DETERMINATION OF THE OIL PIPELINE ROUTE, OIL SPILL PATH AND VOLUME OF OIL BY MULTI-CRITERIA ANALYSIS

PETROL BORU HATLARINDA ÇOK KRİTERLİ ANALİZLE GÜZERGÂH, SIZINTININ YOLU VE HACMİNİN BELİRLENMESİ

ALİ İHSAN DURMAZ

PROF. DR CEVDET COŞKUN AYDIN

Supervisor

Submitted to

Graduate School of Science and Engineering of Hacettepe University

As a Partial Fulfillment to Requirements

For the Award of Degree of Doctor of Philosophy

in Geomatics Engineering

2024

ABSTRACT

DETERMINATION OF THE OIL PIPELINE ROUTE, OIL SPILL PATH AND VOLUME OF OIL BY MULTI-CRITERIA ANALYSIS

Ali İhsan DURMAZ

Doctor of Philosophy, Department of Geomatic Engineering

Supervisor: Prof. Dr. Cevdet Çoşkun AYDIN

January 2024, 146 pages

This thesis study focuses on implementing Geographical Information Systems (GIS) to identify potential spill locations and estimate crude oil pipeline routes.

A groundbreaking approach introduces a least-cost path algorithm, which aids in determining an optimal pipeline route that navigates topological and geographical complexities. This optimal path ensures both environmental preservation and socio-economic sustainability. A comparison is carried out between a conventional route-finding technique and the GIS-based approach, thus shedding light on the strengths and limitations of both methods in the context of pipeline planning and construction efficiency.

In the experimental results, the simplified route exhibited a shorter length of 148.99 km compared to the existing 155.83 km route, and also demonstrated lower costs of 129,053.00 compared to the existing route's 160,958.00.

Furthermore, the study pioneers a cartographic line simplification technique aimed at reducing complex topological combinations and eliminating unnecessary detours in pipeline routes. This strategy results in a more practical and realistic approach toward pipeline construction by removing high vertex points from the proposed route. Notably, the number of vertex points was reduced to 170 in the simplified route compared to 772 in the 30 m DEM route.

Exploiting GIS technology, remarkably Digital Elevation Models (DEMs), and state-of-the-art algorithms, the research predicts possible pipeline leakages and spills. Upon meticulous analysis, the accuracy of the sampled dataset improved from 84% to 93% after excluding erroneous pixels. High-risk regions can be identified by assessing terrain slope, pipeline pressure, and soil type. This proactive approach enables effective emergency planning and better resource allocation and potentially mitigates the environmental impact of oil spills.

In conclusion, this study highlights the immense potential of merging GIS capabilities and innovative algorithms in pipeline route planning and spill prediction, thus reducing potential environmental damage from oil spills.

Keywords: Geographical Information Systems (GIS), oil pipeline route estimation, spill location prediction, least-cost path algorithm, environmental impact.

ÖZET

PETROL BORU HATLARINDA ÇOK KRİTERLİ ANALİZLE GÜZERGÂH, SIZINTININ YOLU VE HACMİNİN BELİRLENMESİ

Ali İhsan DURMAZ

Doktora, Geomatik Mühendisliği Bölümü

Tez Danışmanı: Prof. Dr. Cevdet Coşkun AYDIN

Ocak 2024, 146 sayfa

Bu tez çalışması, petrol boru hattı boyunca potansiyel sızıntı konumlarının belirlenmesi ve ham petrol boru hattı rotalarının Coğrafi Bilgi Sistemi (CBS) teknolojisi ile tahmin ve tespit edilmesini hedeflemektedir.

Çalışmada yenilikçi bir yaklaşımla, bir en düşük maliyet yolu algoritması kullanılmıştır. Bu algoritma topolojik ve coğrafi karmaşıklıkların üstesinden gelebilen bir boru hattı rotası belirlemealgortimasıdır. Bu optimal yol hem çevresel koruma hem de sosyo-ekonomik sürdürülebilirlik sağlamaktadır. Çalışmada konvansiyonel bir rota belirleme tekniği ile CBS tabanlı yaklaşım uygulamalı olarak karşılaştırılmıştır., Böylece boru hattı planlama ve inşaat verimliliği bağlamında her iki yöntemin güçlü ve zayıf yönleri üzerine değerlendirmeler yapılmıştır.

Çalışmada, deneysel sonuçlara göre, basitleştirilmiş rota, mevcut 155,83 km’lik rotaya kıyasla 148,99 km olacak şekilde daha kısa bir uzunlukta ve ayrıca mevcut rotanın 160.958,00 birimlik maliyetine karşılık 129.053,00 birimlik daha düşük algoritmik maliyeti olduğu ortaya konulmuştur.

Ayrıca, çalışmada boru hattı rotalarında karmaşık topolojik kombinasyonları azaltmayı ve gereksiz dolambaçları ortadan kaldırmayı hedefleyen bir kartografik çizgi basitleştirme tekniği kullanılmıştır. Bu strateji, önerilen rotadan yüksek köşe noktalarını çıkararak daha pratik ve gerçekçi bir boru hattı inşaatı yaklaşımı ortaya koymuştur. Sonuç olarak, basitleştirilmiş rotada 772 noktaya kıyasla 170 nokta bulunduğu gözlemlenmiştir.

Bu araştırmada CBS teknolojisi, özellikle Dijital Yükseklik Modeli (DEM) ve en güncel algoritmaları kullanarak, olası boru hattı sızıntıları ve dökülmeleri tahmin edebilmektedir. Detaylıca yapılan bir analizin ardından, hatalı pikseller çıkarıldıktan sonra örneklenen veri kümesinin doğruluğu %84'ten %93'e yükselmiştir. Arazi eğimi, boru hattı basıncı ve toprak türü gibi parametreleri değerlendirerek, yüksek riskli bölgeler belirlenebilir. Bu proaktif yaklaşım, etkili acil durum planlaması, daha iyi kaynak tahsisini sağlar ve potansiyel olarak petrol sızıntılarının çevresel etkisini hafifletebilmektedir.

Sonuç olarak, bu çalışma, boru hattı rotası planlama ve sızıntı tahmini konusunda CBS yeteneklerinin ve yenilikçi algoritmaların birleştirilmesinin büyük potansiyeli ortaya çıkarılmış, böylece petrol sızıntıları nedeniyle potansiyel çevresel zararların azaltılması söz konusu olmuştur. Sayısal sonuç cümle/leri yazılmalı ve ayrıca yöntemin eksikliği ifade edilmeli, çalışma bölgesi anlatılmalı, geleceğe yönelik öneriler sunulmalıdır, özette bu ifadelere mutlak yer verilmelidir.

Anahtar Kelimeler: Coğrafi Bilgi Sistemleri, Dijital Yükseklik Modeli , petrol boru hattı rotası tahmini, Sızıntı konumu tahmini, En düşük maliyetli yol algoritması, Çevresel etki.

ACKNOWLEDGEMENTS

I want to thank my advisor, Prof. Dr. Cevdet Coşkun AYDIN, for their great support and advice. They really helped shape this study.

I'm also thankful to Hacettepe University's Geomatics Engineering department for letting me use their advanced research tools and resources. This project wouldn't be possible without their great research environment.

I must also mention the constant support of my parents, siblings, friends, colleagues, and family, especially my wife, Dr. Nur Efşan DURMAZ. Her patience and encouragement were really important to me during this work.

To everyone I mentioned and others who helped in big or small ways, I'm very grateful. This project was a team effort, and I'm happy I got to work with such amazing people.

Thank you.

02/01/2024

Ali İhsan DURMAZ

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS

Abberviations

CBS	Coğrafi Bilgi Sistemlerini
DYM	Dijital Yükseklik Model
GIS	Geographical Information Systems
DEM	Digital Elevation Model
MCDM	Multi-Criteria Decision Making
AHP	Analytic Hierarchy Process
TOPSIS	Ttechnique for Order Preference by Similarity to Ideal Solution
ELECTRE	Elimination and Choice Expressing Reality
VNIR	Visible-Near Infrared
SWIR	Short-Wave Infrared
SAR	Synthetic Aperture Radar
LIDAR	Light Detection and Ranging
SRTM	Shuttle Radar Topography Mission
FD	Flow Direction
FA	Flow Accumulation
Esri	Environmental Systems Research Institute
GRASS	Geographic Resources Analysis Support System
SAGA	System for Automated Geoscientific Analyses
LCPA	Least Cost Path Analysis
LCDA	Least Cost Distance Algorithm
CR	Consistency Ratio
CI	Consistency Index
RI	Random Consistency Index

MP	Muş Project
USEPA	US Environmental Protection Agency
EEA	European Environment Agency
PHMSA	Pipeline and Hazardous Materials Safety Administration
EGIG	European Gas Pipeline Incident Data Group
SCADA	Supervisory Control and Data Acquisition
CORS	Continuously Operating Reference Stations

1. INTRODUCTION

In the modern era, oil has been used as a primary energy source in numerous sectors, so it is almost impossible to get rid of it suddenly. It is extracted from wells frequently 8,000 meters from the Earth's surface [1]. The extraction procedure requires innovative technology and a hefty expenditure. About 69,000 barrels of crude oil were pumped daily in 2000, almost increasing to over 135,000 barrels per day in 2021 in the US [2]. One of the examples that best explains this situation is that 7 companies in the top 10 of the 500 largest in the world in 2020 are oil and automobile companies [3].

The relevance of pipelines has grown significantly in today's economic environment because of the increasing population and rising energy needs [4]. Constructing energy pipelines is a vital task not only for energy-producing nations but also for meeting the growing energy demands of the world. Numerous benefits come from carefully choosing and designing an ideal pipeline route, including significant time and money savings during construction and reducing environmental harm and adverse effects on nearby populations [5].

According to the CIA's Factbook, over 300,000 kilometers of oil pipelines lie underground [6]. In other words, the existing oil pipeline network could round the globe 7.5 times. Despite this extensive network, only around 5% of all pipelines are offshore, a tiny percentage compared to those onshore. The reason for this, offshore pipelines are far more expensive than their onshore counterparts, costing around three times as much (Table 1). Another factor that discourages the widespread use of offshore pipes is the logistical difficulty of maintaining and repairing underwater pipelines.

Type	Beyond 2013 (Miles)	Beyond 2013 (Cost)	Cost for 4-10 in.	Cost for 12-20 in.	Cost for 22-30 in.
Onshore	42,565	$132 billion	$2.9 billion	$19.7 billion	$41 billion
Offshore	2,27	$12 billion	$558 million	$3.8 billion	$7.9 billion

Table 1. Pipeline Construction Cost [7]

Whether the initial extraction site is on land or in the sea, the majority of the refining for petroleum takes place on terrestrial sites. In actuality, land-based environments are where oil spills most frequently happen, typically during the transportation phase. Among the causes of oil spills, problems with the pipeline itself are at the top. These problems may include defective welds, landslides that compromise structural integrity, or malfunctioning machinery. Operator mistakes and, sadly, purposeful activities like terrorist attacks are other human-related causes. Moreover, Earthquakes also contribute to oil spills by potentially causing severe damage to pipelines. Additionally, a seemingly less dramatic but no less significant problem is corrosion, which gradually weakens the structure of the pipelines, leading to leaks and spills over time [8, 9].

Planning a pipeline route requires carefully taking into account a number of factors, such as topographical and geological characteristics, proximity to oil and gas sources, population centers, and existing infrastructure [10]. To lessen the environmental impact and improve the effectiveness of pipeline routes, thorough feasibility studies and environmental impact assessments are required. The efficiency of energy transportation can be increased by choosing economically viable pipeline routes, ensuring a steady and dependable supply of renewable energy to various sectors, including businesses, households, and power generation facilities [11]. The traditional pipeline engineering and construction method is a challenging and complex procedure including topographic maps and zoning plans at a scale of 1:25,000 [12].

Furthermore, in the traditional pipeline engineering method, governmental departments' contributions have crucial importance because they are the primary source of data and standards from various specialist fields. A thorough route design process is built on information about the existing infrastructure, including roads and rivers, the locations of military zones, potential natural barriers, and other potential difficulties. Additionally, because so many factors must be considered, choosing the best route for a pipeline is a very difficult process. Each criterion has a distinct risk and benefit coefficient. To make the best pipeline route decision, benefits and risks must be evaluated simultaneously [12, 13]. Differences in these variabilities of benefit and risk increase the complexity of the pipeline routing process.

Another crucial aspect of designing oil pipeline routes is incorporating contingency plans for worst-case scenarios, including the occurrence of leaks [14]. It is critical to precisely estimate the potential oil release volume that could occur when automated shutdown valves are closed [15]. Understanding the area's geography, hydrological processes, and meteorological conditions is necessary to forecast where and how the leaking oil could disseminate. To a prompt and efficient reaction, detailed emergency response scenarios are created based on these forecasts. An utterly effective pipeline design incorporates preventive steps to optimize safety and sustainability [16]. This all-encompassing strategy protects adequate energy transportation and the environment's integrity.

One of the main goals of this research/thesis project is to identify, assess, and compare a wide range of potential hazards and criteria in order to choose the best route and the one with the lowest environmental cost, especially in terms of land use. The project's evaluation of the environmental harm brought on by oil spills in terrestrial areas serves as its secondary goal. It plans to develop a new technique for analyzing spill direction and accumulation specifically for onshore oil spills in addition to looking into/developing an algorithm for estimating potential leak volumes using GIS technologies. The study will aid in effective environmental management and decision-making by providing practical techniques for identifying and assessing oil leaks on land, enhancing our understanding, and reducing oil pollution risks in terrestrial areas.

Experimental research was conducted in this study on the route determination part. Two alternative methodologies, contemporary and traditional, are applied to the same pipeline route, and results are compared to better comprehend the findings in the study's route determination section. The physical obstacles of the contemporary method, for example, military zones that are forbidden for construction, were taken as the same as the traditional method. However, topographic obstacles, for example, slopes that are steep enough to prevent the operation of construction equipment, were determined by analysis. It is important to understand that every physical obstacle of the contemporary method comes from the traditional method. Some of these physical obstacles are consideration of input received from government entities, evaluation via field surveys, and other potential obstructions. In the contemporary method, computers evaluate many options simultaneously and choose the optimum route. This strategy seeks to reduce any human mistake that could be made when assessing these inputs [17]. The contemporary technique improves route selection accuracy and efficiency by quickly processing and analyzing enormous volumes of data using modern computer capabilities [18]. This technology-driven approach can optimize the selection process and ultimately find the best acceptable path for the intended goal while reducing the risks associated with human biases and limitations.

Furthermore, this study will be special among academic investigations due to its exclusive emphasis on meticulous topographic classifications during the pipeline route selection. These classifications involve using sophisticated Geographic Information System (GIS) analyses to locate distinctive features within a given area, such as ridges, flatlands, steep terrains, and water channels. Instead of viewing these elements as discrete parts, this research aims to understand the landscape as a continuous whole. Another point distinguishing this study from other academic studies on route selection is that the effect of a line-based simplification procedure using the point removal method on the resultant construction route was assessed. Regarding resolving construction-related concerns, this strategy's efficacy was evaluated.

The other challenge is choosing a pipeline route with several factors to consider [17]. Additionally, there might be many difficulties during the project phase. Due to its robust and efficient tools that provide accurate and quick findings, GIS has been utilized increasingly in Multi-Criteria Decision Making (MCDM) studies to solve these issues and streamline problem-solving. MCDM has been used in several scientific publications [19-23]. The analytic hierarchy process (AHP), the technique for order preference by similarity to ideal solution (TOPSIS), and elimination and choice expressing reality (ELECTRE) are only a few of the strategies utilized today to carry out MCDM processes [24]. For this study, researchers evaluated the criteria using the AHP method. In general, GIS capabilities enable the examination of all criteria, and geographic database administration makes it manageable to handle large amounts of geometric and attribute data. GIS is capable of determining several route plans [25].

Putting safety and maintenance first is not enough to ensure environmentally friendly and sustainable oil pipeline transportation. It demands putting strict controls in place, such as thorough analyses, cutting-edge leak detection systems, and premium pipeline construction supplies. The industry can effectively reduce the environmental risks associated with oil spills and support greener energy infrastructure by implementing these practices. To ensure a prompt response to potential spills, comprehensive crisis management plans must be created, regularly reviewed, and updated. Rapid containment and cleanup procedures must be part of these plans. To advance the integration of our energy needs with environmental preservation, it is essential to invest in ongoing research and development of greener and safer pipeline technology. By improving our capacity to predict and manage terrestrial oil spills, this technology may enable the development of more potent environmental protection measures. In conclusion, the goal of this research is to efficiently design and route oil pipelines while minimizing their negative effects on the environment. In the first section of this dissertation, the author intends to review the extensive investigation focused on route determination. Our knowledge of the intricate factors affecting the effective design and routing of oil pipelines will increase as a result of this empirical study. The thesis's next section will focus on preventative measures, conducting a thorough analysis of potential oil pipeline leak scenarios and proactive prevention techniques.

Oil seepage footprints, a sign of hydrocarbon accumulations, may now be found using visible and invisible remote sensing technologies. Using different types of light waves, like visible-near infrared (VNIR) and short-wave infrared (SWIR), hidden signs of oil leaks can be detected. Also, short and long-wave infrared light waves are used to find visible leak marks. These methods allow for a detailed and accurate mapping of oil leaks [26, 27]. Furthermore, Synthetic Aperture Radar (SAR), a high-resolution radar system, is effective in locating visible and invisible oil seeps, regardless of the weather or the presence of daylight [27, 28]. These technologies provide helpful resources for oil exploration, environmental monitoring, and spill response plans. On the contrary, the technology described here is not utilized for prevention but to unveil the extent of the problem.

In the environmental research realm, the harm that oil spills do to aquatic ecosystems frequently outweighs the harm that terrestrial oil pollution causes [29-32]. However, it should not be overlooked that land-based oil contamination presents severe threats to terrestrial ecosystems. Studies frequently examine how deeply oil spills may penetrate different soil types, mainly to determine whether or not the pollutants can reach groundwater aquifers [33-35]. Geographical Information Systems (GIS) are also used in research to simulate actual spill accidents, analyze the effects of disasters after they happen, and provide matching maps of environmental damage [36, 37].

The current work adds to this discussion by creating instruments for locating probable terrestrial leak locations. The scope of current research is broadened to include lateral spread and possible surface ecosystem effects in addition to vertical oil spill dispersal. This point of view, permits a more thorough understanding of the effects of terrestrial oil spills, intending to develop more successful prevention and mitigation measures.

In this thesis, researchers suggest a method utilizing a Geographical Information System (GIS) to address the problems brought on by land-based oil spills. This tool can predict the possible spill volume and determine the direction of oil spreading. Although established flow direction and accumulation analysis algorithms exist in GIS systems like GRASS and ArcGIS, they might not be enough for oil spills. The reason for that, in contrast to floods, oil spills start at one location and spread outward from there.

Due to this, a novel method was created to forecast spill direction for onshore oil spills that were modeled after the GRASS [38, 39] and ArcGIS [40, 41] "eight directions" method. Still, neighborhood relations were included that was more suitable for oil spills. Additionally, this research will look at a recently developed method that uses GIS to estimate possible oil spill amounts. This technology could increase our ability to anticipate and control terrestrial oil spills, leading to more effective environmental protection techniques.

In summary, this research project focuses on efficiently designing and routing oil pipelines while minimizing environmental impact. The author plans to examine the thorough investigation centered on route determination in the first section of this dissertation. This empirical study will advance our understanding of the complex factors affecting the efficient design and routing of oil pipelines. The subsequent section of the thesis will delve into preventative measures, conducting a comprehensive analysis of potential oil pipeline leak scenarios and strategies to avoid such incidents proactively.

2. PIPELINE ROUTE SELECTION

2.1. Digital Elevation Model (DEM)

A specific form of digital data representation of the topography or surface of the land is known as a digital elevation model (DEM). It is essentially a digital 3D map of the landscape of a place, where elevation data is captured and represented by a grid of square cells, or "pixels," for short. In this grid, each pixel is given a unique numerical value representing the elevation or altitude of that particular geographic place above a specified vertical datum, often meaning sea level [42].

DEMs are often created using various data-collecting techniques, such as satellite imaging, LIDAR (Light Detection and Ranging), or photogrammetry created from aerial photography. In some instances, they could also be based on information from ground surveys [42]. Depending on the data-gathering technique and the intended application, the resolution of a DEM, which is effectively the size of each pixel in real-world terms, might vary significantly. When doing activities that call for a precise understanding of topography, such as urban planning, environmental modeling, or construction, high-resolution DEMs are particularly helpful since they give in-depth information.

When examined as a whole, the elevation data stored within each pixel of a Digital Elevation Model (DEM) offers a comprehensive, three-dimensional depiction of the surface features of a terrain. This representation includes portraying hills, valleys, slopes, and other topographic attributes [43]. Due to this capability, DEMs have proven valuable in numerous disciplines, including geology, geography, forestry, civil engineering, and land use planning.

For instance, in hydrological modeling, DEMs may assist in forecasting the flow direction and accumulation of water over a landscape, an essential component of watershed management [43]. Similarly, DEMs in geology can help comprehend the effects of landslides or erosion. To study, develop, and manage the physical landscapes of the planet, a digital elevation model is a vital tool in many scientific, governmental, and economic fields.

The outstanding global Digital Elevation Model (DEM) dataset created by the Shuttle Radar Topography Mission (SRTM) has excellent resolution, accuracy, and geographic coverage, making it appropriate for various applications. Each pixel of the SRTM DEM corresponds to an area of the Earth's terrestrial surface roughly 30 meters by 30 meters large, with a spatial resolution of around 30 meters [44]. All places, including Turkey, regularly uphold this universal resolution.

This extensive dataset, which uses cutting-edge radar technology, is freely available to the public and is extensively used in many different sectors. Applications like topographical analysis, hydrological modeling, geological mapping, and infrastructure planning, among others, all benefit greatly from it. Also, SRTM DEM helps in land type sorting in this research.

2.2. Topography Classification

Ridges, streams, flat land, and steep terrain should all be included in the topography while determining the optimum pipeline route. This categorization makes strategic planning for development, upkeep, and potential environmental effects possible [12].

Ridges fall within the first group and offer several unique benefits. Ridges are long, narrow elevations of land that are often higher than the surrounding terrain and frequently have slopes on both sides. They almost represent no flood danger due to their height, an important factor in pipeline building. Nevertheless, the early building phase may be difficult due to its high height and rugged terrain.

Flat terrain, the second category, is usually characterized by minimal slope or elevation difference. While construction on flat terrains might be relatively straightforward due to the lack of significant physical impediments, other factors should be considered. These regions often coincide with agricultural sites, meaning that the construction of pipelines might disrupt local farming activities or potentially cause environmental concerns. Thus, acquiring necessary permissions and mitigating the potential impacts on these lands become essential to project planning.

Streams, the third kind, needs special consideration. Water bodies that run in a channel on the surface of the Earth are called streams. Special spatial considerations are required when building pipelines near or across streams to avoid the danger of water pollution and safeguard the local ecosystems. Engineers must also consider the possibility of erosion and the danger of pipeline exposure over time.

Lastly, steep terrain forms the fourth category. Constructing a pipeline on steep terrain is an engineering challenge, as it often requires extensive earthworks and additional structural support to ensure the stability of the pipeline. These additional measures generally mean higher costs than construction on flat terrain or ridges. Moreover, pipelines on steep terrain require more intensive maintenance due to landslides and soil erosion risk.

Digital Elevation Model (DEM) data clipped 3 km within the buffer zone around the project provides valuable information for evaluating these topographic categories. This data facilitates the visualization of the landscape's highs and lows, thereby assisting in selecting the most optimal pipeline path and considering the environmental implications and potential costs.

2.2.1. Extracting Ridges and Streams

To assure effectiveness, safety, and the lowest environmental impact, oil pipelines, which are essential for transporting crude oil across vast distances, must be carefully planned. This planning procedure' selection of the best route is crucial.

Ridges offer several advantages for pipeline routing. First, its distance from agricultural regions is important because it reduces possible crop damage and conflict with farming activities. Second, their resistance to erosion guarantees the long-term stability of the pipes put in place there. This stability results from the ridges' steep, sloping topography preventing water from pooling, which prevents soil erosion. Finally, because ridges have a low potential for water collection, there is less chance of floods, silt buildup, and water-caused pipeline damage. As a result, ridges can offer pipelines a durable, dependable route.

On the other hand, installing a pipeline might be complicated near streams. Construction may become more challenging due to their perpendicular crossing of possible pipeline routes, necessitating specialist methods such as horizontal drilling or installing precast concrete armor. More importantly, streams provide a significant danger of water erosion, compromising a pipeline's integrity and eventually resulting in leaks or failures. Streams are often avoided while building pipeline routes due to the considerable risk of erosion they provide.

Planning a pipeline's path requires considering hills and streams since they contribute to water buildup. Pipeline instability and erosion can result from water buildup. Due to their sloping structure, ridges naturally prevent water buildup, whereas streams act as conduits for water movement, creating potential erosion areas. By identifying possible risk regions for water-related pipeline damage, modern GIS platforms can compute water accumulation in these locations using flow direction and flow accumulation functions.

2.2.1.1. Flow Direction (FD)

Flow direction (FD) analysis is essential for studying and interpreting terrain characteristics using a Digital Elevation Model (DEM). By analyzing elevation data, FD analysis enables us to ascertain the most likely path of water or other substances as they flow along slopes. It accomplishes this by considering the landscape's gravitational pull and topographic characteristics, creating a hypothetical flow path. The analysis is crucial for various applications, such as understanding watershed boundaries, drainage patterns, and potential flood zones, which are vital for environmental and urban planning. Additionally, it aids in predicting soil erosion patterns and facilitating efficient land-use strategies [45].

The process of flow direction analysis operates in a specific manner. It begins with the pixel directly to the left of the central pixel, which is assigned a value of 1. Moving clockwise from this pixel, each subsequent pixel is assigned a value twice that of its predecessor, following a geometric progression. This value assignment continues until reaching the pixel at the top, assigned a value of 128 (Figure 1). This systematic approach allows for representing the terrain gradient within the DEM.

However, real landscapes are rarely simple, and there are scenarios where multiple potential pathways for descent exist from the central pixel to its neighboring pixels. In such cases, it is necessary to compute the value of the steepest descent direction by considering the values of all possible routes and adjusting them relative to the value of the central pixel. This refinement enables a more precise depiction of the terrain's gradient, considering the various flow routes that may be present.

Although its initial complexity, flow direction analysis is essentially a method designed to illustrate and comprehend the changes in terrain gradient captured in the Digital Elevation Model. By assigning specific values to each pixel and adjusting them based on potential flow routes, it becomes possible to identify the overall path of the steepest descent from any given point in the DEM. This valuable information supports numerous applications, ranging from hydrological modeling to effective watershed management and pipeline route planning.

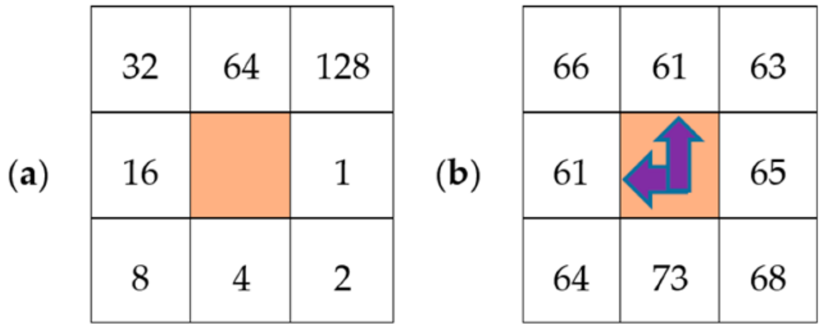


Figure 1. Calculation of Flow Direction

2.2.1.2. Flow accumulation (FA)

A crucial tool for assessing the water accumulation in a specific landscape based on the flow direction of the terrain is the Flow Accumulation (FA) analysis. This method is especially useful in environmental evaluations, hydrological modeling, and related studies. It generates a raster representation that assigns a water weight to each pixel and visualizes the accumulated water weight across the grid of a landscape [46].

Each cell, the fundamental unit of a raster, is given one unit of FA weight at the start of the analysis. This mass is an estimated amount of water. The analysis is based on how these weights move across the grid. They are moved based on the steepest descent or the direction in that water would flow naturally in the environment. According to this theory, the cells adjust their FA weight, shifting the water weight to neighboring cells that are lower or "downhill."

Areas of the landscape that do not accumulate water are represented by pixels with a zero value in the FA analysis's final output, typically ridges or high points. This conclusion is reached because, in nature, ridges do not serve as points of convergence where the water begins its descent, splitting into various paths along the contour of the landscape. Therefore, these ridge areas where water does not accumulate are represented by a zero value in the FA analysis.

Conversely, pixels with higher values indicate the presence of water-collecting areas, also known as stream channels. These regions are distinguished by the flow of water from higher ground to lower ground, which results in the accumulation of more water weight. A higher water accumulation is indicated by a pixel in the FA analysis having a value greater than zero.

Typically, the FA analysis is presented graphically for easier interpretation. For instance, the middle image (Figure 2) could show the direction of travel from each cell. Essentially, this image shows the route that water would likely take as it moved from one cell to the next while following the gradient of the steepest descent.

In Figure 2, the number of cells contributing water to each cell can be seen. Folow accumaltion helps us estimate the amount of water each cell will likely collect. If more cells flow into a particular cell, it suggests the presence of a stream channel. On the other hand, if fewer cells contribute to water, it indicates a ridge or higher area where water does not accumulate as much.

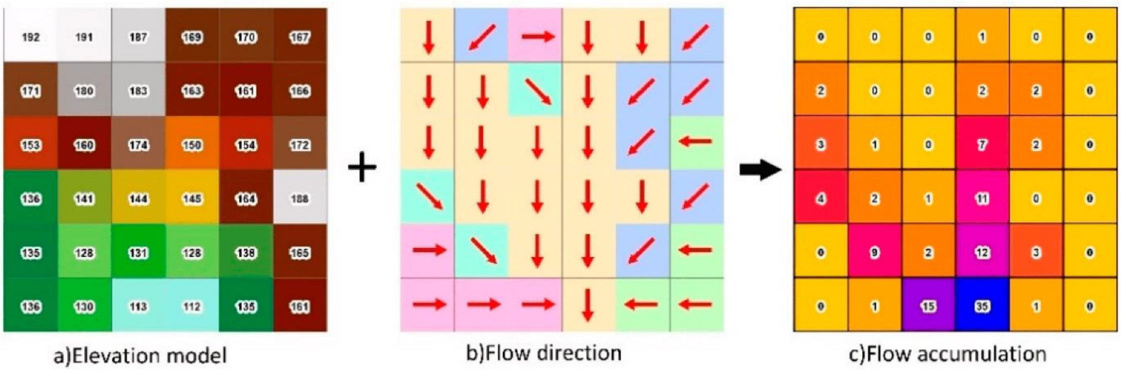


Figure 2. Calculation of Flow Accumulation

FA analysis plays a crucial role in identifying ridges and streams within a Digital Elevation Model (DEM) by analyzing the flow direction values derived from the DEM. FA analysis shows FA values for each pixel, distinguishing areas where water accumulates and potentially forming stream channels from those associated with ridges where water does not accumulate (Figure 3).

A threshold value is often applied to the FA values to facilitate the identification of stream channels. Any pixel with a FA value exceeding this threshold is considered a potential stream channel, while pixels below the threshold are categorized as non-stream areas.

It is important to note that selecting the threshold value involves some degree of subjectivity and should be carefully considered. Values above the threshold indicate higher water accumulation and a higher likelihood of stream channels. However, there may still be uncertainties regarding whether a particular pixel represents an actual stream channel. Yellow values denote these uncertainties in right image of Figure 3, representing pixels ranging from 0 to the chosen threshold value.

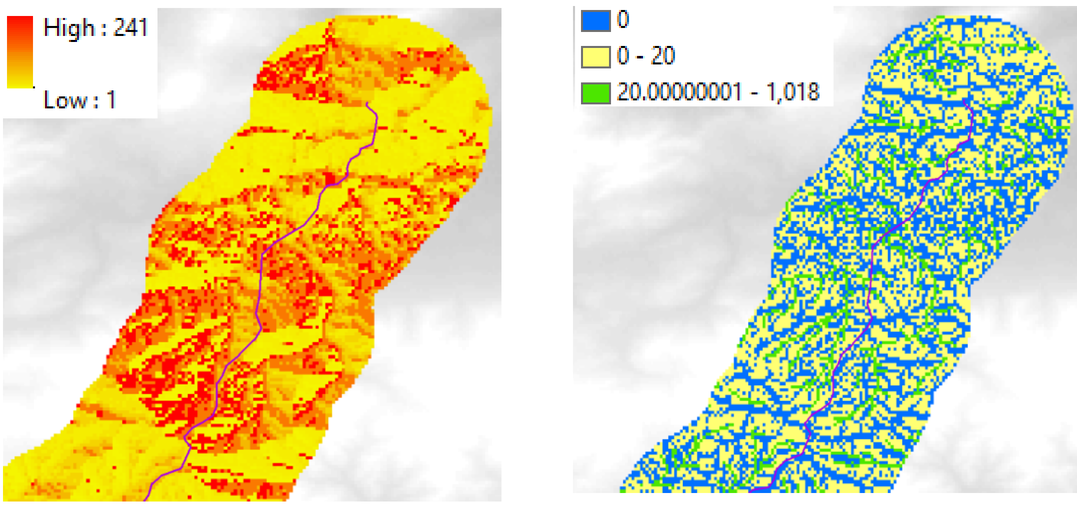


Figure 3. Flow Direction (left) and Accumulaion (right)

2.2.2. Flat Terrain and Steep Terrain Extraction

The term "slope" in engineering is instrumental in constructing and routing energy pipelines. This term expresses the gradient or inclination of a terrain, acting as a numerical measure that illustrates the steepness of the surface on which a pipeline is planned to be constructed. This slope value provides insights into the workability of the terrain and shapes the decisions regarding deploying heavy machinery and measures to prevent erosion.

Working on steep terrains, particularly those exceeding a slope of 30%, poses a significant challenge for construction operations. The fundamental limitation is that heavy machinery and equipment essential for site preparation and excavation cannot function optimally on steep slopes. This constriction in the operating efficiency of the equipment slows down the overall progress of work and increases the complexity of operations.

Steep terrains also heighten the risk of erosion, a natural geological phenomenon where the Earth's surface wears away due to the action of water, wind, or ice. The force of gravity acts more strongly on steep slopes, thus making these areas more susceptible to the downward movement of soil and rock. This inherent erosion risk on steep terrains further complicates the pipeline construction process.

On the other hand, flat terrains are considered more advantageous for pipeline construction rather than steep terrain. These areas enable the optimal use of heavy machinery and exhibit lesser susceptibility to erosion, thereby minimizing the related risks.

The qualitative discussions around slopes are systematically quantified through slope calculations, determined using the arc tangent (or atan) function. This mathematical slope measure is calculated as the arc tangent of the ratio of the change in the vertical direction (delta y) to the change in the horizontal direction (delta x). This process of slope calculation, typically visualized using diagrams like Figure 4, provides a numeric perspective to the workability of the terrain, thus assisting engineers in route planning and optimizing the pipeline construction process. The information derived from this calculation is critical to the preliminary site analysis, assisting engineers to anticipate and prepare for potential challenges in pipeline construction [47].

$$Slope\ degree = ATAN\left(\sqrt{\left(\left[\frac{dz}{dx}\right]2 + \left[\frac{dz}{dy}\right]2\right)}\right) \times \frac{180}{pi}$$

For horizontal direction change:

$$\left[\frac{dz}{dx}\right] = \left((NE + 2E + SE) - \frac{NW + 2W + SW}{8 \times horizontal\ pixel\ size}\right)$$

For vertical direction change:

$$\left[\frac{dz}{dy}\right] = \frac{(SW + 2S + SE) - (NW + 2N + NE)}{8 \times vertical\ pixel\ size}$$

NW	N	NE
W		E
SW	S	SE

Figure 4. Calculation of Slope

In pipeline construction, Geographic Information System (GIS) software is employed to conduct a slope analysis, effectively categorizing the terrain into flat and steep areas, as illustrated in Figure 5. This analysis is performed on data from a Digital Elevation Model (DEM), which provides the rate of maximum elevation change for each pixel.

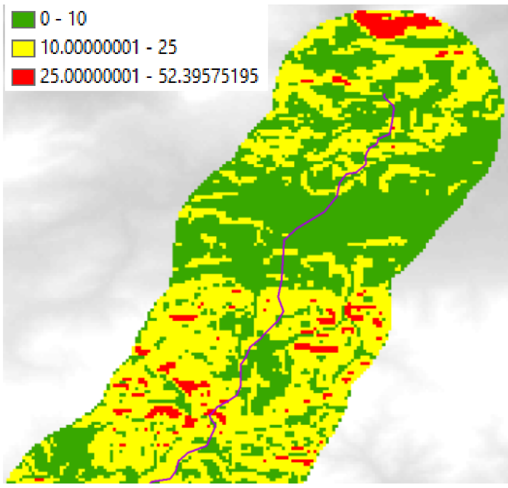


Figure 5. Results of Slope Analysis

For our project, a slope value threshold of 20% is established. Due to slope relatively gentle gradient, pixels with a slope value lower than this threshold are classified as flat sites. These flat areas are generally preferable for pipeline construction like ridges.

On the other hand, pixels with a slope value higher than the 20% threshold are considered steep sites. These areas, with their significant elevation change, represent more difficult terrains for pipeline construction due to factors like machinery operation and erosion risk.

Thus, slope analysis using GIS and DEM data is a key process for informed decision-making in pipeline construction, helping to differentiate between more and less favorable terrains based on a set slope threshold.

2.2.3. Merging Topography

2.2.3.1. What is Map Algebra?

Map algebra tools are integral components in Geographic Information System (GIS) software, facilitating the manipulation and analysis of raster data. These raster datasets are composed of grid cells with numerical values representing various geographic attributes. Map algebra tools enable the execution of arithmetic and logical operations on these raster datasets, creating new datasets derived from existing data.

One of the most widely utilized map algebra tools is the Raster Calculator, a significant feature of the ArcGIS suite developed by Environmental Systems Research Institute (Esri). In this study, the authors preferred using Esri's Raster Calculator. The Raster Calculator allows users to execute various mathematical operations on raster data. The tool operates using map algebra expressions, enabling calculations on cell values across one or more raster datasets. These mathematical operations span basic arithmetic, such as adding or subtracting values, to more complex processes, like calculating slope or aspect from a digital elevation model (DEM).

The syntax used in the Raster Calculator is algebraic, facilitating the combination of datasets and constants through mathematical operators. In addition, the tool permits the application of various predefined functions, including but not limited to logarithmic, trigonometric, and statistical functions.

The result of these operations is a new raster dataset that can be saved and used for further analysis. In essence, map algebra tools, such as the Raster Calculator in ArcGIS, are fundamental to spatial analysis and modeling. They enable extracting valuable insights from raster data, enhancing understanding spatial patterns and relationships.

Apart from the Raster Calculator in ArcGIS, several other GIS software programs have equivalent map algebra tools. For instance, GRASS (Geographic Resources Analysis Support System) GIS offers raster map algebra tools such as r.mapcalc and r.series. MapInfo's equivalent tool, the Grid Calculator, allows mathematical operations and functions on grid-based spatial data. QGIS and SAGA (System for Automated Geoscientific Analyses) GIS offer raster calculators for raster map algebra, supporting a variety of operators and functions across multiple layers. Finally, ERDAS IMAGINE includes a Raster Calculator tool for algebraically manipulating image bands. Although unique in their functionalities and capabilities, each tool facilitates mathematical operations on raster data for sophisticated spatial analysis.

2.2.3.2. Merging Process

Geographic Information Systems (GIS) help check the land's details for building pipelines. It's used to see how slanted the land is and how much water is there. Flow accumulation is used on Digital Elevation Model (DEM) data, which shows water collection at each map spot. Slope analysis on DEM data shows how slanted the whole map is. The aim is to have a model with types: Steep Terrain, Ridges, Flat Terrain, and Stream Channels. The slope and water collection maps are named "slope" and "flw_accum".

First, Steep Terrains are areas with 20% or more slope. In ArcGIS, this is noted as Con("slope"≥ 20,1,4). Areas that match get a value of 1, others get 4. This is saved as result1.

Second, Ridges are spots with less than 20% slope and no water. This is Con(("flw_accum" == 0) & ("slope" < 20),2,4) in ArcGIS. Matching spots get a value of 2; others get 4. This becomes result2.

Third, Flat Terrains have less than 20% slope with some water. In ArcGIS, it's Con(("flw_accum">0) & ("flw_accum" ≤ 100) & ("slope"< 20),3,4). Matching spots get 3, others 4. This is result3.

Fourth, Stream Channels are spots with less slope and lots of water. In ArcGIS, it's Con(("flw_accum" > 100) & ("slope"< 20),0,4). Matching spots get 0, others 4. This is saved as result4.

Fifth, the four saved results are put together. Unwanted Category 4 pixels are removed. Images are joined with Con("result1"==1,1,0) + Con("result2"==2,2,0) + Con("result3"==3,3,0). This is saved as final_result.

Lastly, there's a check step. If done right, the 0 spots in result3 match those in final_result. In short, this step-by-step method uses GIS to turn land features into clear numbers. This helps make good choices when building pipelines.

2.3. Limitations, Barriers, and Geospatial Data Layers

2.3.1. Limitations

In strategizing and carrying out oil pipeline placement, particular environments can present substantial obstacles, thereby being labeled as "less suitable areas". These zones, encompassing agricultural irrigation grounds, dam reservoirs, and urban areas with significant hazards, do not strictly disallow pipeline construction. However, they demand an elevated level of caution due to inherent risks. Consequently, these zones mandate additional financial outlays for establishing and maintaining safety protocols, rendering them less preferred for pipeline routing.

A prime example of such areas is wetlands utilized for agricultural activities. These areas are laden with substantial investments like irrigation channels and well-drilling apparatus, rendering them less desirable for direct pipeline routing. However, the governing bodies responsible for these agricultural wetlands may allow pipeline routing, granted that special precautions are employed to avoid damage to existing water channels. Another words, although these sites are not highly recommended for pipeline routing, they can be utilized if the added financial responsibility for the maintenance of the pipeline and the protection of the agricultural infrastructure is accepted.

Another representative of such inappropriate areas is the reservoirs of dams. These reservoirs serve crucial functions like water storage and flood control, and it is typically discouraged by governmental departments to route pipelines through these areas unless it is essential. When a dam reservoir surrounds the planned pipeline corridor, it becomes necessary to route the pipeline through the reservoir, accepting the additional costs for the upkeep and repair due to potential environmental impacts.

Residential areas are another example of "inappropriate areas" for oil pipeline routing, due to the high concentration of human activity and the associated risks. Despite the potential for disruption and the necessity for enhanced safety measures, these areas cannot always be avoided in the pipeline's path, particularly in urban regions. Constructing pipelines through these areas necessitates substantial financial commitment toward advanced safety protocols, continuous monitoring, and community engagement to ensure transparency and public safety. Therefore, while routing oil pipelines through residential areas is feasible, it involves accepting and managing additional risks and costs to ensure the pipeline's integrity and the community's safety.

The concept of land-use conflict analysis (LCDA) accommodates these inappropriate areas, albeit with increased costs due to the necessary safety measures. This cost is factored into the analysis by assigning each cell in the digital grid a weight, with inappropriate areas assigned higher weights to reflect the extra cost. The most cost-effective pipeline route is then determined based on the total weight of the path. Thus, the complexity of oil pipeline routing through inappropriate areas is made evident by these considerations.

2.3.2. Barriers

Certain government institutions, including municipalities, have expressed concerns about allowing pipeline projects to pass through their designated areas of responsibility. One of the primary reasons for their opposition is the potential risk of fire and explosion associated with high-pressure pipelines. Due to the safety implications, municipalities have decided not to permit the construction of pipelines within their zoning areas. These areas are designated as restricted zones to implement this restriction and are assigned a null value on the cost surface raster model.

Another crucial consideration when determining pipeline routes is security. Military zones are deemed off-limits for pipeline projects due to security reasons. These areas are restricted for any activities that may pose a risk or threat to the security and operations of the military. Consequently, pipeline projects are strictly prohibited from passing through such zones to ensure the integrity and safety of military operations.

In addition to safety and security concerns, topography plays a significant role in selecting suitable pipeline locations. Areas with a topographic slope exceeding 30 percent are generally considered unsuitable for pipeline construction. Such steep slopes can present considerable challenges during the installation and maintenance of pipelines and may increase the likelihood of accidents or pipeline failure. These areas are assigned a null value on the cost surface raster model to address this, effectively removing them from consideration during the path-finding process.

In the context of Least Cost Path Analysis (LCPA) and Least Cost Distance Analysis (LCDA), it is crucial to account for and properly handle these restricted areas. By assigning null values to the restricted zones within the cost surface raster model, LCPA and LCDA algorithms can effectively exclude these areas from the analysis. LCDA algorithms ensure that the resulting path or distance calculations focus on feasible and safe landscape portions while considering pipeline construction's inherent risks and constraints.

Therefore, using a straightforward and comprehensible approach, restricted areas such as municipal zoning areas, military zones, and regions with steep topography can be adequately addressed and excluded from the pipeline planning and analysis processes. Assigning null values to these areas within the cost surface raster model enables LCPA and LCDA algorithms to factor in the exclusion of these zones, facilitating the identification of the lowest cost path or distance while considering the associated risks and constraints.

2.3.3. Perpendicular Crossing Obstacles

In the challenging landscape of project design, obstacles, particularly those crossed vertically, emerge as key considerations that demand substantial attention. These obstacles, prevalent in various settings, are pivotal in influencing the trajectory of line-based geometrical design, encompassing the entire spectrum of operational corridors. These complexities necessitate their consideration in route planning and design, as an oversight could lead to significant challenges.

High-voltage power lines are a prominent example of such vertically crossed obstacles. These lines present not just a physical barrier but also carry the risk of an electromagnetic interference effect. In practical terms, this means that the proximity of an energy pipeline to these power lines could potentially result in corrosion damage to the pipeline due to electromagnetic interference. The significance of this challenge underscores the need for careful planning to ensure that power pipelines cross these high-voltage power lines vertically. Additionally, it is vital to implement specialized preventive measures to mitigate the risk of corrosion and maintain the pipeline's integrity.

Adding another layer to this intricate terrain of obstacles are geological fault lines. These naturally occurring features can pose significant challenges for pipeline placement. It is generally advised to avoid crossing fault lines with pipelines. However, regulations sometimes dictate that crossing these fault lines is inevitable. As a result, in these instances, a vertical crossing is preferred, further emphasizing the importance of vertical crossings in the design and planning process.

Highways present another type of obstacle that necessitates vertical crossing. The guidelines generally disallow parallel alignment between roads and pipelines within a 50 m radius, thus making vertical crossing the only viable option. This constraint demands careful planning and design consideration to ensure pipeline routes' safe and effective implementation.

The illustration of another category encompassing vertically crossed obstacles introduces agricultural irrigation water channels into the mix. These channels, which may be found on the surface or beneath it, pose unique challenges to pipeline routing. To navigate these obstacles, vertical crossing guidelines have been defined in the Least Cost Path Analysis (LCPA) framework, where ring buffers are generated around these obstacles.

Considering the vertical resolution of the Digital Elevation Model (DEM) data, buffer zones of 100, 200, and 300 meters were generated around these obstacles for this project. This arrangement stratifies the cost associated with each buffer zone the innermost level carrying a cost twice as high as the middle-level buffer zone. In contrast, the outermost level carries a cost two times lower than the middle level. This proportional cost allocation further reinforces the critical role that vertical crossing considerations play in completing such projects (Figure 6).

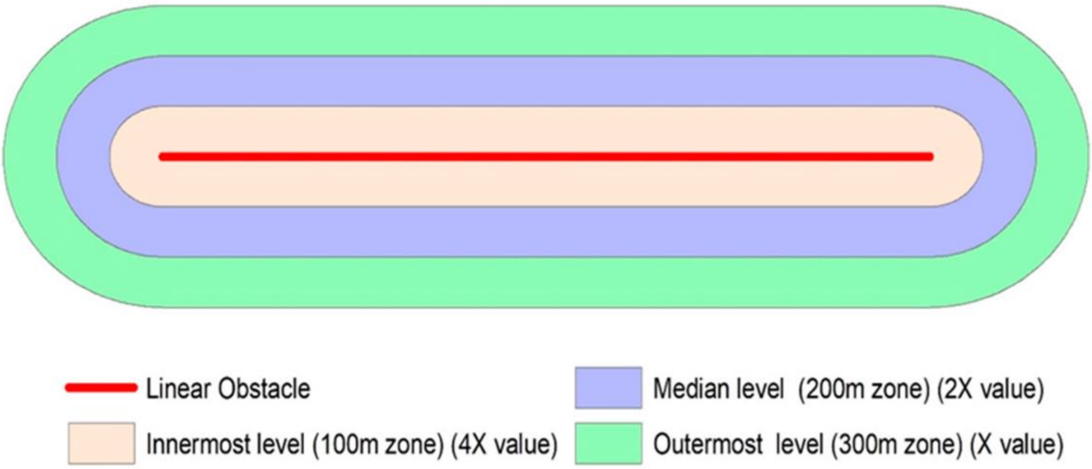


Figure 6. Method of Perpendicular Crossing Obstacles

2.4. Multi-Criteria Decision Making

Designing or planning the route for a pipeline is a complex process involving considering multiple criteria, which need to be evaluated simultaneously to derive the most suitable solution. Harmonizing these diverse criteria is paramount, as difficulties may arise due to potential conflicts among all the variables involved.

Such scenarios highlight the significance of effective decision-making processes in resolving these complexities.

In the context of route design studies, an array of criteria must be carefully examined and collectively evaluated. These criteria can play a critical role in determining the ultimate route selection. Certain criteria might be given preference, others that carry significant importance, and some that are indispensable. Consequently, it becomes crucial to identify these different factors' impact ratios and systematically rank them according to their importance.

This integral stage of the process involves statistical analyses to determine the necessary factors and define their impact rates on the route. These analyses employ the methodologies under Multi-Criteria Decision Making (MCDM), a sub-discipline of operations research that provides a robust framework for structuring these numerous, potentially conflicting factors. MCDM methods facilitate identifying and prioritizing the most suitable alternatives, providing an objective approach to handling complex decision-making scenarios.

2.4.1. Analytical Hierarchy Process (AHP)

Among various MCDM methods, the AHP is particularly renowned and widely utilized. AHP offers an analytical technique that is capable of managing complicated decision problems. It streamlines complex decision-making stages into a series of pairwise comparisons, thereby simplifying the decision-making process [47].

AHP's core functionality lies in its ability to consider the essential criteria and assess various alternative options to arrive at the most effective solution. This method generates weights associated with each criterion based on the decision maker's pairwise comparisons, thereby determining the importance and priority of the weights. Each factor is assigned evaluation scores according to its significance, and the weight of these scores directly influences the performance of the decisions.

In the current study, two different applications of AHP were employed, with their weights assumed to have equal importance. This decision ensures a balanced evaluation and comprehensive consideration of all the factors involved. Consequently, AHP compiles an overall score for each option by integrating the weights and scores of the criteria. This total score is then used to determine the ranking of the options, providing a systematic and logical order of preference.

AHP's versatility and adaptability make it an effective tool in various fields and applications, such as cultural heritage, education, and route selection. Its ability to handle quantitative and qualitative data and facilitate consensus-building in group decision-making scenarios is particularly noteworthy.

In the study, AHP was used for our pipeline route selection problem. This choice was motivated by AHP's several unique advantages, such as its versatility, intuitive design, robustness, and ability to effectively handle complex, multi-criteria decision-making scenarios. Furthermore, AHP provides a consistency measure, the Consistency Ratio (CR), that validates the decision-makers judgments, thus enhancing the reliability and accuracy of the decisions.

The Consistency Ratio is calculated based on the Principal Eigenvalue (λ_{max}), a mathematical measure of the variance observed in the set of pairwise comparisons. The Consistency Index (CI) is then derived from this Principal Eigenvalue using the formula $CI = (\lambda_{max} - n) / (n - 1)$, where n is the number of elements being compared [48]. The Consistency Ratio is obtained by comparing the Consistency Index to the Random Consistency Index (RI), an average index value derived from a large sample of random pairwise comparison matrices.

In summary, the Principal Eigenvalue and the Consistency Ratio in AHP provide a robust mechanism to assess the quality and reliability of the judgments made in the decision-making process [48]. These features are instrumental in ensuring that the final decision or priority ranking is valid and robust. This combination of systematic prioritization, pairwise comparison, and consistency validation offered by AHP strengthens the decision-making process in pipeline route selection, offering an efficient and reliable approach to handling the complexities of multi-criteria decision-making scenarios.

2.4.2. Example of AHP

Choose the most efficient laptop from three alternatives: Laptop A, B, and C. The selection will be predicated on one key criterion: performance. The Analytic Hierarchy Process (AHP) will be utilized for this multi-criteria decision-making problem.

We begin by constructing a pairwise comparison matrix for the performance criterion. Each element in this matrix is determined using a scale from 1 to 9, where 1 denotes equal importance, and 9 denotes extreme importance of one over the other.

An exemplary pairwise comparison matrix could appear as follows:

	Laptop A	Laptop B	Laptop C
Laptop A	1	3	1/2
Laptop B	1/3	1	1/5
Laptop C	2	5	1

The elements of this matrix indicate that, for instance, Laptop A is considered to have thrice the performance of Laptop B and half the performance of Laptop C.

Next, this matrix was normalized to compute each alternative's average normalised value. This involves dividing each value by the sum of its respective column and averaging the values in each row.

Upon finding the sum of each column and normalizing the matrix, the following was obtained:

	Laptop A	Laptop B	Laptop C
Laptop A	0.375	0.333	0.294
Laptop B	0.125	0.111	0.059
Laptop C	0.5	0.556	0.588

The final average normalized values are computed as follows:

Laptop A	0.334	**%33.4**
Laptop B	0.098	**%9.8**
Laptop C	0.548	**%54.8**

Based on the performance criterion, Laptop C is deemed the most optimal selection.

2.5. Finding Best Route in GIS

Network Analysis and Least Cost Path Analysis (LCPA) are essential methods in Geographic Information Systems (GIS). Nevertheless, they are different in their ways and are used in different situations.

In simple terms, Network Analysis is like studying a map of roads, rail lines, or anything interconnected. It is used to find the best route between different points on this map. This 'best' route could be the shortest, fastest, or closest to a specific location.

For example, imagine you have a city's road map. Every road junction is a point; the roads connecting these points are the links. Now, if a delivery company wants to find the fastest way to deliver a package from one point to another, they would use Network Analysis. This method will consider road length, speed limits, and traffic conditions to find the fastest route.

On the other hand, LCPA is used to find the best path between two points on a big, continuous area, like a landscape. The 'best' or 'cheapest' here can mean the shortest distance, least time, or even least environmental damage [49].

So, how does LCPA work? The GIS system adds up the 'cost' of all possible paths from one point to another and then chooses the one with the lowest cost. For example, you are planning a new hiking trail in a park. LCPA could help find a short and not too steep path [50].

When you compare the two, Network Analysis is used for clearly divided and interconnected systems like roads or railway networks. LCPA, however, is used for more open systems, where there are many choices for a route, and the 'cost' of moving can change across the area.

So, both Network Analysis and LCPA are used to find the best route or path. However, the critical difference is in the type of system they are used for and how they calculate the 'cost' of different routes.

2.5.1. Least Cost Path Analysis (LCPA)

LCPA is a versatile tool within the Geographic Information Systems (GIS) universe. It is the process of determining an optimal path between two locations within a defined network, where 'optimal' is defined by the lowest cumulative cost. This cost can be evaluated in different terms, such as distance, time, or any other resource pertinent to the scenario as defined above.

The advantages of raster-based data over vector data become particularly noticeable in linear infrastructures like pipelines. Unlike many other geographic features, pipelines cover vast distances without a strictly defined geographic layout. Hence, raster data's pixelated, grid-like structure provides the flexibility and precision necessary to delineate these pathways [51].

Raster data offers a unique advantage in LCPA because it enables easy computation of costs. Given its grid structure, raster data can seamlessly incorporate other raster format data, providing a robust framework to model different criteria. This adaptability broadens the analysis's scope, making it applicable to various complex scenarios.

The methodology of LCPA involves scanning the eight adjacent cells around each raster cell and gravitating toward the cell with the smallest accumulated value. This approach ensures the pathway chosen is the most cost-effective, as per the predetermined criteria, be it distance, time, or other resources.

LCPA's utility extends beyond mere pathway determination. It can facilitate route selection, planning, and final definition, making it an invaluable tool in solving multifaceted route-related issues. By utilizing GIS-based LCPA, these complex problems can be addressed effectively and efficiently.

One area where LCPA has proven especially beneficial is routing energy pipelines. Using raster-based data, LCPA can evaluate various factors such as the terrain, land-use, and potential environmental impact to determine the most cost-effective pipeline route. Consequently, LCPA helps minimize economic expenditure and potential environmental disruption, showcasing its true value.

Picturing LCPA in a broader context, we could imagine its potential applications in urban planning or logistics. For instance, in a densely populated city, LCPA could be used to determine the most efficient bus or subway routes, reducing commuting time for residents and easing traffic congestion. In logistics, LCPA could aid in figuring out the most cost-effective delivery routes, saving both time and fuel costs. These examples serve to underscore the adaptability and wide-ranging applications of LCPA.

2.6. Line Simplification

Line simplification is a technique used in Geographic Information Systems (GIS) to reduce the detail in spatial data. This method typically decreases the data needed to represent a particular feature (such as a road or river) while maintaining its essential shape and attributes.

Several line simplification algorithms exist, such as the Ramer-Douglas-Peucker algorithm, a recursive endpoint-based algorithm. In this method, a line is simplified by repeatedly eliminating points close to the line defined by the endpoints. Another line simplification algorithm is the Visvalingam-Whyatt method which removes points based on the area of the triangle formed by each point and its two neighbors [52].

Line simplification might be required after an Analytical Hierarchy Process (AHP) based route selection algorithm for several reasons:

The efficiency of construction: Complex geometries often require more specialized materials, tools, and skills to execute, which can add time and expense to a project. Simplified geometry, conversely, can be constructed using more standard methods, making the construction process more efficient and cost-effective.

Reduction of Noise: Some routes generated through AHP might contain minor variations or noise due to imperfections in the data. Line simplification can help to smooth out these irregularities, making the routes easier to follow.

Improving readability: When presenting the results to a user, a more straightforward line might be more understandable and pleasing to the eye. Too many details can lead to confusion, especially when dealing with complex routes.

Overall, line simplification can help to make the output of a route selection algorithm more useful and efficient, both from a computational perspective and in terms of user interaction and understanding.

2.6.1. Point Remove Algorithm (Ramer-Douglas-Peucker algorithm)

Line simplification, also known as polyline simplification or curve simplification, is a process that aims to reduce the complexity of a line or curve while retaining its essential shape and characteristics. The goal is to represent the line or curve with fewer vertices or points, resulting in smaller data size and computational requirements without significantly altering its visual appearance or important features.

One commonly used algorithm for line simplification is the Ramer-Douglas-Peucker algorithm. Here is how it generally works:

1. Input: The algorithm takes a set of vertices that define the original line or curve.

2. Distance calculation: The algorithm computes the perpendicular distance between each vertex and the line segment formed by the first and last vertices.

3. Maximum distance determination: It identifies the vertex with the maximum distance, representing the point that deviates the most from the simplified line.

4. Splitting the line: The line is divided into two segments at the vertex with the maximum distance.

5. Recursion: Steps 2-4 are recursively applied to the resulting line segments, independently simplifying each part.

6. Termination condition: The recursion stops when all remaining vertices have distances below a predefined threshold or when a desired level of simplification is achieved.

7. Output: The simplified line or curve is represented by the retained vertices.

The Ramer-Douglas-Peucker algorithm effectively reduces the complexity of lines or curves by iteratively removing non-essential vertices while preserving the overall shape. It provides a straightforward and widely used method for line simplification without explicitly comparing it to other algorithms [52].

After the process of line simplification has been carried out, it is crucial to evaluate its impact on the overall cost of the proposed route. Although the application of line simplification may result in a slight increase in the route cost but reduce the total length, this increment is typically insignificant compared to the potential expenses associated with constructing pipelines with excessive bends and twists. These additional construction costs can arise when attempting to accommodate the precise path of the simplified line.

Creating a buffer zone that surpasses the predetermined tolerance value may be necessary to ensure that the simplified route aligns with eliminating undesired locations. This buffer zone is a precaution against any potential deviations during the simulation. It is incorporating a larger buffer zone aids in preventing the pipeline from traversing through areas where access is undesired or not permissible.

By considering the line simplification approach and the implementation of a buffer zone, the proposed pipeline route can strike a balance between cost optimization and meeting the desired entry requirements. This approach facilitates a streamlined construction process and reduces the likelihood of encountering unnecessary complications or conflicts during the implementation phase.

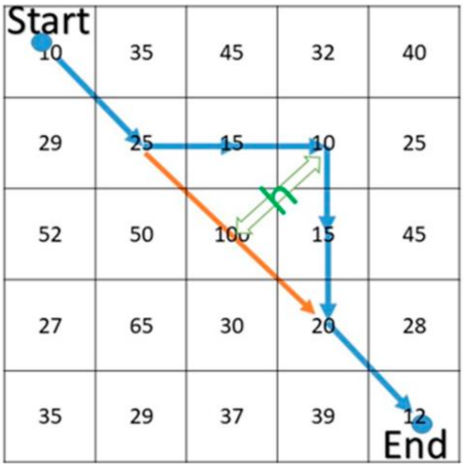


Figure 7. Example of Point Remove Algorithm

When designing a route using the Least-Cost Distance Algorithm (LCDA) from the starting point to the destination (as shown in Figure 7), the initial cost was determined to be 107 (10+25+15+10+15+20+12), resulting in three vertex points. However, after optimizing the route, the cost increased to 167 (10+25+100+20+12), but with the advantage of having no vertex points (Figure 7). To simplify the route, "h" values were computed for each vertex, and if a value exceeded 100 m, the corresponding point was eliminated from the route. This simplification aimed to raise the cost while reducing the total length.

2.7. Experimental Study

2.7.1. Site Selection

The study area is situated in the Southeast Anatolia Region of Turkey and within the boundaries of three provinces: Muş, Ağrı, and Erzurum (Figure 8). The project under investigation involves the development of a oil pipeline route within rural areas, which proje called the Muş Project (MP). The pipeline route starts from Ağrı Eleşkirt/Yayladüzü village and extends to the Muş plain.

At the starting point of the pipeline route, the altitude is considerably high, and the land is characterized by rough terrain unsuitable for agriculture. However, as the route progresses towards the Muş plain, the terrain becomes less rugged and passes through agricultural land. Agricultural activities surround the villages near Ağrı and Erzurum. Within the 3 km corridor of the project, there are no provincial centers or highly populated areas.

Another crucial aspect is the geographic restrictions that influence the pipeline's path. In the area designated for the MP, there are zones in which the pipeline is forbidden from crossing for various reasons, ranging from environmental impact concerns to legal restrictions. The inability to route the pipeline through these regions introduces complexity to the planning process.

There are also regions where the pipeline needs to be installed perpendicularly. Though it might seem arbitrary, this arrangement usually prevents potential environmental or structural issues. These complexities add another layer of intricacy to the engineering and construction process, requiring detailed planning and strategizing.

The MP also needs to pass through some areas with an added layer of precaution. These areas might contain sensitive ecosystems or risk factors requiring enhanced safety measures. Such a requirement showcases the project's commitment to environmental responsibility and safety.

Adding to the challenges faced by the MP is the notably rugged topography of the project area. The terrain encompasses a variety of geographical elements, including steep slopes, ridges, and flat expanses. Navigating such diverse terrain demands different engineering solutions and strategies to ensure the stability and integrity of the pipeline.

To highlight, the decision to prefer the MP over oil pipelines in this study is driven by its modernity, the comprehensive and up-to-date opinion data it offers, and the geographic challenges associated with the project area. These specific circumstances surrounding the MP underscore the unique considerations in its planning and route selection.

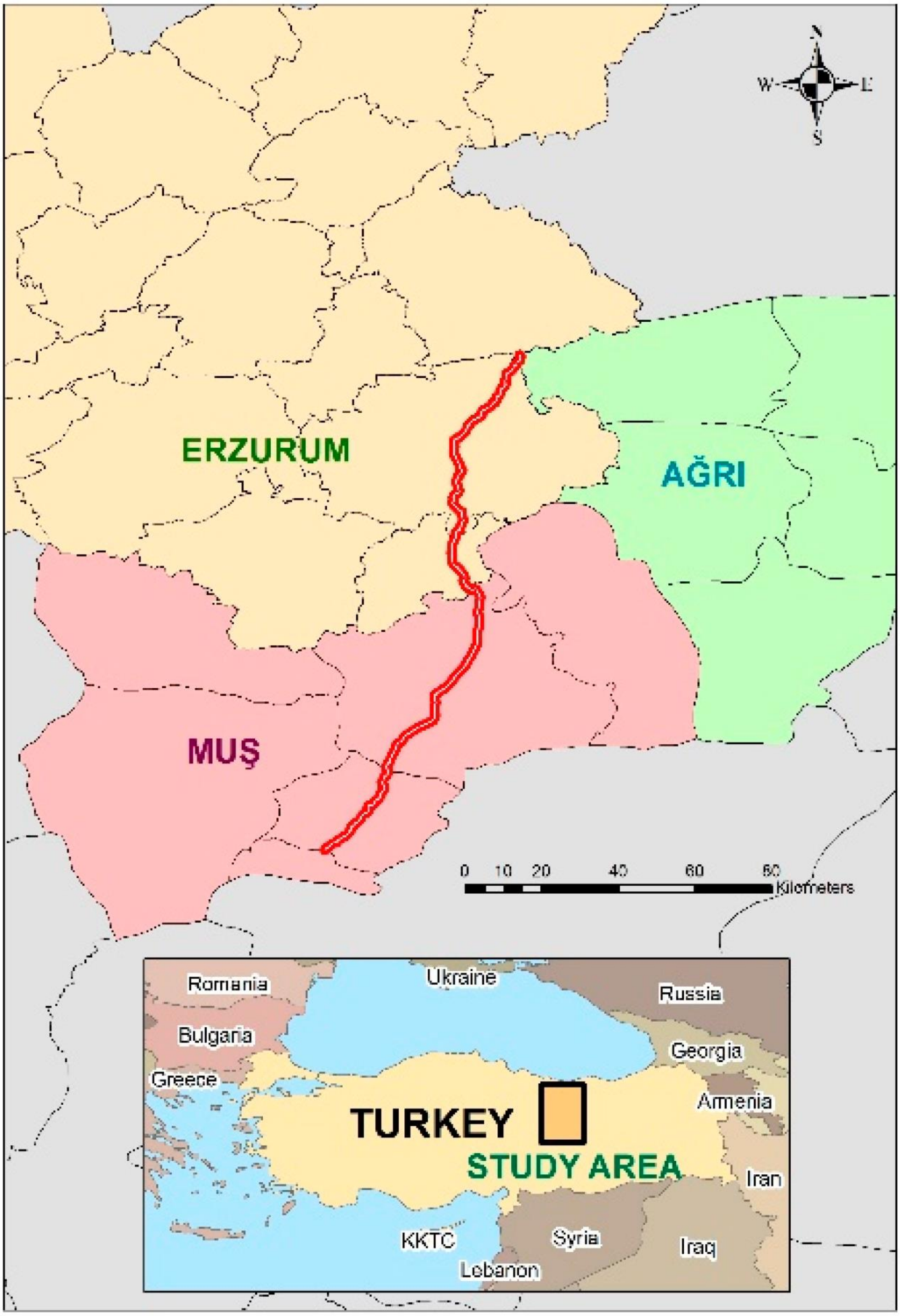


Figure 8. MP Location

2.7.2. Project Data and Methodology

2.7.2.1. Project Data

The pipeline route traditionally established was obtained from the engineering firm involved in the route determination process. The study area was then outlined by generating a 3 kilometers buffer zone around this predefined route. The established route will be evaluated against a new GIS technology-generated route. The accuracy of these two methods will subsequently be compared to assess the effectiveness of the traditional method versus the contemporary method.

The Power Line dataset is sourced from Türkiye Elektirk İletim A.Ş. Headquarters and provided in a digital format. It represents a line feature with a scale of 1/25,000. In order to accommodate the requirement of perpendicular crossings, ring buffers of 100, 200, and 300 meters were applied.

The Highway data is obtained from Türkiye Cumhuriyeti Karayolları12. Region and is available in paper format. It is represented as a raster, and its scale is 1/25,000. Like the Power Line data, perpendicular crossings were enforced by implementing 100, 200, and 300 meters ring buffers.

The Dam dataset is sourced from Devlet Su İşeri Headquarters 17. Region and is provided in a paper format. It is represented as a raster, and its scale is 1/25,000. This area can be traversed under special security measures.

The Military Security Zone data is obtained from MUŞ İl Jandarma Komutanlığı and is available in paper format. It is represented as a raster, and its scale is 1/25,000. The dataset defines a prohibited area, and a 100-meter buffer is integrated into the model around the military borders.

Muş TEDAŞ Provincial Directorate provides the Power Line dataset in a digital file format. It represents a line feature with a scale of 1/25,000. As with the previous Power Line data, perpendicular crossings are enforced using 100, 200, and 300 meters ring buffers.

The Highway data is sourced from Türkiye Cumhuriyeti Karayolları 11. Region and is available in paper format. It is represented as a raster, and its scale is 1/25,000. Similar to other highway data, perpendicular crossings are required, and ring buffers of 100, 200, and 300 meters are applied.

Devlet Su İşleri Headquarters provides the Dam Basin dataset in a digital format. It represents a polygon feature, and its scale is 1/25,000. This area is not strictly prohibited, but certain security measures must be considered.

Karayolları Headquarters provide the Highway data in a digital file format. It represents a line feature, and its scale is 1/25,000. As with the previous highway data, perpendicular crossings are enforced using 100, 200, and 300 meters ring buffers.

Incorporating this additional information, we have also identified village locations using Google Earth to ensure the project does not infringe upon settlement areas. Our model has classified These village positions as restricted zones, with a 1,000-meter buffer implemented around each. This approach further strengthens the data set, enhancing our ability to make informed and respectful decisions regarding the project's infrastructure layout.

The DEM (Digital Elevation Model) data is available from NASA in a digital file format, offering a resolution of 30 meters. It is represented as a raster and used for topographic classification, distinguishing flat terrains, ridges, steep terrains, and stream channels.

Detailed maps showing the topographical and environmental barriers related to the project area are shown below.

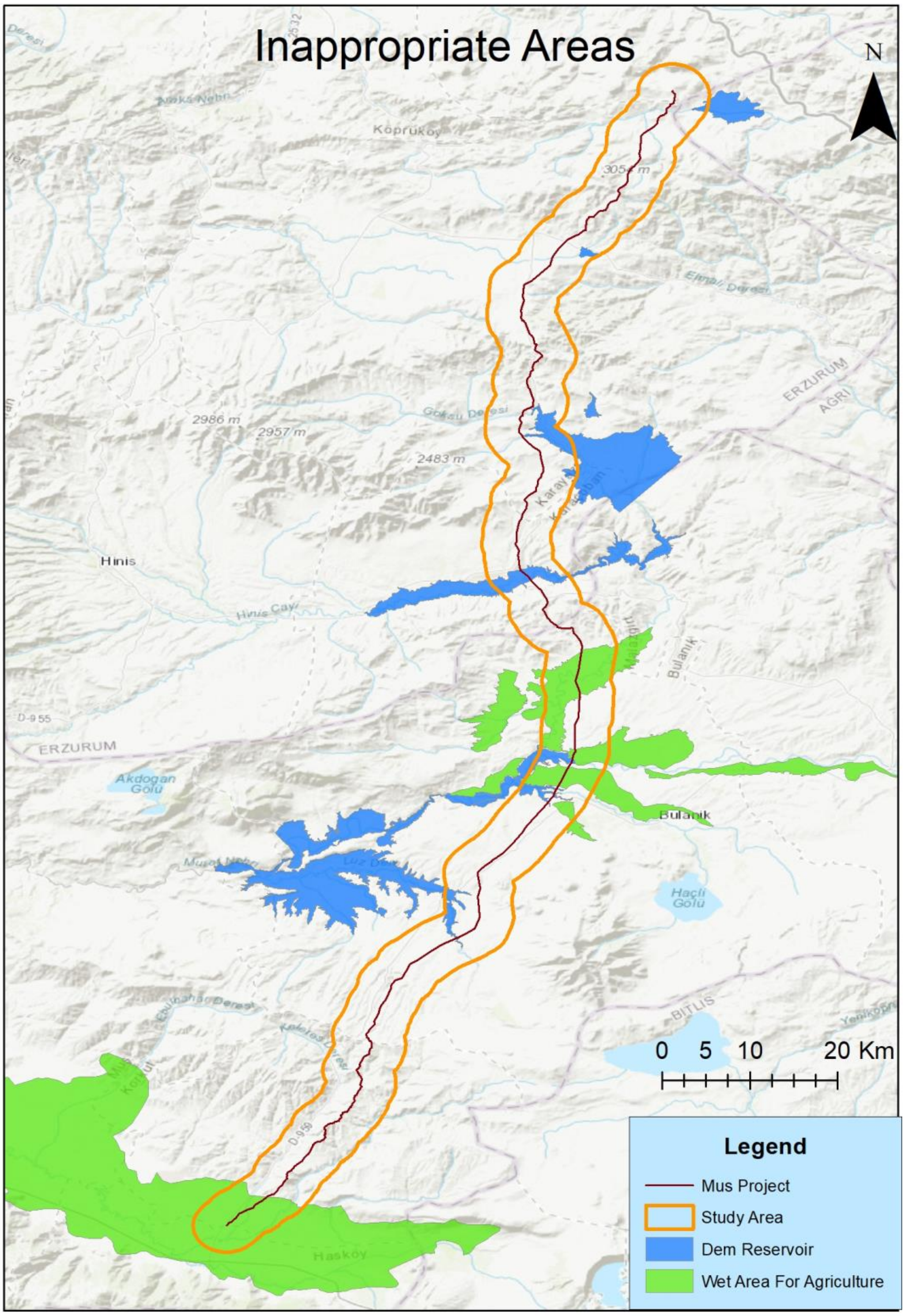


Figure 9. Inappropriate Areas

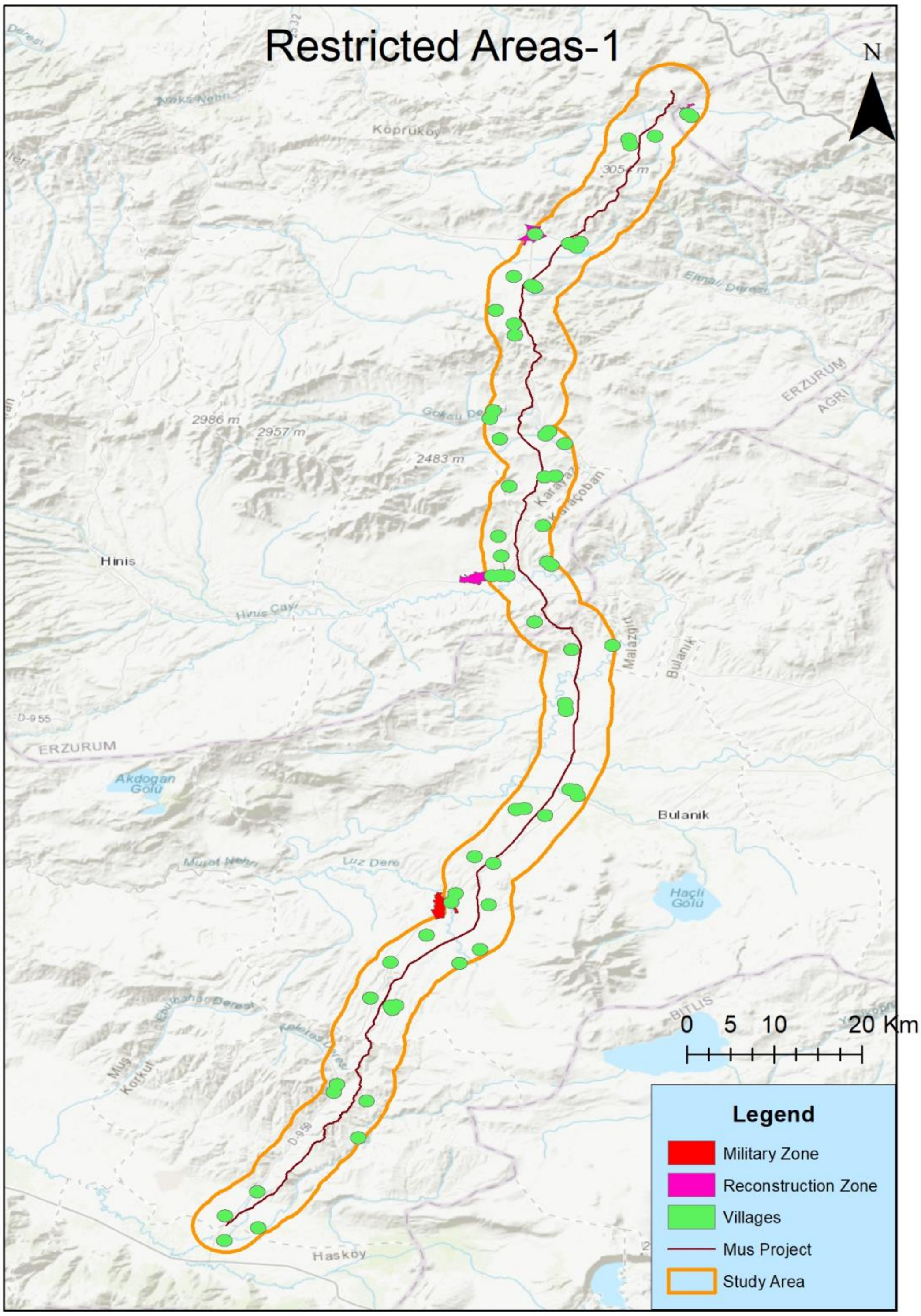


Figure 10. Restricted Areas

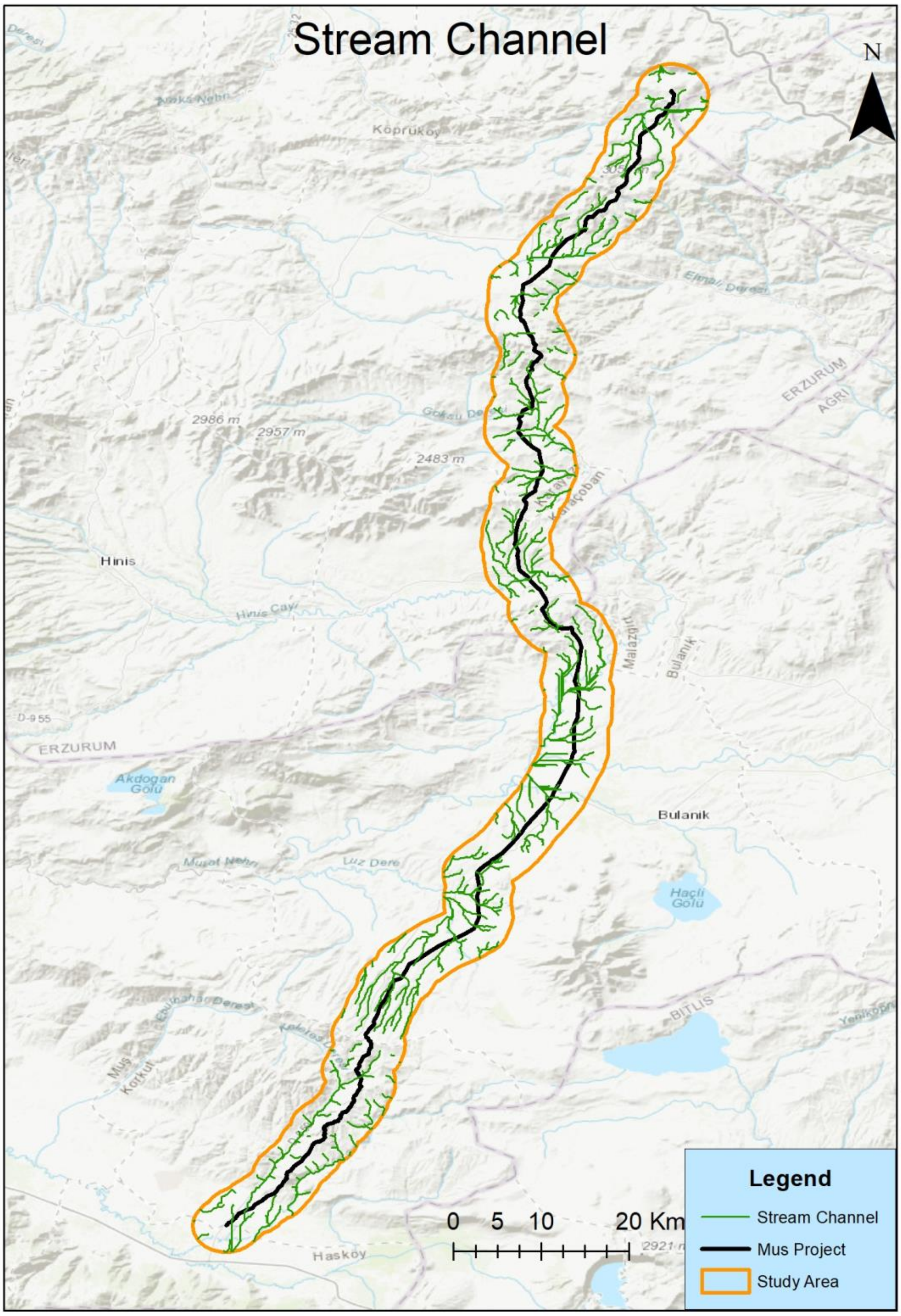


Figure 11. Stream Channels

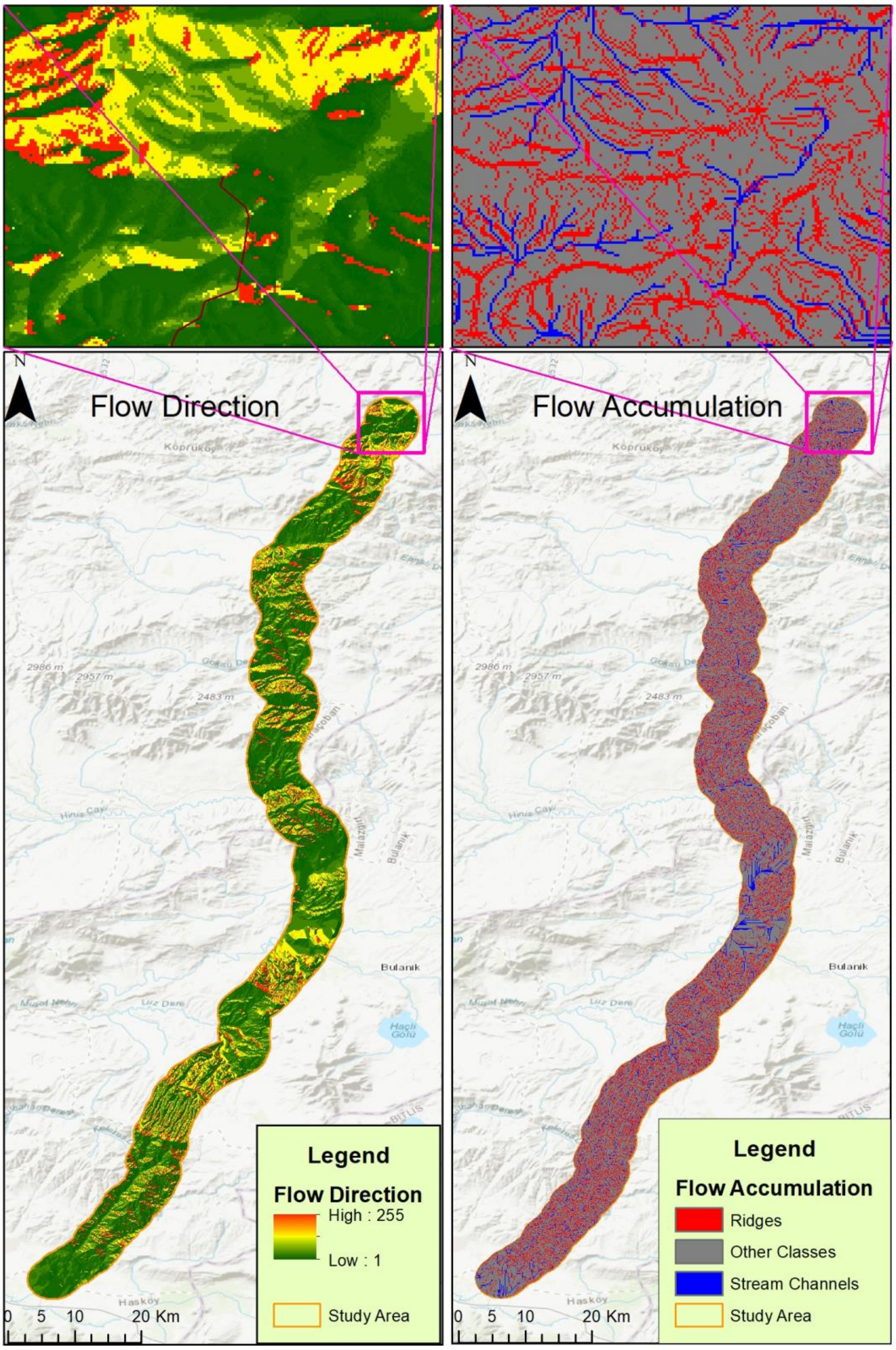


Figure 12. Flow Direction and Accumulation of MP

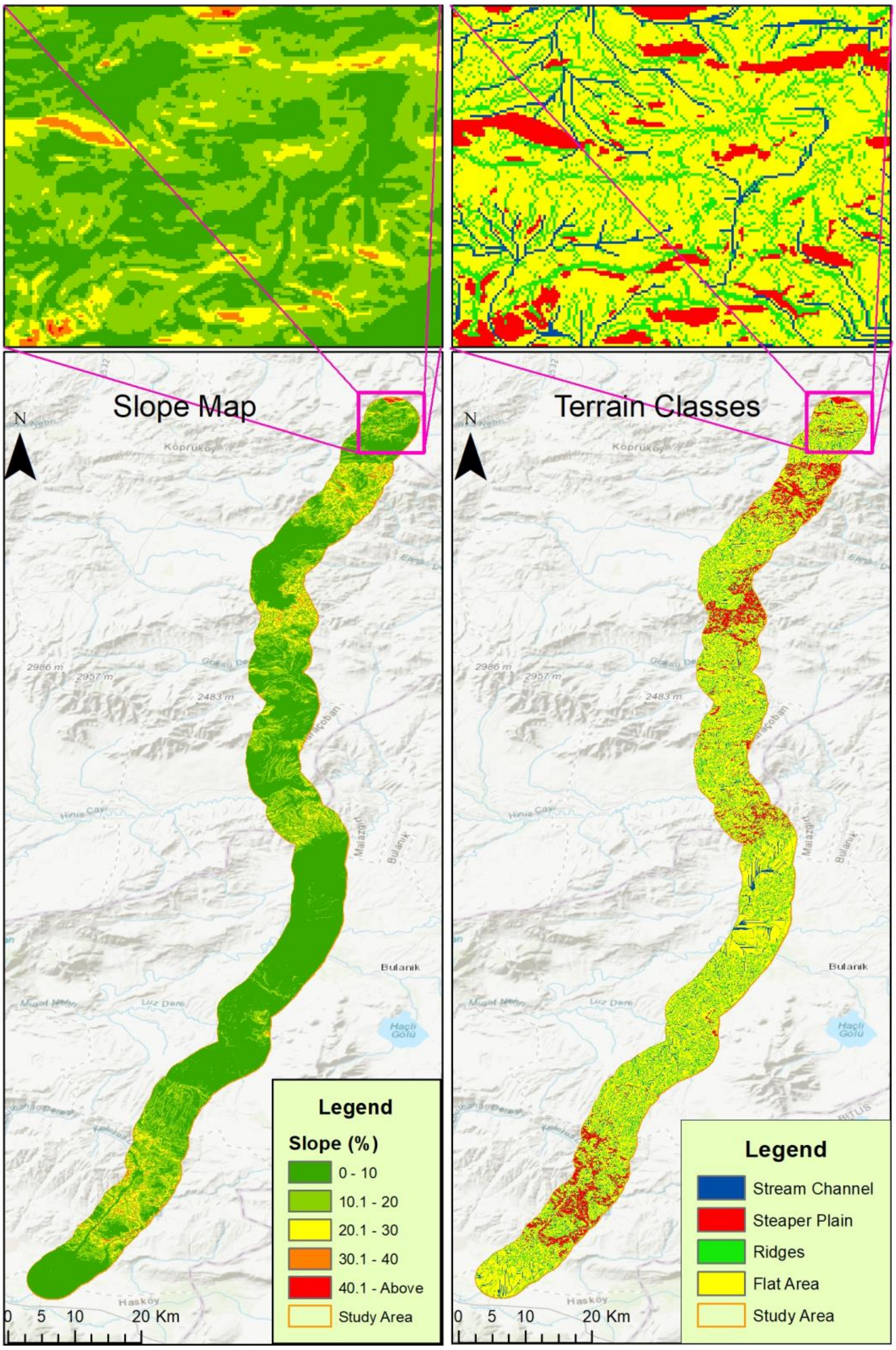


Figure 13. Slope and Terrain Classification of MP

2.7.2.2. Methodology

The procedure for determining the suitable pipeline route comprised the following detailed steps:

Step-1: Defining the Study Area: The traditional method created a buffer zone of 3 kilometers around the pipeline route. This defined region, the study area, is the foundation for subsequent analyses and calculations.

Step-2: Extracting Relevant SRTM DEM Data: SRTM DEM data, the specific portion that falls within the confines of the defined project area, was extracted. This isolated data represents the topography of the project site, which is necessary for later stages of analysis.

Step-3: Slope Analysis: The extracted SRTM DEM data was then used for slope analysis, determining the incline within the project area. This step is crucial as it provides insights into the physical gradient of the land, a factor that significantly impacts pipeline construction.

Step-4: Flow Direction and Flow Accumulation Analyses: Sequentially, flow direction, and accumulation analyses were carried out on the extracted SRTM DEM data. These hydrological assessments reveal how water flows across the landscape, highlighting potential issues related to erosion or water accumulation that could affect the pipeline's integrity.

Step-5: Setting Thresholds and Merging: Following the comprehensive evaluation of the slope and flow accumulation results by researchers, a benchmark value of 100 was set. The merging process, as described under the section on Topography Classification, was implemented using these established values. Consequently, the terrain was classified into four continuous categories: ridges, flat land, steep terrain, and streams.

Step-6: Institutional Inputs and Null Area Identification: Using institutional views collected from relevant authorities, areas prohibited for passage were identified. If these regions required additional protection, corresponding buffer zones were defined. In the model derived from Step-5, these specific zones were marked as "null" using map algebra tools.

Step-7: Cost Analysis Survey: A survey was initiated employing the Analytic Hierarchy Process (AHP) method. The survey focused on pipeline construction engineers who were asked to comparatively evaluate areas involving extra costs for passage and areas necessitating steep crossing. The resulting data facilitated the computation of the algorithmic cost of each obstruction.

Step-8: Topographical Cost Determination: The AHP method was further employed to ascertain the algorithmic cost associated with topography. This step involved analyzing the algorithmic costs of ridges, flat land, steep terrain, and streams, ultimately determined by pipeline construction specialists.

Step-9: Ring Buffer Creation: For every data point planned for a steep crossing, ring buffers of 100, 200, and 300 meters were developed. The algorithmic cost value derived from the AHP was assigned to these buffers: twice the value for the 100m ring buffer, the original value for the 200m buffer, and half for the 300m ring buffer. Subsequently, the vector data was converted to a raster format for future use.

Step-10: Institutional Cost Assignment: Algorithmic cost values found with AHP were assigned to all data with algorithmic cost collected from the institution's opinions. These fields are converted to raster format with new cost values.

Step-11: Data Integration and LCPA Application: The raster data generated from steps 6, 9, and 10 were combined using a map algebra tool. Subsequently, the Least Cost Path Analysis (LCPA) was executed with the origin and destination points defining the pipe's path. The Geographical Information System (GIS) subsequently computed the new route.

Step-12: Raster to vector process: The route calculated in raster format with LCPA is converted to vector data format through the raster to vector process

Step-13: Route Simplification: The point removal method with 30m tolerances alleviated unnecessary bends in the calculated route and produced a more linear trajectory. This technique, part of line simplification methods, was applied to the route devised in step 11, effectively reducing unwanted noise and complexities.

2.7.2.3. Results of the Questionnaire and the Establishment of Cost Weights

In assessing the weights of various obstacles encountered in pipeline construction, a comprehensive survey was administered to professionals from diverse backgrounds. This approach sought to leverage their expertise in determining the significance of topography and other impediments in the construction process. The survey, comprising mutual comparisons for all criteria, was distributed among twelve individuals from different roles in the pipeline construction industry to capture a range of perspectives. However, due to certain discrepancies, only ten responses were deemed valid for analysis. The remaining two were excluded from the evaluation process due to inconsistencies, thereby ensuring the integrity of the data and the validity of the conclusions drawn from it.

Upon reviewing the questionnaires, an AHP matrix was developed. This method organized the diverse responses in a structured manner for comprehensive analysis. A combined measure was derived by averaging similar responses from validated surveys. These results were then rounded to the nearest number to enhance accuracy. Such refinement ensured data integrity and streamlined interpretation, transforming raw survey responses into valuable insights for pipeline construction.

Calculating topographic weights:

1	Ridges
2	Flat land
3	Steep terrain
4	Streams

Consistency ratio:2.6%
Principal Eigen Value:4.071

	1	**2**	**3**	**4**
1	1	1/2	1/3	1/2
2	2	1	1/2	1/2
3	3	2	1	2
4	2	2	1/2	1

Table 2. AHP Matrix for Topography

After completing the requisite computations, the weight coefficients were determined as follows.

Ridges	Flat land	Steep Terrain	Streams
%12.0	%19.1	%41.8	%27.1

Table 3. Weight of Topography

Calculating infrastructural weights:

1	Dam Reservoirs
2	Wet Lands
3	Water Channel
4	Power Lines
5	Fault Lines
6	Agricultural Irrigation Channel
7	Highways

Consistency ratio:1.9%
Principal Eigen Value:7.156

	1	2	3	4	5	6	7
1	1	3	1	2	1	3	2
2	1/3	1	1/3	1/2	1/4	1/2	1
3	1	3	1	1	1/2	1	1
4	1/2	2	1	1	1/2	1	1
5	1	4	2	2	1	3	3
6	1/3	2	1	1	1/3	1	1
7	1/2	1	1	1	1/3	1	1

Table 4. AHP Matrix for Infrastructure Obstacles

After completing the requisite computations, the weight coefficients were determined as follows.

Dam R.	Wet L.	Water C.	Power L.	Fault L.	A.I.C.	Highways
%21.7	%6.4	%14.0	%15.5	%25.9	%10.4	%10.0

Table 5. Weight of Infrastructure Obstacles

The obstacles were evaluated in two categories based on topography and infrastructure, and the percentage values for each obstacle were computed. The two distinct categories have been evaluated as equivalent obstacles, and the cost percentages calculated separately for each category have been directly considered as costs in the LCPA. In the LCPA, areas where the cost is high represent less preferable locations, while areas with low costs indicate regions that are most convenient for pipeline construction from a technical perspective. The resulting cost percentage values are also consistent with this deduction. Subsequently, the cost surface of the entire model was generated, and LCPA was performed using ArcGIS (Figure 14).

In Figure 14, the white spaces indicate the locations through which we do not wish the pipeline route to pass, and as a result of the analysis, a turquoise colored route has been generated. It's visually clear that the generated route shows significant deviations in some areas from the traditional route, represented by the purple color. Both the traditionally created route and the one created with the new method have been compared in detail, based on various criteria, in the section below.

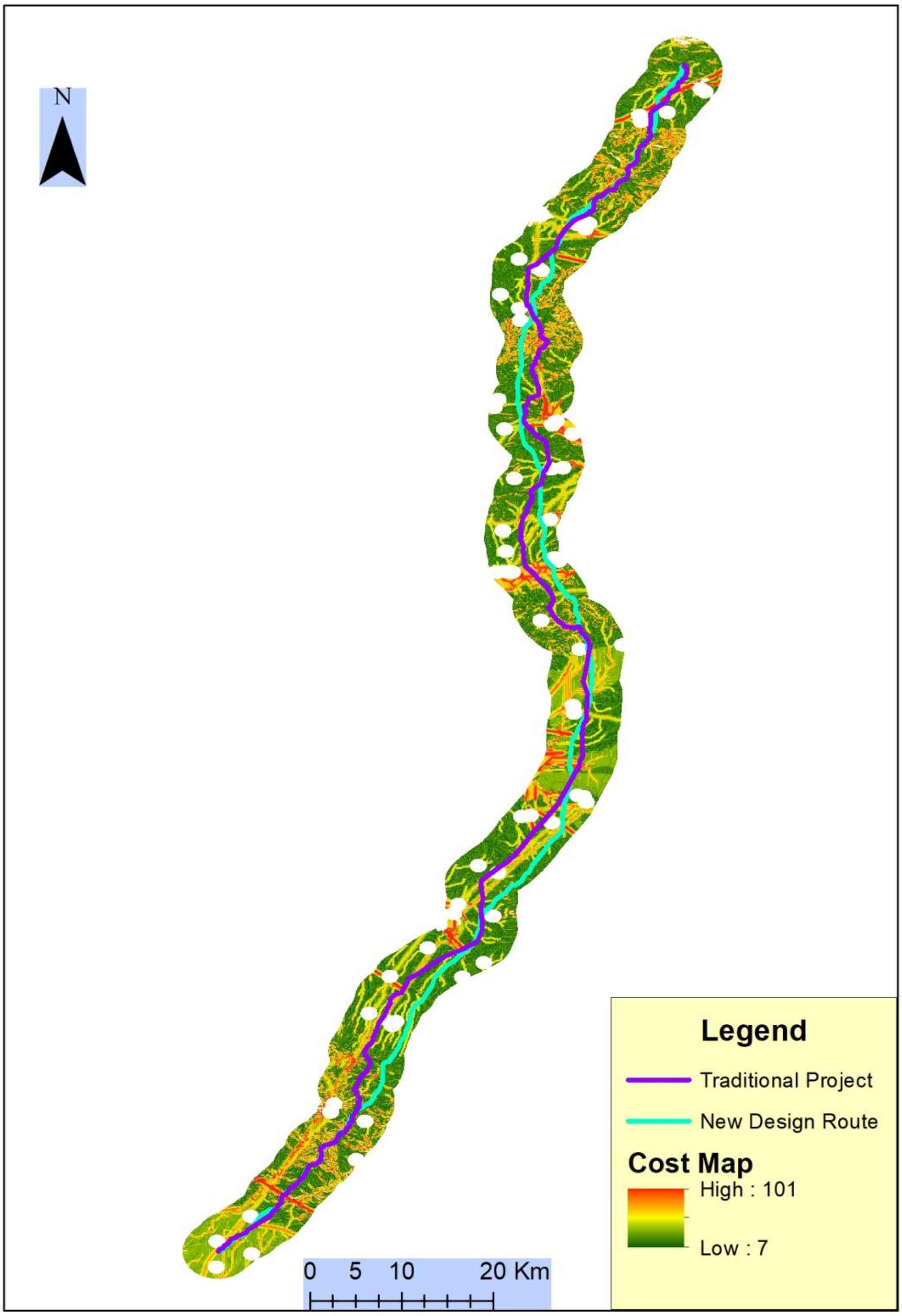


Figure 14. Result of MP Pipeline Path

2.8. Results

	Existing	30 m	100m	Simplified
Length(km)	155,83	153,47	151,12	148,99
Cost	160958	104983	145425	129053
Ridges (km)	54,44	77,70	36,47	57,14
Flat areas (km)	91,45	69,06	95,76	82,39
Stream channels(km)	5,09	3,46	5,54	4,28
Slope greater than 20%	4,85	3,25	13,35	5,18
Ridges + flat area (km)	145,89	146,76	132,23	139,53
Length in prohibited areas (m)	4832,61	0,00	0,00	463,11
Power line intersection count	Five times	Three times	Three times	Three times
Fault line intersection count	Five times	Three times	Three times	Three times
Irrigational water channels intersection count	Three times	Two times	Two times	Two times
Highway intersection count	Eleven times	Seven times	Seven times	Seven times
Stream channel (100m buffer zone)	12,76	8,68	9,00	9,03
Dam reservoir(km)	2,75	2,21	2,46	2,50
Irrigational agriculture area(km)	14,05	12,92	12,34	12,81
Number of vertex points	247,00	772,00	265,00	170,00

Table 6. Comparing Path Results

The results revealed that the simplified route exhibited a shorter length (148.99 km) compared to the existing route (155.83 km), the 30 m DEM route (153.47 km), and the 100 m DEM route (151.12 km), indicating a reduction in pipeline length with the simplified approach. Additionally, the simplified route demonstrated lower costs (129,053.00) compared to the existing route (160,958.00), the 30 m DEM route (104,983.00), and the 100 m DEM route (145,425.00), suggesting potential cost savings with the simplified pipeline design.

Furthermore, the simplified route showed a slightly larger combined length of ridges and flat areas (139.53 km) compared to the existing route (145.89 km) and the 100 m DEM route (132.23 km), while being slightly smaller than the 30 m

DEM route (146.76 km). This indicates improvements in engineering design aspects.

Moreover, the simplified route exhibited a notable decrease in the length of pipeline passing through prohibited areas (463.11 m) compared to the existing route (4832.61 m), indicating an improved avoidance of restricted regions and a successful routing outcome.

The simplified route also encountered fewer intersections with power lines, fault lines, irrigational water channels, and highways than the existing and DEM-based routes. This reduction in intersection count signifies the advantages of the simplified route for pipeline planning and implementation, minimizing potential conflicts with these features.

Lastly, the number of vertex points was highest for the 30 m DEM route (772 points), followed by the simplified route (170 points), and the 100 m DEM route (265 points). To optimize pipeline efficiency and reduce breakpoints along the route, the researchers recommended using cartographic simplification techniques. This approach aimed to enhance the overall performance and design of the pipeline system.

3. OIL SPILL MODELLING AND VOLUME CALCULATION

Oil spills pose significant environmental and economic risks due to their potential to cause severe damage to natural ecosystems. Various factors contribute to onshore oil spills, with the primary causes being leaks at the drilling point, leaks in oil pipelines and storage tanks, and accidents during oil transportation. These incidents harm the environment, leading to long-term ecological degradation, harm to wildlife populations, and disruptions to local communities that rely on affected ecosystems for their livelihoods [53].

To effectively address these challenges, it is crucial to have accurate information about the location and volume of oil spills. In the United States, the US Environmental Protection Agency (USEPA) plays a pivotal role in registering and monitoring oil spill incidents, while in Europe, the European Environment Agency (EEA) fulfils a similar function. These agencies collect and analyze data on oil spill locations, volumes, and other relevant information, which are crucial for assessing the extent of damage and formulating effective response strategies. By studying historical spill data, patterns can be identified, enabling policymakers, industry professionals, and environmentalists to develop targeted measures to mitigate future spills.

In addition to the USEPA and EEA, organizations such as the Pipeline and Hazardous Materials Safety Administration (PHMSA) in the USA and the European Gas Pipeline Incident Data Group (EGIG) in Europe specifically record and analyze pipeline spill data. These organizations are vital in monitoring pipeline integrity, identifying vulnerabilities, and implementing measures to prevent leaks and spills. By gathering data on pipeline incidents, including causes and locations, these organizations contribute to a better understanding of the factors determining to onshore oil spills.

Statistical information compiled by these agencies reveals that pipelines significantly cause both onshore and offshore oil spills. Pipeline failures can occur for various reasons, including corrosion, material defects, poor maintenance, or external factors such as excavation damage [54]. The risks associated with pipeline transportation necessitate developing and implementing stringent inspection and maintenance programs to detect potential weaknesses and address them promptly. Regular inspections, adherence to industry standards, and advanced technologies such as inline inspection tools and acoustic monitoring systems can help identify and mitigate potential pipeline failures before they result in spills.

Furthermore, oil storage tanks represent another significant cause of onshore oil spills. These tanks, which store large quantities of oil for various purposes, can develop leaks due to structural weaknesses, inadequate maintenance, or improper handling [55]. Effective storage tank management practices, including regular inspections, proper maintenance, and secondary containment systems, are crucial to prevent spills. Additionally, implementing advanced technologies such as automated leak detection systems can provide early warning signals and enable swift response in case of tank failures.

Although statistical information and records can be used to analyze the causes and consequences of oil spills, taking proactive measures before these events occur is paramount. Geographic Information System (GIS) analysis can play a significant role in achieving this. GIS integrates geographical data with analytical capabilities, allowing for identifying vulnerable areas and predicting potential spill scenarios based on topographic variables. GIS analysis can provide insights into the possible spread and distribution of oil leakage in horizontal and vertical directions by considering terrain features, elevation, and proximity to environmentally sensitive areas. This information enables stakeholders to prioritize prevention efforts, target inspections, and maintenance activities, and develop effective emergency response plans tailored to specific locations and potential spill scenarios.

Moreover, integrating GIS technology with predictive modeling techniques allows for a more accurate assessment of the potential volume of oil that could leak from pipeline cracks. By incorporating factors such as pipeline characteristics, flow rates, and environmental conditions, predictive models can estimate the potential volume of oil release and its dispersion in the surrounding areas. This knowledge aids in developing contingency plans, resource allocation, and implementing measures to minimize the environmental impact of oil spills.

Today, UAV, satellite and photogrammetric images are used along with GIS to detect the possible pipeline leak route [56]. With the help of these images, the situation of the land before the leak and the situation after the leak can be compared. This makes it easier to apply the algorithms developed for leak detection to the field in terms of both route accuracy and sensitivity.

In summary, addressing the causes and consequences of onshore oil spills requires a multi-faceted approach encompassing accurate data collection, rigorous inspections, and applying advanced technologies such as GIS analysis, images and predictive modeling. By understanding the factors contributing to oil spills and their potential impacts, stakeholders can implement targeted preventive measures to minimize the occurrence and mitigate the consequences of such incidents. GIS analysis allows for assessing vulnerable areas and predicting spill scenarios, enabling informed decision-making and effective emergency response planning. Ultimately, these efforts contribute to protecting the environment, preserving natural resources, and the well-being of communities affected by oil spills.

3.1. Supervisory Control and Data Acquisition (SCADA)

Supervisory Control and Data Acquisition (SCADA) is crucial in modern industrial control systems. It facilitates the monitoring, controlling, and real-time data collection via the control center for these systems. It is a vital intelligence gathering, control, and supervision node for diverse industrial operations. With technological advancements, machine learning and artificial intelligence can be implemented to analyze the collected data, improving system efficiency and effectiveness [57, 58].

One salient application of SCADA can be found within pipeline systems, where it brings several remarkable capabilities. To illustrate, it provides an automated start-up and shutdown functionality. This is significant for operations involving equipment such as pumps, where SCADA systems can autonomously initiate or cease their operation based on various system parameters or conditions.

In addition to this, SCADA systems are equipped with a mechanism for an emergency shutdown. This functionality activates when the pipeline pressure falls critically low, or leakage is detected. The system can rapidly respond to potential hazards through such mechanisms, thereby maintaining system integrity and minimizing potential environmental and financial damage.

Moreover, the SCADA system aids in configuring the pipeline infrastructure, which includes the operations of valves - whether they need to be opened or closed. This function offers fine control over the pipeline operations, making the system adaptive and responsive to varying operational needs.

Another noteworthy feature provided by SCADA systems is real-time modeling. This functionality assists in eliminating any erroneous readings by simultaneously examining multiple data sets. By identifying and excluding inaccurate data, real-time modeling helps maintain the credibility and accuracy of the system's data, thus enhancing decision-making processes.

Furthermore, SCADA can detect leaks by monitoring for severe pressure and flow rate drops. Upon detecting such a drop, the system can pinpoint the location of the leakage and initiate preventive measures. This capability aids in timely leak detection and remediation, mitigating any substantial impact on system performance and the environment.

Batch tracking represents another major functionality provided by SCADA. It enables the separation of different shipments at the destination point, ensuring accurate tracking and allocation of resources. This function, therefore, brings a significant degree of efficiency and accountability to the overall pipeline operation.

A function related to accuracy and validation in SCADA systems is meter proving. Here, various parameters, such as the transported product's pressure, temperature, density, and flow rate, can be compared at many different points. This process ensures the accuracy and reliability of meter readings, contributing to the overall system performance and data credibility.

Regarding communication, SCADA systems utilize diverse methods such as copper cables, radio links, GPRS modems, and fiber cables. Modern systems often incorporate more than one of these methods with redundancy, ensuring a reliable and consistent data exchange between the SCADA system and the equipment.

Upon detecting a leak in an oil pipeline, SCADA systems are programmed to automatically shut down the pump systems and valves before and after the leakage site. By doing so, the system minimizes the leakage volume and ensures the safety and efficiency of pipeline operations, ultimately showcasing the comprehensive functionality of SCADA in industrial control systems.

3.2. Oil Spill Volume Calculation

Despite high-speed fiber connections linking the SCADA system and pipeline equipment, the flow rate will be limited by the time between leak detection and valve closure. Furthermore, an additional flow can occur due to trapped oil, resulting from establishing atmospheric pressure equilibrium.

3.2.1. Calculation of Leakage Volume from Oil Storage Tanks

The likelihood of onshore oil spills resulting from in-ground oil storage tank rupture is minimal. The primary causes of tank rupture are lightning, maintenance or hot work activities, operational errors, equipment failures, and intentional sabotage [59]. The primary concern associated with oil storage tanks is the potential for explosions. To mitigate this risk, these tanks are designed with floating roofs to prevent oil evaporation and reduce the likelihood of an explosion. However, it is important to note that even with such measures in place, the risk of explosion cannot be eliminated. Therefore, further preventive and mitigation measures must be implemented to minimize tank rupture risk [60]. These measures include regular inspections and maintenance, installing lightning protection systems, utilizing fire detectors, and implementing tank cooling systems. By employing these strategies, the risk of rupture in storage tanks can be significantly reduced. If a rupture occurs in an oil storage tank, the volume of oil above the rupture point may escape. The calculation of volume to flow in a regularly shaped storage tank depends on parameters such as the height of the tank (h), the rupture height from the tank bottom (l), and the base area of the tank (S).

The volume of oil that will flow from the oil tank if no measures are taken

$$V = (h - l).S \qquad [m^3]$$

If the volume of the round, irregularly shaped storage tank is

$$V = \pi \int_{h-l}^{h} [f(x)]^2 dx \qquad [m^3]$$

3.2.2. Calculation of Leakage Volume from Oil Pipelines

The total leakage volume refers to the quantity of fluid that escapes between a damaged section of a pipe and the point at which a valve is fully closed. It encompasses the cumulative volume of fluid that flows until the pressure within the system is balanced after the valves have been shut, assuming no corrective actions are taken in oil pipelines.

3.2.2.1. Leakage Volume in Time until Valves Shut-in

The US Department of the Interior, specifically the Bureau of Ocean Energy Management, has proposed two distinct approaches for estimating the leakage volume resulting from a rupture in a pipeline [61]. It is important to note that these methods are not applicable for assessing minor fractures or pinhole leaks in pipelines.

- IDpipe [in]: Pipeline internal Diameter
- Lpipe [ft]: Pipeline length
- $X_{ovf}^{initial}$[Dimensionless] : Oil volume fraction at ambient pressure and temperature
- X_{ovf}^{amb}[Dimensionless] : Oil and gas densities at ambient pressure and temperature
- $\rho_o^{initial} and \rho_g^{initial}$ [lb/ft³]: Oil and gas densities at initial operational conditions
- $\rho_o^{amb} and \rho_g^{amb}$ [lb/ft³]: Oil and gas densities at ambient pressure and temperature
- GOR [scf/stb]: Gas-oil ratio at standard conditions in pipeline
- ρ_L^{stc} [lb/ft³] and γo [-] (specific gravity, dimensionless): Oil density at the standard condition in the pipeline
- ρ_g^{stc} [lb/ft³], γg [-] (Specific gravity, dimensionless): Pipeline gas density at the standard condition
- Q [stb/d]: Pipeline flow rate
- t [min]: Time until valve close

The basic formula is:

$$V_{Pre-Shut} = \frac{Q.t}{1140} \quad \text{[bbls]}$$

The advanced formula is:

Calculating of total volume of pipe

$$V_{pipe} = \left(\frac{ID_{Pipe}}{24}\right)^2 .\pi.L_{pipe} \qquad [ft^3]$$

Calculating the initial mass

$$m_{tot}^{initial} = \left(\rho_o^{initial}.V_{pipe}.X_{ovf}^{initial}\right) + \left(\rho_g^{initial}.V_{pipe}.\left(1 - X_{ovf}^{initial}\right)\right) \qquad \text{[lb]}$$

Calculating the total mass

$$m_{tot}^{amb} = \left(\rho_o^{amb}.V_{pipe}.X_{ovf}^{amb}\right) + \left(\rho_g^{amb}.V_{pipe}.\left(1 - X_{ovf}^{amb}\right)\right) \qquad \text{[lb]}$$

Calculating the total mass released

$$m_{rel} = m_{tot}^{initial} - m_{tot}^{amb} \qquad \text{[lb]}$$

Calculating the gas mass fraction at standard conditions

$$X_{gmf}^{stc} = \frac{1}{1+\frac{\rho_L^{stc}.5.614583}{(GOR.\rho_g^{stc})}} \qquad \text{[-]}$$

Calculate the volume of oil releases. Also, this is the basic formula.

$$V_{Pre-Shut} = \frac{Q.t}{1140} \qquad \text{[bbls]}$$

Calculating the volume of oil released. This equation has taken from the advanced formula.

$$V_{rel}^{stc} = 0.1781.\frac{m_{rel}\left(1-X_{gmf}^{stc}\right)}{\rho_o^{stc}} + V_{Pre-Shut} \qquad \text{[bbls]}$$

3.2.2.2. Volume of Flow That May Occur after Valves Shut-In

Following the detection of a leak in oil pipelines, valves are promptly closed to mitigate environmental pollution. Without any intervention, the flow of oil will persist until the internal pressure of the pipe aligns with the external pressure, as previously discussed. The total volume of oil confined between two valves can be determined using the formula

$$V_{pipe} = \left(\frac{ID_{Pipe}}{24}\right)^2 .\pi.L_{pipe} \qquad [ft^3]$$

However, it is essential to note that not all of this volume will spill. The specific volume of oil that will be discharged from the trapped space between two valves can be calculated through GIS analysis.

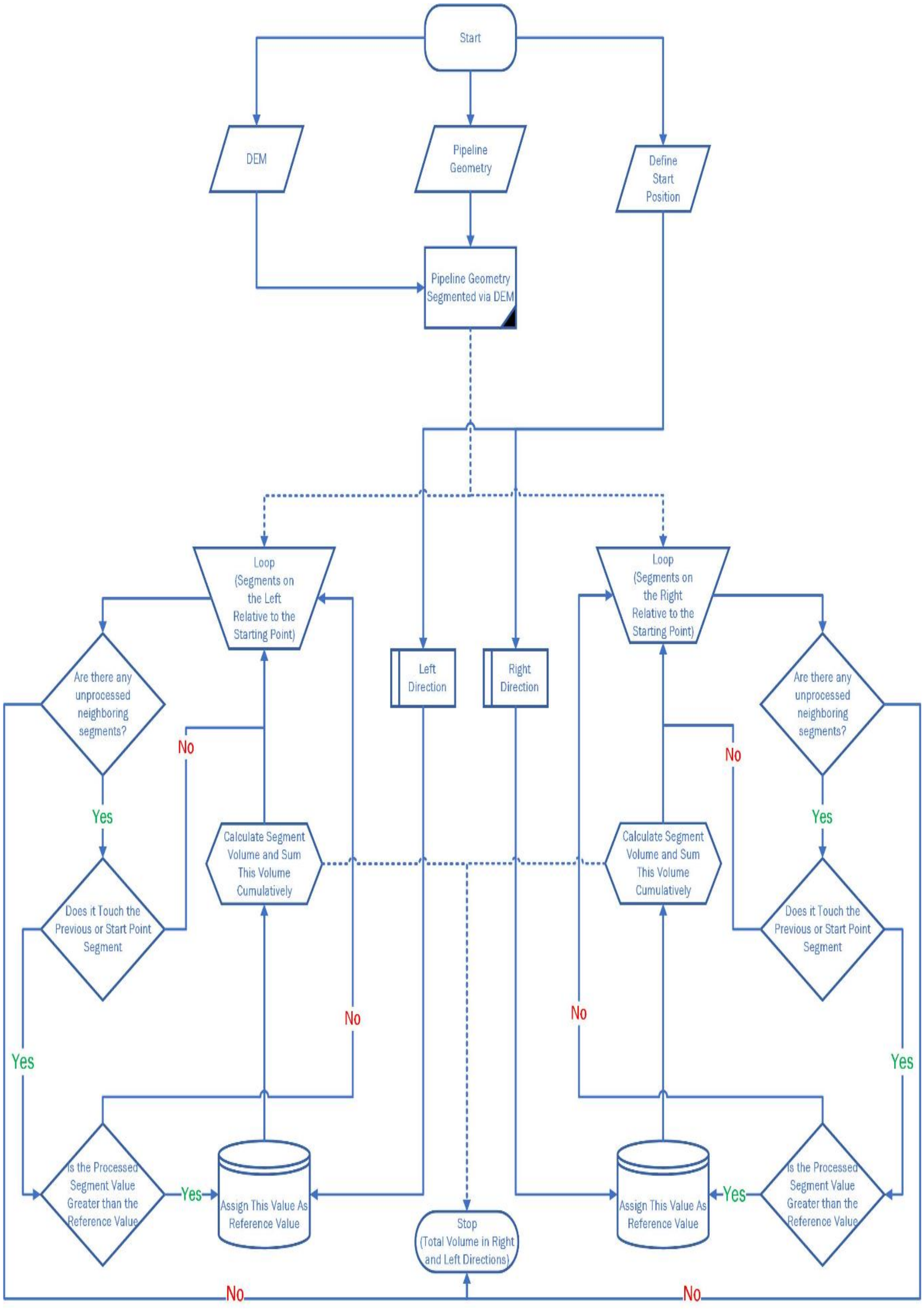


Figure 15. Flow Chart of Pipeline Spill Value Calculation

A Python-based algorithm utilizing a PostgreSQL database and GIS has been developed to analyze the volume of oil that will be discharged after the closure of valves. The algorithm's working principle can be comprehensively understood by reviewing its step-by-step process, as depicted in Figure 15.

Step 1: Input data supply

DEM data of the target region, pipeline vector drawing with coordinates, and leak location coordinates on the pipeline are provided as input.

Step 2: Overlapping Pipeline Geometry and DEM Data

The pipeline geometry and DEM data are overlapped to identify the areas where they coincide.

This overlapping process helps segment the pipeline based on the DEM data.

Step 3: Intersection with Starting Point and Reference Value Recording

The DEM data is intersected with the starting point of the pipeline.

A randomly selected segment, either in the right or left direction, is designated as the processed segment.

The height value at the intersection point is recorded as the reference value.

Step 4: Calculation of the Volume for the Selected Segment

The volume of the selected pipeline segment is calculated.

This volume is recorded as the total leakage volume.

The selected segment is marked as processed to avoid redundancy.

Step 5: Loop for Segment Inspection

The algorithm enters a loop to inspect all parts of the pipeline route segmented with DEM data.

This loop iterates through the following sub-steps:

a. Sub-step 5a: Check if Segment Has Been Processed

The algorithm checks whether the selected segment has been processed before.

If it has not been processed, a new segment is randomly selected, and the loop restarts from Step 5.

If it has been processed, the algorithm proceeds to the next sub-step.

b. Sub-step 5b: Geometric Touch Check

The algorithm checks whether the loop segment geometrically touches the processed segment.

If there is no touch, a new unprocessed segment is randomly selected, and the loop restarts from Step 5.

If there is a touch, the algorithm moves to the next sub-step.

c. Sub-step 5c: Path Update and Volume Calculation

Within each iteration of the loop, the algorithm updates the path based on the height value of the processed segment.

If the height value of the processed segment is smaller than the reference height value, the path is updated.

If the height value is greater than or equal to the reference value, the height of the processed segment becomes the new reference height value.

The volume of the processed segment is calculated, and the total leakage volume value is added to this volume.

The newly calculated volume is recorded as the total leakage volume.

The processed segment is marked as selected, and the loop restarts with the newly selected segment.

Step 6: Switching to Unselected Direction

After inspecting all segments in one direction, the algorithm switches to the unselected direction (right or left).

The height value of the intersection point between the DEM data and the starting point is reassigned as the reference value.

Step 7: Repeating Step 5 for the New Direction

The loop described in Step 5 is repeated for the newly selected direction.

The algorithm goes through the same sub-steps described in Step 5 for the new direction.

By following these steps, the GIS-based algorithm, in conjunction with the PostgreSQL database and Python programming language, determines the volume of oil that will flow after the valves are closed. The algorithm considers the DEM data, pipeline geometry, and the coordinates of the leak location to estimate the total leakage volume accurately.

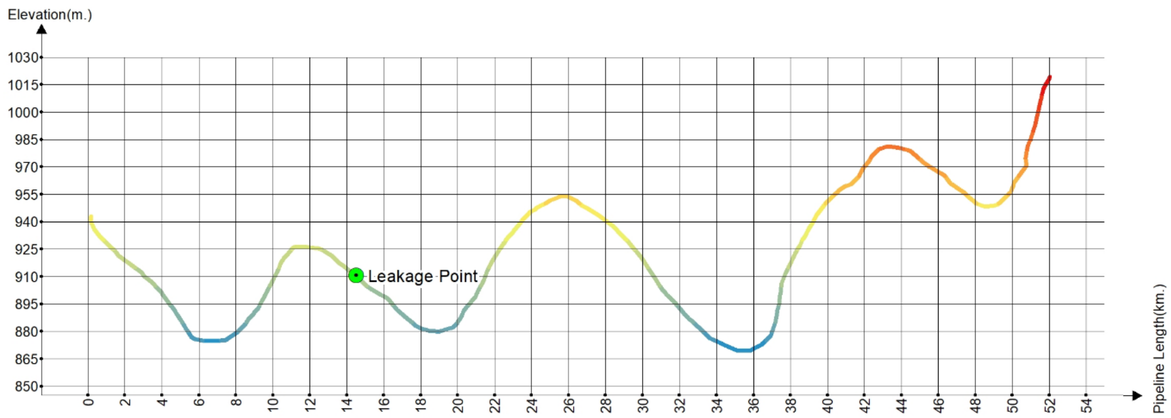


Figure 16. How Pipeline Spill Value Calculate (color shows height).

The developed Algorithm has been applied to a pipeline segment whose elongation section representation is like Figure 16.

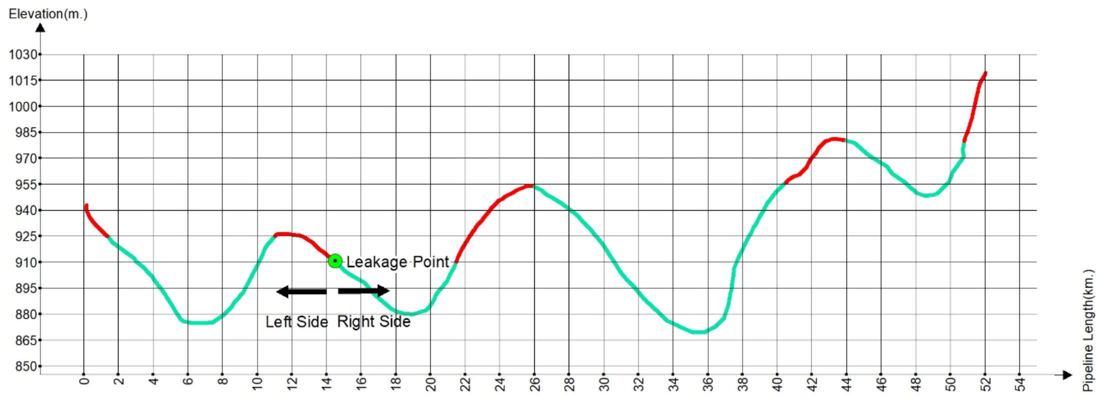


Figure 17. The Result of Pipeline Spill Value in Chart

The application yielded anticipated and satisfactory outcomes when executed in both the right and left directions, starting from the specified leak point. In Figure 17, the regions highlighted in red represent areas where oil is projected to be discharged. Conversely, the green-colored regions indicate the oil segments that remain due to the influence of the topographical features, as depicted in Figure 17.

3.3. Horizontal Distribution Of Oil Spill On Surface

Several widely recognized hydrology analyses based on Geographic Information Systems (GIS) exist, including flow direction, flow accumulation, and sink detection algorithms. While these analysis methods may appear relevant to onshore oil spills based on their names, they are not directly applicable to such scenarios. These algorithms typically operate by uniformly evaluating equal amounts of water drops across each Digital Elevation Model (DEM) cell and analyzing all cells. They are commonly utilized for flood modeling or extracting topographical features, such as ridges, stream channels, or depressions [62].

In the context of terrestrial oil spills, they typically occur due to pipeline cracks or unintentional accidents on drilling rigs, resulting in a gradual spread of the spilled liquid across the affected area. This process involves gradually releasing an exact quantity of oil, and progressively dispersing it into the surrounding ground from a specific location. Consequently, the application of conventional hydrological algorithms, as previously mentioned, proves inadequate in addressing the unique characteristics of an oil spill.

The primary criterion for accurately determining the route of an oil spill lies in identifying the presence of depressions or holes in the flow path. In such instances, the spilled liquid accumulates until its height aligns with that of the depression. Generally, oil flows downhill from higher to lower elevations. Consequently, when employing a GIS-based solution to simulate an oil spill, the liquid consistently follows the path of the lowest neighboring cell. However, if all neighboring cells possess higher elevations than the current cell, the oil accumulates to a height equivalent to that of the lowest neighboring cell before proceeding further.

The soil's absorption rate is another critical factor influencing the length and extent of the oil spill's flow path. Various soil types exhibit distinct absorption capacities, determining the amount of liquid absorbed. In a GIS-based analysis, it is possible to define the absorption rate of the liquid based on the specific soil type within a given unit area. This information helps refine the simulation model, providing a more accurate representation of the oil spill's behavior.

Additionally, it is important to consider various factors contributing to reducing the spilled oil volume. These factors may include evaporation, attachment of oil to vegetation within the soil, small cracks in the ground, and other similar phenomena. These losses should be considered to provide a more realistic estimation of the oil spill's impact.

The oil spill analysis algorithm should be designed to terminate when the cumulative losses along the spill path exceed the initially considered volume of oil. This ensures the simulation accurately reflects the real-world scenario and prevents overestimating potential impacts.

By considering these specific parameters and incorporating them into a comprehensive GIS-based analysis, it becomes possible to simulate the path and behavior of an oil spill, thereby facilitating more accurate assessments of the spill's potential impacts on the surrounding environment and enabling the development of effective response strategies.

Oil spill analysis was coded using the arcpy library on ArcGIS by following the steps below (Figure 18).

1. In the initial stage of this analysis, various inputs are fed into the application. These inputs consist of Digital Elevation Model (DEM) data, information on the volume of the oil that has leaked, a map detailing different soil types in the area, and where the leak started. These inputs serve as a basis for the algorithm to conduct its operations.

2. The second step involves integrating the DEM data and the soil type map to create a surface model. This model illustrates the terrain's elevation and the type of soil found at each location. This is achieved by conducting an intersection analysis within the Geographical Information System (GIS), which overlays the two data types to create a combined visual representation. The rectangular pixels may become somewhat distorted at this stage due to the complex interactions between different data layers. However, such distortion is considered insignificant for this algorithm.

3. Following this, an intersection analysis is performed between the leak's starting point and the DEM data within the GIS. This process identifies the pixel where the leak starts and tracks its path on the model. The elevation value of this pixel is then noted down and set as the reference height for further steps in the algorithm.

4. The algorithm then runs in a loop until the total volume of the leak, calculated by the system, meets or exceeds the leaked volume input at the beginning of the process. The various steps within this loop are as follows:

a. The algorithm first identifies the pixel with the smallest elevation value along the path of the leak. The elevation value of this pixel is then set as the reference height for the next stage of the algorithm.

b. If other pixels along the leak path have an elevation equal to the reference height, they are marked as the reference path. The algorithm then goes into an iterative process, examining the surrounding pixels and adding any with equal height to the reference path. This is performed using an endless loop or a recursive function, a coding technique that allows a function to call itself. This process is akin to a breadth-first search algorithm, a strategy for searching in a graph when breadth (neighbors to a node) is prioritized before depth (children of a node).

c. At this stage, the algorithm calculates the volume of oil accumulated in pixels with a height less than the reference height along the leak path. This is computed by multiplying the pixel area being processed by the difference between the reference height and the height of the pixel in question. The formula can be written as:

Pixel-based Puddle Volume = Area of the Processed Pixel * (Height of Reference Pixel - Height of the Processed Pixel)

d. The algorithm then calculates the amount of oil absorbed by each section of the DEM, based on the unit volume absorption amount for the specific type of soil in that location.

e. At this point, the algorithm accounts for additional losses due to small surface cracks, evaporation, and oil adhering to vegetation. This is done by defining a constant loss parameter proportional to the calculated path length. The total losses are then calculated by multiplying the path length by the constant loss parameter.

f. The loop is terminated as soon as the combined volumes of oil lost in steps c, d, and e meet or exceed the total volume of the oil leak as given in the input parameters.

In the developed Algorithm, the soil type is an optional parameter. A fixed absorption rate is given if this data does not exist.

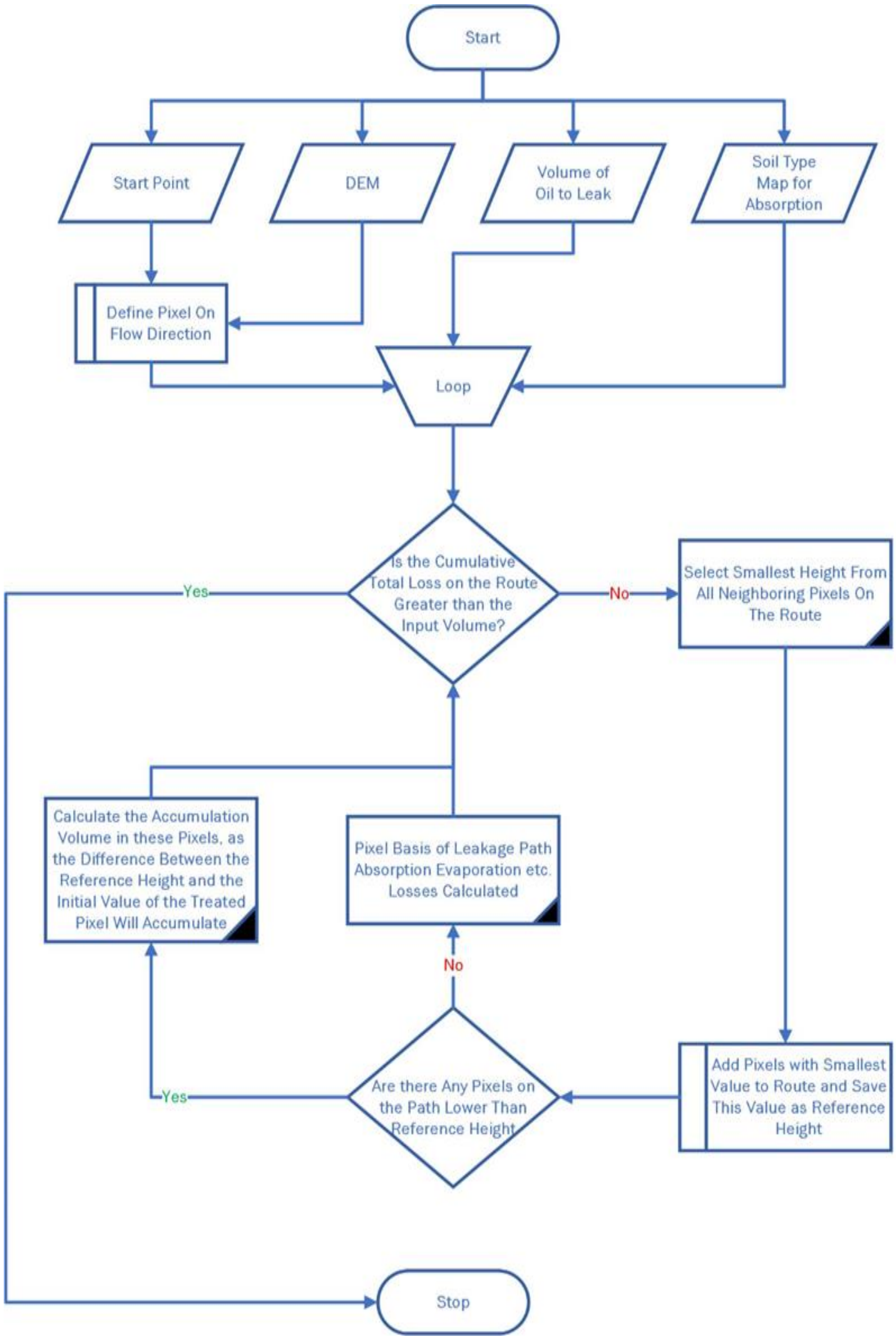


Figure 18. The Algorithm of Horizontal Oil Spill Distribution

3.3.1. Lowest Neighbor Problem

In the realm of raster-based analysis, there are fundamentally two ways in which we define a pixel's neighbors, the '4-pixel neighborhood relation' and the '8-pixel neighborhood relation'.

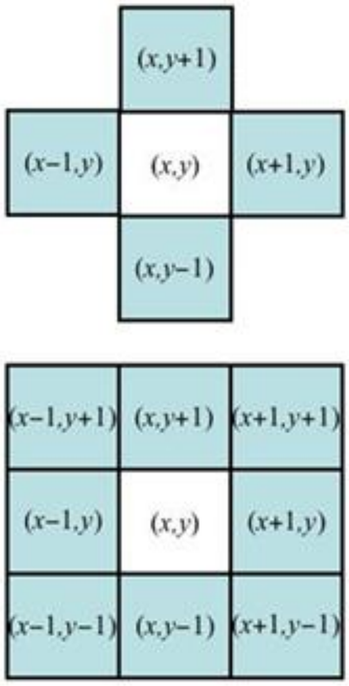


Figure 19. Pixel Neighborhoods

When explain to the 4-pixel neighborhood relation, In this case, each pixel is viewed in relation to its four immediate neighbors, situated in the cardinal directions of North, South, East, and West. If single pixel with coordinates (x, y) are taken into consideration, its neighbors would be found at the coordinates (x, y+1) for the pixel to the North, (x, y-1) for the pixel to the South, (x+1, y) for the pixel to the East, and finally, (x-1, y) for the pixel to the West (top image in Figure 19). Only the pixels that share an edge with the central pixel are considered neighbors in this configuration.

On the other hand, the 8-pixel neighborhood relation expands the concept of a pixel's neighbors to include those pixels that share a vertex with the central pixel. Those pixels situated diagonally to the central pixel must also be considerated.

In addition to the four coordinates detailed in the 4-pixel neighborhood relation, the neighbors would also include (x+1, y+1) for the pixel to the Northeast, (x+1, y-1) for the pixel to the Southeast, (x-1, y-1) for the pixel to the Southwest, and (x-1, y+1) for the pixel to the Northwest (bottom image in Figure 19).

In the realm of oil spill analytical studies, the traditional understanding of neighboring pixels undergoes a transformation. Within this domain, our focus isn't solely on stationary pixels. Instead, we delve into pixels that craft an ever-evolving and enlarging trajectory. As the oil spill proliferates, so does the trajectory, and concomitantly, the neighboring pixels amplify in quantity, undergoing dynamic modifications as the trajectory integrates novel pixels (Figure 20).

Should one approach the study of oil spill analytics through the conventional lens of raster-oriented trajectory discernment, it would necessitate a perpetual documentation of coordinates pertaining to all adjacent pixels. With each inclusion of a fresh pixel into the spill trajectory, such documentation demands revisions to reflect the evolving vicinity of the impacted pixels. Such an approach would undeniably introduce heightened computational intricacy due to the perpetually mutable data.

An optimized methodology can be employed to circumvent this computational intricacy: transmuting Digital Elevation Model (DEM) data into a vectorial format, including their altitudinal metrics. The vectorial data paradigm, employing vertices, lines, and polygons for terrestrial representation, typically offers enhanced adaptability and is adept at encapsulating intricate geospatial attributes with heightened accuracy compared to its raster counterpart. This metamorphosis ensures the retention of pivotal data for oil spill analytics without the computational challenges inherent in incessant updates of adjacent pixel data.

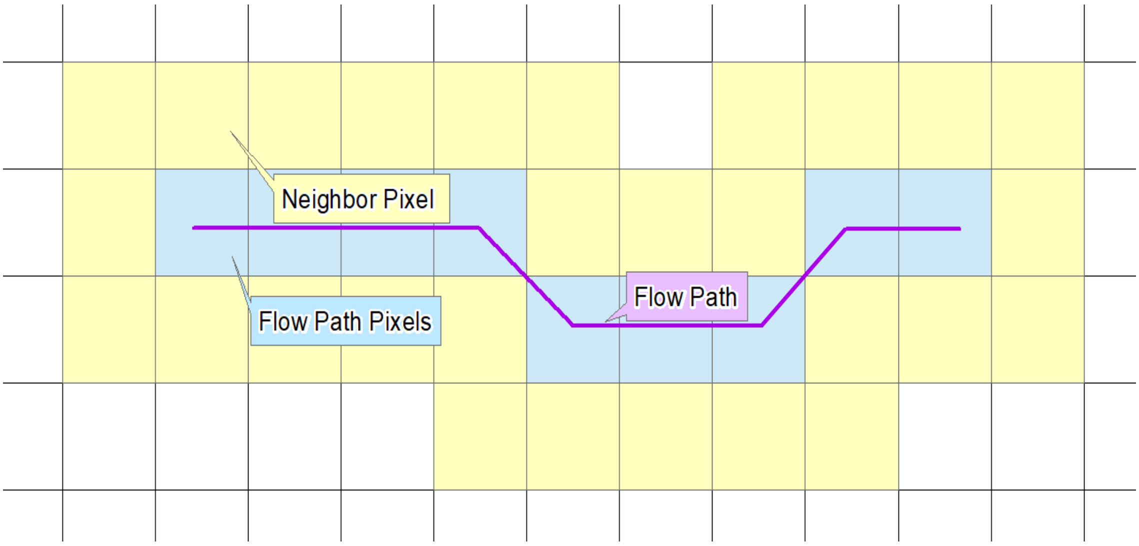


Figure 20. Neighbor Relation in Horizontal Oil Spill Distribution

3.3.2. Oil Puddle Problem

In addressing the critical issue of oil spills, there is a key parameter to be identified and understood—'barrier pixels'. In the context of an oil spill, 'barrier pixels' refer to specific digital markers on the spill's path. Each spill region is represented as a pixelated grid, with each pixel given a numerical value that signifies its 'height' or relative elevation.

A unique trait that distinguishes barrier pixels is their role in fluid accumulation. Drawing parallels with a dam or blockade, these barrier pixels retain the oil spill until such a point when the 'height' of the leaked oil behind them matches their own height value. At this juncture, just like a dam at capacity, the oil begins to overflow and continues along its path.

In fluid accumulation, the height of the neighboring pixels plays a crucial role. This procedure particularly involves the pixel with the smallest height value among the neighbors. Fluid builds up when this pixel's height is larger than the previously processed pixel's height. The quantity of this buildup is ascertained by the difference in height values between the barrier pixel and the pixel processed before it. This difference measures the amount of fluid accumulating before reaching the barrier pixel's 'capacity' and spilling over.

As the fluid, or oil, permeates through the grid, each pixel on the predicted route carefully inspects its height value. Intriguingly, fluid accumulation will occur in every pixel with a height less than that of the last identified barrier pixel. This behavior is analogous to the natural fluid movement across varying elevations, which flows from higher to lower regions until a barrier is surpassed.

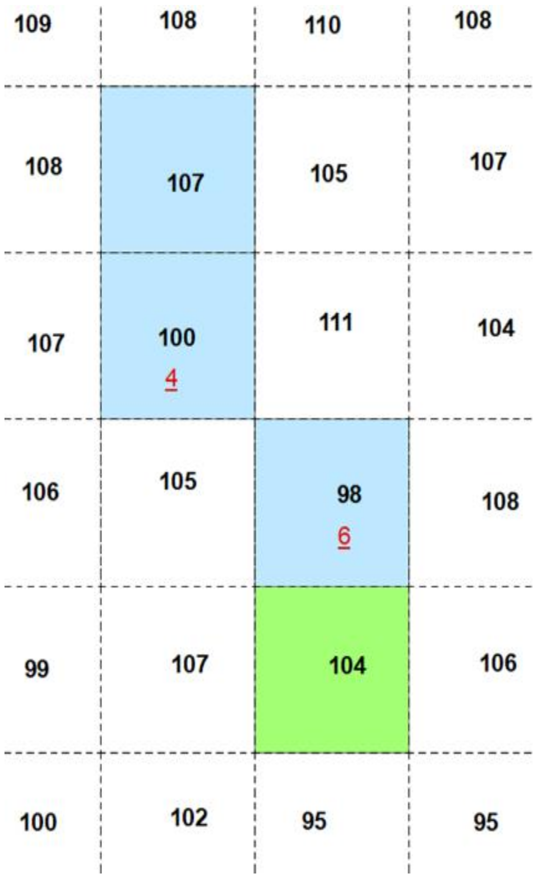


Figure 21. Oil Puddle Problem

To illustrate this, consider an image-based scenario. After processing a pixel with a value of 98, it is found that all the neighboring pixels have a higher value than 98. This scenario signals the commencement of fluid accumulation up until the height of the smallest neighboring pixel. In this instance, the smallest neighboring pixel has a height of 104. Consequently, the pixel with a height of 98 will accumulate 6 meters of fluid, computed by subtracting 98 from 104. Similarly, a pixel with a height of 100 will accumulate 4 meters of fluid, representing the difference between 104 and 100 (Figure 21).

In essence, understanding the behavior of barrier pixels and the dynamics of fluid accumulation is an essential part of mitigating oil spills. This detailed explanation enhances comprehension of the mechanisms at play in this context, supporting effective strategies to manage and reduce the environmental impacts of oil spills.

3.3.3. Neighbor's Neighbor Problem

In real-world scenarios, liquid, like water or oil, typically flows along a gradient from higher elevations to lower ones. This principle is echoed in Geographic Information Systems (GIS), where the motion of liquid is modelled from higher to lower cells within a grid representing the terrain. An essential factor to consider while calculating this flow direction is the treatment of flat cells within the Digital Elevation Model (DEM), which represents the surface of the Earth in a digital format.

In the DEM, cells are essentially pixels assigned specific elevation values. In cases where multiple cells within the neighborhood share the same elevation, the fluid is modeled to traverse these flat cells. This scenario resembles how water would flow over a flat surface in the physical world, distributing itself evenly across the plane.

Our analytical process necessitates a further step after identifying the lowest pixels on the fluid's projected path. Neighbouring cells with the same elevation values as these lowest path pixels must be examined. This inspection aims to determine whether these equal-elevation cells are adjacent or connected to the flow path pixels, implying that they form part of the boundary of the fluid's path.

This step serves to extend the currently calculated flow path. It acknowledges that fluid won't necessarily follow a strict path of descending elevations, but might also spread laterally across areas of the same height. By doing so, we ensure that our model accurately reflects the potential for fluid to spread across equal elevations.

Let's examine an illustrative example to clarify this concept further. Consider an image that represents the flow of a liquid from an area with an elevation value of 107 to an area with a value of 94. A pixel with 96 (represented in green) has been processed on this image. The next step in our application would be to designate cells with an elevation value of 95 (shown in yellow) as part of the projected flow path.

However, our task does not end here. All neighboring cells of these 95-value cells must also be examined to determine if any other cells have an equal elevation value of 95. These cells form part of the flow path since the fluid can spread to these areas. This way, the flow path is expanded to include these same-elevation cells, providing a more comprehensive understanding of the fluid's trajectory (Figure 22).

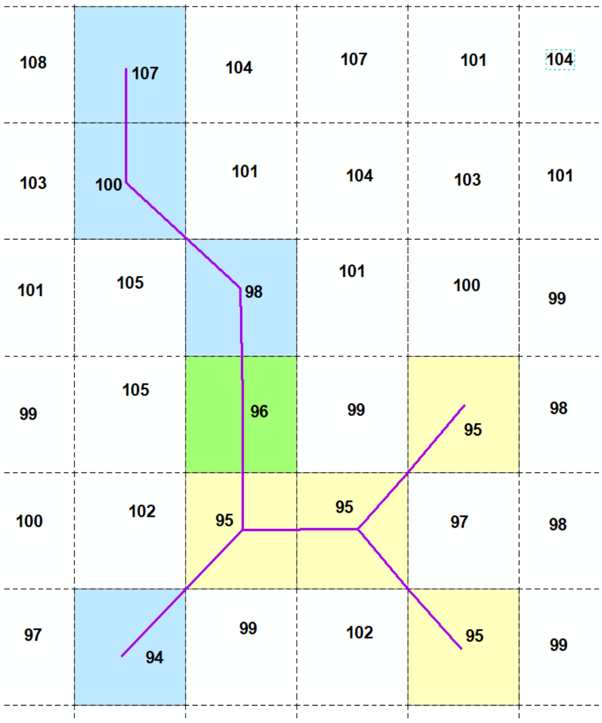


Figure 22. Neighbor's Neighbor Problem

3.3.4. Soil Absorption and Saturation Problem

Within oil spill mitigation, the volume of oil or 'liquate' that flows over a given terrain is influenced by several crucial parameters. Among them, the formation of oil puddles, the absorption capabilities of the soil, and the saturation level play significant roles. A profound understanding of these components can substantially enhance the prediction and control of oil spills.

The first parameter, oil puddles, pertains to oil accumulation in certain parts of the terrain. This concept elucidates how oil, rather than distributing uniformly over the surface, tends to gather and form 'puddles' or pools in specific areas, especially in depressions or low-lying regions. Understanding the formation and behavior of these oil puddles is crucial as it affects the volume of oil that spreads during a spill. Calculating the volume of these puddles essentially involves determining the depth and surface area of these pools, which can then be combined to derive the volume of oil contained within.

The next parameter revolves around the absorption or retention capacity of the soil. This characteristic can differ substantially based on the soil type or lithology. Different soils have varying capacities to absorb or hold oil, directly affecting the volume and direction of the oil flow. Recognizing this, leveraging lithology - the study of general rock physical characteristics - can produce more accurate predictions of oil flow paths.

Saturation plays a pivotal role in influencing the behavior of oil spills. Notably, an inverse relationship exists between saturation and absorption. When the saturation level of a terrain rises, its absorption capacity diminishes. This phenomenon is because a highly saturated surface has reached its holding limit, leaving minimal room for further absorption. By adjusting the absorption rate, control over saturation can be achieved. For example, heightening the absorption value decreases saturation, while reducing it leads to increased saturation. This balance between absorption and saturation is a key determinant in managing the behavior of oil spills on a terrain.

In the computational model tailored for oil spill analysis, two options are provided to account for soil absorption. The first option is useful if detailed soil type maps are available. Users can then employ specific water holding values from experimental studies or prior academic research, reflecting the accurate absorption capacities of various soils, enhancing the model's precision.

The second option, more streamlined, is utilized when detailed soil type information isn't available. Here, a constant value, representing a standard soil water holding capacity, is defined. This value applies uniformly across the model, offering a generalized estimate of the soil's absorption ability. While not as exact as soil-specific data, this approach still furnishes a practical approximation for oil spill prediction and management.

3.3.5. Algorithmic Oil Path Results

Calculating the leakage volume and tracing the path of leaks in oil pipelines are critical for sustainable environmental policies. Another significant aspect of this research is conducting these calculations prior to the emergence of potential issues, thereby enabling the implementation of preventative and protective measures.

The algorithm for calculating leakage volume in oil pipelines proves extremely valuable for pipeline operators in deciding the location of valves, as it operates throughout all points of the given pipeline. Furthermore, once the valve locations are marked on the same algorithm, rerunning the algorithm will allow observation of the potential impact of the proposed valve.

The path calculation algorithm can be applied to all points on the oil pipeline (with submillimeter horizontal resolution) by incorporating a loop into the existing algorithm. However, it should not be overlooked that this process will take a certain amount of time, depending on the length of the oil pipeline and the processing power of the computer being used. The determined leakage path can be cross-analyzed with water sources around the oil pipeline on a GIS basis, which will be useful in deciding where and how to take precautions against potential environmental disaster scenarios.

Figure 23 illustrates a scenario where lithology data is not available. It visually represents elevation values obtained from DEM data, denoted by black numbers. The flow path cells within the blue boundaries indicate the water's path. Within the flow path, the top number indicates the sequential order of the flow direction, ranging from 1 to 23 cells. Red numbers also represent the accumulation amount at the bottom of the flow path. This depiction allows for a clear understanding of the flow direction and the corresponding accumulation values associated with each step along the path.

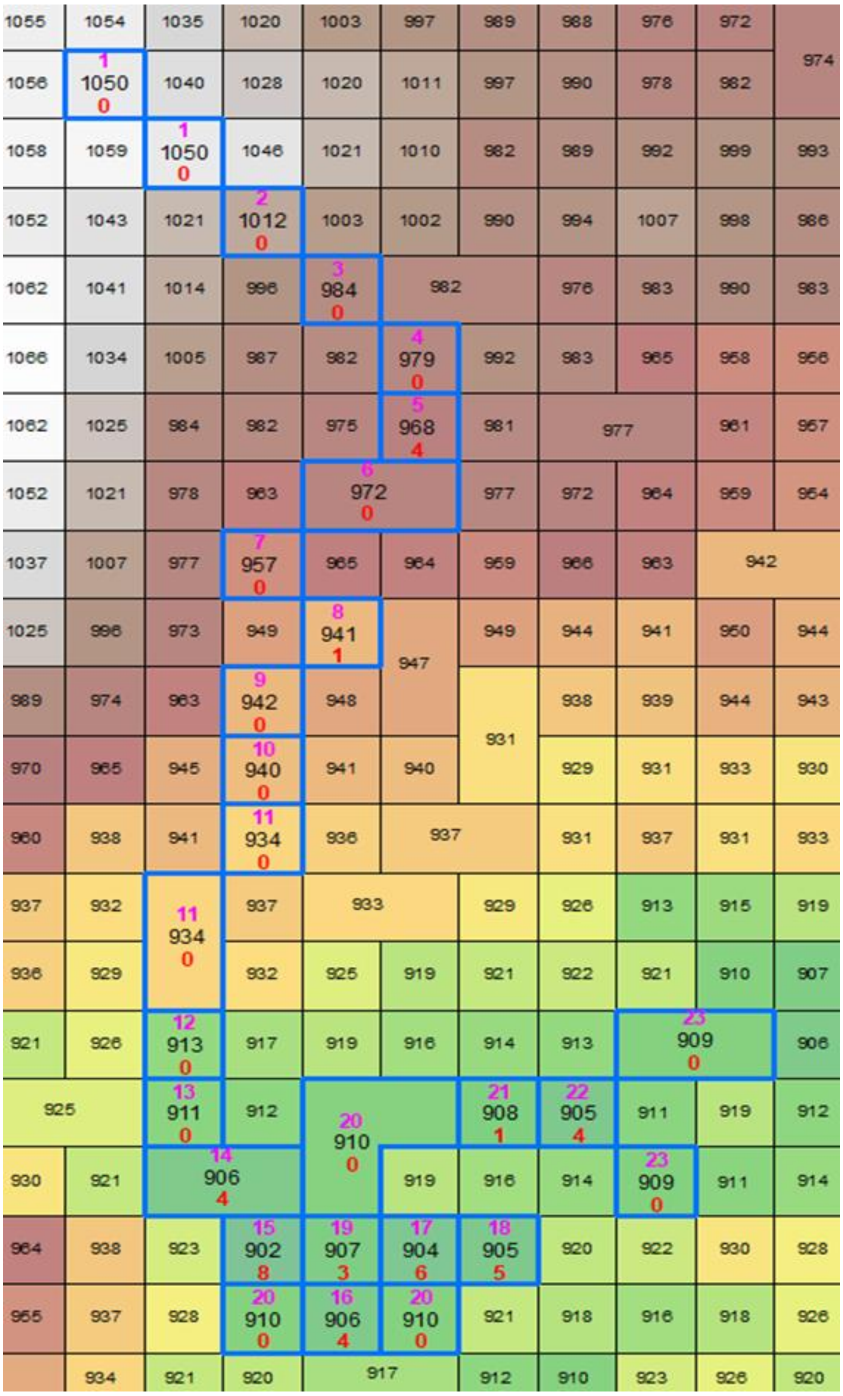


Figure 23. Oil Path Results without Lithology Data

Figure 24 demonstrates the flow path direction when soil type data is available. To incorporate the soil information, the pixels in the image are divided into smaller segments. Each segment represents a different type of soil, characterized by varying absorption rates. The flow path pixels are highlighted in different colors, with each color corresponding to a specific soil type. This color-coded representation aids in visualizing the flow path and identifying the distinct soil types involved. Additionally, the red numbers below the flow path indicate the sequential order of progress for the individual cells. By incorporating the soil type data, this image provides valuable insights into the flow direction and the influence of different soil characteristics on the overall hydrological process.

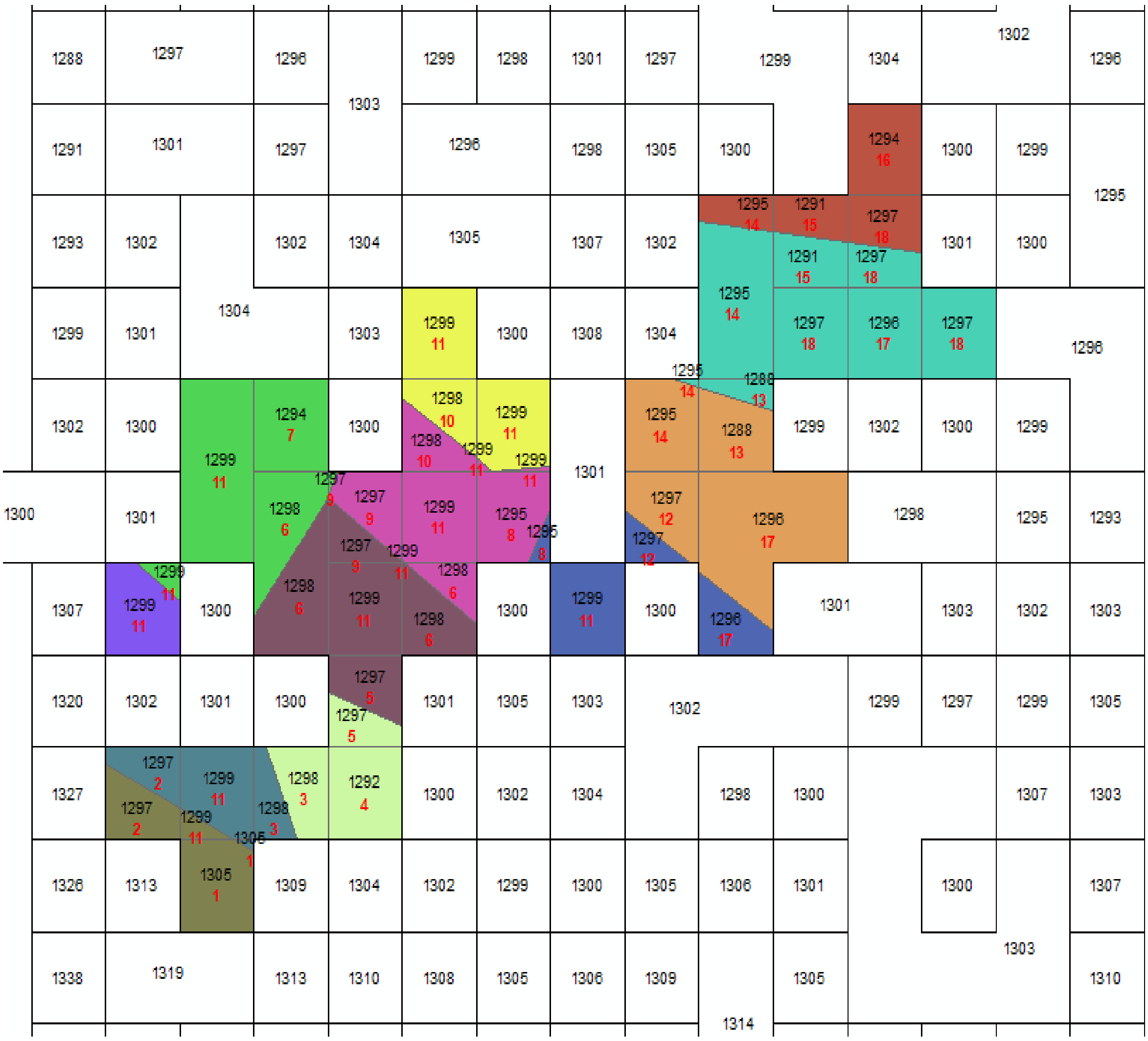


Figure 24. Oil Path Results with Lithology Data

Calculating the leakage path when developing an algorithm for oil pipeline leaks involves initially identifying a single direction from the starting point of the leak. However, considering the possibility of dispersion at the starting point, it would be beneficial to run the algorithm at multiple randomly selected points in areas where a leakage risk is anticipated. This approach would enhance the accuracy and effectiveness of the algorithm in identifying potential leak paths. In Figure 25, the algorithm is executed at randomly selected points, and the results are displayed with a color gradient representing the water accumulation levels, ranging from green to red. This color-coding effectively illustrates the varying degrees of water accumulation at different points along the pipeline, providing a clear visual representation of the potential impact areas in the event of a leak

Figure 25. Multiple oil spill directions

4. EXPERIMENTAL STUDY

In the "Oil Spill Modelling and Volume Calculation" section, an experimental study has been conducted using photogrammetric methods to test the algorithm described.

4.1. What is Photogrammetry Briefly

Photogrammetry is a complex scientific method that uses sources of electromagnetic radiation, especially photographs, to determine the positions and measurements of objects or areas. Its mathematical foundation is based on geometric and projection equations to process the information from the photographs [63].

This method is widely used in remote sensing, mapping, geographic information systems, urban planning, and many other fields. It processes data from photographs to create three-dimensional (3D) models, maps, or other visual outputs based on mathematical and geometric principles [63].

The key to this process is understanding and correctly applying the photographs' internal and external orientation parameters. Internal parameters provide information about how the photo was taken, defining camera calibration, lens focal length, optical center position, and camera sensor characteristics. This information provides insights about the camera's configuration at the time of the shot [64].

External parameters provide information about where and in which direction the photo was taken, giving details about the photo's geographical location, altitude, and orientation. These parameters are crucial in determining the photo's position and orientation in the real world.

Other essential elements of photogrammetric modeling are tie points and control points. Tie points mark locations that correspond to the same object in two or more photographs and help to relate the images. Control points are spots with known coordinates in the real world and are identified in the photographs. They ensure the accuracy of the model and align the created 3D model with real-world coordinates. Along with these points, stereo image overlay is also vital. It is the process of overlaying two photographs to get 3D depth information. This overlay is possible when two photos overlap by a specific amount. Horizontally, the overlap is not less than typically 60%, and vertically, it is not less than 30% [65]. These overlaps are necessary for accurate 3D data and help in correctly matching the tie points.

In addition to these aspects, collinearity equations play a pivotal role in photogrammetry. These equations describe the mathematical relationship between the 3D coordinates of a point in the physical world and its 2D representation in an image. Essentially, collinearity equations ensure that the lines connecting 3D points to their 2D counterparts and the camera's perspective center are co-linear. This implies that if you extend a line from the camera's lens through a point in the image, it will intersect with the actual location of that point in the physical world. This fundamental principle is crucial for accurately transforming and correlating the 3D and 2D spaces, enabling precise measurements and modeling in photogrammetric applications. By rigorously applying these equations, photogrammetry can achieve high levels of accuracy in mapping and modeling various environments, whether it's for topographical mapping, architectural studies, or archaeological documentation.

$$x_a = x_p - c\frac{r_{11}(\chi_A - \chi_0) + r_{21}(Y_A - Y_0) + r_{31}(Z_A - Z_0)}{r_{13}(\chi_A - \chi_0) + r_{23}(Y_A - Y_0) + r_{33}(Z_A - Z_0)} + dist_x \qquad (1)$$

$$y_a = y_p - c\frac{r_{12}(\chi_A - \chi_0) + r_{22}(Y_A - Y_0) + r_{32}(Z_A - Z_0)}{r_{13}(\chi_A - \chi_0) + r_{23}(Y_A - Y_0) + r_{33}(Z_A - Z_0)} + dist_y \qquad (2)$$

In the collinearity equations formula (1) and (2);

x_a and y_a stands for image coordinates

X_A, Y_A and Z_A describes for ground coorinates

X_0, Y_0 and Z_0 are external orientation parameters

x_0, y_0 and c defines internal orientation parameters

$dist_x$ and $dist_y$ are for coefficients

Recently, photogrammetry has been used for aerial photos, satellite images, drone shots, and even smartphone cameras. Advances in technology, new algorithms, and software have made photogrammetry faster, more accurate, and accessible. Moreover, it's used in processing high-resolution, multi-band images, surface modeling, vegetation analyses, and even restoration of historical structures. All in all, photogrammetry is an indispensable method to extract metric information about the Earth from photographs.

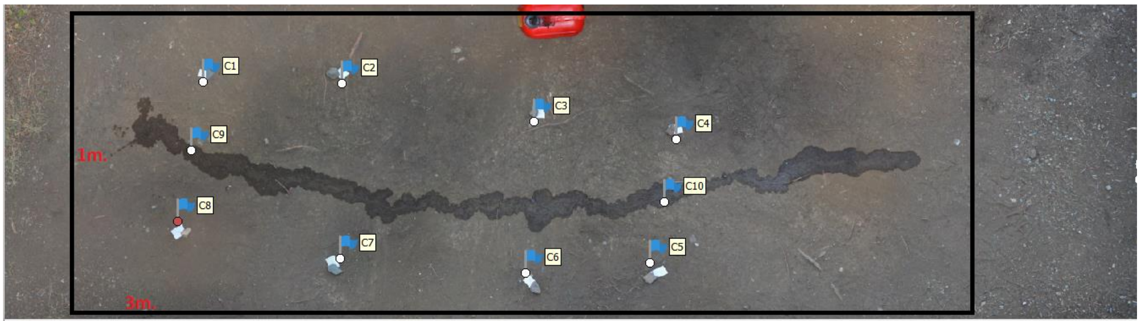
4.2. Study Site and 3D Photogrammetric Models

The experimental study was conducted at the Çankaya location in Ankara. The objective of the experimental study was to recreate a miniature simulation of a real petroleum leak and to evaluate the outputs of a designed algorithm within this context. For this purpose, artificial barriers on the project site have been cleared, making the area ready for application. On the site, 10 control points have been marked with the help of GPS to cover the route of the experimental oil spill. Initially, around 70 high resolution photos were taken with a Canon D5700 to create a DEM (Digital Elevation Model) of the empty surface. After the flow was complete, another set of 70 photos was taken with the same camera for creating orthophoto.

The study utilized 2 liters of gasoline with the aim of accurately simulating a real petroleum leak. The designated area for the experiment was approximately 1 meter in width and 3 meters in length. Control points' positions were measured in

10-minute intervals using GNSS receivers that can connect to the CORS (Continuously Operating Reference Stations) network. When these benchmark points were balanced, the observed total error was found to be less than 7mm. In photogrammetric applications, marking the control points in the captured images resulted in a pixel-based total error observed to be less than 0.5 pixels. Figure 26 displays the control points on the orthomosaic created after the completion of the leak.

For each of the two applications 2 photogrammetric models (before and after leak) were generated using Agisoft Metashape. Figures 27 and 28 display the positions of the captured images.



Reference

Markers	Easting (m)	Northing (m)	Altitude (m)	Accuracy (m)	Error (m)	Projections	Error (pix)
C1	479044.636000	4416462.546000	971.377000	**0.005000**	0.004002	21	0.534
C2	479045.100000	4416462.539000	971.320000	**0.005000**	0.003257	36	0.526
C3	479045.742000	4416462.412000	971.204000	**0.005000**	0.005307	48	0.507
C4	479046.221000	4416462.350000	971.139000	**0.005000**	0.003991	37	0.534
C5	479046.132000	4416461.935000	971.110000	**0.005000**	0.005687	40	0.501
C6	479045.715000	4416461.903000	971.177000	**0.005000**	0.002206	40	0.454
C7	479045.093000	4416461.952000	971.256000	**0.005000**	0.007304	31	0.468
C8	479044.551000	4416462.077000	971.343000	**0.005000**	0.002865	16	0.500
C9	479044.594000	4416462.312000	971.362000	**0.005000**	0.005073	19	0.429
C10	479046.177000	4416462.143000	971.132000	**0.005000**	0.013359	41	0.472
Total Error							
Control points					0.006113		0.495

Figure 26. Error values calculation for the model after the leak

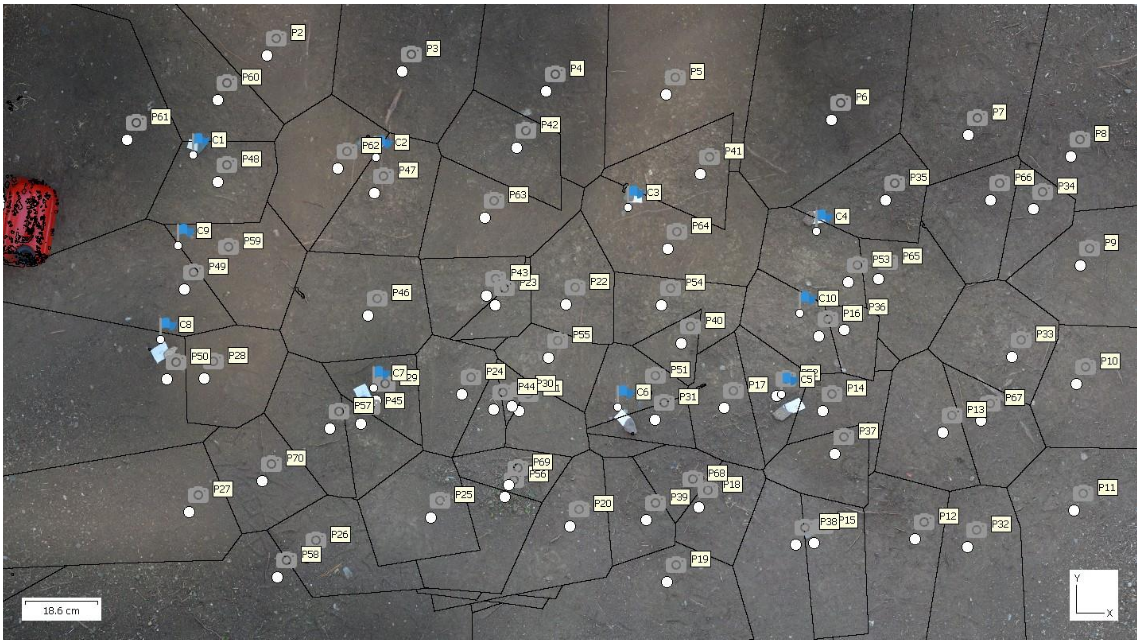


Figure 27. Image and Photogrammetric Benchmarks Locations Before Spill

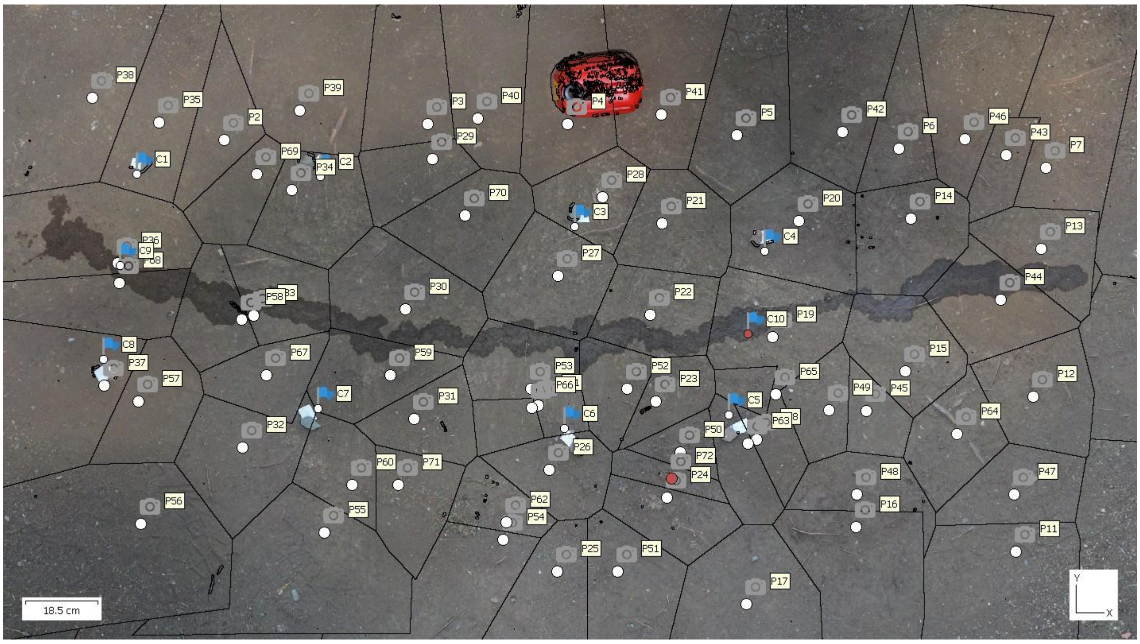


Figure 28. Image and Photogrammetric Benchmarks Locations After Spill

4.3. Camera Calibration and Geneartaing 3D Modeling

Researchers at Hacettepe University have decided to employ the Agisoft application for orthophoto and DEM production due to its convenience in both licensing and 3D modeling. After capturing images, a Nikon D5200 with an 18mm focal length, camera calibration was performed following the guidelines provided in Agisoft's documentation. A wide-screen monitor was utilized to display a marked chessboard pattern consisting of black and white squares, referred to as a calibration target. At least 10 images of the calibration target were taken from different angles.

By adhering to the given instructions, the necessary parameters for camera calibration were calculated. These calibrated parameters will be used for further processing in the experimental study.


```xml
<?xml version="1.0" encoding="UTF-8"?>
<calibration>
  <projection>frame</projection>
  <width>6000</width>
  <height>4000</height>
  <f>4607.5382883548918</f>
  <cx>32.819561268028032</cx>
  <cy>-57.553519603999511</cy>
  <b1>0.21571805957467546</b1>
  <b2>1.2697168315769469</b2>
  <k1>-0.10760831260001989</k1>
  <k2>0.043125633396674516</k2>
  <k3>-0.040769766940518273</k3>
  <k4>0.03668132188938427</k4>
  <p1>0.00010069941101074302</p1>
  <p2>-0.00064595178360849035</p2>
  <date>2023-07-16T05:40:52Z</date>
</calibration>
```


Table 7. Camera Calibration Paramters

4.4. Evaluating Oil Spill Route Using With Developed Algorithm

The present study involved the development of an algorithm utilizing the ArcGIS platform to detect pathways of petrol leakage. The analysis and interpretation of outcomes relied upon the DEM data and orthomosaic image generated via the Agisoft software. To accommodate the algorithm's requirement of a 16-bit pixel depth within ArcGIS, the images were rescaled to match this pixel depth.

Furthermore, the horizontal resolution of the DEM produced in Agisoft was initially observed to be around 1mm, which was deemed excessively high for achieving the algorithm's optimal performance. Furthermore, the horizontal length of the petroleum leakage in the narrowest section on the orthomosaic has been measured about 2cm and Considering that the error value of the control points was approximately 0.7 millimeters, it was decided to use a horizontal resolution of 1cm. The vertical resolution of the generated DEM data was scaled to 1mm for the study, as a height change of 0.5 centimeters was calculated in the studied area

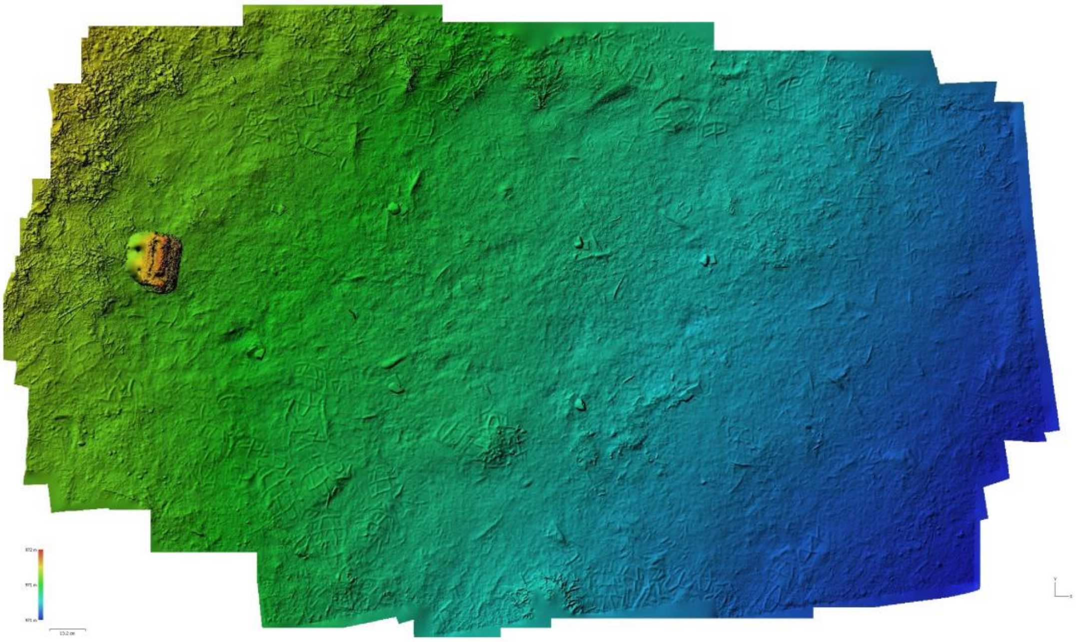


Figure 29. Agisoft Dem Result

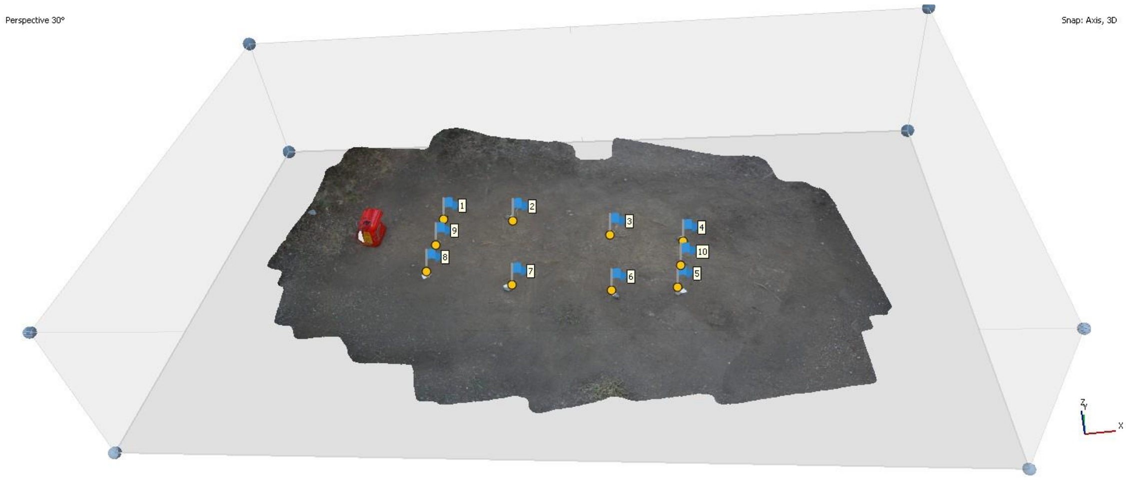


Figure 30. Orthomosaic image of the terrain before the gasoline was spilled

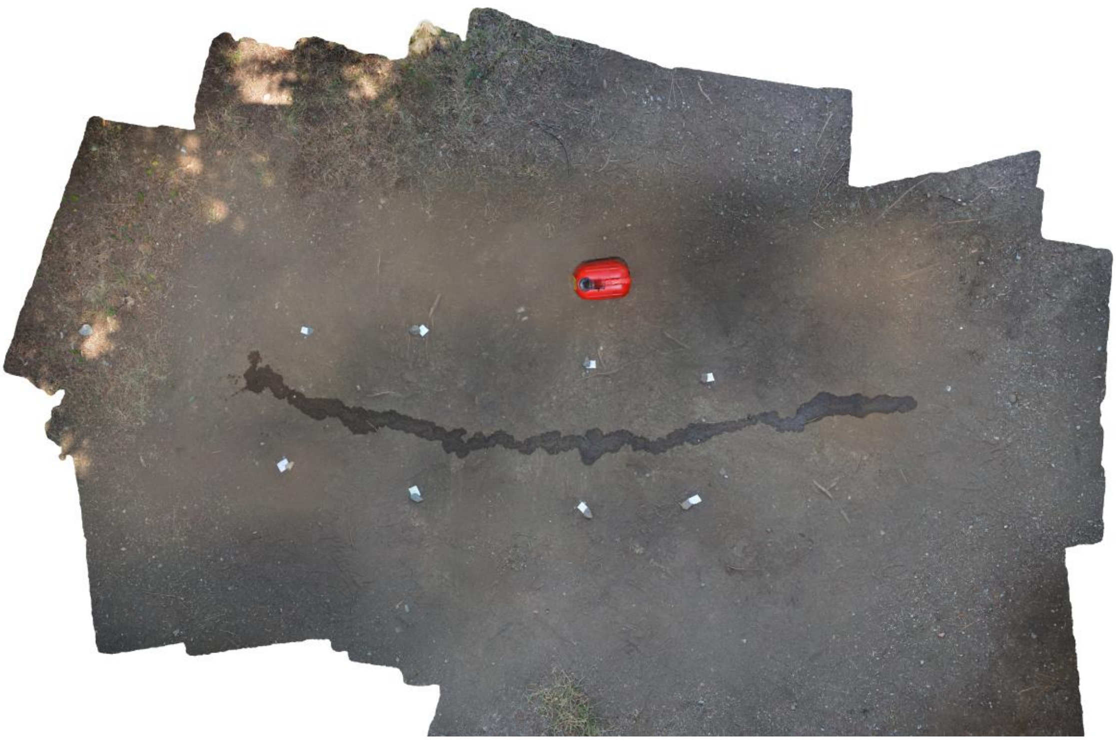


Figure 31. Orthomosaic image after the gasoline was spilled.

Figure 32. Generated Dem and Orthomosaic in ArcGIS

4.5. Experimental Study Results

The DEM and orthomosaic image generated using Agisoft were opened in the ArcGIS program (Figure 32). After the flow was completed, the leakage pathway was digitized using polygon geometry on the produced orthomosaic. Subsequently, the developed algorithm was applied to the re-evaluated DEM data to calculate the algorithmic flow pathway. The actual leakage pathway obtained from the orthomosaic was then compared with the leakage pathway generated by the algorithm (Figure 33).

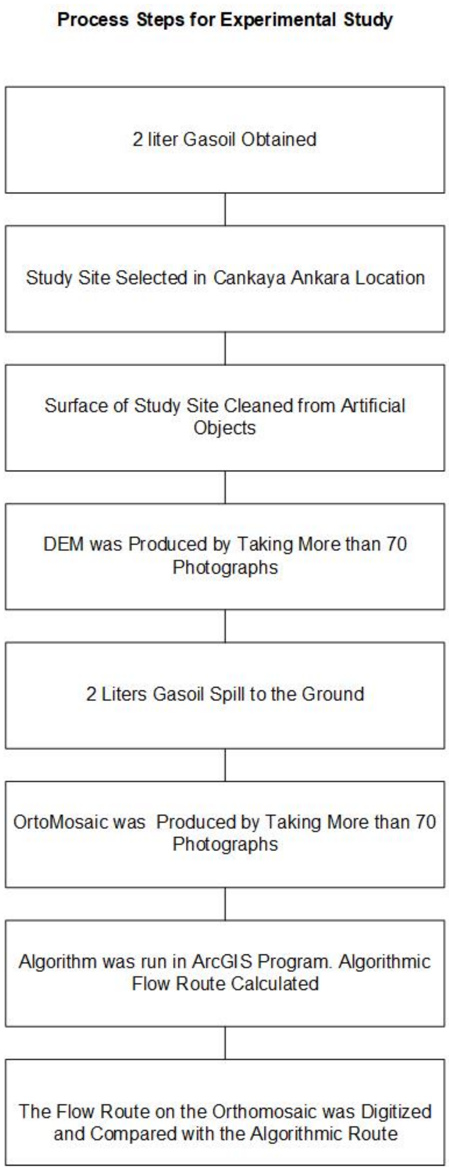


Figure 33. Experimental Study Steps

When comparing the results obtained through the algorithmic calculations with the real-world petroleum leakage route, the following conclusions have been drawn; the algorithm was able to achieve an accuracy of 84.75% when predicting the 2.5-meter-long real-world petroleum leakage route by analyzing 295 pixels out of which 250 pixels intersect with the actual route (Figure 34-35).

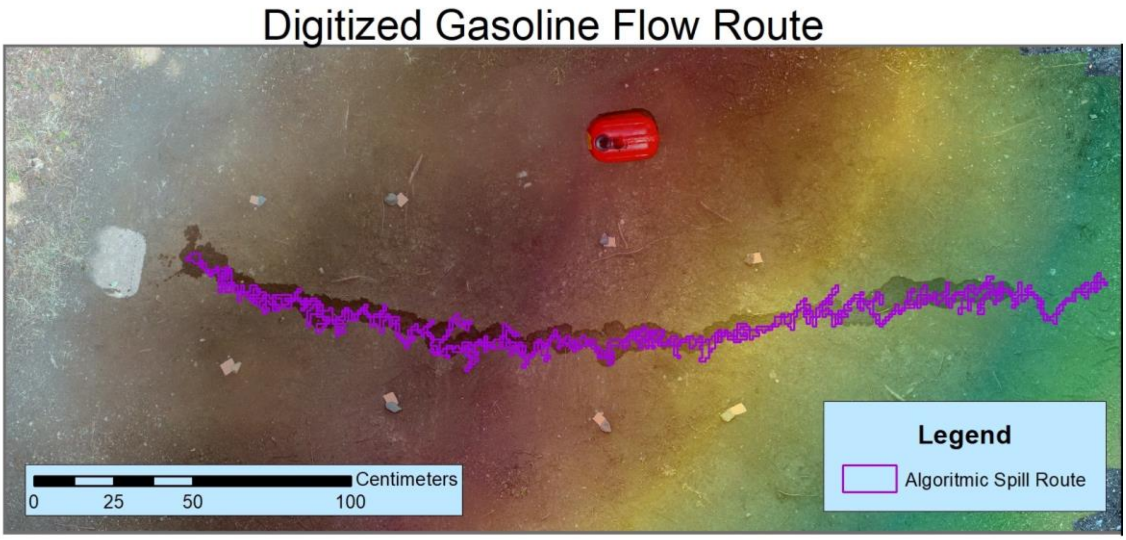


Figure 34. Compresion of Algorithmic and Real Spill Path

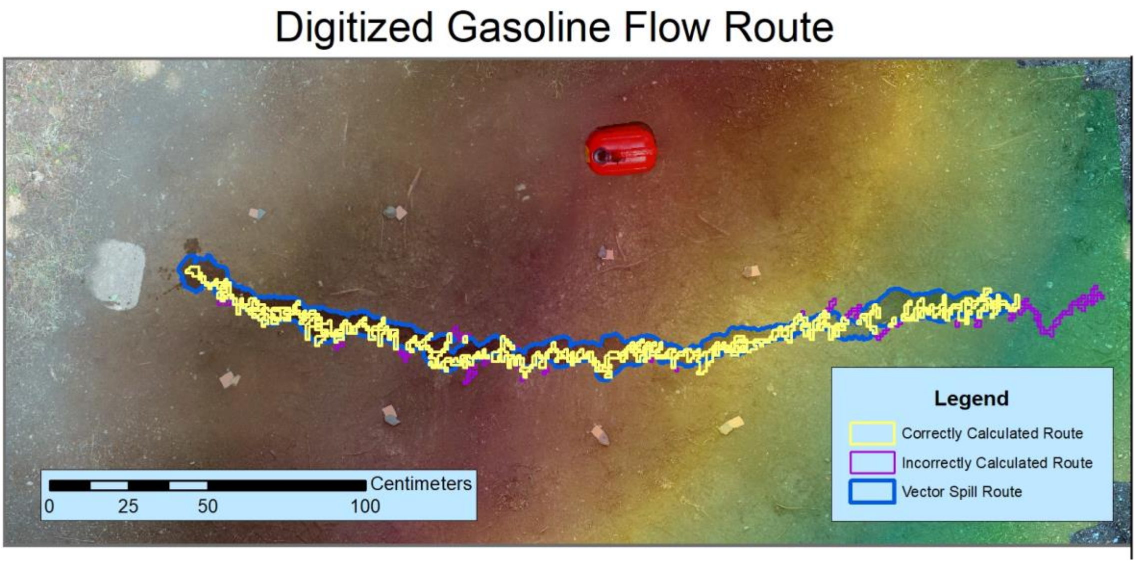


Figure 35. Results of Algorithmic and Real Spill Path

When the reason for the 84% error coming from was examined, it was seen that this problem was caused by the "Neighbor's Neighbor Problem" explained in section 3.3.3. While the algorithm determines pixels of equal height along the flow route, pixels with the same height are also included in the process due to vertical resolution. It was determined that when these pixels were excluded from the calculation, the pixel accuracy of the model in determining the route increased to 93%. During the process, pixels that were outside the route but provided the connection were included in the calculation (Figure 36-37)

	Accuracy Before Excluding Erroneous Pixels	Accuracy After Excluding Erroneous Pixels
Accuracy	%84	%93

Table 8. Final Oil Spill Result Table

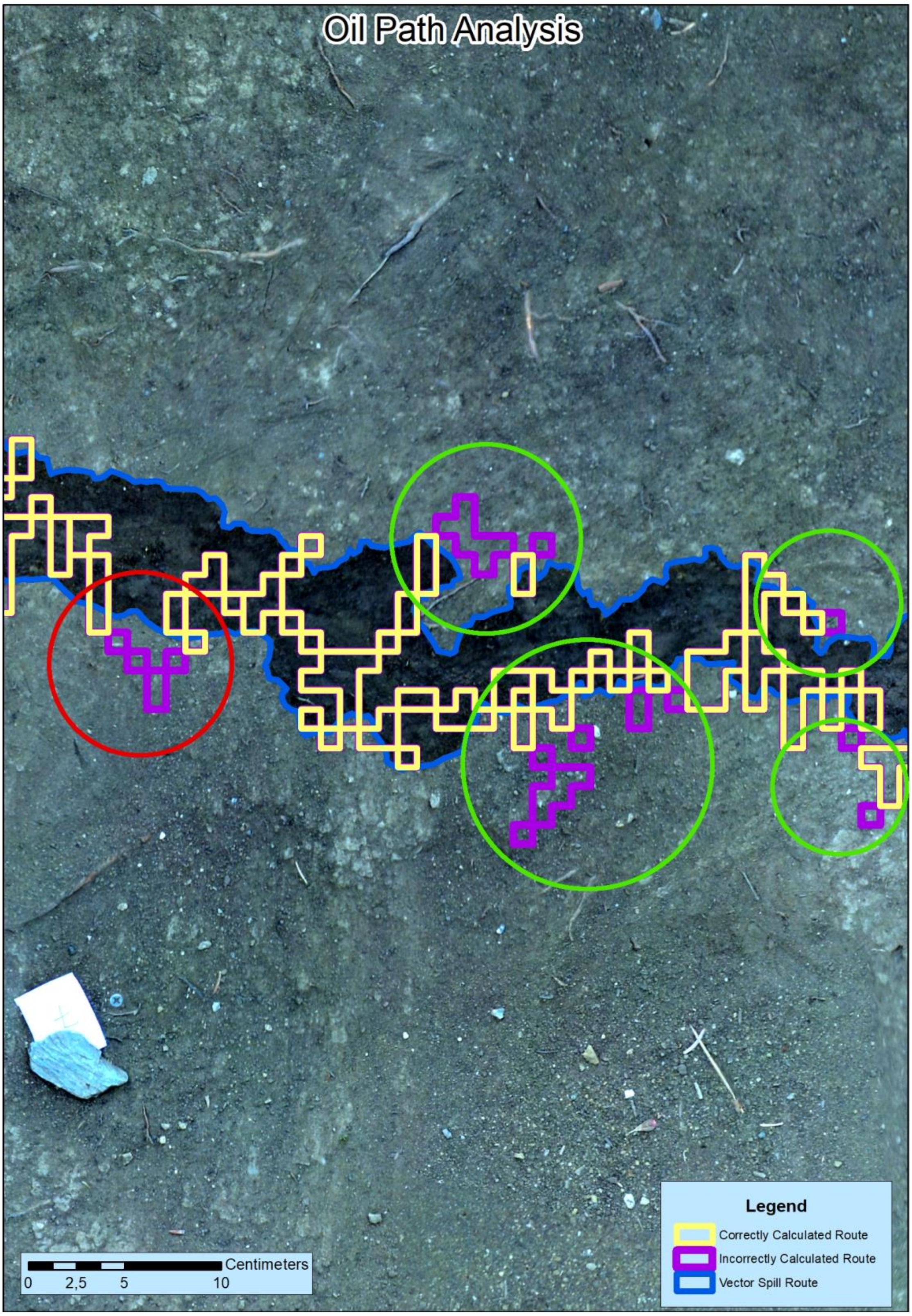


Figure 36. Oil Path Analysis Map

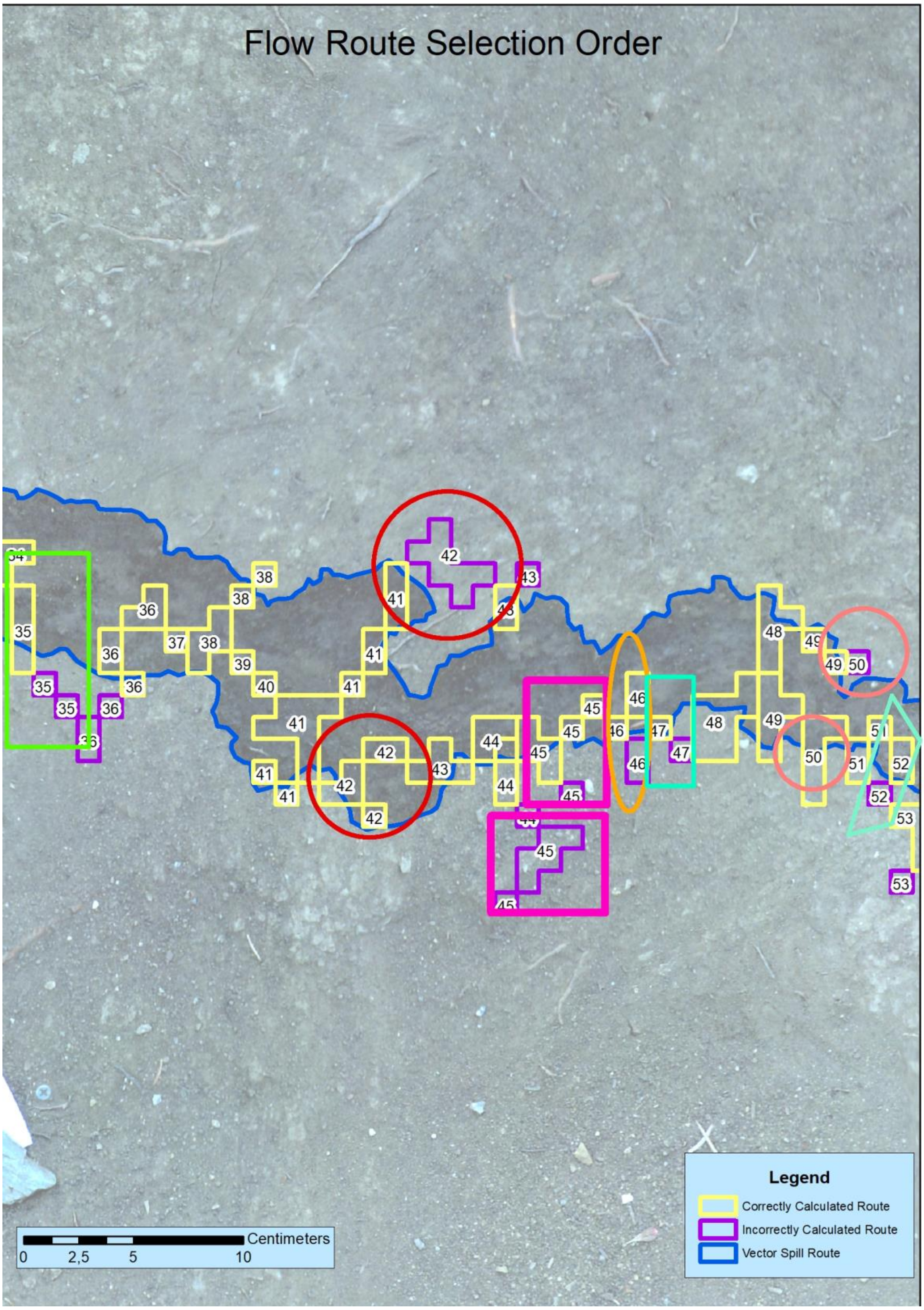


Figure 37. Flow Route Selection Order

5. CONCLUSION

In conclusion, this study has demonstrated the immense potential of Geographical Information Systems (GIS) base programming in planning oil pipeline routes and predicting potential oil spills. The research has first revealed how to find the optimal pipeline route that minimizes topological and geographical complexities. This approach ensures both environmental preservation and socio-economic sustainability. Moreover, the study examines how a determined volume of oil would spread on land surfaces, which will enable the implementation of proactive measures to reduce environmental oil pollution. In both solutions, unique algorithms were developed to enhance route optimization and spill route prediction.

This study has highlighted the importance of topographic classifications during pipeline route selection. These classifications involve identifying distinctive features such as ridges, flatlands, steep terrains, and water channels within a specific area, utilizing advanced GIS analyses. Also, the study has sought to understand the landscape as a continuous unit rather than seeing these components as discrete parts. In addition, the study has also introduced a simple pipeline path by removing complicated patterns and avoiding needless extra turns by using a line simplification algorithm. This strategy results in a more practical and realistic approach toward pipeline construction by removing high vertex points from the proposed route.

Reflecting on the study's results, significant enhancements in pipeline route planning have been observed after the line simplification algorithm was applied to the route. These enhancements include reducing the pipeline's total length from 155.83 kilometres to a more efficient 148.99 kilometres, representing a decrease in algorithmic cost of approximately 20%. This optimization has notably improved the pipeline's interactions with environmental obstacles and barriers.

Furthermore, the findings demonstrate that the results based on topographic classification have noticeably improved.

Furthermore, the research has exploited GIS technology, particularly Digital Elevation Models (DEMs), and state-of-the-art algorithms to predict possible pipeline leakages and spills. High-risk regions can be identified by assessing terrain slope, pipeline pressure, and soil type. This proactive approach enables effective emergency planning and better resource allocation and potentially mitigates the environmental impact of oil spills. In addition to the above, the study suggests that incorporating broader data sets, such as geological and lithological data, could further enhance the accuracy of pipeline route planning and spill prediction. The study also proposes intersecting the pipeline route with watershed boundaries and evaluating the results. This approach could lead to the identification of optimal valve locations, thereby enhancing the efficiency of the pipeline system and reducing the risk of oil spills. However, a limitation of this approach is that initially, the algorithm can identify only a single direction from the leak's starting point. To address this, it is proposed to run the algorithm at multiple randomly selected points in areas with anticipated leakage risks, thereby improving the accuracy and effectiveness in identifying potential leak paths.

The results of the algorithm developed for predicting oil spills have been simulated with real gasoile using photogrammetric acquisition. It has been observed that the spill route calculated by the algorithm aligns satisfactorily with the actual spill route. While the spill route was calculated with an 84% accuracy, it has been found that when pixels miscalculated due to sensitivity are disregarded; the accuracy increases to 93%.

This research has underscored the importance of merging GIS capabilities and innovative algorithms in pipeline route planning and spill prediction, thus reducing potential environmental damage from oil spills. The findings of this study can be instrumental in enhancing the efficiency of pipeline planning and construction, facilitating effective emergency planning, and mitigating the environmental impact of oil spills.

Future research should continue to explore and refine these methods, further improving the accuracy and efficiency of pipeline route planning and spill prediction. There are widespread crude oil pipelines in the world and terrestrial oil spill for crude oil can be added to the model. The behavior of crude oil, influenced by its viscosity and interaction with different soil types, presents complexities not covered in this study. This integration would greatly enhance the research and could lead to more inclusive models for pipeline spill predictions.

6. COMMENT

This document makes several significant contributions to the academic literature, particularly in Geographical Information Systems (GIS) and environmental management.

Firstly, the research introduces a novel approach to oil pipeline route planning that integrates GIS technology with a least-cost path algorithm. This innovative method addresses the complex issue of pipeline route selection, which has been a persistent challenge in the oil industry. The approach allows for considering various geographical and topological factors, thereby ensuring a more environmentally friendly and socio-economically sustainable pipeline route. This contribution expands the current understanding of pipeline route planning and provides a practical solution that industry practitioners can adopt.

Secondly, the document contributes to the literature by proposing a cartographic line simplification technique. This technique simplifies the pipeline route by reducing complex topological combinations and eliminating unnecessary detours. This strategy enhances the practicality and realism of pipeline construction, which has been a significant gap in the existing literature. The technique also has potential applications in other fields that involve route planning, such as transportation and logistics.

Thirdly, the research utilizes GIS technology and advanced algorithms to predict potential oil spills. This proactive approach to spill prediction significantly contributes to the literature, allowing for better emergency planning and resource allocation. The method can potentially mitigate the environmental impact of oil spills, a critical concern in the oil industry and environmental management.

Fourthly, the document emphasizes the importance of detailed topographic classifications in pipeline route selection. This approach views the landscape as a continuous unit rather than discrete parts, a novel perspective in the literature. This contribution can enhance the accuracy and efficiency of pipeline route planning and has potential implications for other fields that involve geographical planning.

Finally, the research demonstrates the effectiveness of a technology-driven method in pipeline route selection. This method can process and analyze large volumes of data quickly and accurately, thereby optimizing the selection process. This contribution is particularly relevant in the era of big data and has potential applications in various fields that involve data-driven decision-making.

In conclusion, this document substantially contributes to the academic literature by introducing innovative pipeline route planning and spill prediction methods. These contributions address critical challenges in the oil industry and potentially impact other fields. The research sets a new direction for future GIS and environmental management studies.

7. REFERENCES

[1] H. Wang, Y. Ge, L. Shi, Technologies in deep and ultra-deep well drilling: Present status, challenges and future trend in the 13th Five-Year Plan period (2016–2020), Natural Gas Industry B, 4 (2017).

[2] U.S.E.I. Administration, Thousand Barrels per Day U.S. , U.S. Energy Information Administration, 2023.

[3] F. 500, Global 500, Fortune 500, 2020.

[4] C. Aydin, S. Karadavut, The impact of increasing natural gas use on the environment and population in Ankara, Turkey, Fresenius Environmental Bulletin, 18 (2009) 1559-1566.

[5] S. Huseynli, Determination of the most suitable oil pipeline route using GIS least cost path analysis, 2015.

[6] cia.gov.tr, Field Listing Pipelines, https://www.cia.gov/, THE WORLD FACTBOOK, 2023.

[7] C.E. Smith, Worldwide Pipeline Construction: Crude, products plans push, OIL&GAS JOURNAL, (2013).

[8] B. Freedman, Environmental science : A Canadian perspective, 2nd ed., Toronto : Prentice Hall2001.

[9] C. Popescu, M.R. Gabor, Quantitative Analysis Regarding the Incidents to the Pipelines of Petroleum Products for an Efficient Use of the Specific Transportation Infrastructure, Processes, 9 (2021) 1535.

[10] Y. Xie, X. Ma, H. Ning, Z. Yuan, T. Xie, Energy efficiency evaluation of a natural gas pipeline based on an analytic hierarchy process, Advances in Mechanical Engineering, 9 (2017) 168781401771139.

[11] X. Hou, J. Zhou, L. Zhang, Q. Yang, Construction and measurement of China's comprehensive energy dependence index, Energy Reports, 7 (2021) 4516-4529.

[12] A.İ. Durmaz, E.Ö. Ünal, C.C. Aydın, Automatic Pipeline Route Design with Multi-Criteria Evaluation Based on Least-Cost Path Analysis and Line-Based

Cartographic Simplification: A Case Study of the Mus Project in Turkey, ISPRS International Journal of Geo-Information, 8 (2019) 173.

[13] V. Yildirim, T. Yomralioglu, R. Nisanci, H.E. Çolak, Ş. Bediroğlu, E. Saralioglu, A spatial multicriteria decision-making method for natural gas transmission pipeline routing, Structure and Infrastructure Engineering, 13 (2017) 567-580.

[14] T. Wu, Y. Chen, Z. Deng, L. Shen, Z. Xie, Y. Liu, S. Zhu, C. Liu, Y. Li, Oil pipeline leakage monitoring developments in China, Journal of Pipeline Science and Engineering, (2023) 100129.

[15] Pipeline Oil Spill Volume Estimator, Minerals Managemnt Services2002.

[16] M. Mishra, V. Keshavarzzadeh, A. Noshadravan, Reliability-based lifecycle management for corroding pipelines, Structural Safety, 76 (2019) 1-14.

[17] M. Al-Anbari, N. Al-Ansari, H. Jasim, GIS and Multicriteria Decision Analysis for Landfill Site Selection in Al-Hashimyah Qadaa, Natural Science, 06 (2014) 282-304.

[18] M.M. Najafabadi, F. Villanustre, T.M. Khoshgoftaar, N. Seliya, R. Wald, E. Muharemagic, Deep learning applications and challenges in big data analytics, Journal of Big Data, 2 (2015) 1.

[19] G. Kabir, R. Sadiq, S. Tesfamariam, A review of multi-criteria decision-making methods for infrastructure management, Structure & Infrastructure Engineering: Maintenance, 10 (2014).

[20] R. Khosravanian, D.A. Wood, Selection of high-rate gas well completion designs applying multi-criteria decision making and hierarchy methods, Journal of Natural Gas Science and Engineering, 34 (2016) 1004-1016.

[21] J.L. Osorio-Tejada, E. Llera-Sastresa, S. Scarpellini, A multi-criteria sustainability assessment for biodiesel and liquefied natural gas as alternative fuels in transport systems, Journal of Natural Gas Science and Engineering, 42 (2017) 169-186.

[22] A. Abudeif, A. Moneim, A.F. Farrag, Multicriteria decision analysis based on analytic hierarchy process in GIS environment for siting nuclear power plant in Egypt, Annals of Nuclear Energy, 75 (2015) 682-692.

[23] S.H. Terh, K. Cao, GIS-MCDA based cycling paths planning: a case study in Singapore, Applied Geography, 94 (2018) 107-118.

[24] J. Seyedmohammadi, F. Sarmadian, A.A. Jafarzadeh, M.A. Ghorbani, F. Shahbazi, Application of SAW, TOPSIS and fuzzy TOPSIS models in cultivation priority planning for maize, rapeseed and soybean crops, Geoderma, 310 (2018) 178-190.

[25] J.J. Kunda, J. Kunda, N. Anyanwu, A. Jajere, Land suitability analysis for agricultural planning using GIS and multi criteria decision analysis approach in Greater Karu Urban Area, Nasarawa State, Nigeria, (2013).

[26] S. Asadzadeh, C. Souza Filho, Spectral remote sensing for onshore seepage characterization: A critical overview, Earth-Science Reviews, 168 (2017).

[27] M. Fingas, C.E. Brown, A Review of Oil Spill Remote Sensing, Sensors, 18 (2018) 91.

[28] R. Jatiault, D. Dhont, L. Loncke, D. Dubucq, Monitoring of natural oil seepage in the Lower Congo Basin using SAR observations, Remote Sensing of Environment, 191 (2017) 258-272.

[29] R. Lardner, G. Zodiatis, Modelling oil plumes from subsurface spills, Marine Pollution Bulletin, 124 (2017) 94-101.

[30] M. Gług, J. Wąs, Modeling of oil spill spreading disasters using combination of Langrangian discrete particle algorithm with Cellular Automata approach, Ocean Engineering, 156 (2018) 396-405.

[31] M. Nevalainen, I. Helle, J. Vanhatalo, Estimating the acute impacts of Arctic marine oil spills using expert elicitation, Marine Pollution Bulletin, 131 (2018) 782-792.

[32] A.-L. Balogun, S.T. Yekeen, B. Pradhan, K.B. Wan Yusof, Oil spill trajectory modelling and environmental vulnerability mapping using GNOME model and GIS, Environmental Pollution, 268 (2021) 115812.

[33] V. Ciriello, I. Lauriola, S. Bonvicini, V. Cozzani, V. Di Federico, D.M. Tartakovsky, Impact of Hydrogeological Uncertainty on Estimation of Environmental Risks Posed by Hydrocarbon Transportation Networks, Water Resources Research, 53 (2017) 8686-8697.

[34] S. Liu, W. Yi, Y. Liang, Environmental consequence analysis of oil spills from onshore pipelines with parametric uncertainty, Process Safety and Environmental Protection, 141 (2020).

[35] S. Bonvicini, G. Antonioni, V. Cozzani, Assessment of the risk related to environmental damage following major accidents in onshore pipelines, Journal of Loss Prevention in the Process Industries, 56 (2018) 505-516.

[36] J. Durango-Cordero, M. Saqalli, C. Laplanche, M. Locquet, A. Elger, Spatial Analysis of Accidental Oil Spills Using Heterogeneous Data: A Case Study from the North-Eastern Ecuadorian Amazon, Sustainability, 10 (2018) 4719.

[37] A.S. Akinwumiju, A.A. Adelodun, S.E. Ogundeji, Geospatial assessment of oil spill pollution in the Niger Delta of Nigeria: An evidence-based evaluation of causes and potential remedies, Environ Pollut, 267 (2020) 115545.

[38] Computes flowlines, flowpath lengths, and flowaccumulation, 2023.

[39] r.watershed - Calculates hydrological parameters and RUSLE factors.

[40] Flow Accumulation.

[41] Flow Direction.

[42] G. Saritha, T. Saravanan, K. Anbumani, J. Surendiran, Digital elevation model and terrain mapping using LiDAR, Materials Today: Proceedings, 46 (2021) 3979-3983.

[43] W. Jiang, J. Yu, Q. Wang, Q. Yue, Understanding the effects of digital elevation model resolution and building treatment for urban flood modelling, Journal of Hydrology: Regional Studies, 42 (2022) 101122.

[44] T.-N.-D. Tran, B.Q. Nguyen, N.D. Vo, M.-H. Le, Q.-D. Nguyen, V. Lakshmi, J.D. Bolten, Quantification of global Digital Elevation Model (DEM) – A case study of the newly released NASADEM for a river basin in Central Vietnam, Journal of Hydrology: Regional Studies, 45 (2023) 101282.

[45] Z. Li, T. Yang, C.-Y. Xu, P. Shi, B. Yong, C.-s. Huang, C. Wang, Evaluating the area and position accuracy of surface water paths obtained by flow direction algorithms, Journal of Hydrology, 583 (2020) 124619.

[46] K. de Jong, D. Panja, D. Karssenberg, M. van Kreveld, Scalability and composability of flow accumulation algorithms based on asynchronous many-tasks, Computers & Geosciences, 162 (2022) 105083.

[47] M. Ligas, P. Banasik, Conversion between Cartesian and geodetic coordinates on a rotational ellipsoid by solving a system of nonlinear equations, Geodesy and Cartography, 60 (2011) 145-159.

[48] W.C. Wedley, Consistency prediction for incomplete AHP matrices, Mathematical and Computer Modelling, 17 (1993) 151-161.

[49] S. Bagli, D. Geneletti, F. Orsi, Routeing of power lines through least-cost path analysis and multicriteria evaluation to minimise environmental impacts, Environmental Impact Assessment Review, 31 (2011) 234-239.

[50] D.M. Atkinson, P. Deadman, D. Dudycha, S. Traynor, Multi-criteria evaluation and least cost path analysis for an arctic all-weather road, Applied Geography, 25 (2005) 287-307.

[51] J.A. Greenberg, C. Rueda, E.L. Hestir, M.J. Santos, S.L. Ustin, Least cost distance analysis for spatial interpolation, Computers & Geosciences, 37 (2011) 272-276.

[52] B. Liu, X. Liu, D. Li, Y. Shi, G. Fernandez, Y. Wang, A Vector Line Simplification Algorithm Based on the Douglas–Peucker Algorithm, Monotonic Chains and Dichotomy, ISPRS International Journal of Geo-Information, 9 (2020) 251.

[53] S.E. Chang, J. Stone, K. Demes, M. Piscitelli, Consequences of oil spills

a review and framework for informing planning, Ecology and Society, 19 (2014).

[54] S.Z. Halim, M. Yu, H. Escobar, N. Quddus, Towards a causal model from pipeline incident data analysis, Process Safety and Environmental Protection, 143 (2020) 348-360.

[55] R.D.C.F.S. Silva, D.G. Almeida, R.D. Rufino, J.M. Luna, V.A. Santos, L.A. Sarubbo, Applications of Biosurfactants in the Petroleum Industry and the Remediation of Oil Spills, International Journal of Molecular Sciences, 15 (2014) 12523-12542.

[56] M. Fahimipirehgalin, E. Trunzer, M. Odenweller, B. Vogel-Heuser, Automatic Visual Leakage Detection and Localization from Pipelines in Chemical Process Plants Using Machine Vision Techniques, Engineering, 7 (2021) 758-776.

[57] T. Spyridopoulos, T. Tryfonas, J. May, Incident Analysis & Digital Forensics in SCADA and Industrial Control Systems, IET Conference Proceedings, Institution of Engineering and Technology, 2013, pp. 6.1-6.1.

[58] G. Geiger, T. Hazel, D. Vogt, Integrated SCADA-based approach for pipeline security and operation, 2010 Record of Conference Papers Industry Applications Society 57th Annual Petroleum and Chemical Industry Conference (PCIC), 2010, pp. 1-8.

[59] J.I. Chang, C.-C. Lin, A study of storage tank accidents, Journal of Loss Prevention in the Process Industries, 19 (2006) 51-59.

[60] H. Ibrahim, Hazard Analysis of Crude Oil Storage Tank Farm, International Journal of ChemTech Research, (2018).

[61] U.S.D.o.t. Interior, Pipeline Oil Spill Volume Estimator Paperback, CreateSpace Independent Publishing Platform2015.

[62] S.K. Jenson, J.O. Domingue, Extracting topographic structure from digital elevation data for geographic information-system analysis, Photogrammetric Engineering and Remote Sensing, 54 (1988) 1593-1600.

[63] N.C. Noya, Á.L. García, F.C. Ramírez, Combining photogrammetry and photographic enhancement techniques for the recording of megalithic art in north-west Iberia, Digital Applications in Archaeology and Cultural Heritage, 2 (2015) 89-101.

[64] T. Luhmann, C. Fraser, H.-G. Maas, Sensor modelling and camera calibration for close-range photogrammetry, ISPRS Journal of Photogrammetry and Remote Sensing, 115 (2016) 37-46.

[65] H.A. Sadeq, Accuracy assessment using different UAV image overlaps, Journal of Unmanned Vehicle Systems, 7 (2019) 175-193.

ATTACHMENTS

APPENDIX 1 – Surveys

Determining the Pipeline Route: Prioritizing Environmental and Infrastructure Elements

Dear participant,

Thank you for agreeing to take part in this survey. Your input will significantly contribute to determining the most appropriate route for a proposed pipeline. The purpose of this survey is to assess the relative importance of various environmental and infrastructure components in order to find the most optimal pipeline route.

Before we begin, let's clarify how to fill out the survey:

Example Question: Forest vs. Grassland? ___

In this question, you're asked to decide between a forest and a grassland. If you believe the forest is less critical when considering the pipeline route, underline or circle "Forest". Then, assign a number from 1 to 9 to denote its priority or importance. For instance, if you believe it's of low importance, you might assign it a 2.

So, your completed answer might appear as: Forest vs. Grassland? 2

In the event that you consider both options to be of equal importance, you should underline or circle both, and write '1' next to both.

Now, please continue with the survey.

Section 1: Natural Landforms

1. Ridges vs Flat land ? 2
2. Ridges vs Steep terrain ? 4
3. Ridges vs Streams ? 2
4. Flat land vs Ridges ? 2
5. Flat land vs Steep terrain ? 3
6. Flat land vs Streams ? 2
7. Steep terrain vs Ridges ? 4
8. Steep terrain vs Flat land ? 3
9. Steep terrain vs Streams ? 2
10. Streams vs Ridges ? 1
11. Streams vs Flat land ? 3
12. Streams vs Steep terrain ? 2

1

13. Dam Reservoirs vs Wet Lands ? 3
14. Dam Reservoirs vs Water Channel ? 1
15. Dam Reservoirs vs Power Lines ? 2
16. Dam Reservoirs vs Fault Lines ? 1
17. Dam Reservoirs vs Agricultural Irrigation Channel ? 3
18. Dam Reservoirs vs Highways ? 2
19. Wet Lands vs Dam Reservoirs ? 3
20. Wet Lands vs Water Channel ? 4
21. Wet Lands vs Power Lines ? 2
22. Wet Lands vs Fault Lines ? 4
23. Wet Lands vs Agricultural Irrigation Channel ? 3
24. Wet Lands vs Highways ? 1
25. Water Channel vs Dam Reservoirs ? 1
26. Water Channel vs Wet Lands ? 4
27. Water Channel vs Power Lines ? 2
28. Water Channel vs Fault Lines ? 1
29. Water Channel vs Agricultural Irrigation Channel ? 1
30. Water Channel vs Highways ? 1
31. Power Lines vs Dam Reservoirs ? 1
32. Power Lines vs Wet Lands ? 2
33. Power Lines vs Water Channel ? 2
34. Power Lines vs Fault Lines ? 2
35. Power Lines vs Agricultural Irrigation Channel ? 1
36. Power Lines vs Highways ? 2
37. Fault Lines vs Dam Reservoirs ? 1
38. Fault Lines vs Wet Lands ? 4
39. Fault Lines vs Water Channel ? 2
40. Fault Lines vs Power Lines ? 2

41. Fault Lines vs Agricultural Irrigation Channel ? 3

42. Fault Lines vs Highways ? 2

43. Agricultural Irrigation Channel vs Dam Reservoirs ? 3

44. Agricultural Irrigation Channel vs Wet Lands ? 3

45. Agricultural Irrigation Channel vs Water Channel ? 2

46. Agricultural Irrigation Channel vs Power Lines ? 3

47. Agricultural Irrigation Channel vs Fault Lines ? 3

48. Agricultural Irrigation Channel vs Highways ? 1

49. Highways vs Dam Reservoirs ? 2

50. Highways vs Wet Lands ? 1

51. Highways vs Water Channel ? 1

52. Highways vs Power Lines ? 2

53. Highways vs Fault Lines ? 2

54. Highways vs Agricultural Irrigation Channel ? 1

We greatly value your insights and appreciate your contribution to this important process. Thank you for your time and input.

Determining the Pipeline Route: Prioritizing Environmental and Infrastructure Elements

Dear participant,

Thank you for agreeing to take part in this survey. Your input will significantly contribute to determining the most appropriate route for a proposed pipeline. The purpose of this survey is to assess the relative importance of various environmental and infrastructure components in order to find the most optimal pipeline route.

Before we begin, let's clarify how to fill out the survey:

Example Question: Forest vs. Grassland? ___

In this question, you're asked to decide between a forest and a grassland. If you believe the forest is less critical when considering the pipeline route, underline or circle "Forest". Then, assign a number from 1 to 9 to denote its priority or importance. For instance, if you believe it's of low importance, you might assign it a 2.

So, your completed answer might appear as: Forest vs. Grassland? 2

In the event that you consider both options to be of equal importance, you should underline or circle both, and write '1' next to both.

Now, please continue with the survey.

Section 1: Natural Landforms

1. Ridges vs Flat land ? 1
2. Ridges vs Steep terrain ? 3
3. Ridges vs Streams ? 3
4. Flat land vs Ridges ? 2
5. Flat land vs Steep terrain ? 3
6. Flat land vs Streams ? 2
7. Steep terrain vs Ridges ? 4
8. Steep terrain vs Flat land ? 3
9. Steep terrain vs Streams ? 2
10. Streams vs Ridges ? 1
11. Streams vs Flat land ? 3
12. Streams vs Steep terrain ? 2

1

13. Dam Reservoirs vs Wet Lands ? 2
14. Dam Reservoirs vs Water Channel ? 1
15. Dam Reservoirs vs Power Lines ? 2
16. Dam Reservoirs vs Fault Lines ? 1
17. Dam Reservoirs vs Agricultural Irrigation Channel ? 3
18. Dam Reservoirs vs Highways ? 2
19. Wet Lands vs Dam Reservoirs ? 3
20. Wet Lands vs Water Channel ? 4
21. Wet Lands vs Power Lines ? 2
22. Wet Lands vs Fault Lines ? 4
23. Wet Lands vs Agricultural Irrigation Channel ? 3
24. Wet Lands vs Highways ? 1
25. Water Channel vs Dam Reservoirs ? 1
26. Water Channel vs Wet Lands ? 4
27. Water Channel vs Power Lines ? 2
28. Water Channel vs Fault Lines ? 1
29. Water Channel vs Agricultural Irrigation Channel ? 2
30. Water Channel vs Highways ? 1
31. Power Lines vs Dam Reservoirs ? 1
32. Power Lines vs Wet Lands ? 2
33. Power Lines vs Water Channel ? 2
34. Power Lines vs Fault Lines ? 2
35. Power Lines vs Agricultural Irrigation Channel ? 1
36. Power Lines vs Highways ? 2
37. Fault Lines vs Dam Reservoirs ? 2
38. Fault Lines vs Wet Lands ? 2
39. Fault Lines vs Water Channel ? 3
40. Fault Lines vs Power Lines ? 2

41. Fault Lines vs Agricultural Irrigation Channel ? 3

42. Fault Lines vs Highways ? 2

43. Agricultural Irrigation Channel vs Dam Reservoirs ? 3

44. Agricultural Irrigation Channel vs Wet Lands ? 3

45. Agricultural Irrigation Channel vs Water Channel ? 2

46. Agricultural Irrigation Channel vs Power Lines ? 3

47. Agricultural Irrigation Channel vs Fault Lines ? 3

48. Agricultural Irrigation Channel vs Highways ? 1

49. Highways vs Dam Reservoirs ? 2

50. Highways vs Wet Lands ? 1

51. Highways vs Water Channel ? 1

52. Highways vs Power Lines ? 2

53. Highways vs Fault Lines ? 2

54. Highways vs Agricultural Irrigation Channel ? 1

We greatly value your insights and appreciate your contribution to this important process. Thank you for your time and input.

Determining the Pipeline Route: Prioritizing Environmental and Infrastructure Elements

Dear participant,

Thank you for agreeing to take part in this survey. Your input will significantly contribute to determining the most appropriate route for a proposed pipeline. The purpose of this survey is to assess the relative importance of various environmental and infrastructure components in order to find the most optimal pipeline route.

Before we begin, let's clarify how to fill out the survey:

Example Question: Forest vs. Grassland? ___

In this question, you're asked to decide between a forest and a grassland. If you believe the forest is less critical when considering the pipeline route, underline or circle "Forest". Then, assign a number from 1 to 9 to denote its priority or importance. For instance, if you believe it's of low importance, you might assign it a 2.

So, your completed answer might appear as: (Forest) vs. Grassland? 2

In the event that you consider both options to be of equal importance, you should underline or circle both, and write '1' next to both.

Now, please continue with the survey.

Section 1: Natural Landforms

1. Ridges vs Flat land ? 3
2. Ridges vs Steep terrain ? 2
3. Ridges vs Streams ? 2
4. Flat land vs Ridges ? 1
5. Flat land vs Steep terrain ? 2
6. Flat land vs Streams ? 3
7. Steep terrain vs Ridges ? 3
8. Steep terrain vs Flat land ? 2
9. Steep terrain vs Streams ? 3
10. Streams vs Ridges ? 3
11. Streams vs Flat land ? 2
12. Streams vs Steep terrain ? 3

1

Section 2: Infrastructure Elements

13. Dam Reservoirs vs Wet Lands ? 2
14. Dam Reservoirs vs Water Channel ? 1
15. Dam Reservoirs vs Power Lines ? 1
16. Dam Reservoirs vs Fault Lines ? 2
17. Dam Reservoirs vs Agricultural Irrigation Channel ? 2
18. Dam Reservoirs vs Highways ? 3
19. Wet Lands vs Dam Reservoirs ? 2
20. Wet Lands vs Water Channel ? 2
21. Wet Lands vs Power Lines ? 1
22. Wet Lands vs Fault Lines ? 2
23. Wet Lands vs Agricultural Irrigation Channel ? 1
24. Wet Lands vs Highways ? 2
25. Water Channel vs Dam Reservoirs ? 2
26. Water Channel vs Wet Lands ? 2
27. Water Channel vs Power Lines ? 2
28. Water Channel vs Fault Lines ? 3
29. Water Channel vs Agricultural Irrigation Channel ? 2
30. Water Channel vs Highways ? 2
31. Power Lines vs Dam Reservoirs ? 1
32. Power Lines vs Wet Lands ? 3
33. Power Lines vs Water Channel ? 1
34. Power Lines vs Fault Lines ? 2
35. Power Lines vs Agricultural Irrigation Channel ? 1
36. Power Lines vs Highways ? 2
37. Fault Lines vs Dam Reservoirs ? 3
38. Fault Lines vs Wet Lands ? 5
39. Fault Lines vs Water Channel ? 2
40. Fault Lines vs Power Lines ? 2

41. Fault Lines vs Agricultural Irrigation Channel ? ___3___

42. Fault Lines vs Highways ? ___5___

43. Agricultural Irrigation Channel vs Dam Reservoirs ? ___3___

44. Agricultural Irrigation Channel vs Wet Lands ? ___2___

45. Agricultural Irrigation Channel vs Water Channel ? ___1___

46. Agricultural Irrigation Channel vs Power Lines ? ___1___

47. Agricultural Irrigation Channel vs Fault Lines ? ___3___

48. Agricultural Irrigation Channel vs Highways ? ___2___

49. Highways vs Dam Reservoirs ? ___2___

50. Highways vs Wet Lands ? ___2___

51. Highways vs Water Channel ? ___2___

52. Highways vs Power Lines ? ___2___

53. Highways vs Fault Lines ? ___5___

54. Highways vs Agricultural Irrigation Channel ? ___2___

We greatly value your insights and appreciate your contribution to this important process. Thank you for your time and input.

Determining the Pipeline Route: Prioritizing Environmental and Infrastructure Elements

Dear participant,

Thank you for agreeing to take part in this survey. Your input will significantly contribute to determining the most appropriate route for a proposed pipeline. The purpose of this survey is to assess the relative importance of various environmental and infrastructure components in order to find the most optimal pipeline route.

Before we begin, let's clarify how to fill out the survey:

Example Question: Forest vs. Grassland? ___

In this question, you're asked to decide between a forest and a grassland. If you believe the forest is less critical when considering the pipeline route, underline or circle "Forest". Then, assign a number from 1 to 9 to denote its priority or importance. For instance, if you believe it's of low importance, you might assign it a 2.

So, your completed answer might appear as: (Forest) vs. Grassland? 2

In the event that you consider both options to be of equal importance, you should underline or circle both, and write '1' next to both.

Now, please continue with the survey.

Section 1: Natural Landforms

1. Ridges vs Flat land ? 3
2. Ridges vs Steep terrain ? 5
3. Ridges vs Streams ? 1
4. Flat land vs Ridges ? 3
5. Flat land vs Steep terrain ? 2
6. Flat land vs Streams ? 4
7. Steep terrain vs Ridges ? 4
8. Steep terrain vs Flat land ? 2
9. Steep terrain vs Streams ? 2
10. Streams vs Ridges ? 1
11. Streams vs Flat land ? 2
12. Streams vs Steep terrain ? 2

Section 2: Infrastructure Elements

13. Dam Reservoirs vs Wet Lands ? 3
14. Dam Reservoirs vs Water Channel ? 2
15. Dam Reservoirs vs Power Lines ? 3
16. Dam Reservoirs vs Fault Lines ? 3
17. Dam Reservoirs vs Agricultural Irrigation Channel ? 3
18. Dam Reservoirs vs Highways ? 3
19. Wet Lands vs Dam Reservoirs ? 3
20. Wet Lands vs Water Channel ? 4
21. Wet Lands vs Power Lines ? 3
22. Wet Lands vs Fault Lines ? 4
23. Wet Lands vs Agricultural Irrigation Channel ? 1
24. Wet Lands vs Highways ? 2
25. Water Channel vs Dam Reservoirs ? 2
26. Water Channel vs Wet Lands ? 4
27. Water Channel vs Power Lines ? 3
28. Water Channel vs Fault Lines ? 4
29. Water Channel vs Agricultural Irrigation Channel ? 1
30. Water Channel vs Highways ? 2
31. Power Lines vs Dam Reservoirs ? 3
32. Power Lines vs Wet Lands ? 3
33. Power Lines vs Water Channel ? 2
34. Power Lines vs Fault Lines ? 3
35. Power Lines vs Agricultural Irrigation Channel ? 1
36. Power Lines vs Highways ? 1
37. Fault Lines vs Dam Reservoirs ? 3
38. Fault Lines vs Wet Lands ? 4
39. Fault Lines vs Water Channel ? 4
40. Fault Lines vs Power Lines ? 1

41. Fault Lines vs Agricultural Irrigation Channel ? ____3____

42. Fault Lines vs Highways ? ____4____

43. Agricultural Irrigation Channel vs Dam Reservoirs ? ____2____

44. Agricultural Irrigation Channel vs Wet Lands ? ____2____

45. Agricultural Irrigation Channel vs Water Channel ? ____1____

46. Agricultural Irrigation Channel vs Power Lines ? ____1____

47. Agricultural Irrigation Channel vs Fault Lines ? ____3____

48. Agricultural Irrigation Channel vs Highways ? ____1____

49. Highways vs Dam Reservoirs ? ____3____

50. Highways vs Wet Lands ? ____2____

51. Highways vs Water Channel ? ____2____

52. Highways vs Power Lines ? ____1____

53. Highways vs Fault Lines ? ____4____

54. Highways vs Agricultural Irrigation Channel ? ____1____

We greatly value your insights and appreciate your contribution to this important process. Thank you for your time and input.

Determining the Pipeline Route: Prioritizing Environmental and Infrastructure Elements

Dear participant,

Thank you for agreeing to take part in this survey. Your input will significantly contribute to determining the most appropriate route for a proposed pipeline. The purpose of this survey is to assess the relative importance of various environmental and infrastructure components in order to find the most optimal pipeline route.

Before we begin, let's clarify how to fill out the survey:

Example Question: Forest vs. Grassland? ___

In this question, you're asked to decide between a forest and a grassland. If you believe the forest is less critical when considering the pipeline route, underline or circle "Forest". Then, assign a number from 1 to 9 to denote its priority or importance. For instance, if you believe it's of low importance, you might assign it a 2.

So, your completed answer might appear as: Forest vs. Grassland? 2

In the event that you consider both options to be of equal importance, you should underline or circle both, and write '1' next to both.

Now, please continue with the survey.

Section 1: Natural Landforms

1. Ridges vs Flat land ? 2
2. Ridges vs Steep terrain ? 2
3. Ridges vs Streams ? 3
4. Flat land vs Ridges ? ~~X~~ 2
5. Flat land vs Steep terrain ? 3 (Steep terrain)
6. Flat land vs Streams ? 1
7. Steep terrain vs Ridges ? 2
8. Steep terrain vs Flat land ? 3
9. Steep terrain vs Streams ? 3
10. Streams vs Ridges ? 2
11. Streams vs Flat land ? 3
12. Streams vs Steep terrain ? 3

1

Section 2: Infrastructure Elements

13. Dam Reservoirs vs Wet Lands ? 4
14. Dam Reservoirs vs Water Channel ? 1
15. Dam Reservoirs vs Power Lines ? 2
16. Dam Reservoirs vs Fault Lines ? 2
17. Dam Reservoirs vs Agricultural Irrigation Channel ? 4
18. Dam Reservoirs vs Highways ? 1
19. Wet Lands vs Dam Reservoirs ? 3
20. Wet Lands vs Water Channel ? 4
21. Wet Lands vs Power Lines ? 4
22. Wet Lands vs Fault Lines ? 5
23. Wet Lands vs Agricultural Irrigation Channel ? 4
24. Wet Lands vs Highways ? 2
25. Water Channel vs Dam Reservoirs ? 1
26. Water Channel vs Wet Lands ? 4
27. Water Channel vs Power Lines ? 3
28. Water Channel vs Fault Lines ? 2
29. Water Channel vs Agricultural Irrigation Channel ? 2
30. Water Channel vs Highways ? 2
31. Power Lines vs Dam Reservoirs ? 2
32. Power Lines vs Wet Lands ? 4
33. Power Lines vs Water Channel ? 1
34. Power Lines vs Fault Lines ? 2
35. Power Lines vs Agricultural Irrigation Channel ? 2
36. Power Lines vs Highways ? 1
37. Fault Lines vs Dam Reservoirs ? ~~4~~ 2
38. Fault Lines vs Wet Lands ? 5
39. Fault Lines vs Water Channel ? 2
40. Fault Lines vs Power Lines ? 2

41. Fault Lines vs Agricultural Irrigation Channel ? 2

42. Fault Lines vs Highways ? 4

43. Agricultural Irrigation Channel vs Dam Reservoirs ? 4

44. Agricultural Irrigation Channel vs Wet Lands ? 4

45. Agricultural Irrigation Channel vs Water Channel ? 1

46. Agricultural Irrigation Channel vs Power Lines ? 1

47. Agricultural Irrigation Channel vs Fault Lines ? 2

48. Agricultural Irrigation Channel vs Highways ? 2

49. Highways vs Dam Reservoirs ? 2

50. Highways vs Wet Lands ? 2

51. Highways vs Water Channel ? 2

52. Highways vs Power Lines ? 3

53. Highways vs Fault Lines ? 4

54. Highways vs Agricultural Irrigation Channel ? 2

We greatly value your insights and appreciate your contribution to this important process. Thank you for your time and input.

Determining the Pipeline Route: Prioritizing Environmental and Infrastructure Elements

Dear participant,

Thank you for agreeing to take part in this survey. Your input will significantly contribute to determining the most appropriate route for a proposed pipeline. The purpose of this survey is to assess the relative importance of various environmental and infrastructure components in order to find the most optimal pipeline route.

Before we begin, let's clarify how to fill out the survey:

Example Question: Forest vs. Grassland? ___

In this question, you're asked to decide between a forest and a grassland. If you believe the forest is less critical when considering the pipeline route, underline or circle "Forest". Then, assign a number from 1 to 9 to denote its priority or importance. For instance, if you believe it's of low importance, you might assign it a 2.

So, your completed answer might appear as: Forest vs. Grassland? 2

In the event that you consider both options to be of equal importance, you should underline or circle both, and write '1' next to both.

Now, please continue with the survey.

Section 1: Natural Landforms

1. Ridges vs Flat land ? ___3___
2. Ridges vs Steep terrain ? ___3___
3. Ridges vs Streams ? ___2___
4. Flat land vs Ridges ? ___2___
5. Flat land vs Steep terrain ? ___1___
6. Flat land vs Streams ? ___2___
7. Steep terrain vs Ridges ? ___3___
8. Steep terrain vs Flat land ? ___1___
9. Steep terrain vs Streams ? ___2___
10. Streams vs Ridges ? ___2___
11. Streams vs Flat land ? ___4___
12. Streams vs Steep terrain ? ___2___

1

Section 2: Infrastructure Elements

13. Dam Reservoirs vs Wet Lands ? 2
14. Dam Reservoirs vs Water Channel ? 1
15. Dam Reservoirs vs Power Lines ? 2
16. Dam Reservoirs vs Fault Lines ? 2
17. Dam Reservoirs vs Agricultural Irrigation Channel ? 4
18. Dam Reservoirs vs Highways ? 2
19. Wet Lands vs Dam Reservoirs ? 2
20. Wet Lands vs Water Channel ? 2
21. Wet Lands vs Power Lines ? 2
22. Wet Lands vs Fault Lines ? 4
23. Wet Lands vs Agricultural Irrigation Channel ? 4
24. Wet Lands vs Highways ? 1
25. Water Channel vs Dam Reservoirs ? 2
26. Water Channel vs Wet Lands ? 2
27. Water Channel vs Power Lines ? 2
28. Water Channel vs Fault Lines ? 1
29. Water Channel vs Agricultural Irrigation Channel ? 2
30. Water Channel vs Highways ? 2
31. Power Lines vs Dam Reservoirs ? 2
32. Power Lines vs Wet Lands ? 2
33. Power Lines vs Water Channel ? 2
34. Power Lines vs Fault Lines ? 1
35. Power Lines vs Agricultural Irrigation Channel ? 2
36. Power Lines vs Highways ? 2
37. Fault Lines vs Dam Reservoirs ? 2
38. Fault Lines vs Wet Lands ? 4
39. Fault Lines vs Water Channel ? 2
40. Fault Lines vs Power Lines ? 2

41. Fault Lines vs Agricultural Irrigation Channel ? ____4____

42. Fault Lines vs Highways ? ____2____

43. Agricultural Irrigation Channel vs Dam Reservoirs ? ____4____

44. Agricultural Irrigation Channel vs Wet Lands ? ____4____

45. Agricultural Irrigation Channel vs Water Channel ? ____2____

46. Agricultural Irrigation Channel vs Power Lines ? ____2____

47. Agricultural Irrigation Channel vs Fault Lines ? ____4____

48. Agricultural Irrigation Channel vs Highways ? ____1____

49. Highways vs Dam Reservoirs ? ____2____

50. Highways vs Wet Lands ? ____2____

51. Highways vs Water Channel ? ____2____

52. Highways vs Power Lines ? ____2____

53. Highways vs Fault Lines ? ____2____

54. Highways vs Agricultural Irrigation Channel ? ____1____

We greatly value your insights and appreciate your contribution to this important process. Thank you for your time and input.

Determining the Pipeline Route: Prioritizing Environmental and Infrastructure Elements

Dear participant,

Thank you for agreeing to take part in this survey. Your input will significantly contribute to determining the most appropriate route for a proposed pipeline. The purpose of this survey is to assess the relative importance of various environmental and infrastructure components in order to find the most optimal pipeline route.

Before we begin, let's clarify how to fill out the survey:

Example Question: Forest vs. Grassland? ___

In this question, you're asked to decide between a forest and a grassland. If you believe the forest is less critical when considering the pipeline route, underline or circle "Forest". Then, assign a number from 1 to 9 to denote its priority or importance. For instance, if you believe it's of low importance, you might assign it a 2.

So, your completed answer might appear as: Forest vs. Grassland? 2

In the event that you consider both options to be of equal importance, you should underline or circle both, and write '1' next to both.

Now, please continue with the survey.

Section 1: Natural Landforms

1. Ridges vs Flat land ? ___2___
2. Ridges vs Steep terrain ? ___5___
3. Ridges vs Streams ? ___1___
4. Flat land vs Ridges ? ___2___
5. Flat land vs Steep terrain ? ___3___
6. Flat land vs Streams ? ___2___
7. Steep terrain vs Ridges ? ___4___
8. Steep terrain vs Flat land ? ___3___
9. Steep terrain vs Streams ? ___2___
10. Streams vs Ridges ? ___1___
11. Streams vs Flat land ? ___3___
12. Streams vs Steep terrain ? ___2___

1

Section 2: Infrastructure Elements

13. Dam Reservoirs vs Wet Lands ? 4
14. Dam Reservoirs vs Water Channel ? 2
15. Dam Reservoirs vs Power Lines ? 1
16. Dam Reservoirs vs Fault Lines ? 2
17. Dam Reservoirs vs Agricultural Irrigation Channel ? 4
18. Dam Reservoirs vs Highways ? 2
19. Wet Lands vs Dam Reservoirs ? 4
20. Wet Lands vs Water Channel ? 2
21. Wet Lands vs Power Lines ? 1
22. Wet Lands vs Fault Lines ? 2
23. Wet Lands vs Agricultural Irrigation Channel ? 2
24. Wet Lands vs Highways ? 2
25. Water Channel vs Dam Reservoirs ? 2
26. Water Channel vs Wet Lands ? 2
27. Water Channel vs Power Lines ? 2
28. Water Channel vs Fault Lines ? 2
29. Water Channel vs Agricultural Irrigation Channel ? 1
30. Water Channel vs Highways ? 1
31. Power Lines vs Dam Reservoirs ? 1
32. Power Lines vs Wet Lands ? 1
33. Power Lines vs Water Channel ? 2
34. Power Lines vs Fault Lines ? 3
35. Power Lines vs Agricultural Irrigation Channel ? 1
36. Power Lines vs Highways ? 1
37. Fault Lines vs Dam Reservoirs ? 2
38. Fault Lines vs Wet Lands ? 2
39. Fault Lines vs Water Channel ? 2
40. Fault Lines vs Power Lines ? 3

2

41. Fault Lines vs Agricultural Irrigation Channel ? 4

42. Fault Lines vs Highways ? 3

43. Agricultural Irrigation Channel vs Dam Reservoirs ? 3

44. Agricultural Irrigation Channel vs Wet Lands ? 2

45. Agricultural Irrigation Channel vs Water Channel ? 2

46. Agricultural Irrigation Channel vs Power Lines ? 2

47. Agricultural Irrigation Channel vs Fault Lines ? 4

48. Agricultural Irrigation Channel vs Highways ? 2

49. Highways vs Dam Reservoirs ? 2

50. Highways vs Wet Lands ? 2

51. Highways vs Water Channel ? 1

52. Highways vs Power Lines ? 1

53. Highways vs Fault Lines ? 3

54. Highways vs Agricultural Irrigation Channel ? 2

We greatly value your insights and appreciate your contribution to this important process.
Thank you for your time and input.

Determining the Pipeline Route: Prioritizing Environmental and Infrastructure Elements

Dear participant,

Thank you for agreeing to take part in this survey. Your input will significantly contribute to determining the most appropriate route for a proposed pipeline. The purpose of this survey is to assess the relative importance of various environmental and infrastructure components in order to find the most optimal pipeline route.

Before we begin, let's clarify how to fill out the survey:

Example Question: Forest vs. Grassland? ___

In this question, you're asked to decide between a forest and a grassland. If you believe the forest is less critical when considering the pipeline route, underline or circle "Forest". Then, assign a number from 1 to 9 to denote its priority or importance. For instance, if you believe it's of low importance, you might assign it a 2.

So, your completed answer might appear as: (Forest) vs. Grassland? 2

In the event that you consider both options to be of equal importance, you should underline or circle both, and write '1' next to both.

Now, please continue with the survey.

Section 1: Natural Landforms

1. Ridges vs Flat land ? ___2___
2. Ridges vs Steep terrain ? ___2___
3. Ridges vs Streams ? ___3___
4. Flat land vs Ridges ? ___3___
5. Flat land vs Steep terrain ? ___2___
6. Flat land vs Streams ? ___3___
7. Steep terrain vs Ridges ? ___2___
8. Steep terrain vs Flat land ? ___2___
9. Steep terrain vs Streams ? ___1___
10. Streams vs Ridges ? ___3___
11. Streams vs Flat land ? ___2___
12. Streams vs Steep terrain ? ___2___

1

Section 2: Infrastructure Elements

13. Dam Reservoirs vs Wet Lands ? ___4___
14. Dam Reservoirs vs Water Channel ? ___2___
15. Dam Reservoirs vs Power Lines ? ___3___
16. Dam Reservoirs vs Fault Lines ? ___2___
17. Dam Reservoirs vs Agricultural Irrigation Channel ? ___4___
18. Dam Reservoirs vs Highways ? ___2___
19. Wet Lands vs Dam Reservoirs ? ___4___
20. Wet Lands vs Water Channel ? ___3___
21. Wet Lands vs Power Lines ? ___2___
22. Wet Lands vs Fault Lines ? ___5___
23. Wet Lands vs Agricultural Irrigation Channel ? ___1___
24. Wet Lands vs Highways ? ___1___
25. Water Channel vs Dam Reservoirs ? ___2___
26. Water Channel vs Wet Lands ? ___2___
27. Water Channel vs Power Lines ? ___1___
28. Water Channel vs Fault Lines ? ___1___
29. Water Channel vs Agricultural Irrigation Channel ? ___2___
30. Water Channel vs Highways ? ___1___
31. Power Lines vs Dam Reservoirs ? ___3___
32. Power Lines vs Wet Lands ? ___2___
33. Power Lines vs Water Channel ? ___1___
34. Power Lines vs Fault Lines ? ___2___
35. Power Lines vs Agricultural Irrigation Channel ? ___2___
36. Power Lines vs Highways ? ___1___
37. Fault Lines vs Dam Reservoirs ? ___2___
38. Fault Lines vs Wet Lands ? ___5___
39. Fault Lines vs Water Channel ? ___1___
40. Fault Lines vs Power Lines ? ___2___

2

41. Fault Lines vs Agricultural Irrigation Channel ? 5

42. Fault Lines vs Highways ? 3

43. Agricultural Irrigation Channel vs Dam Reservoirs ? 4

44. Agricultural Irrigation Channel vs Wet Lands ? 1

45. Agricultural Irrigation Channel vs Water Channel ? 1

46. Agricultural Irrigation Channel vs Power Lines ? 2

47. Agricultural Irrigation Channel vs Fault Lines ? 5

48. Agricultural Irrigation Channel vs Highways ? 1

49. Highways vs Dam Reservoirs ? 2

50. Highways vs Wet Lands ? 3

51. Highways vs Water Channel ? 1

52. Highways vs Power Lines ? 1

53. Highways vs Fault Lines ? 3

54. Highways vs Agricultural Irrigation Channel ? 1

We greatly value your insights and appreciate your contribution to this important process.
Thank you for your time and input.

Determining the Pipeline Route: Prioritizing Environmental and Infrastructure Elements

Dear participant,

Thank you for agreeing to take part in this survey. Your input will significantly contribute to determining the most appropriate route for a proposed pipeline. The purpose of this survey is to assess the relative importance of various environmental and infrastructure components in order to find the most optimal pipeline route.

Before we begin, let's clarify how to fill out the survey:

Example Question: Forest vs. Grassland? ___

In this question, you're asked to decide between a forest and a grassland. If you believe the forest is less critical when considering the pipeline route, underline or circle "Forest". Then, assign a number from 1 to 9 to denote its priority or importance. For instance, if you believe it's of low importance, you might assign it a 2.

So, your completed answer might appear as: Forest vs. Grassland? 2

In the event that you consider both options to be of equal importance, you should underline or circle both, and write '1' next to both.

Now, please continue with the survey.

Section 1: Natural Landforms

1. Ridges vs Flat land ? ___2___
2. Ridges vs Steep terrain ? ___4___
3. Ridges vs Streams ? ___3___
4. Flat land vs Ridges ? ___2___
5. Flat land vs Steep terrain ? ___2___
6. Flat land vs Streams ? ___2___
7. Steep terrain vs Ridges ? ___4___
8. Steep terrain vs Flat land ? ___2___
9. Steep terrain vs Streams ? ___2___
10. Streams vs Ridges ? ___3___
11. Streams vs Flat land ? ___2___
12. Streams vs Steep terrain ? ___2___

1

Section 2: Infrastructure Elements

13. Dam Reservoirs vs Wet Lands ? 5
14. Dam Reservoirs vs Water Channel ? 1
15. Dam Reservoirs vs Power Lines ? 3
16. Dam Reservoirs vs Fault Lines ? 1
17. Dam Reservoirs vs Agricultural Irrigation Channel ? 3
18. Dam Reservoirs vs Highways ? 3
19. Wet Lands vs Dam Reservoirs ? 4
20. Wet Lands vs Water Channel ? 3
21. Wet Lands vs Power Lines ? 3
22. Wet Lands vs Fault Lines ? 5
23. Wet Lands vs Agricultural Irrigation Channel ? 1
24. Wet Lands vs Highways ? 2
25. Water Channel vs Dam Reservoirs ? 2
26. Water Channel vs Wet Lands ? 5
27. Water Channel vs Power Lines ? 2
28. Water Channel vs Fault Lines ? 2
29. Water Channel vs Agricultural Irrigation Channel ? 1
30. Water Channel vs Highways ? 2
31. Power Lines vs Dam Reservoirs ? 2
32. Power Lines vs Wet Lands ? 3
33. Power Lines vs Water Channel ? 2
34. Power Lines vs Fault Lines ? 3
35. Power Lines vs Agricultural Irrigation Channel ? 2
36. Power Lines vs Highways ? 2
37. Fault Lines vs Dam Reservoirs ? 1
38. Fault Lines vs Wet Lands ? 5
39. Fault Lines vs Water Channel ? 2
40. Fault Lines vs Power Lines ? 2

41. Fault Lines vs Agricultural Irrigation Channel ? ___3___

42. Fault Lines vs Highways ? ___2___

43. Agricultural Irrigation Channel vs Dam Reservoirs ? ___3___

44. Agricultural Irrigation Channel vs Wet Lands ? ___1___

45. Agricultural Irrigation Channel vs Water Channel ? ___1___

46. Agricultural Irrigation Channel vs Power Lines ? ___2___

47. Agricultural Irrigation Channel vs Fault Lines ? ___3___

48. Agricultural Irrigation Channel vs Highways ? ___2___

49. Highways vs Dam Reservoirs ? ___3___

50. Highways vs Wet Lands ? ___2___

51. Highways vs Water Channel ? ___2___

52. Highways vs Power Lines ? ___2___

53. Highways vs Fault Lines ? ___2___

54. Highways vs Agricultural Irrigation Channel ? ___2___

We greatly value your insights and appreciate your contribution to this important process.
Thank you for your time and input.

Determining the Pipeline Route: Prioritizing Environmental and Infrastructure Elements

Dear participant,

Thank you for agreeing to take part in this survey. Your input will significantly contribute to determining the most appropriate route for a proposed pipeline. The purpose of this survey is to assess the relative importance of various environmental and infrastructure components in order to find the most optimal pipeline route.

Before we begin, let's clarify how to fill out the survey:

Example Question: Forest vs. Grassland? ___

In this question, you're asked to decide between a forest and a grassland. If you believe the forest is less critical when considering the pipeline route, underline or circle "Forest". Then, assign a number from 1 to 9 to denote its priority or importance. For instance, if you believe it's of low importance, you might assign it a 2.

So, your completed answer might appear as: Forest vs. Grassland? 2

In the event that you consider both options to be of equal importance, you should underline or circle both, and write '1' next to both.

Now, please continue with the survey.

Section 1: Natural Landforms

1. Ridges vs Flat land ? 3
2. Ridges vs Steep terrain ? 3
3. Ridges vs Streams ? 4
4. Flat land vs Ridges ? 1
5. Flat land vs Steep terrain ? 2
6. Flat land vs Streams ? 2
7. Steep terrain vs Ridges ? 3
8. Steep terrain vs Flat land ? 2
9. Steep terrain vs Streams ? 3
10. Streams vs Ridges ? 3
11. Streams vs Flat land ? 1
12. Streams vs Steep terrain ? 3

1

13. Dam Reservoirs vs Wet Lands ? ___5___
14. Dam Reservoirs vs Water Channel ? ___2___
15. Dam Reservoirs vs Power Lines ? ___2___
16. Dam Reservoirs vs Fault Lines ? ___2___
17. Dam Reservoirs vs Agricultural Irrigation Channel ? ___3___
18. Dam Reservoirs vs Highways ? ___2___
19. Wet Lands vs Dam Reservoirs ? ___5___
20. Wet Lands vs Water Channel ? ___2___
21. Wet Lands vs Power Lines ? ___2___
22. Wet Lands vs Fault Lines ? ___4___
23. Wet Lands vs Agricultural Irrigation Channel ? ___2___
24. Wet Lands vs Highways ? ___1___
25. Water Channel vs Dam Reservoirs ? ___2___
26. Water Channel vs Wet Lands ? ___4___
27. Water Channel vs Power Lines ? ___2___
28. Water Channel vs Fault Lines ? ___1___
29. Water Channel vs Agricultural Irrigation Channel ? ___2___
30. Water Channel vs Highways ? ___1___
31. Power Lines vs Dam Reservoirs ? ___2___
32. Power Lines vs Wet Lands ? ___2___
33. Power Lines vs Water Channel ? ___2___
34. Power Lines vs Fault Lines ? ___2___
35. Power Lines vs Agricultural Irrigation Channel ? ___2___
36. Power Lines vs Highways ? ___1___
37. Fault Lines vs Dam Reservoirs ? ___2___
38. Fault Lines vs Wet Lands ? ___4___
39. Fault Lines vs Water Channel ? ___1___
40. Fault Lines vs Power Lines ? ___2___

41. Fault Lines vs Agricultural Irrigation Channel ? 2

42. Fault Lines vs Highways ? 3

43. Agricultural Irrigation Channel vs Dam Reservoirs ? 2

44. Agricultural Irrigation Channel vs Wet Lands ? 2

45. Agricultural Irrigation Channel vs Water Channel ? 2

46. Agricultural Irrigation Channel vs Power Lines ? 2

47. Agricultural Irrigation Channel vs Fault Lines ? 2

48. Agricultural Irrigation Channel vs Highways ? 1

49. Highways vs Dam Reservoirs ? 1

50. Highways vs Wet Lands ? 1

51. Highways vs Water Channel ? 1

52. Highways vs Power Lines ? 2

53. Highways vs Fault Lines ? 3

54. Highways vs Agricultural Irrigation Channel ? 1

We greatly value your insights and appreciate your contribution to this important process. Thank you for your time and input.

APPENDIX 2 – Programming Leakage Volume from Oil Pipelines

```sql
CREATE TABLE public.petrol_demo
(
    gid integer NOT NULL DEFAULT
nextval('petrol_demo_gid_seq'::regclass),
    gridcode bigint,
    cap smallint,
    parca smallint,
    uzunluk numeric,
    hacim numeric,
    islem smallint,
    orig_fid integer,
    hesap numeric,
    geom geometry(MultiLineString,4326),
    CONSTRAINT petrol_demo_pkey PRIMARY KEY (gid)
)
```

Table 9. Creating Leakage Volume Table on PostgreSQL

```python
#!/usr/bin/env python
#-*-coding:utf-8-*-

import psycopg2
from datetime import datetime
startTime = datetime.now()

# Database connection setup
baglanti_text = "dbname=A_petrol" + " " + "user=postgres" + " " +
"password=postgres" + " " + "port=5432"
table = 'petrol_demo'
conn = psycopg2.connect(baglanti_text)
db = conn.cursor()

# Query to count the number of rows in the table
sorgu = 'SELECT count(*) FROM [3];'.format(table)
db.execute(sorgu)
conn.commit()
kac_oge_var = (db.fetchall()[0][0])

# Function to find the next row to process
def islmid_bul(conn, db, table):
    # ...
    return islem_id, baslangic, yukseklik, hacim

# Function to update the 'hesap' column of a specific row
def math_hesap(conn, db, table, id, hacim):
    # ...
```

```

# Get initial values for processing
islem_id, baslangic, bas_yukseklik, bas_hacim = islmid_bul(conn, db, table)

# Function to retrieve neighboring row based on conditions
def komsuluk(conn, db, id, table):
    # ...
    return [bulunanid, yukseklik, hacim]

ikinci = 0
kactane = kac_oge_var
math_toplam_hacim = 0
yukseklk_maks = bas_yukseklik

# Loop to process all parts of the pipe stored in the database
while True:
    # Check if the end of the loop is reached and reset variables
    if islem_id == -1:
        islem_id = baslangic
        yukseklik = bas_yukseklik
        yukseklk_maks = bas_yukseklik
        ikinci = ikinci + 1

    # Processing for the second iteration of the loop
    if ikinci == 2:
        # Assumption that approximately half the flow goes to the pipe where the opening occurs
        math_toplam_hacim = math_toplam_hacim + (bas_hacim) / 2

        # Small value assigned to prevent errors when there is no flow in the selected part
        if math_toplam_hacim == 0:
            math_toplam_hacim = 0.001

        # Update the 'hesap' column of the first part with the calculated volume
        math_hesap(conn, db, table, islem_id, math_toplam_hacim)

        # Break the loop when all parts are processed
        if baslangic == kac_oge_var:
            break

        math_toplam_hacim = 0
        islem_id, baslangic, bas_yukseklik, bas_hacim = islmid_bul(conn, db, table)
        ikinci = 0
        yukseklik = bas_yukseklik
        yukseklk_maks = bas_yukseklik

    # Find the next unprocessed neighboring part
    sonuc = komsuluk(conn, db, islem_id, table)
    islem_id = sonuc[0]
    yukseklik = sonuc[1]
    hacim = sonuc[2]

```

```python
    # Update the reference height value if the current part's
height is higher
    if yukseklik >= yukseklk_maks:
        yukseklk_maks = yukseklik
        math_toplam_hacim = math_toplam_hacim + hacim

db.close()

# Print the execution time of the algorithm
print(datetime.now() - startTime)
```

Table 10. Pipeline Spill Value Calculator Code in Python

For the algorithm to operate, it is imperative that the table named "petrol_demo" is initially produced in the PostgreSQL database, using the provided code. The resulting table should then be sectioned using the help of geographic analyses into grid cells and filled as shown below. The code can be executed after the Python database connection settings are configured.

gid: This represents the primary key of the table.

gridcode: This denotes the altitude value of each pipeline segment intersected with the DEM (Digital Elevation Model).

cap: This signifies the pipeline's diameter and is used for volume calculations.

parca indicates the remaining sections between the installed valves on the pipeline. For example, the part from the start to the first valve should be numbered 1, and the section from the first valve to the second should be numbered 2.

uzunluk: This is the length of the pipeline segment intersecting with the DEM.

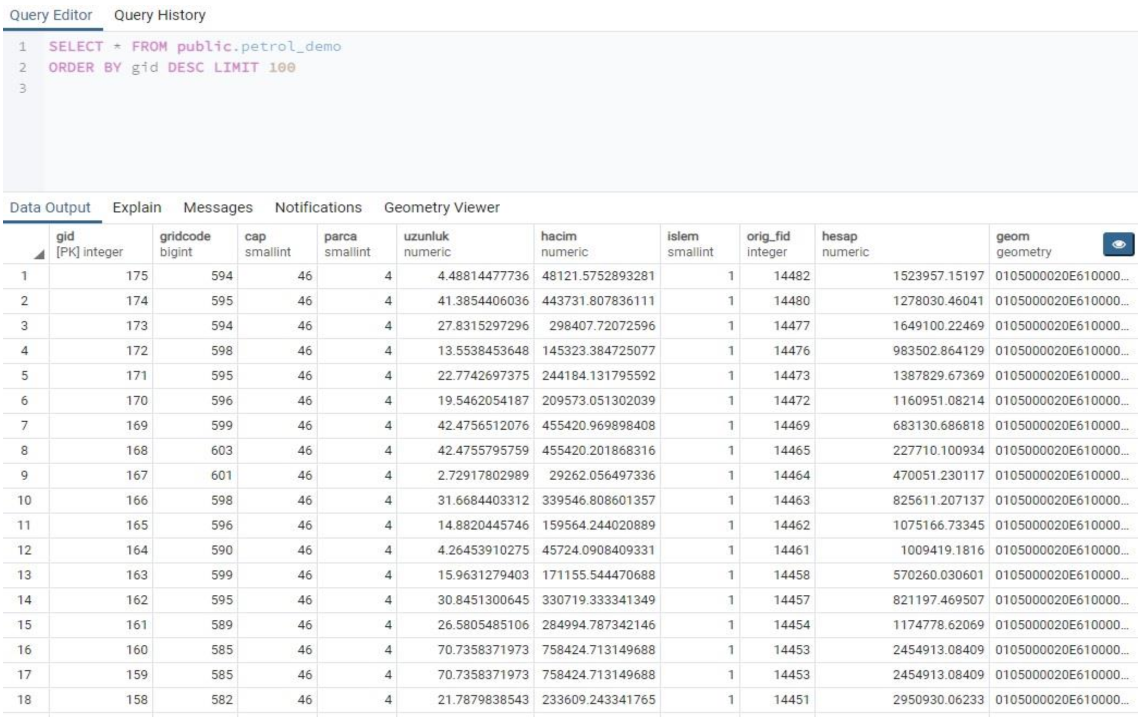
hacim: This is the volume in cubic meters, calculated using the pipe's diameter and length according to the cylinder volume calculation.

islem: This is used by the developed algorithm and stores whether an operation has been previously performed on a cell. The default value to be entered in the database should be 0.

orig_fid: This is a unique value given to each segment produced by intersecting the DEM with the pipeline axis, but it is not used in the algorithm.

hesap: This is the result produced by the algorithm. It holds the calculation of the total volume that will flow from the related part in both left and right directions.

geom: This is the path's geometry, held as a multiline string in geometry type.



	gid [PK] integer	gridcode bigint	cap smallint	parca smallint	uzunluk numeric	hacim numeric	islem smallint	orig_fid integer	hesap numeric	geom geometry
1	175	594	46	4	4.48814477736	48121.5752893281	1	14482	1523957.15197	0105000020E610000...
2	174	595	46	4	41.3854406036	443731.807836111	1	14480	1278030.46041	0105000020E610000...
3	173	594	46	4	27.8315297296	298407.72072596	1	14477	1649100.22469	0105000020E610000...
4	172	598	46	4	13.5538453648	145323.384725077	1	14476	983502.864129	0105000020E610000...
5	171	595	46	4	22.7742697375	244184.131795592	1	14473	1387829.67369	0105000020E610000...
6	170	596	46	4	19.5462054187	209573.051302039	1	14472	1160951.08214	0105000020E610000...
7	169	599	46	4	42.4756512076	455420.969898408	1	14469	683130.686818	0105000020E610000...
8	168	603	46	4	42.4755795759	455420.201868316	1	14465	227710.100934	0105000020E610000...
9	167	601	46	4	2.72917802989	29262.056497336	1	14464	470051.230117	0105000020E610000...
10	166	598	46	4	31.6684403312	339546.808601357	1	14463	825611.207137	0105000020E610000...
11	165	596	46	4	14.8820445746	159564.244020889	1	14462	1075166.73345	0105000020E610000...
12	164	590	46	4	4.26453910275	45724.0908409331	1	14461	1009419.1816	0105000020E610000...
13	163	599	46	4	15.9631279403	171155.544470688	1	14458	570260.030601	0105000020E610000...
14	162	595	46	4	30.8451300645	330719.333341349	1	14457	821197.469507	0105000020E610000...
15	161	589	46	4	26.5805485106	284994.787342146	1	14454	1174778.62069	0105000020E610000...
16	160	585	46	4	70.7358371973	758424.713149688	1	14453	2454913.08409	0105000020E610000...
17	159	585	46	4	70.7358371973	758424.713149688	1	14453	2454913.08409	0105000020E610000...
18	158	582	46	4	21.7879838543	233609.243341765	1	14451	2950930.06233	0105000020E610000...

Figure 38. The Result of Pipeline Spill Value in Database

When the code is executed with the related gids, the seepage flow caused by gravity and topography will be calculated for each segment on the pipeline.

Upon execution, the algorithm generates an output as described above. When it is necessary to rerun the algorithm, it is essential to reset the 'islem' and 'hesap' columns to zero (Figure 38). This requirement is due to the logic based on the developed algorithm.

APPENDIX 3 – Programming Horizontal Oil Distribution

```
import arcpy
arcpy.CheckOutExtension("Spatial")
arcpy.env.overwriteOutput = 1

# The line where the starting point of the oil leak is taken as a
variable with arcpy
baslangic=arcpy.GetParameterAsText(0)
# The line where the volume of oil subject to distribution is
defined with arcpy
petrol_miktari=float(arcpy.GetParameterAsText(1))
# The rate of rise of oil according to horizontal resolution in
very high horizontal resolution dem data is defined with arpy, it
comes from the interface
hacim_orani=float(arcpy.GetParameterAsText(2))
# The user defines whether to enter the lithology value from the
interface
litoloji_var_yok=arcpy.GetParameterAsText(3)
# If lithology is not defined, the absorption amount based on a
stable pixel
pixel_emme=float(arcpy.GetParameterAsText(4))

mxd = arcpy.mapping.MapDocument("CURRENT")

pathmxd=(mxd.filePath).encode('utf8')
pathmxdlist=pathmxd.split("\\")
pathmxdlist.pop(len(pathmxdlist)-1)
pathmxd="\\".join(pathmxdlist)
workspace=pathmxd
arcpy.env.workspace=workspace

# The starting point entered by the user is saved as shp
arcpy.FeatureClassToFeatureClass_conversion(baslangic,
workspace+r"\data\output", "baslangic.shp")

# From the starting point, the dem value is cut from a region
where the most leakage will occur considering the dem horizontal
resolution and from now on, the transactions will be made on this
dem data
arcpy.Buffer_analysis(baslangic,workspace+r"\data\output\kesme_bu
ffer.shp","10 Kilometers","FULL","ROUND","ALL")
arcpy.gp.ExtractByMask_sa(workspace+r"\toolbox\tr_dem_wgs.tif",
workspace+r"\data\output\kesme_buffer.shp",workspace+r"\data\outp
ut\kesme_raster.tif")
# The dem data in raster format is converted to vector format for
processes such as neighborhood analysis
arcpy.RasterToPolygon_conversion(workspace+r"\data\output\kesme_r
aster.tif", workspace+r"\data\output\calisma_alan.shp",
"NO_SIMPLIFY","VALUE")

# New column structures below are added to the dem data converted
to vector format for calculations
arcpy.AddField_management(workspace+r"\data\output\calisma_alan.s
hp", "durum", "SHORT")
```

```
arcpy.AddField_management(workspace+r"\data\output\calisma_alan.s
hp", "yukselme", "FLOAT")
arcpy.AddField_management(workspace+r"\data\output\calisma_alan.s
hp", "alan", "FLOAT")
arcpy.AddField_management(workspace+r"\data\output\calisma_alan.s
hp", "biriken", "FLOAT")
arcpy.AddField_management(workspace+r"\data\output\calisma_alan.s
hp", "lito_emme", "FLOAT")
arcpy.AddField_management(workspace+r"\data\output\calisma_alan.s
hp", "sira", "SHORT")

# Depending on whether the user shows the lithology value, the
dem converted to vector is divided into parts according to the
lithology layer. If lithology is not shown, the dem value is not
divided
if litoloji_var_yok=="Stabil Deger":

arcpy.MakeFeatureLayer_management(workspace+r"\data\output\calism
a_alan.shp", "dem_lyr")
else:

arcpy.Intersect_analysis([workspace+r"\data\litoloji.shp",workspa
ce+ r"\data\output\calisma_alan.shp"],
workspace+r"\data\output\calisma_alan2.shp", "", "" "")

arcpy.MakeFeatureLayer_management(workspace+r"\data\output\calism
a_alan2.shp", "dem_lyr")

# The area value of each pixel is calculated, this value will be
used in accumulation operations
arcpy.CalculateField_management("dem_lyr",
"alan",'!shape.area@SQUAREMETERS!', "PYTHON_9.3")

# The first pixel where the initial leak at the starting point
will start is found by intersection analysis
arcpy.SelectLayerByLocation_management ("dem_lyr", "INTERSECT",
baslangic,"","NEW_SELECTION")
f1 = "GRIDCODE"
liste_komsular=[]
for row in sorted(arcpy.da.SearchCursor("dem_lyr", [f1])):
      liste_komsular.append(row[0])
# The pixel with the smallest height value among the pixels
touching the starting pixel is selected
min_yukselme=min(liste_komsular)

# A value of 1 is assigned to the selected pixels indicating that
the operation has been performed and the height value of the
starting pixel is written to the elevation
arcpy.SelectLayerByLocation_management ("dem_lyr",
"BOUNDARY_TOUCHES", "","","NEW_SELECTION")
experssion = '\"GRIDCODE\" ='+str(int(min(liste_komsular)))
arcpy.SelectLayerByAttribute_management ("dem_lyr",
"SUBSET_SELECTION",experssion)
arcpy.CalculateField_management("dem_lyr", "durum",'1',
"PYTHON_9.3")
arcpy.CalculateField_management("dem_lyr",
"yukselme",'!GRIDCODE!', "PYTHON_9.3")
```

```
i=1
# The loop enters until the total loss amount is greater than or
equal to the entered leak volume
while True:
        # The leak route on which the operation has been performed
is selected, the loss volume will be calculated on this selection
        arcpy.SelectLayerByAttribute_management ("dem_lyr",
"NEW_SELECTION",'"durum"=1')

        # Total loss volume due to lithology absorption and
accumulation is calculated
        if litoloji_var_yok=="Stabil Deger":
                arcpy.Statistics_analysis("dem_lyr",
workspace+r"\toolbox\tablo.gdb\sonuc", [["biriken",
"SUM"],["biriken","COUNT"]])
                f1,f2 = "SUM_biriken","COUNT_biriken"
                for row in
arcpy.da.SearchCursor(workspace+r"\toolbox\tablo.gdb\sonuc", [f1,
f2]):
                        pass

                deger=row[0]+pixel_emme*row[1]
        else:
                arcpy.Statistics_analysis("dem_lyr",
workspace+r"\toolbox\tablo.gdb\sonuc", [["biriken",
"SUM"],["lito_emme","SUM"]])
                f1,f2 = "SUM_biriken","SUM_lito_emme"
                for row in
arcpy.da.SearchCursor(workspace+r"\toolbox\tablo.gdb\sonuc", [f1,
f2]):
                        pass
                deger=row[0]+row[1]

        # If the total loss is greater than or equal to the leak
volume, it exits the loop
        if deger>=petrol_miktari:
                break

        # All the leak routes processed so far are found, all
pixels neighboring this route are selected
        arcpy.SelectLayerByLocation_management ("dem_lyr",
"BOUNDARY_TOUCHES", "","","NEW_SELECTION")
        arcpy.SelectLayerByAttribute_management ("dem_lyr",
"REMOVE_FROM_SELECTION",'"durum"=1')

        # The smallest pixel value among the pixels neighboring the
current leak route is determined
        f1 = "GRIDCODE"
        liste_komsular=[]
        for row in sorted(arcpy.da.SearchCursor("dem_lyr", [f1])):
                liste_komsular.append(row[0])

        min_yukselme=min(liste_komsular)
        experssion = '\"GRIDCODE\" ='+str(int(min(liste_komsular)))
```

```
        # All pixels with the smallest height value among
neighboring pixels are selected, these pixels will be assigned as
processed pixels later
        arcpy.SelectLayerByAttribute_management ("dem_lyr",
"SUBSET_SELECTION",experssion)

        onceki_sayi =
int(arcpy.GetCount_management("dem_lyr").getOutput(0))
        sonraki_sayi=onceki_sayi+1

        # It is checked whether there is a pixel value equal to or
smaller than the detected height value around the pixels with the
lowest height among the neighbors
        while True:
                if onceki_sayi>=sonraki_sayi:
                        break
                onceki_sayi =
int(arcpy.GetCount_management("dem_lyr").getOutput(0))

                arcpy.SelectLayerByLocation_management ("dem_lyr",
"BOUNDARY_TOUCHES", "","","NEW_SELECTION")
                arcpy.SelectLayerByAttribute_management ("dem_lyr",
"REMOVE_FROM_SELECTION",'"durum"=1')
                arcpy.SelectLayerByAttribute_management ("dem_lyr",
"SUBSET_SELECTION",experssion)

                sonraki_sayi =
int(arcpy.GetCount_management("dem_lyr").getOutput(0))

        # All newly determined pixels are added to the leak route
        arcpy.CalculateField_management("dem_lyr", "durum",'1',
"PYTHON_9.3")
        # A sequence number is given to the selected pixels about
which order the operation was performed
        arcpy.CalculateField_management("dem_lyr", "sira",i,
"PYTHON_9.3")

        # If there are pixels with a height value greater than the
newly found minimum neighbor pixel height, there will be
accumulation in these pixels, the accumulation volume on the
detected route is calculated
        experssion = '\"durum\"=1 AND
\"yukselme\"<='+str(min_yukselme)
        arcpy.SelectLayerByAttribute_management ("dem_lyr",
"NEW_SELECTION",experssion)
        arcpy.CalculateField_management("dem_lyr",
"yukselme",min_yukselme, "PYTHON_9.3")
        experssion = "(!yukselme!-!GRIDCODE!)*!alan!"
        arcpy.CalculateField_management("dem_lyr",
"biriken",experssion, "PYTHON_9.3")

        # If the absorption value comes from lithology, the total
absorption in the pixels is calculated
        if litoloji_var_yok!="Stabil Deger":
                experssion = "!emme!"
                arcpy.CalculateField_management("dem_lyr",
"lito_emme",experssion, "PYTHON_9.3")
```

```python
        i=i+1
        arcpy.AddMessage(i)
# The calculated result information is recorded as soon as the
total loss amount is greater than or equal to the leak volume
arcpy.AddMessage(deger)
arcpy.SelectLayerByAttribute_management ("dem_lyr",
"NEW_SELECTION",'"durum"=1')
arcpy.FeatureClassToFeatureClass_conversion("dem_lyr",workspace+r
"\data\output", "cikti.shp")
arcpy.AddField_management(workspace+r"\data\output\cikti.shp",
"sonuc", "FLOAT")
arcpy.CalculateField_management(workspace+r"\data\output\cikti.sh
p", "sonuc",'!yukselme!-!GRIDCODE!', "PYTHON_9.3")

newlayer =
arcpy.mapping.Layer(workspace+r"\data\output\cikti.shp")
df = mxd.activeDataFrame
arcpy.mapping.AddLayer(df, newlayer, "TOP")
mxd.save()
```

Table 11. Horizontal Oil Distribution Code in Python

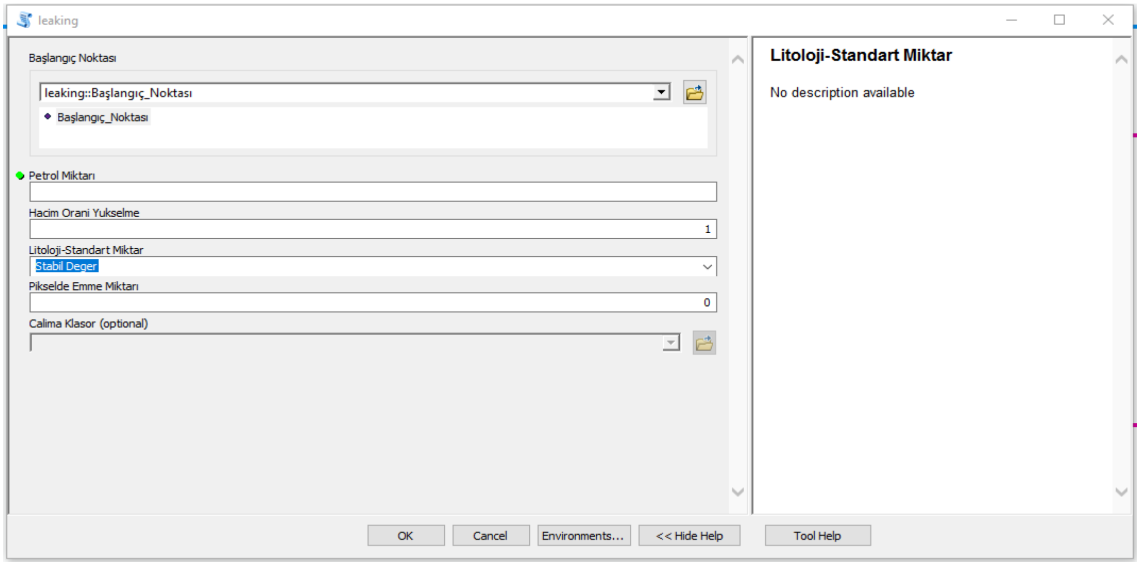


Figure 39. Interface of Oil Spill Distribution Application

Creating an interface within the arctoolbox environment is necessary to properly function the provided code. This interface should include a graphical window displaying a screenshot (Figure 39), allowing users to define input parameters. It should be noted that the DEM and Lithology data are currently hardcoded into the system, without any enhancements to facilitate their modification through the interface.

APPENDIX 3 – PUBLICATIONS DERIVED FROM THE DISSERTATION

Durmaz, A.İ.; Ünal, E.Ö.; Aydın, C.C. Automatic Pipeline Route Design with Multi-Criteria Evaluation Based on Least-Cost Path Analysis and Line-Based Cartographic Simplification: A Case Study of the Mus Project in Turkey. ISPRS Int. J. Geo-Inf. 2019, 8, 173. https://doi.org/10.3390/ijgi8040173