA	9.46%	Good	5	0.47
					Fair	3	0.28
					Poor	1	0.09
Hydrometeorology	17.9%	Rainfall (mm/y)	R _l	10.88%	422-397	5	0.54
					367-397	4	0.44
					346-367	3	0.33
					314-346	2	0.22
					272-314	1	0.11
		Runoff (mm)	R _f	7.04%	> 368	5	0.35

Table 6.2 (continued): Weights determined for each decision parameter through the fuzzy AHP analysis and the ratings assigned to criteria classes.

Clusters	Weight	Criteria	ID	Weight	Classes	Ratings	Global weight		
Groundwater protection	19.4%	Proximity to public wells (m)	PPW	3.69%	341-368	4	0.28		
					319-341	3	0.21		
					290-319	2	0.14		
					234-290	1	0.07		
					> 800	5	0.18		
		Groundwater quality	37.4%	Vadose zone thickness (m)	VZT	15.73%	500-800	4	0.15
							300-500	3	0.11
							150-300	2	0.07
							0-150	1	0.04
							> 40	5	0.79
Groundwater quality	37.4%			Electrical conductivity (µS/cm)	EC	6.17%	25-40	4	0.63
							10-25	3	0.47
							5-10	2	0.31
							0-5	1	0.16
							345-1000	5	0.31
		Groundwater quality	37.4%	Electrical conductivity (µS/cm)	EC	6.17%	1000-1257	4	0.25
							1257-1590	3	0.19
							1590-2143	2	0.12
							2143-3620	1	0.06
							0.16-1.26	5	0.73
Sodium adsorption ratio (meq/l)	SAR			14.51%	1.26-1.90	4	0.58		
					1.90-2.57	3	0.44		
					2.57-4.13	2	0.29		
					4.13-7.58	1	0.15		

Table 6.2 (continued): Weights determined for each decision parameter through the fuzzy AHP analysis and the ratings assigned to criteria classes.

Clusters	Weight	Criteria	ID	Weight	Classes	Ratings	Global weight
		Chloride (mg/l)	Cl ⁻	16.75%	9-64	5	0.84
					64-114	4	0.67
					114-162	3	0.50
					162-350	2	0.34
					> 350	1	0.17

Therefore, a rigorous and transparent sensitivity analysis can enhance the credibility and reliability of the MAR suitability mapping results. In line with, the present study examined the sensitivities of the employed criteria to the fuzziness degrees in order to underpin the stability of the fuzzy AHP decision framework and its corresponding outcomes. To achieve this, different fuzziness degrees ranging from 1.2 to 2.0 (with a step of 0.2) were considered, and the resulting changes in the criteria weights were explored (Figure 10). The figure quite revealing that except for the POSA criterion which exhibit slight variation with the change in the degree of fuzziness, there were no major changes in the rankings of decision criteria. Hence, the outcomes of the efforts devoted to sensitivity analysis suggested that the proposed fuzzy AHP approach posed significant stability.

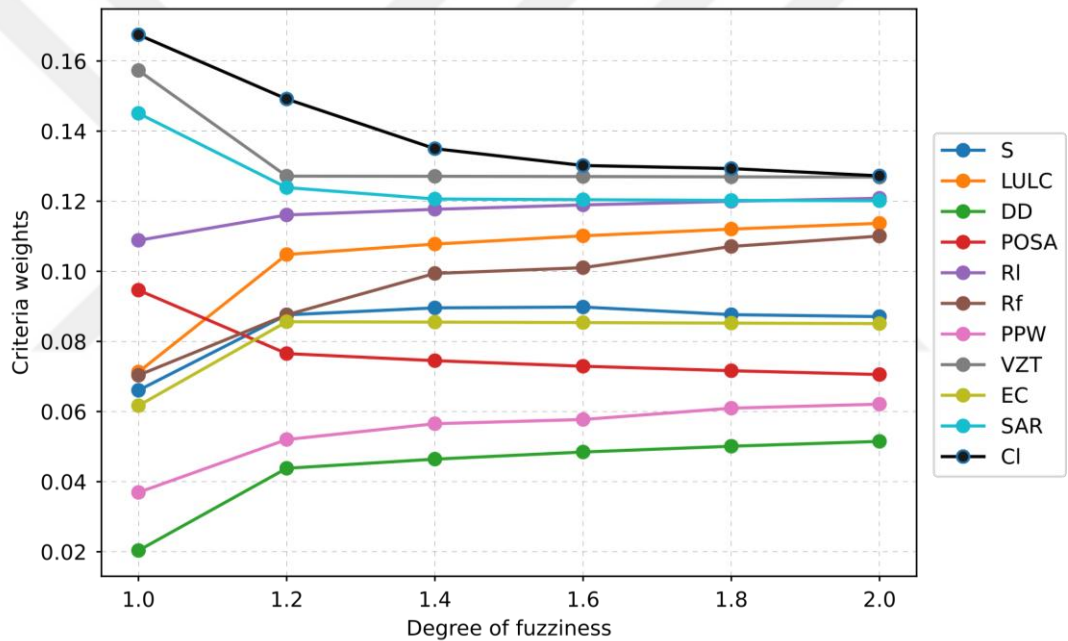


Figure 6.8 : Sensitivity analysis with respect to different fuzziness degrees.

6.6 Overall Outcome of the Integrated Model

The integration of thematic layers to generate the overall suitability map was carried out in the prioritization process. In the present study, the 11 raster layers were standardized to a common scale and used as input variables for the WOA algorithm. The existing literature recognized the utility of several standardization techniques, e.g., typical fuzzy membership, AHP method, linear and step functions, rating technique, etc., which ensure the decision layers are in a similar scale (Fuentes & Vervoort, 2020; Kamangar et al., 2019; Papadopoulos et al., 2022; Rahman et al., 2012). Due to its

practical utilization (Fuentes & Vervoort, 2020; Kazakis, 2018; Shadmehri Toosi et al., 2020), this study adopted the rating technique to simplify the analysis. A rating factor of 5 was assigned to cells having a higher potential for dry well success, while those posing least suitability were represented by 1 (Table 6.2). Moreover, the WOA in the WhiteboxTools enables the inclusion of a restriction layer during the process, making it an ideal and useful tool for the development of suitability maps that automatically incorporates constraint layers.

Utilizing the DRASTIC-SWARA method, vulnerable regions of the aquifer were evaluated, and areas classified as high and very high vulnerability levels were deemed unsuitable for MAR structures. In contrast, areas categorized as moderate, low, and very low vulnerability were considered suitable for the recharge activities. The overall outcome of this process is illustrated in Figure 6.9a, which reveals that 28.24% of the study area is unsuitable for MAR infrastructure, and the remaining 71.76% is suitable. According to Figure 6.9a, the majority of the unsuitable areas are located in the northwestern and central regions of Kayseri city. To further refine the suitability analysis, areas identified as suitable for recharge operations were taken into account to calculate the MSL index through the WOA. The obtained MSL index was classified into four distinct categories, namely very low, low, moderate, and high. The resulting final suitability map is presented in Figure 6.9b. The findings showed that 13.34% and 24.65% of the investigated area are classified as very low and low suitability, respectively. The reason for such low suitability in those identified regions could be linked to the presence of low groundwater quality with high Cl^- , SAR, and EC concentrations especially in the center and northwestern part of the aquifer. Additionally, those areas are characterized by the presence of shallow water table (less than 10m) implying a thin vadose layer and thereby low contaminants attenuation potential in those zones. A substantial 20.79% of the study area was classified as having moderate suitability, concentrated primarily in the northeastern and southern parts of the city. The regions classified as having high suitability, which constitute 12.98% of the total area, are predominantly located also in the northeastern and southern parts of the city. These areas are characterized by low to very low Cl^- and SAR concentrations, thick vadose zones, and good to fair POSA, all of which enhance their suitability potential, making them favorable sites for constructing drywells. Furthermore, the absence of the least weighted LULC classes such as industrial,

commercial and urban fabric as wells as the presence of flat terrain further assist the suitability potential of those zones for MAR application.

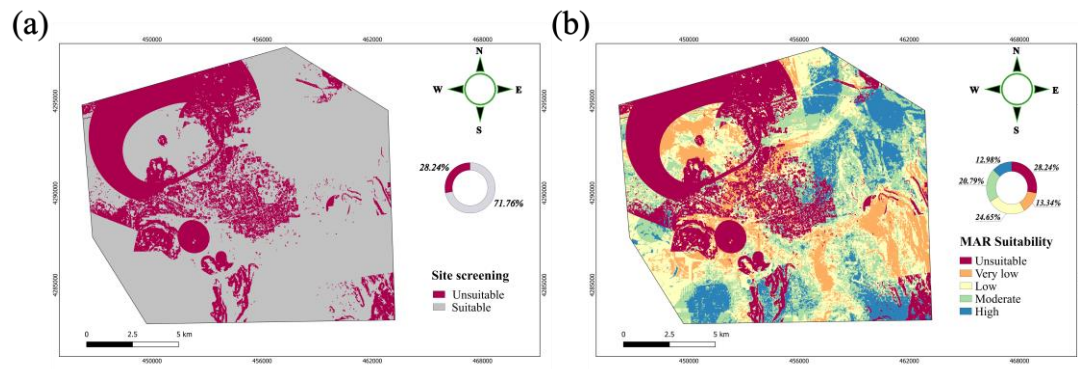


Figure 6.9 : Generated maps through (a) the constraint and (b) final drywell suitability mapping process.



7. CONCLUSIONS AND RESEARCH PERSPECTIVES

7.1 Concluding Remarks

In the context of escalating water demand due to population growth and an increasingly arid climate, the imperative to adopt sustainable practices to mitigate challenges encountered by fresh water resources notably subsurface systems has gained pronounced urgency worldwide. Amidst these circumstances, MAR has arisen as a promising technology capable of addressing the challenges confronting subsurface water resources while concurrently facilitating groundwater replenishment. However, the attainment of favorable outcomes in MAR initiatives is intrinsically linked to the meticulous selection of suitable sites for the recharge structures. The extant body of literature underscores the auspicious role played by the integration of GIS and MCDA techniques in facilitating investigations of MAR potential. Thus, the establishment of a robust GIS-MCDA scheme enables the comprehensive assessment of large geographic areas, while concurrently alleviating computational burdens and financial constraints in MAR potential assessment. The primary focus of this thesis resides in the development of robust multi-tiered decision frameworks for identifying sites conducive to the implementation of MAR initiatives across various scales.

Hence, this research encompassed investigations conducted at the national, watershed, and urban levels. Concerning the national scale, as detailed in Chapter 3 of this thesis, a comprehensive map depicting the suitability of MAR sites was generated for the arid climate context of Djibouti, employing a hybrid MCDA approach. A thorough compilation of criteria pertaining to surface, environmental, and subsurface dimensions were identified, and their relative importance was determined using the fuzzy AHP algorithm. Subsequently, the TOPSIS technique was employed to prioritize the study area based on the weighted decision layers. Sensitivity analysis was also employed to ensure the robustness and stability of the decision framework. The results of the analysis highlighted the significance of rainfall, slope, and NDVI as the most influential decision criteria in identifying regions suitable for MAR implementation. Conversely, the fuzzy AHP determined that depth to groundwater and

drainage density were comparatively less influential in the decision-making process. In terms of the prioritization of the study area, it was observed that approximately 10.63%, 23.20%, and 31.06% of the country, corresponding to approximately 2,466 km², 5,382 km², and 7,206 km², respectively, exhibited very high, high, and moderate suitability for hosting MAR activities. Furthermore, the sensitivity analyses conducted to evaluate the stability of the framework indicated its robustness, as there was no significant change in the ranks of the criteria with respect to the various degree of fuzziness values and considerably lower variations were observed in RMSE values computed based on closeness coefficients.

Regarding Chapter 4, a holistic decision-making framework was proposed for a prominently favored and widely adopted MAR technology within arid and semi-arid regions. The imperative of achieving water security is notably heightened in regions characterized by aridity and semi-aridity, wherein dependence on groundwater resources is pronounced. Consequently, in acknowledgment of this circumstance, RWH has emerged as a prominently preferred and extensively implemented mitigation measure among the spectrum of proposed strategies in those regions. Yet, the task of identifying suitable areas for the establishment of RWH infrastructure presents substantial challenges for decision-makers and carries the risk of failure if not adequately investigated. In this vein, Chapter 4 presents a novel approach, coupling the fuzzy AHP and VIKOR algorithms, to determine the significance levels of the decision criteria and identify promising regions for conducting RWH activities in the southeastern basin of Djibouti. The major findings of this research underscore the importance of the environment and physical clusters in assessing the RWH potential, while revealing that the socio-economic criteria group was undervalued based on the fuzzy AHP results obtained from the preferences of the experts who participated in the pairwise questionnaire. Consequently, rainfall, slope, and runoff occupy the podium as the most weighted decision parameters, whereas the distance to roads is the least determinant criterion for the RWH site suitability assessment. Regarding the prioritization of alternatives, the results indicate that 86.77km² (6.39%), 394.09km² (29.02%), and 391.64km² (28.84%) of the investigated basin display very high, high, and moderate suitability, respectively, to host RWH structures. On the other hand, 485.48km² (35.75%) of the basin fall between very low and low suitability. Additionally, in order to provide valuable insights to both policy-makers and decision-

makers, the practical application of the proposed framework is elucidated in this section.

Moreover, within the scope of this thesis, MAR potential was assessed at a city level. Chapter 5 of this research is dedicated to a case study conducted in the urban city of Kayseri, wherein an integrated GIS-based MCDA approach was employed to investigate suitable zones for artificial recharge through drywells. In fact, drywells have proven their effectiveness and benefits compared to most MAR technologies in recharging shallow urban aquifers throughout the years, yet they are handicapped by the nonexistence of proper guidelines and standards regarding their implementation in most countries. To address this gap, nine decision criteria were meticulously chosen based on their impact on drywell siting and the success of recharge mechanisms and standardized through the FGD sessions. In this vein, the importance level of each criterion was determined using the fuzzy AHP method, while the application of the TOPSIS model was performed to calculate the closeness coefficients of the alternatives (i.e., sub-regions) with not only respect to the different criteria group but also the overall suitability. The major outcomes of this study indicate that hydraulic conductivity, depth to groundwater, and soil texture play determinant roles in site suitability assessments, while buffer distance from main roads is the least significant decision criterion. The obtained weights were later compared to those adopted in the existing literature. Thus, it was revealed that assigned weights are strongly consistent with the median of each pre-defined set, i.e., surface infiltration technologies and deep injection technologies, for most criterion except hydraulic conductivity which display a much larger importance level in this study in contrast to other MAR sites suitability mapping studies. According to the site suitability maps generated for different criteria groups, the findings pointed out the variations in regions' closeness coefficient values and ranking for individual clusters; however, based on the overall suitability, the city center shows very high to medium suitability for constructing the vadose zone wells. The key findings of this study are that drywell sitting can be viewed as a multidimensional problem that requires not only consideration of subsurface variables but also surface and management parameters to improve infiltration performance, recharged water, and groundwater quality. This type of problem is well suited to MCDA methods since they enable the intervention of multidisciplinary experts to obtain the best overall judgment for robust results. A further advantage of the MCDA

model is that it is very flexible and does not limit the number of parameters that can be included. Thus, in the future, if more criteria influencing drywell site prioritization are identified, the model can easily be adjusted without requiring significant resources and/or time.

Lastly, concerning the last research conducted within the scope of the current thesis a comprehensive framework that combines groundwater vulnerability and MAR site suitability assessments to identify areas with the greatest potential and least susceptibility to contamination for the installation of MAR technologies was introduced and implemented in Kayseri city. To perform the groundwater vulnerability assessment of the study area, different DRASTIC methods were investigated and compared, and the best performing option was used to generate the vulnerability layer and constraint map. In addition, being relevant to the drywell designs, a total of 11 decision criteria which were extracted from an extensive literature survey and confirmed to the experts were selected at first, and then, they were standardized and weighted by means of the pairwise comparison survey before being used as input factors for the WOA algorithm. The results of the vulnerability assessment indicated that the DRASTIC-SWARA had the best match with As and Cl⁻ based on the AUC values of 0.856 and 0.648, respectively. Furthermore, the outcomes of the site screening process demonstrated that 28.24% of the investigated area was unsuitable for recharge activities due to considerable groundwater vulnerability. The fuzzy AHP procedures followed to perform criteria weighting showed that the groundwater quality parameters (i.e., particularly Cl⁻ and SAR) were significant in identifying areas suitable for MAR sitting. On the other hand, the proximity to public wells and drainage density were deemed as the least influential criteria regarding the MAR implementation. Sensitivity analysis further revealed that the proposed fuzzy AHP model was stable and robust, as there were no significant changes in the rankings of decision parameters with varying degrees of fuzziness. Based on the final suitability assessment, the northeastern and southern parts of the study area have shown high to moderate suitability to implement the MAR structures. Therefore, incorporating drywells into the existing infrastructures, particularly the stormwater drainage network of the city, in the corresponding areas would be a viable option to direct the runoff into the subsurface and replenish the stressed unconfined aquifer of the region.

7.2 Implications for Future Attempts

While this thesis provides valuable insights into the evaluation of MAR potential at various levels, it is imperative to acknowledge the persistence of certain limitations and the existence of opportunities for further enhancement, encompassing both methodological and conceptual dimension.

From a conceptual facet:

- Subsequent investigations should consider broadening the spectrum of decision parameters utilized in delineating MAR potential, incorporating additional pertinent criteria contingent upon the availability and accessibility of corresponding datasets. Notably more socio-economic, groundwater quality, and aquifer physical parameters need to be incorporated in the decision frameworks.
- Despite the pertinent literature including mainly expert preferences from academia and water administration sectors in the pairwise surveys, the credibility of the findings could be further enhanced through the incorporation of perspectives from practitioners within the agricultural industry and other relevant stakeholders. Additionally, generating MAR potential maps by considering the perceptions of distinct stakeholders separately, ensuring the comparative analysis of stakeholder perceptions in MAR site suitability mapping could be a valid trajectory for future research endeavors.
- In situations where stormwater is targeted as the recharge source, as exemplified in drywell and RWH projects, the integration of stormwater quality considerations as decision layers within the framework would substantially enhance the reliability of developed maps.
- Model validation presents a complex undertaking within the context of MAR suitability mapping, mainly attributable to the scarcity of documented instances of successful artificial recharge projects across many nations. Nonetheless, the validation of suitability maps pertaining to drywells, for instance, through hydro-chemical data from runoff analysis could offer a promising avenue for future research endeavors. In regions where the suitability mapping designates drywell installation as promising, the

availability of data concerning stormwater pollutants concentration within the corresponding locale would provide additional assurance for construction decisions.

- In the follow up attempts, proposed multi-tiered decision frameworks in this thesis could be coupled with mathematical models for more robust outcomes. Saturated/unsaturated flow and solute transport numerical models could be developed for assessing the short and long-term efficiency of the artificial recharge in the suitable regions identified by the MAR mapping phase.

Regarding the methodological dimension:

- The current thesis employed the ranking and linear fuzzy membership function for the standardization of numerical decision layers. It is important to acknowledge that in future endeavors, alternative fuzzy membership functions, such as trapezoidal, power, and Gaussian, could be investigated.
- In future investigations, the application of other MCDA algorithms beyond AHP and its fuzzified version could be explored in the criteria weighting stage. Specifically, methodologies such as the SWARA, ANP, and their respective fuzzified adaptations (e.g. fuzzy SWARA, fuzzy ANP) hold promise in determining the significance levels of decision criteria.
- The utilization of both AHP and ANP for criteria posing non-interdependence and those having interrelationships among each other, respectively, in the same MCDA framework could be a valuable research direction for future studies.
- Similarly, concerning the facet of the model pertaining to the prioritization of alternatives, while the TOPSIS and VIKOR methodologies provide an elevated degree of mathematical sophistication in contrast to commonly employed GIS overlay techniques, it is advisable to introduce other MCDA-based prioritization approaches within the topic. Thus, the application of methods such as COPRAS, CODAS, PROMETHEE, SPOTIS, and MULTIMOORA could present a promising research avenue in the follow-up efforts.
- In subsequent endeavors, it is recommended to compare the accuracy and similarities of distinct MCDA algorithms. This comparison aims to evaluate

the effectiveness of the proposed models against conventionally utilized GIS-based MCDA approaches, such as the integrated AHP-WLC method.

- Lastly, enriching the presented methodologies by integrating probabilistic-based approaches (such as the Monte Carlo Simulation) offers a fruitful trajectory for examining the interpersonal uncertainties in the proposed framework.





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APPENDICES

APPENDIX A: The conducted pairwise comparison survey and profile of the experts who attended the pairwise questionnaire in the second study.

APPENDIX B: Data source and calculated criteria weights within the third study.



APPENDIX A.1 – A.4 AHP questionnaire.

Which of the following factors is more important than the other in identifying sites suitable for rainwater harvesting structures? Note: If the factor in the row is more important you should answer (X), if the factor in the column is more important you should answer (1/X).

Table A.1 : AHP Questionnaire for the main clusters.

Main clusters	Physical	Environmental	Socio-economic
Physical	1.0		
Environmental	////////	1.0	
Socio-economic	////////	////////	1.0

Table A.2 : AHP Questionnaire for the physical criteria.

Criteria	Slope	LULC	Soil texture	Watershed size
Slope	1.0			
LULC	////////	1.0		
Soil texture	////////	////////	1.0	
Watershed size	////////	////////	////////	1.0

Table A.3 : AHP Questionnaire for the environmental criteria.

Criteria	Rainfall	Runoff	EC (uS/cm)	NDVI
Rainfall	1.0			
Runoff	////////	1.0		
EC	////////	////////	1.0	
NDVI	////////	////////	////////	1.0

Table A.4 : AHP Questionnaire for the socio-economic criteria.

Criteria	PS	DR	PAP	APD
Proximity to settlements (PS)	1.0			
Distances to roads (DR)	////////	1.0		
Proximity to agricultural parcels (PAP)	////////	////////	1.0	
Agricultural parcels density (APD)	////////	////////	////////	1.0

Table A.5 : Profile of the experts who attended the pairwise comparison surveys.

Expert ID	Sector	Job Description	Proficiency	Education Level	Experience (yr)
E1	University	Professor	Hydraulics	Ph.D.	22
E2	University	Professor	Water Resources	Ph.D.	23
E3	University	Assoc. Professor	Water Resources	Ph.D.	20
E4	University	Professor	Remote sensing	Ph.D.	22
E5	Private sector	Engineer	Water Resources	B.Sc.	20
E6	Private sector	Engineer	Hydraulics	M.Sc.	6
E7	Private sector	Engineer	Hydraulics	M.Sc.	10
E8	Water and Sewerage Administration	Engineer	Hydraulics	M.Sc.	6
E9	Municipality	Engineer	Civil Engineering	B.Sc.	24
E10	Governmental Authority (i.e., Ministerial level)	Engineer	Agricultural	M.Sc.	13

APPENDIX B Data source and calculated criteria weights within the third study.

Table B.1 : Overview of thematic layers and corresponding data source.

Source	Dataset	Format	Derived Thematic Layer	ID	Reference
The European Space Agency (ESA)	Copernicus DSM GLO-30	Raster	Slope	S	European Space Agency and Sinergise (2021)
KASKI	Geology	Vector	Lithology	L	-
	Wells data	Raw data	Depth to groundwater	DG	-
			Distance from public wells	DPW	-
	Stormwater network plan	CAD	Stormwater drainage network density	SDND	-
Copernicus Report	CORINE land cover (CLC) 2018	Raster	Land use/land cover	LULC	Büttner et al. (2017)
	DRASTIC model	Map	Soil texture	ST	Değirmenci et al. (2011a)
			Hydraulic conductivity	HC	Değirmenci et al. (2011a)

Table B.2: Aggregate local and global weights of criteria and the rating factor assigned to each class.

Clusters	Weights	Criteria	Weights		Classes	Rating factor
			local	global		
Surface	0.289	Slope (%)	0.262	0.076	0-1	5
					1-3	4
					3-5	3
					5-10	2
					>10	1
		Land use/Land cover (LULC)	0.351	0.101	Forest and seminatural areas	5
					Arable land, permanent crops, pastures and heterogenous agricultural areas	4
					Urban fabric, green urban areas, sports and leisure facilities	3
					Industrial, commercial and transport units	2
					Mine, dump and construction sites	1
		Soil texture	0.387	0.112	Sand	5
					Silt loam	4
					Sandy clay loam	3
					Clay loam	2
					Silty clay loam and sandy clay	1
Economy/ Protection	0.133	Stormwater drainage network density (m/m ²)	0.279	0.037	> 0.025	5
					0.015-0.025	4
					0.005-0.015	3

Table B.2 (continued): Aggregate local and global weights of criteria and the rating factor assigned to each class.

Clusters	Weights	Criteria	Weights		Classes	Rating factor		
			local	global				
	0.578	Buffer distance from public wells (m)	0.578	0.078	0.001-0.005	2		
					0-0.001	1		
					>800	5		
					500-800	4		
					300-500	3		
					150-300	2		
					0-150	1		
		Buffer distance from main roads (m)	0.134	0.018	> 500	5		
					300-500	4		
					150-300	3		
					50-150	2		
					0-50	1		
		Aquifer	0.578	Depth to groundwater (m)	0.309	0.178	> 40	5
							25-40	4
							10-25	3
							5-10	2

Table B.2 (continued): Aggregate local and global weights of criteria and the rating factor assigned to each class.

Clusters	Weights	Criteria	Weights		Classes	Rating factor
			local	global		
					0-5	1
		Lithology	0.106	0.061	Alluvion	5
					Hillside debris	4
					Sandstone	3
					Pyroclastic rock and agglomerate	2
					andesite, basalt and ignimbrite	1
		Hydraulic conductivity (m/day)	0.586	0.339	43.20-47.52	5
					8.64-43.20	4
					6.48-8.64	3
					4.32-6.48	2
					0-4.32	1



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PUBLICATIONS, PRESENTATIONS AND PATENTS ON THE THESIS:

- **Mouhoumed, R. M.**, Ekmekcioğlu, Ö., Başakın, E. E., & Özger, M. (2023). Integrated Fuzzy AHP-TOPSIS Model for Assessing Managed Aquifer Recharge Potential in a Hot Dry Region: A Case Study of Djibouti at a Country Scale. *Water*, 15(14), 2534. <https://doi.org/10.3390/w15142534>
- **Mouhoumed, R. M.**, Ekmekcioglu, O., & Ozger, M. (2023). A hybrid MCDA approach for delineating sites suitable for artificial groundwater recharge using drywells. *Journal of Hydrology*, 620. doi.org/10.1016/j.jhydrol.2023.129387
- **Mouhoumed, R. M.**, & Özger, M. (2023). Identifying promising regions for subsurface dams in Kayseri, Turkey: A coupled GIS and Analytic hierarchy process approach. *International Graduate Research Symposium – Igrs '23*.
- **Mouhoumed, R. M.**, Ekmekcioglu, O., & Ozger, M. (2023). An integrated groundwater vulnerability and artificial recharge sites suitability assessment using GIS-multi criteria decision making approach. *Journal of Hydrology*. (Under Review)
- **Mouhoumed, R. M.**, Ekmekcioglu, O., & Ozger, M. (2023). A holistic Multi-tiered Decision Approach for Evaluating Rainwater Harvesting Potential in Arid Regions: A Case Study of the Southeastern Basin of Djibouti. *Groundwater for Sustainable Development*. (Under Review)