COST-BASED OPTIMIZATION OF LAND APPLICATION OF SLUDGE IN GEDIZ BASIN

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COST-BASED OPTIMIZATION OF LAND APPLICATION OF SLUDGE IN GEDIZ BASIN

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ABSTRACT

COST-BASED OPTIMIZATION OF LAND APPLICATION OF SLUDGE IN GEDIZ BASIN

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Sludge treatment and management is a growing challenge for countries globally. The quantities of sludge continue to increase as new wastewater treatment facilities are built and the existing ones are upgraded to keep up with the growing population. Associated costs are expected to increase with the increasing sludge amounts, and with stricter regulations that require further treatment. Knowing the cost of sludge treatment constitutes approximately half of the cost of wastewater treatment, one of the significant issues to be considered in selecting the appropriate sludge management option for wastewater treatment plants should be optimizing the total cost of sludge management. The main objective of this study is to find the optimal combinations of sludge management options for each integrated WWTP in Gediz Basin for land application. Considered options included different drying and stabilization combinations. A cost-based optimization model was developed comprising of management costs relevant to sludge drying, stabilization, transportation, and land application. In this study, stabilization methods are assigned to WWTPs as anaerobic digestion or aerobic composting depending on sludge production rates; anaerobic digestion for WWTPs producing greater than 1 tonnes/day, aerobic composting for lower rates. 3 different scenarios are considered: land application following on-site sludge drying, off-site drying, and without sludge drying. Best land application locations for each WWTP and optimum costs were determined. The developed optimization model was run using the ArcGIS Model Builder tool. The suitability of lands for application of sludge and real travel distances were determined with the overlay analysis and network analysis via ArcGIS platform, respectively. As a general result of the study, the total investment and operating maintenance costs for sludge management on a scenario basis for WWTPs with high sludge amount appear to be over $100,000. However; It is seen that this cost decreases as the amount of sludge decreases. Also, for WWTPs with high sludge amount, compared to plants with low sludge production; scenario costs were found to be close to each other. Results indicated that the sparse distribution of off-site sludge drying facilities and the wider distribution of suitable agricultural lands for sludge application increased costs. In addition, when the sludge application dosage is adjusted to remain on the safe side, there is no capacity restriction in Gediz Basin in terms of sludge application in agricultural lands. Sensitivity analysis applied on unit costs showed that there may be changes in the optimal pathway of sludge management for WWTPs when there is a change in unit cost.

Keywords: Wastewater sludge, Sludge Treatment, Optimization, Costs

ÖZ

GEDİZ HAVZASINDA ARITMA ÇAMURUNUN TOPRAKTA KULLANIM KAPSAMINDA MALİYET BAZLI OPTİMİZASYONU

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Çamur arıtma ve yönetimi, küresel olarak ülkeler için büyüyen bir zorluktur. Artan nüfusa ayak uydurmak için yeni atık su arıtma tesisleri inşa edildikçe ve mevcut tesisler iyileştirildikçe çamur miktarları artmaya devam etmektedir. Artan arıtma çamuru miktarları ve daha katı mevzuatsal düzenlemeler ile ilişkili olarak maliyetlerin de artması beklenmektedir. Çamur arıtma maliyetinin atıksu arıtma maliyetinin yaklaşık yarısını oluşturduğu bilindiğinden, atıksu arıtma tesisleri için uygun çamur yönetimi seçeneğinin uygulanmasında dikkate alınması gereken önemli konulardan biri de toplam çamur yönetimi maliyetinin optimize edilmesi olmalıdır. Bu çalışmanın temel amacı, toprakta kullanılması kapsamında Gediz Havzası'ndaki her bir atıksu arıtma tesisi için çamur yönetimi seçeneklerinin optimal kombinasyonlarını bulmaktır. Bu çalışmada, atıksu arıtma tesislerine çamur üretim oranlarına bağlı olarak anaerobik çürütme veya aerobik kompostlaştırma olarak stabilizasyon yöntemleri atanmış; günde 1 tondan fazla üretim yapan atıksu arıtma tesisleri için anaerobik çürütme, daha düşük oranlar için aerobik kompostlama düşünülmüştür. 3 farklı senaryo göz önünde bulundurulmuştur. Bunlar: yerinde çamur kurutmanın ardından toprakta kullanılması, çamurun saha dışındaki bir kurutma tesisinde kurutulduktan sonra toprakta kullanılması ve çamurun kurutma olmaksızın toprakta kullanılmasıdır. Her bir atıksu arıtma tesisi bazında çamurun uygulanması için en uygun araziler ve optimum maliyetler belirlenmiştir Geliştirilen optimizasyon modeli ArcGIS Model Builder aracı kullanılarak çalıştırılmıştır. Ayrıca, arazilerin çamur kullanımı için uygunluğu gibi mekansal hususları gerektiren optimizasyon modelinin girdisi ve gerçek mesafelerin hesaplanması ArcGIS platformu üzerinden sırası ile bindirme analizi ve ağ analizi ile oluşturulmuştur. Çalışmanın genel bir sonucu olarak, yüksek çamur miktarına sahip tesislerin senaryolar bazındaki çamur yönetimi toplam yatırım ve işletme bakım maliyetlerinin 100,000 $ üzerinde olduğu görülmektedir. Ancak; çamur miktarı azaldıkça bu maliyetlerin de azaldığı görülmektedir. Ayrıca yüksek çamur miktarına sahip tesisler için düşük çamur üretimi olan tesislere göre; senaryo bazındaki toplam maliyetlerinin birbirine yakın olduğu görülmüştür. Sonuçlar, tesis dışı çamur kurutma tesislerinin seyrek dağılımının ve çamur uygulaması için uygun tarım arazilerinin daha geniş dağılımının maliyetleri artırdığını göstermiştir. Ayrıca çamur uygulama dozu güvenli tarafta kalacak şekilde ayarlandığında, tarım arazilerinde çamur uygulaması açısından Gediz Havzası'nda herhangi bir kapasite kısıtlaması bulunmamaktadır. Birim maliyetlere uygulanan duyarlılık analizi, birim maliyette artış olduğunda atıksu arıtma tesisleri için optimum seçenekte değişiklik olabileceğini göstermektedir.

Anahtar Kelimeler: Atıksu Arıtma Çamurları, Çamur Arıtma, Optimizasyon, Maliyetler

To My Family…

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LIST OF ABBREVIATIONS

Al	Aluminum
C/N Ratio	Carbon/ Nitrogen Ratio
Ca	Calsium
Cd	Cadmium
Co	Cobalt
CORINE	Coordination of Information on the Environment
Cr	Chromium
Cu	Copper
da	Decare
DEHP	Di-2-(ethylhexyl)phthalate
DM	Dry Matter
EU	European Union
GIS	Geographic Information Systems
Hg	Mercury
K	Potassium
kg	Kilogram
km	Kilometer
LAS	Linear alkylbenzene sulphonate
Mg	Magnesium
Mn	Manganese
n.d.	No date

Na	Sodium
Ni	Nickel
NPE	Nonylphenol polyethoxylate
O&M	Operation and Maintanence
PAHs	Polynuclear aromatic hydrocarbon
Pb	Lead
PCBs	Polychlorinated biphenyls
PCDD	Polychlorinated dibenzo-p-dioxins
S	Sulfur
U.S.	United States
EPA	Environmental Protection Agency
VS	Volatile Solid
Content	Content
WWTP-	Wastewater
WWTP/s	Treatment Plant/s
y	year
Zn	Zinc

CHAPTER 1

INTRODUCTION

Today, due to the rapid growth in the population and industry, water usage is increasing. As a result, the need for wastewater treatment is growing as well. This, in return, boosts the total amount of sludge generated during the treatment of wastewater. Yearly sludge amount produced in Turkey is approximately $3.18x10^6$ dry tonnes. In Germany, the country that produces the highest yearly sludge among EU countries, his number is around $2.75x10^6$ dry tonnes (Gunay and Dursun, 2018).

The generated sludge must be managed and disposed in the most appropriate way for environmental and human health conservation. In this context, there are sludge treatment units in WWTP/s in order to make the sludge suitable for its final management option. The typical processes are thickening, stabilization, conditioning, dewatering and drying (Sanin et al., 2011). Beyond treatment plants, management options for sludge are generally the use of sludge as an energy source, landfilling and application on land (WEF, 2009).

Management of sludge treatment and disposal is generally established in accordance with the framework of rules and requirements set by relevant regulations, In USA, the regulation named as "40 CFR Part 503 (the Rule or Regulation). Standards for the Use or Disposal of Sewage Sludge" has been established regarding sludge management (US EPA, 1994). In this regulation, the biosolid term is mainly used in place of treated sludge. In the European Union, there are different regulations which have influence on sludge management. Directives 2000/60/EC on water protection, 91/271/EEC on urban wastewater treatment, 99/31/EC on the landfilling of wastes Directive 2008/98/EC on waste and Directive 2000/76/EC on the incineration of waste are related regulations. “Sewage Sludge Directive 86/278 / EEC” is the most significant enforcement on specifically the application of sludge on land (EUR-Lex,1986). These directives and regulations provide a general framework for sludge management. Limitations and requirements may vary between states in the U.S. and between countries in the EU (Christodoulou & Stamatelatou, 2016). In Turkey, there are also various regulations having related items for sludge management. These are “Regulation on the General Principles of Waste Management” (CSB, 2008a). “Regulation on the Use of Domestic and Urban Sewage Sludge on Soil” (CSB, 2010a). “Regulation on Landfilling of Wastes” (CSB, 2010b), and “Regulation on Urban Wastewater Treatment” (CSB, 2006). In addition to these, transportation of wastes including sludge is regulated in “Communique on the Transport of Wastes on the Highways” (CSB, 2008b).

Among the beneficial usage alternatives for sludge, land application is one of the most widely applied one (Lowman, McDonald and Wing, 2013). According to the results of the studies in the literature, the use of sludge in soil for agricultural purposes leads to an improvement in the physiochemical properties of soil, such as organic matter and water holding capacity (Cele and Maboeta, 2016). In addition, depending on the products grown, the growth rate and biomass yields increase (Abreu-Junior et al., 2017). Among EU countries, Finland uses its sludge completely on soil. France and Sweden use 80% and 60% of the sludge produced for agricultural purposes, respectively (UWWTD, n.d.). The majority (about 80%) of sludge in the UK is recycled to agricultural land (OFWAT, 2020). Also, according to the updated report from EPA about impact of pollutants in land-applied sludge on human health and the environment, US applied approximately 50 % of its produced sludge on land (EPA, 2018).

As well as meeting the requirements set by relevant regulations for land application of sludge, cost is a factor that should be considered (Tymoteusz and Marian, 2018). It is estimated that the average costs of different management options for non-treated sludge is 160–210 EUR/tonnes DM. When the case is using dewatered sludge in agriculture, forestry, or reclamation of degraded areas; costs increase to about 210–300 EUR/tonnes DM (Tymoteusz and Marian, 2018). In order to reduce management costs, optimization can be used. According to a study conducted in a treatment plant in the USA in 1995, up to 65% reduction in chemical dosing cost was observed as a result of equipment modifications, control optimization, and optimization of the chemical addition points (Harvey, 1998). In addition, in accordance with the study conducted on Montreal WWTP, a 40% reduction in chemical dosing cost was observed as a result of the optimization of chemical dosing points within the scope of chemical stabilization on sludge (NRC-CNRC, 2003). The optimization study, regarded sludge allocation to non-irrigated arable lands started from the lands closer to the Ankara Central WWTP, conducted by Görgüner (2013) concluded non-irrigated arable lands in Ankara have a significant potential for the agricultural use of sewage sludge since Ankara sludge is already stabilized, satisfying this criterion in Regulation on the Use of Domestic and Urban Sewage Sludge on Soil (Görgüner, 2013).

The main objective of this study is to decide on the most optimal way in terms of sludge management for each integrated WWTP in the Gediz Basin by integrating the main costs such as drying and stabilization costs and the management costs such as transportation and land application cost of the sludge into the optimization model under context of land application of sludge as the final sludge management method. The ultimate sludge management method is chosen as land application as it is one of the most efficient methods that contributes both to circular economy in terms of cost-effectiveness and supports the development of agricultural products grown in the land where it is applied. There are many studies in the literature supporting these reasons (Abreu-Junior et al., 2017; Latare et al., 2014) Gediz

Basin is selected as the study site because its economy is mostly based on agricultural activities (TOB, 2018). Therefore, the basin can benefit from the beneficial use of sludge as land application. All domestic/urban WWTP/s and WWTP/s of food industries applying biological treatment are included. Information regarding sludge amounts. characteristics and treatment background is taken from the final report of the "Preparation of Sludge Management Plan for Gediz Basin" (CBS, 2017) and Water and Sewage Administration of provinces in the basin. Specific requirements and parameters in accordance with the Regulation on the Use of Domestic and Urban Sewage Sludge on Soil and spatial information derived using GIS, tools are considered for the determination of suitable lands for sludge application. In this study, three different model studies were carried out. Two of them were conducted to provide data to the original optimization model. These two studies are the model established to find suitable areas and the Origin-Destination Matrix study to find travel distances. As well as proposing a cost-optimized land application of sludge in Gediz Basin, this study contributes as developing an GIS-based optimization model to find the most suitable sludge application approach based on cost. In this study, using the optimization model derived, cost-optimization is suggested for sludge treatment, drying, and transportation of sludge for land application based on spatial data analysis in compliance with the relevant requirements in the Regulation on the Use of Domestic and Urban Sewage Sludge on Soil. According to the relevant regulation, sludge must be stabilized for use on land, in order to fulfill this requirement; stabilization suggestions have been made for each WWTP that do not have a stabilization unit yet, and the cost of the proposed stabilization is included in the optimization model. In the "Preparation of Sludge Management Plan for Gediz Basin" study, all possible management options of the sewage sludge and their costs are presented. However, there is no suggestion or recommendation for WWTPs in terms of cost-optimality. Therefore, this study takes cost-optimality into account for the proposal of a sludge management plan with focus on land application as the final beneficial use. In this context, in this study, it was ensured that the most appropriate scenario for the WWTPs in terms of total sludge management cost optimization was selected under 3 different scenarios as drying on-site, drying off-site or application on land without drying. Moreover, with the land suitability model developed for this study, agricultural areas where sludge can be applied have been determined in Gediz basin.

CHAPTER 2

LITERATURE REVIEW

2.1. Wastewater Sludge Characteristics

According to the US Environmental Protection Agency (EPA), sewage sludge or sludge is technically described as the separated solid during the processes of wastewater treatment. EPA also mostly utilizes the "Biosolid" term in corresponding regulations to refer to treated and stabilized sludge that satisfies appropriate conditions for land application. (EPA, n.d.). "Sludge", "Wastewater Sludge" and "Sewage Sludge"are the terms which are used throughout this study.

Main sources of sludge production are urban WWTP/s and industrial WWTP/s (Gurjar and Tyagi, 2017a). In an urban wastewater treatment facility, sludge types are categorized as primary, secondary and chemical sludge according to its generation point throughout the wastewater treatment process (Gurjar & Vinay Kumar Tyagi, 2017a). A typical wastewater treatment flow diagram including generation points and corresponding sludge types are given in Figure 2.1

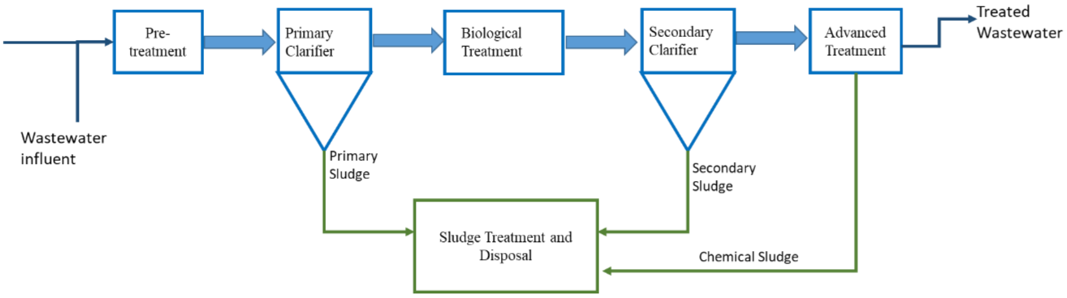


Figure 2.1: Wastewater treatment flow diagram (Turovskii & Mathai, 2006a)

Generation of primary and secondary sludge has a significant impact on the determination of further sludge treatment and disposal since they are carbon rich materials required to be stabilized in contrast to chemical sludge, which mainly constitutes of inorganic and inert materials (Kalavrouziotis, 2017).

Sludge characteristics can be described in three main categories: (i) physical, (ii) chemical and (iii) biological. Significant characteristics of sludge are total solids content and organic matter content. Important chemical properties of sludge are pH ,soluble salt, macro- and micro-nutrients, trace elements, and organic chemicals. Biological features of sludge indicate mainly pathogen content (Colón et al., 2017). Table 2.1 shows the broad range of sludge characteristics in terms of physical,chemical, and biological characteristics.

Table 2.1: Broad range of sludge characteristics (Colón et al., 2017; Herzel et al,. 2016; Hossain et al., 2015; Manara and Zabaniotou, 2012).

Properties	*Unit*	*Range*
VS content	(%)	43 – 80
Ash content	(%)	20 – 57
pH	-	4.5–8.3
Cation exchange capacity	cmol/kg	35-40
Total organic content	g/kg	360–412
C/N ratio	-	7-11.4
Total N	g/kg	15–62
Total P***	g/kg	13-29-
S**	g/kg	8-15
Ca	g/kg	10–38
Mg	g/kg	4–26

Table 2.1: continued

Na	g/kg	0.7–1.5
K	g/kg	1.9–6.5
Al*	g/kg	8
Cu	mg/kg	151–800
Co*	mg/kg	30
Cr	mg/kg	54–500
Ni	mg/kg	17–80
Cd	mg/kg	0.6–3.6
Zn	mg/kg	588–1700
Pb	mg/kg	28–3940
Mn	mg/kg	188–395
Hg	mg/kg	0.4–8
NPE	mg/kg	489–2556
PCBs	mg/kg	0.01–0.35
PHAs	mg/kg	0.01–5.3
DEHP	mg/kg	2–164
LAS	mg/kg	816–3240
PCDD	ng TEQ/kg	7–15

* Untreated mixed (primary + activated) sludge
** Anaerobicly digested sludge
*** Thermally dried sludge

Composition of wastewater and types of wastewater treatment used in WWTP/s have influence on the characteristics and quantity of produced sludge (Kalavrouziotis, 2017). As composition of wastewater generally varies annually, seasonally, or even daily; sludge characteristics can change accordingly. Also, wastewater treatment options applied can alter the characteristics and quantity of the sludge produced. Higher wastewater treatment levels can raise the total volume of generated sludge and the concentrations of contaminants in sludge (Marcos Von Sperling, 2007a). Sludge produced in industrial WWTP/s are more likely to contain toxic materials such as heavy metals, pathogens, or other chemical content, compared to urban sludge. Thus, the techniques applied for sludge treatment and management of produced sludge in industrial WWTP/s differ in accordance with the sludge quality and characteristics (WEF, 2008).

2.2. Wastewater Sludge Generation Rates

Proper management of sludge is one of the critical topics, as there is a huge amount of production worldwide (Grobelak et al., 2019). Global main producers of sludge are Europe,North America and East Asia (Spinosa, 2011; EC, 2016). Annual total amount of sludge produced in EU is estimated as more than 10 million tonnes. Also, approximately 20 million dry tonnes and 8 million dry tonnes of sludge is estimated to be generated in China and U.S., respectively (Seiple et al., 2017). Table 2.2 shows the sludge generation amounts in various countries in different years.

Table 2.2: Sludge generation in various countries in different years (UN-Habitat, 2008; Asian Development Bank, 2012)

Country	***Sewage Sludge (Thousands of dry tonnes)***
Japan (2006)	2000
Korea Republic (-)	1900
Iran (2008)	650
Jordan (2008)	300
Canada (2008)	550
Brazil (2005)	372
Australia and New Zealand (2008)	360

Sludge production rates for the EU-27 member states in 2018 are given in Figure 2.2. This year is selected based on the presence of accurate and comprehensive data (EUROSTAT, n.d.). According to that; Germany, France, and Spain produce higher amounts of sludge than most of the other countries in EU-27.

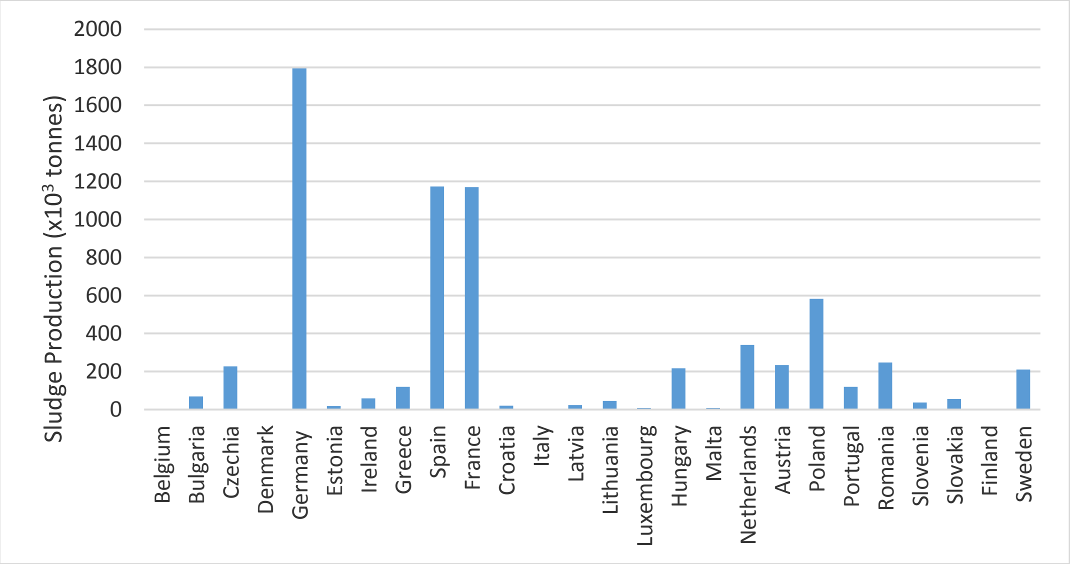


Figure 2.2: Sludge production amounts of EU-27 member states in 2018 (EUROSTAT, 2018)

Figure 2.3 shows the annual sludge amounts generated in domestic and municipal WWTP/s in Turkey. Figures are taken from a project on sludge management of domestic and municipal WWTP/s (EKACYP, 2010). Figures beyond 2010 are projections. It is estimated that sludge generation will considerably increase towards 2040. Approximately, 900.000 tonnes will be generated in Turkey by 2040.

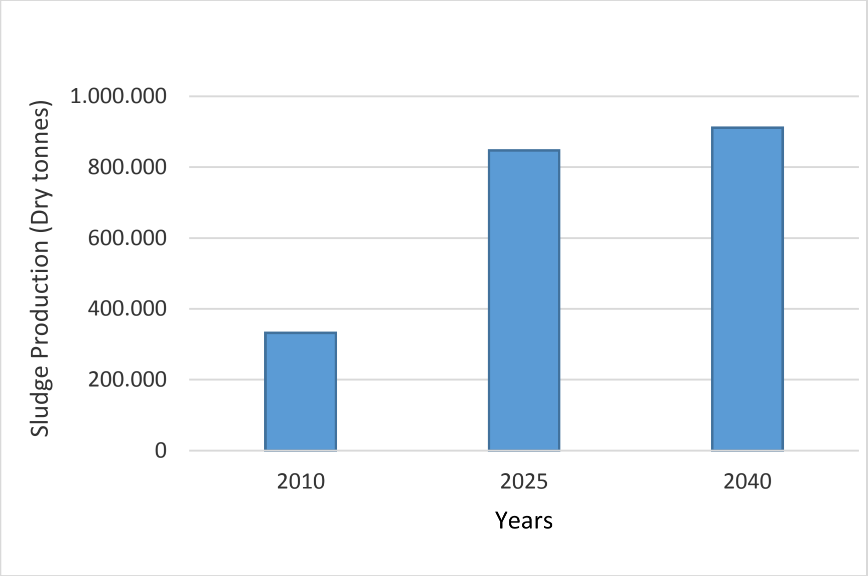


Figure 2.3: Sludge production amount of Turkey by years (EKACYP, 2010)

2.3. Treatment and Management Alternatives of Sludge

2.3.1. Treatment Alternatives of Sludge

The main objective of sludge treatment processes is to reduce sludge volume and render it suitable in terms of human health and environmental safety for ultimate management (Amuda et al., 2008). Sewage sludge treatment is generally designated based on the ultimate management method of sludge. Sludge treatment generally includes thickening, stabilization, dewatering and drying (Umweltbundesamt, 2013). Stabilization, dewatering and drying are discussed below in detail.

2.3.1.1. Sludge Stabilization

U.S., European Union, and Turkish legislations relevant to sludge management require sludge to be stabilized for certain beneficial uses such as application on land. Stabilization of sludge indicates processing in order to eliminate potential environmental deterioration, reduce odor and pathogens and rendering it a more stable product for further disposal/recovery options (Peirce et al., 2000). The stabilization processes can be divided mainly into two, which are biological and chemical stabilization. Under the biological stabilization concept, anaerobic/aerobic digestion and composting are the common applications. Alkaline stabilization is a general method for chemical stabilization (Marcos Von Sperling, 2007b). Selection of a proper stabilization method for sludge is mainly based on a further disposal/recovery option. Aerobic/anaerobic digestion and composting can be appropriate options when sludge is used in agriculture or for landscaping/horticulture applications as a final beneficial usage. Alkaline stabilization can be applied for mainly daily landfill covering (Luduvice, 2007).

Anaerobic digestion is one of the oldest and most widely applied process to reduce both primary and secondary sludge (Foladori et al., 2010). Generally, it is comprised of a two-stage biological process comprising of waste conversion and stabilization (Taricska et al., 2007). Anaerobic digestion process converts organic solids without an oxygen supply into gasses such as methane, carbon dioxide, combination of methane and carbon dioxide from biogas, and stable organic residue. Produced biogas consisting of 48%–65% methane and can be used for power generation. Therefore; it may be possible to obtain profit or reduce operational cost by the sale of the generated power/electricity into the grid system (Kiselev et al., 2019). In addition to the production of a power generative gas, anaerobic digestion forms stabilized sludge of good quality in terms of organic content, as well as eliminated pathogens and reduced odorous emissions. Also, dry matter content of sludge is reduced as a result of this process. Consequently; sludge volume is significantly moderated (Nasir et al., 2012). The residual stabilized sludge resulting from the process can be utilized as a soil conditioner. However, there are also several drawbacks related with this stabilization method. It requires relatively higher capital cost for construction than other stabilization methods. The process is labor-sensitive. Thus, it requires skilled manpower for operation and maintenance. The anaerobic digestion process is governed by highly complex mechanisms, hence maintaining optimal reaction conditions can be challenging (Dillon, 2015). Table 2.3 shows the number of established biogas plants in WWTP/s in different countries and the corresponding amounts of power generation from biogas.

Biogas generation is stated as one of the most promising renewable energy sources worldwide. Along with that, anaerobic digestion of sludge is one of the efficient and reliable ways of generating biogas (Khalid et al., 2011). According to various studies, biogas yield of sludge is reported to be between 150-300 m^3/ dry tonne (GATE & GTZ, 2007; Arthur & Brew-Hammond, 2010; Surroop & Mohee, 2012; Khan et al., 2014; Demirbas et al., 2016). The heating value of biogas is 25-30 MJ/m^3. Typically, 60% of biogas by volume is methane and the efficiency of a gas engine for electric production from methane is generally stated as about 30 % (WBG & WPP, 2015; Martinez, 2016; Syed-Hassan et al., 2017). Therefore, the approximate amount of electricity production from sludge can be estimated to be in the range of 2-4 KWh/m^3 (Arthur, 2009; Surroop & Mohee, 2012).

Table 2.3: Countries with number of biogas plants in WWTP/s and corresponding power generation from biogas generate. (Hanum et al., 2019)

		Biogas Production in WWTP/s (Only from sewage sludge)	
Country	***Year***	***Number of Plants***	***[GWh/y]***
Australia	2017	52	381
Austria	2017	39	18
Brazil	2016	10	210
Denmark	2015	52	281
Finland	2015	16	152

Table 2.3: continued

France	2017	88	442
Germany	2016	1258	3517
Norway	2017	24	223
Korea	2016	49	1234
Switzerland	2017	475	620
Netherlands	2015	80	541
United Kingdom	2016	162	950
United States	2017	1240	n.a.*
Malaysia	2017	35	247

* Not applicable

Aerobic digestion is a solids stabilization process which supplies a limited amount of oxygen to microorganisms to provide oxidation of organic matter (Guyer, 2011). Aerobic digestion uses aerobic bacteria. These type of bacteria rapidly consume organic matter with the help of oxygen and convert it into carbon dioxide, water,and nitrogen compounds (Shammas & Wang, 2007). Aerobic digestion has a relatively lower capital cost compared to anaerobic digestion. It also generates odorless end products. Therefore; its operation is safer with no potential of gas explosion and less odor problems (Turovskiĭ & Mathai, 2006b). Nevertheless, there are disadvantages of aerobic stabilization in comparison to anaerobic digestion. It requires higher operation cost in the form of power cost for supplying oxygen, Methane gas, a beneficial by-product, is not produced during aerobic stabilization. Aerobic stabilization is a temperature-sensitive process and thus its efficiency drops during cold weather. Also, the performance of aerobic digestion is mainly influenced by solid concentration and the type of sludge and mixing-aeration system of the unit (Turovskiĭ & Mathai, 2006b).

Composting is also conducted under aerobic conditions. Micro-organisms decompose organic constituents to relatively stabilized humus-like sludge under aerobic thermophilic conditions. Environmental conditions such as temperature, pH, oxygen concentration, etc.. and sludge characteristic such as moisture content, carbon/nitrogen ratio, etc.. influence the speed and occurrence of composting cycles (Shammas & Wang, 2007). Since composted sludge (compost) can provide more than adequate organic matter and nutrients (such as nitrogen and potassium) to soil and improves soil cation-exchange capacity, compost as an agricultural fertilizer can be efficient in terms of further recovery (US EPA, 2002). Composting process is mainly used by small WWTP/s as a sludge stabilization method, because it is a mechanism capable of handling sludge at a relatively low capacity (Luduvice, 2007). In addition to that, composting method is considerably handy for small-sized WWTP/s in terms of requirement for reduced labor force, additional bulking agent, and land for construction; compared to other biological stabilization methods (Shammas & Wang, 2007).

Alkaline stabilization is a relatively simple process. It mainly consists of potential lime compounds addition to sludge in order to reduce odor and pathogens by maintaining a high pH around 12, which inhibits biological activity (EPA, n.d). Active materials for alkaline stabilization contain hydrated lime, quicklime (calcium oxide) , fly ash, lime and cement kiln dust, and carbide lime. The most commonly used one is quicklime, as it has an ability to provide high heat of hydrolysis and subsequently improves pathogen destruction efficiency (Williford & Chen, 2007). Amount of lime to be added is estimated as 30% of the dry solid content so as to ensure the block of fermentation process (EC, 2001).

The total cost of treatment alternatives mainly encapsulates capital and operation & maintenance (O&M) expenditures. Cost is generally calculated and reported on the unit tonne of sludge produced (EC, 1999). Economically; anaerobic digestion is estimated to be more cost-efficient compared to aerobic digestion, as it provides high yield in terms of power generation (Murray et al., 2008). The total cost of composting method highly varies based upon handling and the capacity of composting mechanism (Mininni et al., 2015).

2.3.1.2. Sludge Dewatering

Sludge dewatering has an objective to remove moisture from sludge for the succeeding proper disposal or recovery option (Bahadori & Smith, 2018). It can convert sludge into sludge cake with solids content in the range of 10% to 40% total solids (Amuda et al., 2008). Dewatering of sludge can be accomplished with either mechanical or natural processes. The basis of natural dewatering processes is natural evaporation and percolation; as well as mechanical dewatering obtained through filtration, squeezing, and compaction (Gurjar & Vinay Kumar Tyagi, 2017b). Mechanical processes commonly include centrifuges, belt filter presses and filter presses. Natural processes are mainly consisted of sludge drying beds and sludge drying lagoons. Increase in the solid concentration of sludge after dewatering is dependent on the application of different dewatering processes (Gurjar & Vinay Kumar Tyagi, 2017b). Table 2.4 shows the potential total solid concentration of dewatered sludge with specified processes.

Table 2.4: Total solid concentration of dewatered sludge with specified processes (Tchobanoglous et al., 2003)

Unit Process	***Total Solid Concentration (%)***
Centrifuge	15-35
Belt filter press	12-30
Filter press	20-45
Drying beds and lagoons	8-25

A particular process can be selected based on different parameters such as type and volume of sludge to be dewatered, required solid concentration of dewatered sludge, and area availability (Turovskiĭ & Mathai, 2006c). Table 2.5 shows all dewatering methods comparatively with their advantageous and disadvantageous aspects.

Table 2.5: Advantages and disadvantages of dewatering processes (Amuda et al., 2008; Gurjar & Vinay Kumar Tyagi, 2017b)

Process	***Advantages***	***Disadvantages***
Centrifuge	• Relatively less space requirement • Fast startup and shutdown capability • Does not require continuous operator attention • Good odor containment	• Relatively high capital cost • Consumes more power per unit of product produced • Requires skilled personnel • Requires periodic repair
Belt filter press	• Relatively low capital. operating and power costs • Easier to maintain the system	• Very sensitive to feed sludge characteristics • Requires large quantity of belt wash water
Filter press	• High cake solid concentration • Low suspended solids in filtrate • Suitable for hard-to-handle sludge • Capacity increase is not challenging	• Batch operation • High capital and labor cost • Requires skilled personal • Often requires inorganic chemical conditioning
Drying beds and lagoons	• Low capital cost when land is readily available • Low energy consumption • Low to no chemical consumption • Least operator attention and skills requirement	• Large area requirement • Requires stabilized sludge • Climate-intensive operation • Labor-intensive operation • Odor potential

2.3.1.3. Sludge Drying

Sludge drying is the removal of water from dewatered sludge with use of energy in order to reduce the volume and weight for efficient transportation, destruction of any biological processes, and compression of sludge (Amuda et al., 2008). The main purpose of sludge drying process is reducing the moisture content of sludge from 10%–50% to 80% (Mengtao & Zhenfeng, 2008). In order to evaporate the water in sludge, a significant amount of energy is required. In general, this energy is provided by either thermal processes such as combustion of various fuels, or through solar radiation (WEF,2014).

Thermal drying is attained mainly through the combustion of fossil fuels to generate heat (Wei et al., 2015). It is a traditional sludge drying method. It is used relatively widely and maturely compared to solar drying (Shugin & Xiaoran, 2004). In accordance with Wei et al. (2015), thermal drying has several advantages and disadvantages compared to solar drying. It is an advantageous process in terms of short processing time, large handling capacity, small space requirement, high volume reduction rate, lower vulnerability to external factors, and hygienization assistance. Ineffective aspects of thermal drying contain large capital investment and high amount of energy consumption leading to increased expenditure for fuel consumption. Also, it generates environmental pollution by exhaust gas emission.

Solar sludge drying implies the utilization of solar radiation as the main energy for sludge drying (Wei et al., 2015). Solar drying of sludge is widely accepted as a serviceable drying method in terms of being a cost-effective and environmentally-friendly technology. Solar drying of sludge is a sensitive method in terms of intensity of solar radiation, humidity of air,bed surface area, and physical and chemical properties of sludge (Kamizela & Kowalczyk, 2019). As advantages, solar drying provides savings in transportation and disposal costs, requires low energy and operational costs. On the other hand, solar drying requires large area and high initial capital cost (Burgess, 2017).

2.3.2. Management Alternatives of Sludge

Following necessary treatment steps,sludge can be recycled or disposed using 3 different methods, in general, which are incineration (thermal processes), landfilling, and land application (agricultural use) (Spinosa, 2011). Information regarding beneficial use or recycling routes of sludge will be given in this section. In addition to these options, sewage sludge can be reused in brick and ceramic production, manufacturing lightweight aggregates, soil improvement material, and landfill cover (Ahmad et al., 2016).

According to Collivignarelli et al. (2019) , in EU-27; land application is the main route for sewage sludge recovery. 50% of sewage sludge is spread over agricultural lands; 28% is incinerated; and 18% is disposed in landfills. Other types of management options are also applied by some of the EU countries. Ireland, Latvia, and Slovakia reuse their sludge in forestry and Sweden utilizes its sludge as a landfill intermediate cover (Collivignarelli et al., 2019). In the USA, about 55% of the produced sludge is utilized for agriculture and land restoration purposes, and 45% is landfilled in municipal solid waste (MSW) landfills and combusted in incineration plants (NEBRA, 2007). Figure 2.4 depicts the information regarding sludge management routes in EU countries

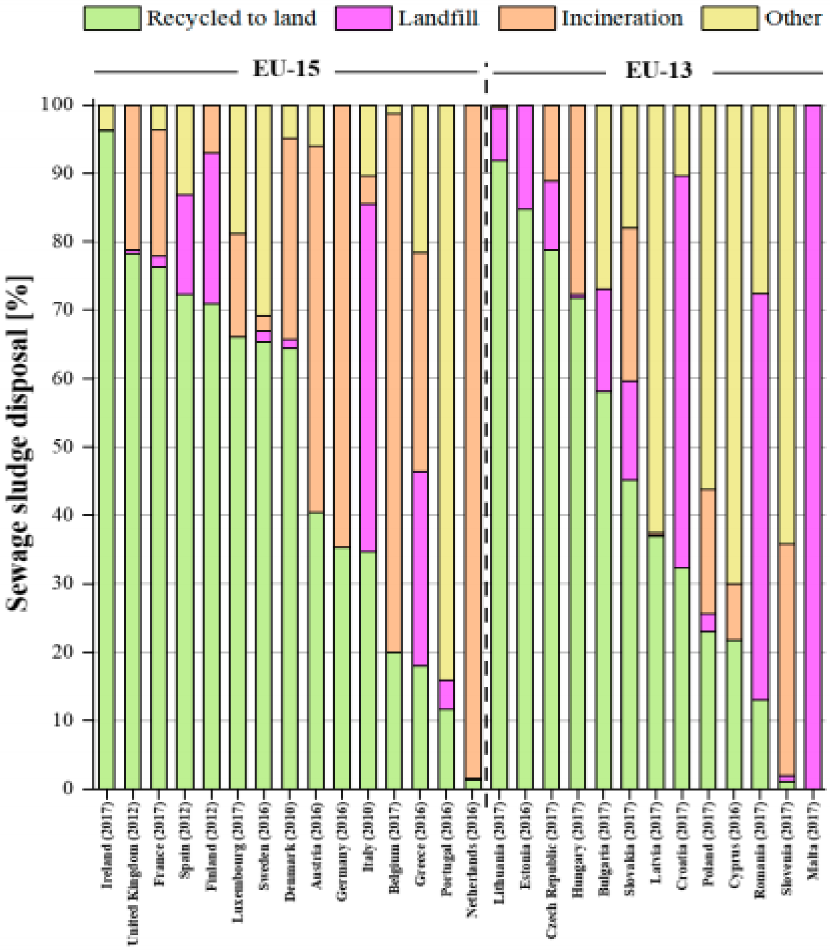


Figure 2.4: Sludge recovery routes in Europe (Collivignarelli et al., 2019)

2.3.2.1. Incineration

Incineration process is composed of complete combustion of the organic content present in sludge (Gurjar & Vinay Kumar Tyagi, 2017c). The most significant parameter for sludge combustion is sludge water content, Sludge cake with 50% to 70% water can be incinerated without an additional fuel, however; sludge cake with more than 70% water may require an additional fuel for combustion (Li et al., 2012). Sludge incineration is practiced in the forms of mono-incineration, co-incineration, or following pyrolysis, and gasification. Mono-incineration is designed for the combustion of sludge intake only. The co-incineration process comprises of incineration of sludge with other substances; mostly municipal wastes,or utilization of sludge as an auxilary fuel in energy generation plants or cement and lime factories (EC, 2001). As an advantageous process; sludge incineration provides great reduction in volume and mass, complete destruction of pathogens, and potential recovery of energy. However; incineration of sludge requires relatively higher capital and operating costs than other sludge management strategies; creates a residual (ash) and emissions which require additional treatment to assure the protection of environment (Turovskiĭ & Mathai, 2006d).

Mono-incineration of sludge is approved to be technically designated and a relatively operation risk-free, as dedicated incineration plants are employed purely for sludge combustion (Gutjahr & Müller-Schaper, 2018). Yet, co-incineration can be preferred for many reasons. Co-incineration of sludge with municipal solid wastes is serviceable in terms of total cost. It has a major objective of reducing the combined cost of incinerating sludge and solid wastes (Tchobanoglous et al., 2014). Co-utilization of sludge enables the operation of already established facilities to combust sewage sludge without major alteration. Thereby, it resolves the additional expenditure for a new processing plant (Syed-Hassan et al., 2017). Co-incineration process is commonly applied in coal-fired thermal power plants, in which sludge is used as an auxiliary fuel. In cement factories, it can be used as an additional raw material or auxiliary fuel. It is also applicable to recover energy in the form of electricity or heat (steam) from such sludge co-combustion processes (Rulkens. 2008).

As newer technologies alternative to sludge combustion, pyrolysis and gasification constitutes thermo-chemical processes which effectuate products such as pyrolytic oil, gases, and coke residue (Blagojevic et al., 2017). Pyrolysis occurs in the absence of oxygen, while in gasification a certain amount of oxygen is added (Blagojevic et al., 2017). Products of these processes are mostly utilized for further heat and power generation (Syed-Hassan et al., 2017).

2.3.2.2. Landfilling

Landfill option comprises of disposal of sludge in ditches or trenches and then covering it with an intermediate cover material, mostly soil. Following the fill-up of the overall capacity, the landfill is sealed (Marcos Von Sperling, 2007c). Landfill gas is generated from the decomposition of wet organic waste under anaerobic conditions in a landfill. Landfill gas is named as biogas which is a fuel (CH_4 and CO_2) obtained by anaerobic decomposition of feedstocks like sewage sludge, municipal solid waste, etc. It can be a useful resource for power generation (Asgari et al., 2011). Yet; an aqueous effluent named as leachate may be generated enhanced by rainwater percolation through landfilled materials, which may constitute a problem relevant to landfilling. Landfill sites create a potential for groundwater contamination from leachate (Marcos Von Sperling, 2007c). Leachate may include large amounts of organic matter as well as ammonia-nitrogen, heavy metals, chlorinated organics, and inorganic salts (Renou et al., 2008).

Landfill disposal may be preferred for sludge having high concentrations of metals or other toxics. Landfilling may be applied for biogas production. Moreover, it can be considered as a relatively inexpensive option for especially the disposal of malodorous sludge (Kajitvichyanukul et al., 2008). However, there are also disadvantages of landfill disposal. Landfilling needs comprehensive planning in terms of a landfill site selection, operation, closure, and post-closure care. Operation of landfilling is labor intensive (Marcos Von Sperling, 2007c).

Landfilling of sludge is applied in two different ways; disposal of sludge in a dedicated (exclusive) landfill or co-disposal with urban wastes (Marcos Von Sperling, 2007c). Dedicated landfills are especially designed for sludge disposal. They are generally constructed with sufficient capabilities to handle specific sludge characteristics and adapt to environmental constraints. In this type of landfill sites, disposed sludge is required to have a solid content higher than 30% (Andreoli et al., 2007). As distinct from exclusive landfilling of sludge, co-disposal with urban wastes accelerates the biodegradation process, which brings enhancement of sludge inoculation potential. The disadvantage of this alternative is the decrease in landfill lifetime when mixed sludge amount is significant (Andreoli et al., 2007).

2.3.2.3. Land Application of Sludge

According to the Environmental Protection Agency (EPA), land application process is mainly described as spreading, spraying, injecting, or incorporating of sewage sludge, including sludge compost materials, on or just below the surface (EPA, 1994). In general, it can be performed for two different purposes, which are land reclamation and agricultural use. Land reclamation is the utilization of sludge on areas where soil is degenerated such as mining areas, etc. and also where fixation for vegetation is required such as golf courses, reclamation sites, etc. Agricultural use is the application of sludge on areas which are occupied for animal or human feed growth. Agricultural use of sludge is performed more widely than for land reclamation (Marcos Von Sperling, 2007c).

Sludge contains a lot of nutritious substances for plant growth such as phosphorus and nitrogen compounds (Wang et al, 2008). Organic nitrogen and inorganic phosphorus form the major parts of the total nitrogen (TN) and total phosphorus (TP) contents in sewage sludge, respectively. The availability of these substances generally depends on the wastewater constituents and treatment processes applied for wastewater and sludge treatment (Moss et al., 2002). Mostly, the amount of sludge to be applied is calculated in accordance with the nutrient requirement of the vegetation or crops. A sufficient amount of nutrient needed by a crop or vegetation is stated as the agronomic rate, while the application rate of sludge based on that rate is defined as the agronomic application rate (Turovskiĭ & Mathai, 2006c).

There are requirements and limitations for land application of sludge as specified in relative regulations in terms of sludge and soil characteristics (Shammas & Wang, 2008). These typically comprise of pathogen, heavy metal, organic contaminant level of sludge, processed treatment steps of sludge, heavy metal accumulation content and geographic characteristics of soil. and growth pattern of agricultural land. In addition to them, the agronomic application rate of sludge is also regulated for proper agricultural usage (Grobelak et al., 2019).

Agricultural use of sludge is explained in detail with regard to its beneficial and disadvantageous aspects. Regulative framework of different countries and worldwide applications are also provided in the following sections.

2.3.2.3.1. Benefits of Agricultural Use of Sludge

Agricultural use of sewage sludge is widely practiced regarding its organic matter content and nutrient supply, especially nitrogen and phosphorus compounds, for the enhancement of soil characteristics and crop production (Urbaniak et al., 2016). Also, sludge can store high concentrations of Calcium (Ca) and Magnesium (Mg). The substantial content of sludge enables it to be a practically good fertilizer, a cheap and a rich soil enhancer (Kacprzak et al., 2017).

With the application of the rich content of sludge, soil is improved in terms of the physiochemical and biological properties. Improvement in physiochemical properties of soil designates increase in water filtration, improved resistance against rainfall impact, improvement in aggregation of soil particles, and improvement in cation exchange capacity. Advancement in biological properties denotes increase in microbial biomass and accordingly enhancement in plant growth (Grobelak et al., 2015).

According to various researches in the literature, sludge application on land benefits the growth qualities of plants and crops under the condition of application at the optimum agronomic application rate. Studies reveal that:

- Growth yield of Eucalyptus plant can be improved (Abreu-Junior et al., 2017).
- Dry weight biomass amount of sunflower can be increased (Morera et al., 2002).
- Biomass amount and grain yield of *Oryza sativa* (Asian Rice) can be escalated (Latare et al., 2014)
- Plant biomass amount of French bean can be augmented (Kumar & Chopra, 2014).
- Biomas yield of wheat growth can be increased (EKACYP, 2010).

Cele and Maboeta (2016) tested the issue regarding improvement in physiochemical properties of soil by conducting an experiment. They have performed research by implementing sludge on an area where *Cynodon dactylon* plant grows with using different application rates. They found significant improvements in soil parameters related to fertility such as in organic matter, water holding capacity, cation-exchange capacity (CEC), ammonium, magnesium, calcium, and phosphorus compounds.

Rajendram et al. (2010) studied the impact of sludge application on soil, plant and feed (silage, hay and grain) by spreading the treated sludge at the rate of 98 dry tonnes/ha to cover about 7.9 ha of farmland. Soil test were performed for 110 days and also for 9 months after application. Results demonstrated that treated sludge application increased the nutrient concentration in soil. Study results also showed that there was an increase in the nutrient concentrations in herbage and grain grown, while no increase was shown in contaminant concentrations in crops grown.

Wang et al. (2021) conducted a study to propose a solution for ever-increasing economic, social and regulatory pressures on land application of anaerobically digested sludge. In this context, the issues can be potentially solved via implementing further stabilization on anaerobically-digested sludge. The existing further stabilization options are mainly oriented towards three aims, namely, to enhance dewaterability, to reduce solids and stabilize sludge and to facilitate metal solubilization.

In the study conducted by Yoshida et al. (2018), long-term impacts of land application are analyzed via life-cycle assessment method. As a conclusion of the study, it was stated that before entering the process of land application, conducting a detailed N flow analysis for sludge by including all sludge treatment stages should be taken into consideration, since the emission of reactive N into the environment is the major driver for almost all non-toxic impact categories. Also, this study highlights that sludge application on land was the life-cycle stage with the greatest positive impact potential, while fertilizer substitution accounted for the greatest impact saving.

Boudjabi and Chenchouni (2021) performed a study which compared the fertilization impact for different sewage sludge application methods, i.e., soil surface application such as ‘mulching’ versus homogenously mixing with soil, on some soil fertility parameters and the productivity of cereal crops. Regardless of the method of sludge application, both soil characteristics and plant growth and yield were significantly improved in fertilized treatments. The outcomes of this study advanced general information on the beneficial effect of soil fertilization using properly treated and applied clean sludge.

With technological improvements, the phosphorus content of sewage sludge can be externally improved (Ens, 2016). Andriamananjara (2016) used a phosphorus radiotracer technique to measure the availability of phosphorus for plants in thermally conditioned sewage sludge in order to state sludge effectiveness as soil fertilizer. As a result of his study, Andriamananjara (2016) supported the application of sludge as fertilizer. He assessed that sludge has a higher agronomic effectiveness in comparison with commercial fertilizer. The study revealed that sludge application enhanced the microbial biomass and therefore phosphorus immobilization in short-term. On the longer-term, the phosphorus captured by this microbial biomass can again become available for plants. Also, sludge can be identified as a non-limited, continuously present, and sustainable fertilizer source (Ens, 2016).

2.3.2.3.2. Potential Risk involved in Agricultural Use of Sludge

As sewage sludge may also contain harmful toxic substances such as heavy metals (Cd, Ni, Cu, Zn, etc.), organic chemicals (PAH, PCDD, etc.) and pathogens, it may cause risky conditions in terms of human and environmental health (Singh & Agrawal ,2008). Especially, bioaccumulation of heavy metals in the food chain can be highly dangerous for human health (Smith, 2009). According to FAO (n.d.), rise in the heavy metal concentration of soil caused by sludge application may lead to increased Cd, Ni, Cu and Zn concentrations in most of the crops grown, particularly in wheat, potato, lettuce, red beet, cabbage, and ryegrass.

Phosphorus and nitrogen load to surface waters generally arise from soil or in runoff. Application of treated sewage sludge on land can indirectly affect this type of loading through its contribution to soil phosphorus content, thereby contributing to increased excess phosphorus compounds in runoff (Brennan et al., 2012). Dissolved phosphorus originating from an agricultural system may also reach to shallow groundwater (Galbally et al., 2013).

Issues regarding the potential risks of sludge application on land due to pathogens mainly address the persistency of microbial activity in sludge despite stabilization treatment (Sidhu & Toze, 2009). The risk relevant with sludge-derived pathogens is designated by their survival ability in the soil environment after land spreading. Soil physiochemical characteristics which are related with the survival of pathogens are considered as soil texture and structure, pH, moisture, temperature, UV radiation, nutrient, and oxygen availability. Persistency of microorganisms in sludge primarily depends on temperature, pH, water content (of treated sewage sludge), and sunlight (Elsas et al., 2011). Persistent pathogens included in soil or sludge can influence the human health through two scenarios. Firstly, pathogens may be transported *via* overland or sub-surface flow to surface and ground waters, and result in contamination in consumable water. Alternatively, pathogenic organisms may accumulate on the crop surface following treated sludge application (Tyrrel and Quinton, 2003).

According to the United Nations Environment Program (UNEP), persistent organic pollutants (POPs), originating from pharmaceuticals, are organic compounds which resist biological and chemical degradation up to a point (UNEP, 2013). These types of products are suspected to be the reasons for some cancers, birth defects, and a dysfunctional immune system. They are typically described as having low water solubility and high lipid solubility. Therefore, they have high potential for bio-accumulation, in addition to have a long half-life in soil, sediment, air, or biota (Yang et al., 2011). Since pharmaceutical and personal care products are commonly used by people, they enter into WWTP/s. Consequently, they can reach environment through treated wastewater discharge into rivers or to agricultural system through land spreading of treated sludge (Yang et al., 2011).

Risk assessment study was performed by Yakamercan et al. (2021) which analyzed human-health risk potentials of the land application of sludge in terms of heavy metal content of soil and sludge. As a result of the study, it was found that although the heavy metal concentration of collected samples was within the legal standards for agricultural land application proposed by the Environmental Protection Agency

(EPA) and the Ministry of Environment and Urbanization of Turkey (MEU), risks may occur especially for sensitive individuals like children. However, this could be prevented with proper application for both ecological and health-safe circumstances.

Although there are several concerns and issues related to the agricultural application of treated sludge, no scientifically-based agreement can be found in the literature about direct adverse effects of sludge application on land (Colón et al.,2017). Issues and considerable concerns are mainly connected with nutrient and metal losses,pathogens and persistent organic pollutants involved in pharmaceutical products (EPA Research, 2017).

2.3.2.3.3. Global and Regional Examples of Agricultural Use of Sludge

Globally, the application rates of sludge on agricultural land vary from country to country. In countries like Brazil, Jordan, Mexico and Turkey; the use of treated sludge in agriculture is low (< 5%); but growing (UN-Habitat, 2008). On the other hand, developed countries such as U.S. and member countries of EU-15 have been utilizing their sludge on agricultural lands for a long while (Mateo-Sagasta et al., 2015). In reference to data in the literature, the most frequent way of agricultural use of sludge is indirect soil application of sludge as compost (Mininni et al, 2015). According to the statistics in Eurostat (2018), 50% of treated sludge is spread on agricultural land, on the average, in EU-15 countries. Norway applies about 90% of its sludge on soil as it is considered as the most environmentally sustainable option. France prefers to utilize nearly 60% of its sludge in agriculture similar to Belgium and Spain (Kominko et al., 2017). However; in Netherlands, Switzerland, Austria and Germany; application of sludge on agricultural areas is slightly decreasing. Potential reasons are the lower suitability of soils for the use of treated sludge for agriculture and high levels of health-related concerns by farmers and the public (European Commision, 2010).

In reference to Water UK (2017), 3.6 million tonnes of sludge is utilized annually for agricultural purposes, which corresponds to 78% of the total sludge amount. This is applied on approximately 150,000 hectares annually, or 1.3% of the agricultural lands in UK. UK government considers the agricultural use to be the most efficient option for sludge recovery in terms of sustainability.

USDA (2015) states that over 8 million tonnes sludge is produced annually in U.S. and 55% of the produced biosolid is applied on agricultural lands with the average N and P concentrations of 3.4% and 2.3%, respectively. According to a fact sheet prepared by Kumar et al. (2017), agronomic application rate of treated sludge is stated as 10 U.S. dry tonnes of biosolid per acre. In relation to this, biosolid application is implemented across only 390,000 acres, which covers 0.12% of the total arable areas in U.S. Also, it is indicated that biosolids are applied frequently on forage and row crops used for animal feed, or grains.

In a European Commission report regarding land application of sludge across Europe, a model has been proposed for the estimation of annual sewage sludge production and percentages to route of agricultural use in 2020 (RPA & WRC, 2010). Table 2.6 shows the sludge production and percentages to route of agricultural use in 2010 and corresponding estimations for 2020.

In the study conducted by Delibacak et al. (2008), treated sludge is applied as a fertilizer on agricultural areas where peanut is planted in the first crop and green bean was planted in the second crop. The aim of this study is to investigated effects of treated sewage sludge on the soil in terms of organic matter (OM) in Typic Xerofluvent soil in Menemen Plain, Western Anatolia İn Turkey. As a result of this study, treated sludge of smaller than 90 ton/ha can be added once in two years for improving soil properties of Typic Xerofluvent soil, which are characterized by low OM content

In the study performed by Hadas et al. (2021), life cycle assessment is conducted on representative assemblage of soils and crops, with weights assigned to each crop type and soil characteristic in order to assess the economic positive impacts of using treated sludge as fertilizer and soil conditioner. The result of this study states that the major amount of savings and regarded points for the farmers includes 159 $/ ha from chemical fertilizer replacement and 75 $ /ha from improvement to the soil's physical properties.

The study conducted by Yaman and Olhan (2011) involves research regarding the economic impacts on wheat production of sludge application as a fertilizer. The data for this study has collected from 39 facilities which use sewage sludge on wheat production and 42 facilities which do not apply sludge as fertilizer from 3 different districts of Ankara. According to the results of research, for facilities utilizes sludge as fertilizer, the wheat yield and profit increase is 17.63% and 64.90%, respectively. Also it is observed that production cost is reduced by 26.01%.

Table 2.6: Sludge production and percentages of agricultural use of sludge in European Countries (RPA & WRC, 2010)

	2010		**2020**	
Country	**Total sludge (tonnes DM/year)**	**Agricultural use (%)**	**Total sludge (tonnes DM/year)**	**Agricultural use (%)**
Bulgaria	47,000	50	51,000	60
Czech Republic	260,000	55	260,000	75
Estonia	33,000	15	33,000	15
Hungary	175,000	75	200,000	60
Latvia	30,000	30	50,000	30
Lithuania	80,000	30	80,000	55

Table 2.6 : continued

Malta	10,000	0	10,000	0
Poland	520,000	40	950,000	25
Slovakia	55,000	50	135,000	50
Slovenia	25,000	5	50,000	15
Austria	273,000	15	280,000	5
Belgium	170,000	10	170,000	10
Denmark	140,000	50	140,000	50
Finland	155,000	5	155,000	5
France	1,300,000	65	1,400,000	75
Germany	2,000,000	30	2,000,000	25
Greece	260,000	5	260,000	5
Ireland	135,000	75	135,000	70
Italy	1,500,000	25	1,500,00	35
Luxembourg	10,000	90	10,000	80
Netherlands	560,000	0	560,000	0
Portugal	420,000	50	750,000	50
Spain	1,280,000	65	1,280,000	70
Sweden	250,000	15	250,000	15

2.3.2.3.4. Regulations Regarding Land Application of Sludge

The most comprehensive and effectual legislations regarding land application of sludge are the “40 CFR Part 503- Standards for the Use or Disposal of Sewage Sludge” in the United States and “The Sewage Sludge Directive 86/278/EEC” of the European Union (EUR-Lex, 1986; US EPA, 1994). Regulations typically require that sewage sludge is subjected to chemical, biological, or heat treatment, or any other process to eliminate the potential for health risks along with its use on land. Also, regulations associated with sludge application on land mostly concern parameters such as heavy metal concentration in sludge and soil, pathogenic content. organic compounds and toxic substances in sludge (Healy et al., 2015).

In accordance with the Sewage Sludge Directive of EU, sludge should be applied on land in such a way that does not create any harmful effect on soil, vegetation, animals and humans. The EU directive also encourages the application of sludge in agriculture as sludge contains valuable agronomic properties. To ensure that sludge application does not impair soil and the harvest, the directive establishes limit values on only the heavy metal concentrations in soil and sludge, in addition to prohibition of sludge utilization on agricultural areas during growing season of fruits and vegetables except fruit trees. The EU directive is implemented as a framework directive; thus, individual member states can establish national legislations regarding new regulative parameters or lower limits compared to the stated ones in the directive (Mininni et al., 2015).

In U.S., the standard establishes general requirements, pollutant limits regarding heavy metal concentrations in sludge, management practices, and operational standards for land application of sludge. It also includes pathogen limit values for sludge and alternative vector attraction reduction requirements. 40 CFR 503 classifies the sludge into class A and class B according to the pathogen concentration in sludge following proper treatment. Class A treated sludge is described as nearly pathogen-free, where Class B is not. For this reason, the standard states some site restrictions on areas where Class B sludge can be applied.

In Turkey, issues regarding the discharge and recovery of wastewater sludge are managed within the scope of the Urban Wastewater Treatment Regulation (CSB. 2006), in general. In addition, within the scope of the Regulation on the Use of Domestic and Urban Sewage Sludge on Soil, there are restrictions and principles regarding the application of sewage sludge on soil (CSB, 2010c). In Turkey’s regulation, limit values are generally lower than the values in other regulations and cover many parameters for both applicable sludge and suitable soil characteristics.

Table 2.7 shows the heavy metal concentration limits (mg/kg DM of sludge) of sludge in regulations of different countries. According to this, heavy metal limits can vary in accordance with sludge pH, sludge type or in regulations associated with different regions.

Table 2.7: Heavy metal concentration limits in sludge in different countries (Christodoulou & Stamatelatou, 2016; Mininni et al., 2015; Collivignarelli et al., 2019; Hudcová et al., 2019; Wisniowska et al., 2019)

State	Cd	Cr	Cu	Hg	Ni	Pb	Zn	As
Germany	10	900	800	8	200	900	4000	-
UK	-	-	-	-	-	-	-	2
Spain [a]	20–40	1500	1000–1750	16–25	300–400	750–1200	2500–4000	-
France	20	1000	1000	10	200	800	3000	-
Italy	20	200	1000	10	300	750	2500	20
Netherlands	1.25	75	75	0.75	30	100	300	15
Austria [b]	2–10	50–500	70–500	0.4–10	25–100	45–500	200–2000	20
Sweden [c]	0.75	40	300	43952	25	25	600	-
Portugal	20	1000	1000	16	300	750	2500	-
Finland	1.5	300	600	1	100	100	1500	25
Denmark	0.8	100	1000	0.8	30	120	4000	25
Ireland	20	-	1000	16	300	750	2500	-

Table 2.7: continued

Greece	20–40	500	1000–1750	16–25	300–400	750–1200	2500–4000	-
Belgium[b]	6–10	100–150	600–800	1–1.6	100	300–500	1500–2000	20–150
Luxembourg	2.5	100	700	43983	80	200	3000	-
Poland	20	500	1000	16	300	750	2500	-
Hungary	10	1000	1000	10	200	750	2500	75
Romania	10	500	500	5	100	300	2000	10
Lithuania[d]	1.5–20	140–400	75–1000	1–8	50–300	140–750	300–2500	-
Slovakia	10	1000	1000	10	300	750	2500	20
Bulgaria	30	500	1600	16	350	800	3000	25
Estonia	20	1000	1000	16	300	750	2500	-
Latvia	2–10	100–600	400–800	3–10	50–200	150–500	800–2500	-
Slovenia	1.5	200	300	43952	75	250	1200	-
US	85	-	4.300	57	420	840	7.500	-
European Union 86/27/EEC	20–40	1500	1000–1750	16–25	300–400	750–1200	2500–4000	-
Turkey	10	1.000	1.000	10	300	750	2.500	-
China[a]	5-20	600-1000	800-1500	5-15	100-200	300-1000	2000-3000	75
Japan	5	500	Not limited	2	300	100	Not limited	50

Table 2.7: continued

Russian Federation	15	500	750	7.5	200	250	1750	10

[a] Different limit values for different sludge pH; [b] Different values for different regions; [c] Value expressed as g/ha.year; [d] Different values for different sludge categories

Table 2.8 shows the heavy metal concentration limits in soil in accordance with the regulations in different countries.

Table 2.8: Limits of heavy metal concentration in soil in different countries (Collivignarelli et al., 2019; Hudcová et al., 2019; Wisniowska et al., 2019)

State	**Cd**	**Cr**	**Cu**	**Hg**	**Ni**	**Pb**	**Zn**	**As**
Germany	0.4–1.5	30–100	20–60	0.1–1	15–70	40–100	60–200	-
United Kingdom[a]	3	-	80–200	1	50–110	300	200–300	50
Spain[a]	1–3	100–150	50–210	1–1.5	30–112	50–300	150–450	-
France	2	150	100	1	50	100	300	-
Italy	1.5	-	100	1	75	100	300	-
Netherlands	0.8	10	36	0.3	30	35	140	-
Austria	0.5–2	50–100	40–100	0.2–1.5	30–70	50–100	100–300	-
Sweden	0.4	60	40	0.3	30	40	100	-
Portugal[a]	1–4	50–300	50–200	1–2	30–110	50–450	150–450	-
Finland	0.5	200	100	0.2	60	60	150	-
Denmark	0.5	30	40	0.5	15	40	100	-

Table 2.8: continued

Ireland	1	-	50	1	30	50	150	-
Greece	1–3	-	50–140	1–1.5	30–75	50–300	150–300	-
Belgium	1.2–1.5	91–100	50–72	1–1.5	20–56	50–120	200	22
Luxembourg	2	150	100	1.5	75	200	300	-
Hungary	1	75	75	0.5	40	100	200	15
Czech Republic	0.4–0.5	55–90	45–60	0.3	45–50	55–60	105–120	15-20
Romania	3	100	100	1	50	50	300	-
Lithuania[b]	1–1.5	50–80	50–80	0.6–1	50–60	50–80	160–260	-
Slovakia	1	60	50	0.5	50	70	150	25
Bulgaria	1.5–3	200	80–200	1.5	75–110	60–120	200–300	25
Estonia	3	100	50	1.5	50	100	300	-
Latvia[a]	0.5–0.9	40–90	15–70	0.1–0.5	15–70	20–40	50–100	-
Slovenia	1	100	60	0.8	50	85	200	-
U.S.	*There is no limitation on soil							
European Union 86/27/EEC	1–3	50–140	1–1.5	30–75	50–300	150–300	1–3	-
Turkey	1 -1.5	60-100	50-100	0.5-1	50-70	70-100	150-200	-

[a] Different limit values for different soil pH; [b] Different limit values for different type of soil;

Some countries also regulate the organic micro-pollutant levels in treated sludge (ng TEQ/kg DM). Organic micro-pollutant limits are generally represented by the summation of all compounds considered within a given category such as AOX, PAH. PCB,etc.

Table 2.9: Limits of organic micro-pollutants in sludge in different countries (Hudcová et al., 2019; Wisniowska et al., 2019**)**

State	AOX	DEHP	LAS	NP/NPE	PAH	PCB	PCDD/F	C5 – C40
Austria								
(Carinthia) [a]	500	-	-	-	6	1	50	-
(Lower Austria)[b]	500	-	-	-	-	-	-	-
(Steiermark)[c]	500	-	-	-	6	0.2	100	-
(Voralberg)	-	-	-	-	-	0.2	100	-
(Upper Austria)	500	-	-	-	-	-	-	-
Belgium	-	-	-	-	-	0.8	-	-
Bulgaria	-	-	-	-	6.5	1	-	-
Croatia	-	-	-	-	-	0.2	100	-
Czech Republic	500				10	0.6	-	-
Denmark	-	50	1300	10	3	-	-	-
France					5[d]			
	-	-	-	-	2.5[d]	0.8	-	-
					2[d]	-	-	-
Germany	500	-	-	-	-	0.2	100	-
Hungary	-	-	-	-	10	1	-	4000
Luxembourg	-	-	-	-	20	0.2	20	-

Table 2.9: continued

Portugal	-	-	5000	450	6	0.8	100	-
Romania	500	-	-	-	5	0.8	-	-
Sweden	-	-	-	50	3	0.4	-	-
Turkey	500	100	2600	50	6	0.8	100	-

[a] Limit applies to all classes of sludge; [b] For Lower Austria. limits are applied to only Quality II class of sludge; [c] For Steirmark region of Austria. limits are applied to only sludge that comes from WWTP/s for more than 30 000 PE; [d] France regulates limit of 5 on fluoranthene. 2.5 on benzo(b)fluoranthene and 2 on benzo(a)pyrene.

Table 2.10 shows the maximum allowable concentrations of pathogens in sewage sludge. Limits applied to pathogens differs from country to country. *Salmonella* sp. is the most commonly controlled microorganisms in sludge by regulations. thus; associated limitations are displayed in a separated column in the table.

Table 2.10: Limits of pathogens in sludge in different countries (Collivignarelli et al., 2019; Wisniowska et al., 2019)

State	**Salmonella sp.**	**Other Pathogens**
Bulgaria	no occurrence in 20 g	Escherichia coli < 100 MPN/g Clostridium perfringens < 300 MPN/g Helminths eggs and larvae. 1unit/kg DM
Czech Republic	no occurrence in 1 g of DM	Thermotolerant coliforms < 10^3 cfu/g DM Enterococci < 10^3 cfu/g DM
Denmark	no occurrence	Faecal streptococci < 100/g

Table 2.10: continued

France	8 MPN/10 g DM	Enterovirus < 3 MPCN/10 g DM Helminths eggs < 3/10 g DM
Finland	no occurrence in 25 g	Escherichia coli < 1000 cfu. < 100 cfu in greenhouse cultivation, where the consumed part is in contact with the substrate
Italy	1000 MPN/g DM	
Lithuania		Escherichia coli ≤ 1000 cfu/g Clostridium perfringens ≤ 100 000 cfu/g Helminths eggs and larvae. 0 units/kg Enterobacteria. 0 cfu/g
Luxembourg		Enterococci – 100/g Helminths eggs cannot be contagious
Poland	no occurrence in 100 g	
Portugal	no occurrence in 50 g	Escherichia coli < 1000 cfu/g
Austria		
(Carinthia)	no occurrence in 1 g	Enterococci < 10^3/g no Helminths eggs
(Lower Austria)	no occurrence in 1 g	Escherichia coli < 100 cfu no Helminths eggs
(Steirmark)	no occurrence in 1 g	Enterococci < 10^3/g

Table 2.10: continued

Slovakia		Thermotolerant coliforms < 2×10^6 cfu/g DM Faecal streptococci < 2×10^6 cfu/g DM
Turkey		Reduced E. coli to 2 log10 (99% treatment required)
U.S.	A Class biosolid – 3 MPN/ 4 g DM	For A class sludge. Fecal coliforms <1000MPN/g DM Enteric viruses <1PFU/4g DM Viable helminth ova <1/4g DM For B Class biosolid. Fecal coliforms <2.000.000MPN/ g DM

* DM= Dry matter of sludge

In addition to the limits provided in above tables, in the Carinthia region of Austria has limits on Molybdenum (Mo) and Selenium (Se). Limit concentrations are 50 mg/ kg and 100 mg/ kg DM of sludge, respectively. In the Vienna region of Austria, Se and Mo have limits of 50 mg/ kg DM of sludge (Hudcová et al., 2019). In U.S. Regulation, Se and Mo concentrations are also limited to 75 mg/ kg and 100 mg/kg DM of sludge, respectively (Wisniowska et al., 2019).

Some countries apply additional restrictions as well on types of lands and vegetation for the land application of sludge. These are summarized below for selected countries or regions.

European Union (**EUR-Lex, 1986):** According to this regulation, utilization of sludge is prohibited on grassland which are to be grazed by animals. Application on areas for forage crops must be up to a minimum of 3 weeks before crops are harvested. Sludge application is forbidden during the growing season in lands where fruits and vegetables are grown, with the exception for fruit trees.

Turkey (CSB, 2010a): According to the Regulation on the Use of Domestic and Urban Sewage Sludge on Soil, stabilization is a compulsory treatment for sludge to be used on an agricultural area. It is forbidden to use stabilized sludge in soils that are used for growing fruit and vegetable products that contact the soil and are eaten raw, except fruit trees. Sludge application area must be located outside the buffer zone of surface water bodies; a minimum of 300 meters away from any surface water body. Slope of the sludge application land must not exceed 12%, and it is forbidden to apply sludge on wetlands, flood plains, frost and snow-covered areas, or saturated soil. Sludge application is banned on natural forest zones.

Denmark (Government of Denmark, 2000): Same restrictions as in European Union legislation are applied for grassland and fruit/vegetable growth. In addition to these, it is also prohibited to use sludge on such areas; wetlands, groundwater protection areas, and forest zones. In addition to these, in order to apply sludge on land, sludge should be stabilized, either through composting or pasteurization.

France (Government of France, 2009): In this regulation, sludge utilization is impeded on frozen and snow-covered ground, inclined surfaces, wetlands, groundwater protection areas, forest soil, as well as the implementation restrictions in the EU Framework Directive. Regulation also permits the use of untreated sludge under certain conditions. With a Decree of May 18. 2009, compensation for risks associated with the spreading of urban or industrial sewage sludge is implemented into regulation.

Germany (Government of Germany, 2017): In addition to the restrictions in the EU Directive, the regulation prohibits the application of treated sludge on groundwater protection zones, areas near surface water and forest soil. It also authorizes the maximum application rate per year as 1.7 ton/ha.year. With a new sludge ordinance entered in the force in 2017, sludge application on soil will only be permitted for sewage sludge from treatment plants with a capacity of less than 100.000 p.e. starting in 2029. From 2032, this will only be allowed for plants with a capacity of less than 50.000 p.e..

Italy (Government of Italy, 2016): Italian legislation is one of the most comprehensive and differentiated legislation from the EU Framework Directive. It only permits the use of sludge on soil having a pH higher than 5 and a cation-exchange capacity smaller than 8 meq 100^{-1} g^{-1}. In addition to the restrictions in the EU Directive, Italy limits the use of treated sludge on inclined surfaces and prohibits sludge application on wetlands or areas which recently received heavy rain. Moreover, it allows a yearly maximum application dosage of 6 tonnes/ha.

Portugal (Government of Portugal, 2009): Portuguese legislation covers a prohibition of sludge application on wetlands, groundwater protection zones, and areas close to surface water together in addition to the restrictions in the EU Directive. In accordance with the legislations, the maximum allowable annual application rate is 6 tonnes/ha.

2.4. Optimization Studies for Sludge Management

Karolinzcak et.al (2020) established an optimization model to minimize sludge treatment cost. The objective function was directly proportional to the BOD_5 load and share of the sludge in total flow. It was stated that the annual cost could be minimized by up to 50% with the help of a subsurface vertical-flow constructed wetland system placed before the biological activated sludge treatment (Karolinczak et al., 2020).

In an optimization study conducted in the Wastewater Treatment Station (WWTS) in Galati- Romania between 2017-2018, the process of using a stabilized sludge that does not contain heavy metals in agriculture was carried out. As a result of this study, it was observed that the cost of chemical fertilizers decreased by 30% with the improvement of soil content (Iticescu et al., 2021). In addition, as a result of a study created to optimize the system due to the increase in wastewater load during the grape harvest in the Palantine region of Germany, it was seen that the electricity usage was reduced by 20% in the use of high load anaerobic digester and the sludge formed was considerably reduced (Fraunhofer-Gesellschaft, 2016).

An optimization study was conducted by Görgüner (2013) in which sludge originating from the Ankara Central WWTP was allocated to non-irrigated arable lands starting from the lands closer to the plant. It was concluded that only 17.1% of the non-irrigated arable lands suitable for land application of sludge could get sewage sludge. Thus; it emphasized that non-irrigated arable lands in Ankara have a significant potential for the agricultural use of sewage sludge since the plant is already producing stabilized sludge, satisfying this criterion of the Regulation on the Use of Domestic and Urban Sewage Sludge on Soil (Görgüner, 2013).

Tsai et al. (2004) developed an optimization study consisting of decision-making framework in handling the incoming wastewater in the system. The study was conducted using dynamic programming and focused on minimizing the cost incurred in a wastewater treatment system while meeting the system constraints on final disposal limits for both water and sludge. Conclusion of the study was establishing new technologies in treatment facilities would ensure cleanliness of the effluent while minimizing cost (Tsai et al., 2004).

In a study conducted by Vadenbo et al. (2014), the thermal treatment of digested sewage sludge generated in the Swiss region of Zürich is modeled and optimized with an environmental perspective. In that study, multi-objective mixed-integer linear programming was used. Co-incineration in municipal solid waste incinerator, co-processing in cement production, and mono-incineration with the prospect of phosphorus recovery were integrated as sludge management options in the optimization model. As an outcome of the study, co-processing in cement production was the optimal solution when minimization of impacts on climate change, toxicity on human, and fossil resource depletion. Mono-incineration with phosphorus recovery was another optimal pathway when model assigned high weights on the constraints of eco-toxicity and mineral resource depletion (Vadenbo et al., 2014).

CHAPTER 3

METHODOLOGY

The study aims to manage the treatment sludge produced in the Gediz Basin through land application in the most cost-effective way. In order to reach this aim, Production points generating sludge suitable for land application in Gediz Basin were identified. Suitable lands for sludge application in the same basin were determined. An optimization model was developed to suggest the most cost-effective strategy for application of sludge on soils within a management period of 20 years while meeting the constraints in accordance with the Regulation on the Use of Domestic and Urban Sewage Sludge on Soil.

Based on the characteristics of sludge, potentially appropriate sludge for land application is produced mainly in domestic/urban WWTP/s and WWTP/s belonging to the industries in food production sector. Thus; only the WWTP/s appropriate within this framework were included in this study. As a result of communications with the water and sewerage administrators in relevant municipalities in the basin,it was seen that all considered WWTPs had sludge thickening and dewatering units. Yet, none of them applied sludge stabilization. However; in accordance with the Regulation on the Use of Domestic and Urban Sewage Sludge on Soil, sludge must be stabilized for land application. Thus; as biological stabilization methods are appropriate for land application (Iticescu et al., 2021), anaerobic digestion and composting methods were selected as the potential stabilization alternatives and incorporated into the optimization model. Information on the data used, the process used in determination of the paths for sludge transportation by trucks, identifation of the suitable areas for sludge application, and optimization model development will be explained in details in the following sections.

The optimization model developed is run on the ArcGIS Pro model builder platform. This platform is guided by the optimization model to provide the optimal pathways in management and allocation of the sludge produced in relevant WWTPs to suitable agricultural lands. While it wasaimed to minimize total costs of sludge treatment and transportation for land application, system constraints were taken into account as well as, will be discussed later. An algorithm was deveoped using the the Suitability Model tool under the Raster Functions section in the ArcMap 10.7 sofware in order to identify the suitable areas for land application of sludge. Required spatial data for the suitability model was obtained from open sources. In order to determine the distances between points of concern, the Origin-Destination Cost Matrix tool was used under the Network Analysis in ArcGIS Pro application. The distances both impacted the sludge transportation cost as well as used to make sure the system constraint on the maximum allowable transportation distance is not violated.

3.1. Description of the Study Area

Gediz Basin is one of the basins located in the west of Turkey. Gediz River Basin has 17,500 km^2 of total surface area (KSM, 2020). The length of the main tributary of the river that gives the basin its name is 401 km (TOB, 2018). Gediz Basin comprises of territories in the juristictions of 6 different provinces; Aydın, Denizli, İzmir, Kütahya, Manisa, and Uşak. A big portion of the surface area is in the Manisa province, Figure 3.1 shows the location and borders of the basin and the portions of the provinces included in the basin.

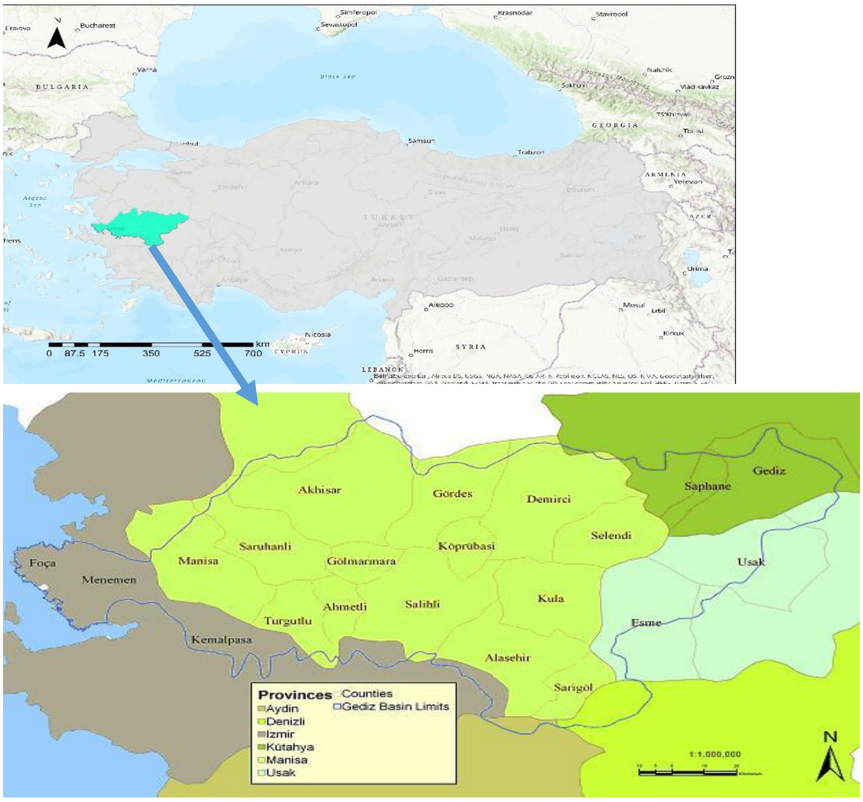


Figure 3.1: The location of Gediz Basin and the distribution of provinces included.

In general,more than half of basin area is naturally covered with mountains. When the land use distribution is examined, it is seen that central plain is mostly covered by agricultural areas, woodland, and bushes. Among the agricultural products in the basin, olives and fruit trees are dominant. In terms of the grown products, sludge can be applied on these lands with regard to the Regulation on the Use of Domestic and Urban Sewage Sludge on Soil. Figure 3.2 shows the proportional distribution of different land uses (TOB, 2018)

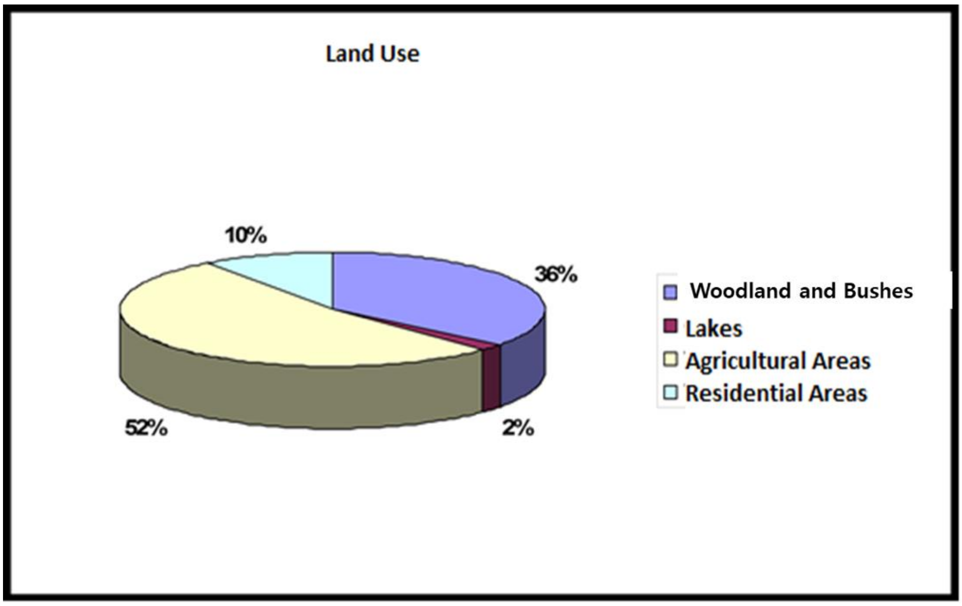


Figure 3.2: Land use distribution in Gediz Basin (TOB, 2018)

For this study, WWTPs which are already in operation are considered in model development. These plants are either domestic wastewater plants or WWTPs of food industry that produce sludge suitable for land application. In Table 0.1 in the Appendix, detailed information regarding 17 domestic/urban WWTP/s that were considered and integrated into the optimization model is provided. Sludge dry matter content (%) of the sludge at those WWTPs were taken from the official reports of KAMAG (EKACYP, 2010) project and through personal communication with related personnel in the Provincial Directorates of the Ministry of Environment and Urbanization. According to the report of Project on Preparation of Sludge Management Plan for Gediz Basin (CSB, 2017), all plants have sludge dewatering and thickening units. Therefore; in the optimization model it was proposed that thickening and dewatering units are already in place and operational as usual. Therefore, costs associated with those units were disregarded in cost calculations. In terms of sludge drying; all WWTP/s located in İzmir (5 WWTP/s) have been sending their sludge to Çiğli Thermal Sludge Drying Facility. Turgutlu and Manisa WWTP/s dry their sludge on-site using their own drying facilities. The WWTP/s which already have sludge drying units or send their sludge to the closest sludge drying facility are not integrated into the optimization model since their sludge is already dry in the current situation and do not require additional investment. As a result, the cost function of the optimization model considered only 17 domestic/urban WWTP/s.

According to Project on Preparation of Sludge Management Plan for Gediz Basin (CBS, 2017), there are 974 industrial facilities in Gediz Basin, and the sector distribution is dominantly food sector. This is followed by metal, chemical and machinery industries. In this study, industrial facilities which are in food sector that produce sufficient amount of sludge daily, which is at least 0.1 tonnes of daily sludge produced, were considered. Another selection criterion for further consideration in the optimization model was that wastewater from the food industry should have not been subjected to chemical treatment. More specifically, sludge from the WWTPs of food industry applying biological or primary treatment were considered. The reason for this is that chemically treated sludge would not be appropriate for land application in terms of its psychochemical content with respect to the criteria set in the Regulation on the Use of Domestic and Urban Sewage Sludge on Soil. There are 34 facilities that meet these criteria. Detailed information of these 34 facilities is given in Table 8.2 in the Appendix. Due to lack of relevant information, it is assumed that the dry matter content of the produced sludge is 25% and no sludge stabilization or drying are applied in industrial WWTPs. It is considered that, in the project report of Preparation of Sludge Management Plan for Gediz Basin (CBS, 2017), sludge belonging to the selected industrial facilities for this study are classified as non-hazardous, which is one of the requirements for the suitability of sludge for land application. Figure 3.3 shows the locations of the WWTP/s belonging to 34 industrial facilities and 17 domestic/urban WWTP/s together with a demonstration of daily sludge production amounts.

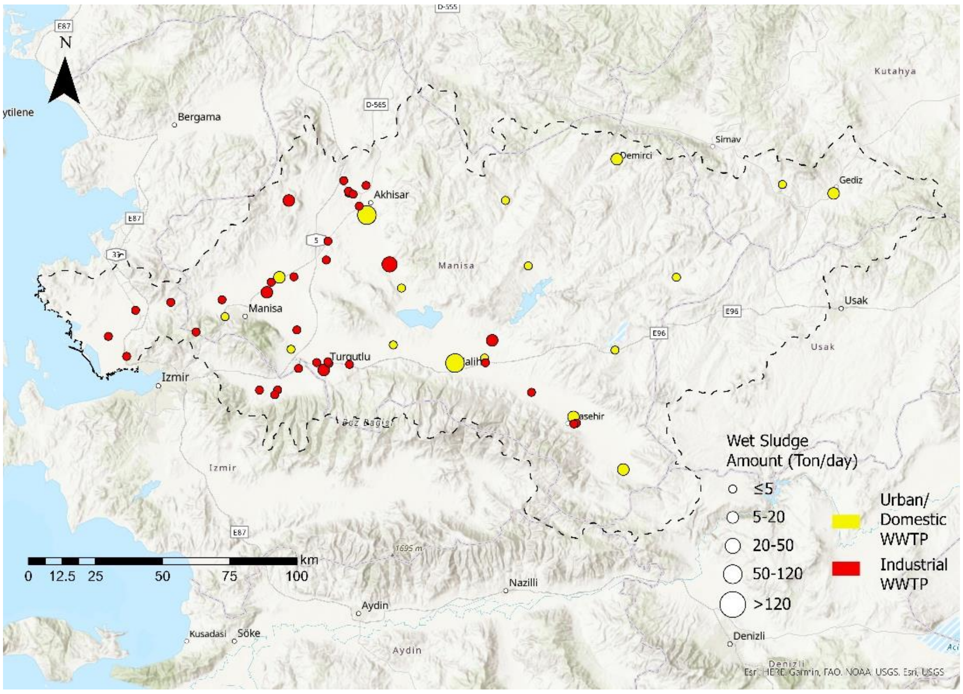


Figure 3.3: Location of WWTP/s considered in the optimization model as symbolized in accordance with their sludge amounts

There are 4 sludge drying facilities in Gediz Basin. One of them is a thermal drying facility and others are solar sludge drying facilities. According to project report of Preparation of Sludge Management Plan for Gediz Basin (CBS, 2017), the Çiğli Thermal Drying Facility has a capacity of 600 wet tonnes/day and each solar drying facility has 120 wet tonnes/day as a sludge intake capacity. Figure 3.4 shows the locations of the sludge drying facilities.

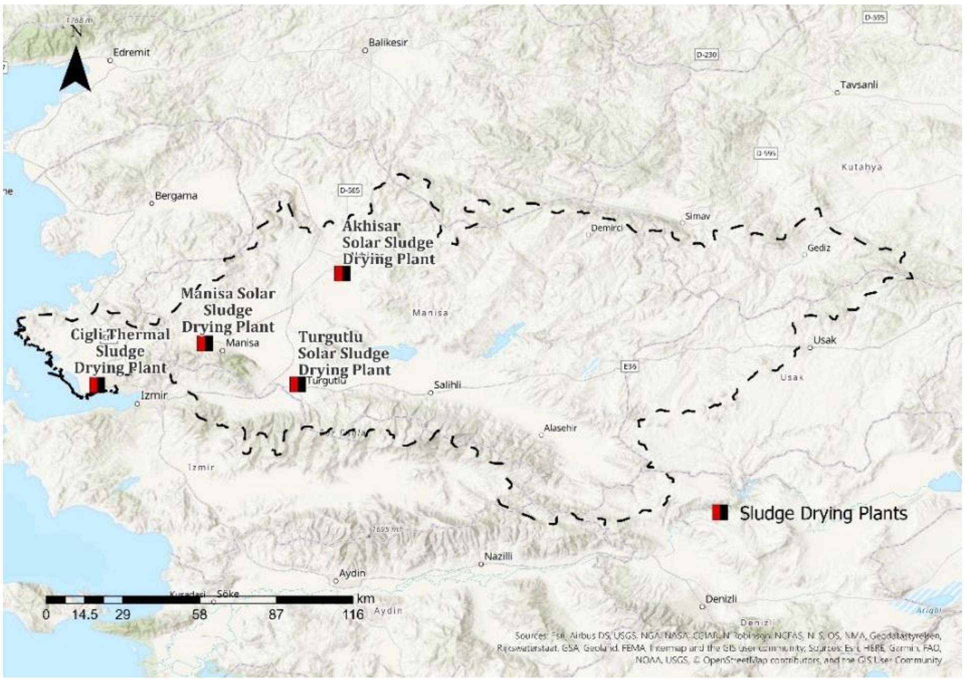


Figure 3.4: Location of sludge drying plants

3.2. Land Suitability Model for Sludge Application

An ArcGIS-based land suitability model was constructed in order to determine the suitable areas for sludge application that meet the constraints and limit values set in the Regulation on the Use of Domestic and Urban Sewage Sludge on Soil. If the concentration of heavy metals is less than 50% of the limit values specified in Annex I-A, the use of stabilized sewage sludge in the soil heavy metal analyzes are not detected in the second and third years within the allowed period.

- If the stabilized sludge is applied to the soil every year based on a ten-year average, the maximum heavy metal amount that can be added to the soil cannot exceed the values given in Annex I-E of. In case of reaching the limit values, it is obligatory to stop the use in the soil.

Table 3.1 shows the limitations, which also constitute system constraints for the optimization model. In the table, data sources used for the given criteria are provided as well. According to the Regulation on the Use of Domestic and Urban Sewage Sludge on Soil,

- Stabilized sludge producers must analyze the soil in on which the stabilized sewage sludge is used in twelve months with respect to the parameters specified in Annex II-A. If the concentration of heavy metals is less than 50% of the limit values specified in Annex I-A, the use of stabilized sewage sludge in the soil heavy metal analyzes are not detected in the second and third years within the allowed period.
- If the stabilized sludge is applied to the soil every year based on a ten-year average, the maximum heavy metal amount that can be added to the soil cannot exceed the values given in Annex I-E of. In case of reaching the limit values, it is obligatory to stop the use in the soil.

Table 3.1: Constraints and limitations in the land suitability model

Parameter	Regulation Limit	Data Source
Slope of land	≤ 12 % suitable > 12 % not suitable	SRTM30, www.usgs.gov
Soil organic matter	Soil organic matter ≤ 5% → suitable > 5% →not suitable	FAO, International Soil Reference and Information Centre -2017 www.soilgrids.org
Soil pH	≥ 6 →suitable < 6 → not suitable	FAO, International Soil Reference and Information Centre -2017 www.soilgrids.org
Groundwater depth	> 1 meter →suitable	(Gediz Havzası Yeraltı Suyu Planlama Projesi. 2014)
Soil sand content (%)	Sandy textured soil → not suitable	FAO, International Soil Reference and Information Centre -2017 www.soilgrids.org

Table 3.1: continued

Land use	Exluding fruit trees – agricultural areas where plants of contact with soil and directly consumable fruit and vegetables are grown. → not suitable natural forests→ not suitable Agricultural areas, pastures → suitable	Corine 2018, data.gov.ie/dataset/corine-landcover-2018
Water resources	Distance ≥ 300 m → suitable	Ministry of Forestation and Water Affairs DSİ
Protected areas (including wetlands)	→ Not suitable	Protected Areas data of Ministry of Forestation and Water Affairs. www.milliparklar.gov.tr

*Limit values for soil heavy metal content as mandated by the regulation could not be included in the land suitability model because of lack of data.

Some assumptions were used to estimate the soil organic matter and sand contents of soils in the basin that would be used in the model. According to Pribyl (2010), soil organic matter content value is two times the organic carbon content of soil. By taking the organic carbon content value from the source mentioned in the If the concentration of heavy metals is less than 50% of the limit values specified in Annex I-A, the use of stabilized sewage sludge in the soil heavy metal analyzes are not detected in the second and third years within the allowed period.

- If the stabilized sludge is applied to the soil every year based on a ten-year average, the maximum heavy metal amount that can be added to the soil cannot exceed the values given in Annex I-E of. In case of reaching the limit values, it is obligatory to stop the use in the soil.

Table 3.1, it was modified in accordance with Pribyl (2010) and included in the model as such. In order to calculate the sand content of soil, soil texture is determined in accordance with soil texture pyramid depicted in Figure 3.5 (NRCS Soils, n.d.) and utilized in the land suitability model.

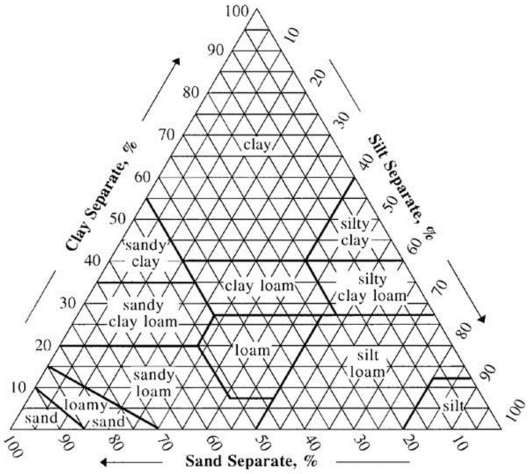


Figure 3.5: Soil texture pyramid (NRCS Soils, n.d.)

Land use information was obtained through Corine-2018 (EEA, n.d.). The long form of Corine is 'Coordination of information on the environment'. It mainly consists of the inventory of European land cover into 44 different land cover classes. Corine also states the differences between classes over four periods since 1990. Under the scope of Corine. both land cover and land cover changes are implemented in high resolution on a cartographic map. (EEA, n.d.) According to the Regulation on the Use of Domestic and Urban Sewage Sludge on Soil, areas where groundwater depth is greater than 1 meter from the ground surface are allowable for sludge application. In order to find out groundwater depths in reference to ground surface, raw data containing specific groundwater observation well locations and groundwater depths in the Gediz Basin (Gündüz, 2018) were used. In order to create the continuous spatial groundwater depth distribution, spatial analysis was conducted. In accordance with Jie et.al (2013) and Ahmadi and Sedghamiz (2006); kriging interpolation method is more suitable for data of high spatial correlation, and IDW is for weak spatial correlation. To reveal the spatial correlation characteristics in the raw groundwater depth data, spatial autocorrelation tool was used. The spatial autocorrelation tool that provides Global Moran's I is a tool that reveals the correlation characteristics according to both feature locations and feature values simultaneously (ESRI, n.d.). Global Moran's I statistic is generally used to evaluate whether an attribute being analyzed is randomly distributed among the features in a study area. According to the p and z values obtained as a result of Global Moran's I statistic, we can understand whether the data is randomly distributed or have a clustered pattern (ESRI, n.d). In accordance with the distribution pattern result, an appropriate interpolation method (whether IDW or kriging) can be chosen to obtain the spatial distribution of a parameter.

Suitable areas for sludge application in the basin are found using screening with the binary overlay model via ArcGIS software. The basin was gridded as 1 km x 1 km cells. In compliance with the restrictions and limit values provided in If the concentration of heavy metals is less than 50% of the limit values specified in Annex I-A, the use of stabilized sewage sludge in the soil heavy metal analyzes are not detected in the second and third years within the allowed period.

- If the stabilized sludge is applied to the soil every year based on a ten-year average, the maximum heavy metal amount that can be added to the soil cannot exceed the values given in Annex I-E of. In case of reaching the limit values, it is obligatory to stop the use in the soil.

Table 3.1, all parameter values were fed into the ArcGIS model builder tool. Binary overlay method is the overlapping of raster layers with assigned value of 1 or 0 for each 1 km X 1 km sized cell in accordance with the restrictions set. “1” is assigned to a cell if that cell is suitable for a given criterion. “0” is assigned if the value or property does not comply with the requirements set by the regulation. In overall, a cell is regarded as suitable for sludge application if all overlapping layers for all parameters considered for suitability for sludge application contain “1”. Figure 3.6 shows a representation and the model builder flowchart for binary overlay analysis designated for the sludge suitability model.

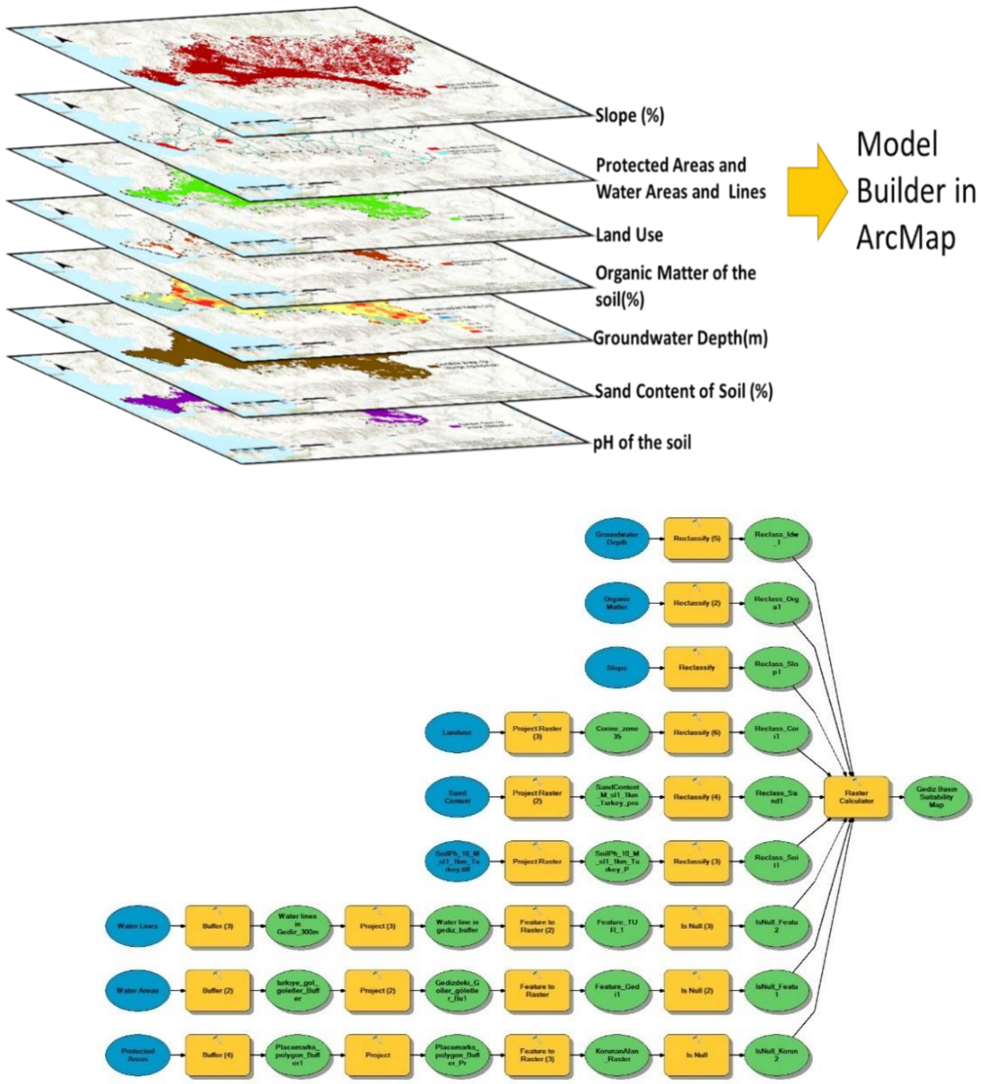


Figure 3.6: Representation of overlay analysis (above) and flowchart of the sludge suitability model (below) in the model builder of ArcGIS. (A figure with a higher resolution can be seen in Figure 0.1 in the Appendix)

As a result of the overlay analysis, suitable areas for sludge application are determined. In order to include these areas in the optimization model, 150 km^2 sized (10 km * 15km) rectangular blocks were created within the basin. This size is chosen through trial-and-error based on the statistical distribution analysis of the sludge applicable agricultural areas within the created blocks of different sizes in

ArcGIS. Attention was given to have blocks of small size, while in all blocks suitable areas for land application of sludge, as restricted by all criteria considered, have a similar size as much as possible. In this way, it was aimed to keep the suitable area square meters in the blocks to be similar to each other and the distances between the centers of the blocks would be the shortest statistically. In the figures below, the block areas used in the trial-and-error approach to determine the grid size are given. During these trials, the main purpose was to ensure the uniform integration of the sludge applicable areas for the optimization model in terms of capacity and to ensure that the distance between the centroids of sludge applicable areas was not extensive, even if the centroids of the appropriate sludge application areas within the blocks are at the farthest two edges of the block. In Figure 3.7, Figure 3.8 and Figure 3.9, the x-axis of the histograms shows the size of the sludge applicable areas within the relevant blocks. The y axis shows the number of considered sized-areas within relevant block.

In Figure 3.7, the size of the blocks was tested as 10 km X 10 km as the first trial. In this trial, the diagonal distance between the two farthest end points of the blocks will be at most 14 km. However; the distribution within the blocks is not uniform as seen in the histogram. In Figure 3.8, relatively more uniform distribution is seen in the sizes compared to blocks in Figure 3.7. In Figure 3.9, it is seen that the amount of suitable areas within the blocks is starting to differ from each other, which indicates that uniformity between the blocks is deteriorated

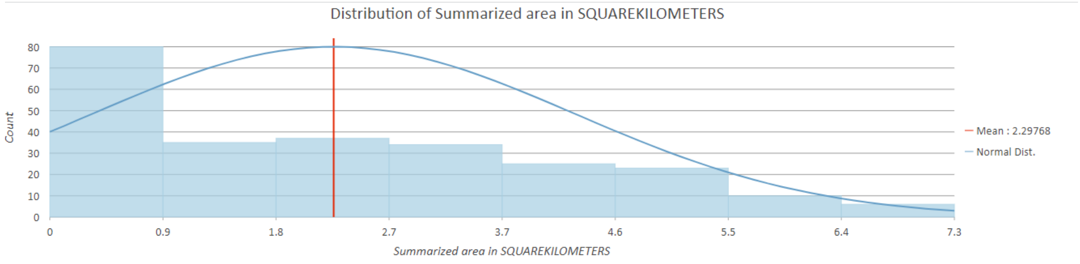


Figure 3.7. Histogram for 10 km x10 km block size

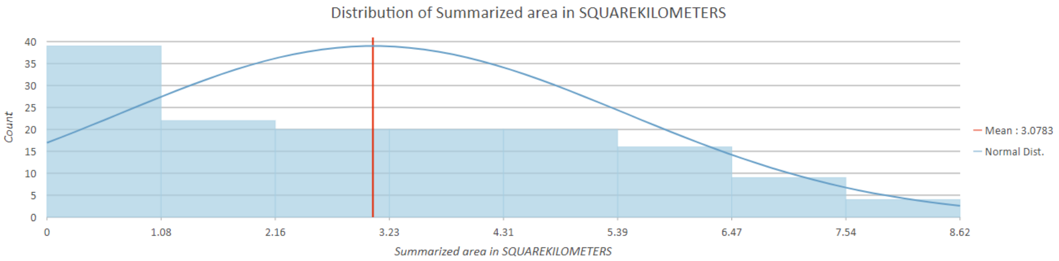


Figure 3.8. Histogram for 10 km x15 km block size

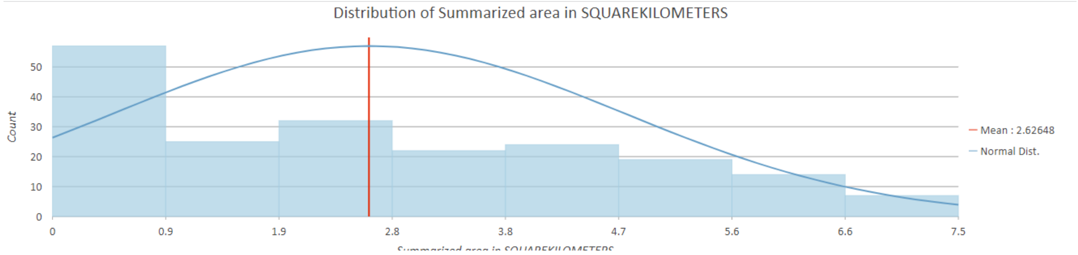


Figure 3.9. Histogram for 10 km x 20 km block size

As can be seen from the histograms in the figures above, the uniform distribution in terms of suitable areas within the blocks is the best for blocks with 10 km x 15 km area. Thus; it will be ensured that the blocks included in the optimization model will have a similar application probability in terms of capacity. The reason for making such a block –sized application is that the areas suitable for the use of sludge in the soil are distributed in small pieces. Therefore, a modification was needed to integrate into the optimization model in terms of central points for transportation cost evaluation and capacity assessment.

The central points of the blocks are included in the model for transportation needs and costs assuming that sludge would be applied at suitable areas in accordance with their calculated capacities using an application dosage of 0.5 tonnes /da. This sludge dosage integrated into the model has been determined in accordance with the literature survey regarding beneficial amount of sludge for application on land (Rutgersson et al., 2020; Markowicz et al., 2011). Generally accepted application dosages for sludge on land is smaller than 1 tonne/decare since the studies show that application dosage larger than 1 tonnes per decare may result in undesirable effects in long term (Rutgersson et al., 2020). The study done by Dhanker et al. (2020) focused on the influence of urban sewage sludge amendment on agricultural soil parameters. As a result of that study in which the effects of different sludge application dosages (0.5,1,2, 5 tonnes/da) on land in laboratory conditions, they found out that amendment with a dosage in the range of 0.5-1.0 tonnes/da ensured adequate mineralization of organic matter without adverse effects on soil health (Dhanker et al., 2020).

Korboulewsky et al. (2002) studied the effects of sewage sludge composts applied at the rates of 1, 3, and 9 tonnes/ha on a vineyard in southeastern France. They quantified the rate of in situ N mineralization, soil organic matter levels, and levels of heavy-metal accumulation in soil. The study revealed that soil organic matter levels increased at all treatment doses, but an application dosage of 3 tonnes/ ha and higher increased the heavy metal concentrations of soil.

The detailed descriptions of sludge parameters used in the model for suitable area determination and optimization model development can be found in the following chapters.

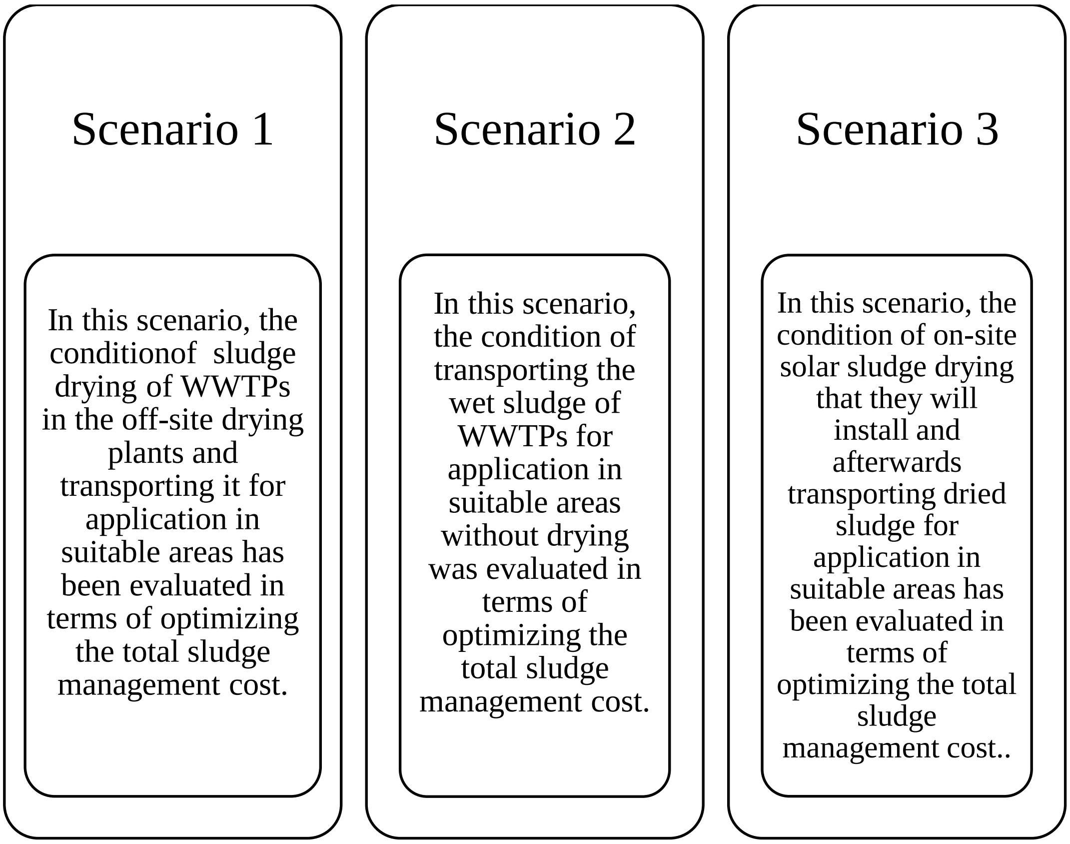
CHAPTER 4

OPTIMIZATION MODEL

The optimization model developed aims to minimize the total cost which is impacted by whether WWTP/s need stabilization, and/or sludge drying. In the model, sludge stabilization method and costs, sludge drying requirement and costs, capacities of sludge drying facilities, and sludge transportation costs to suitable areas and drying facilities were considered. The model is solved using the ArcGIS Pro Model Builder tool. Costs were calculated in US dollars. The developed model is as follows.

The model was established within the scope of 51 facilities, which is the total number of all (Domestic + Industrial) integrated WWTP/s in the first comprehensive bracket. In the first stage, stabilization methods for WWTP/s are assigned with regard to their daily wet sludge production with the integration of capital and O&M costs of each designated method into the optimization model. In this part,2 different stabilization methods are considered which are anaerobic digestion and aerobic composting. For anaerobic digestion as the stabilization method, possible unit income related to electricity generation from biogas production and the revenue obtained from its sale is integrated into cost-optimization model. Afterwards, a second consideration was established in the model in terms of a sludge drying process regarding the restrictions on capacity and distances between WWTP/s and 4 existing sludge drying facilities in the Gediz basin. Regarding the land application point of the model, the capacity and the distance restrictions of the WWTPs to the suitable area centroids are processed in the model. In that regard, the model was run within the scope of 119 centroids which are centroids of suitable agricultural areas within the blocks. The capacities of the suitable areas to which these centroids belong were calculated according to the application dosage of 0.5 tonnes/da and integrated into the model as a capacity restriction.

In this optimization model, 3 different scenarios are processed to find the optimal sludge management options in terms of total sludge management cost. Scenarios are explained in detail in the Figure 4.1


Scenario 1

In this scenario, the conditionof sludge drying of WWTPs in the off-site drying plants and transporting it for application in suitable areas has been evaluated in terms of optimizing the total sludge management cost.

Scenario 2

In this scenario, the condition of transporting the wet sludge of WWTPs for application in suitable areas without drying was evaluated in terms of optimizing the total sludge management cost.

Scenario 3

In this scenario, the condition of on-site solar sludge drying that they will install and afterwards transporting dried sludge for application in suitable areas has been evaluated in terms of optimizing the total sludge management cost..

Figure 4.1: Scenarios İntegrated into Optimization Model.

Within the scope of the scenarios mentioned above, the capacities of off-site drying facilities, sludge application capacities of suitable areas; and travel distances between WWTPs -drying plants, drying plants -suitable area centroids, and WWTPs -centroids are integrated as constraints. The dollar had an average inflation rate of 3.07% per year between 2017 and 2021 (CPI. 2021). Therefore, it is integrated into unit cost parameters of the model.

Min (Z_i) =

Stabilization

$$* \sum_{i=1}^{51} \Bigg(K_i \Bigg((AD_i \Bigg(100\,000 * (1+0{,}03) * S_i * 0{,}05 - \left(\frac{65}{1+0{,}03} * S_i * 0{,}05 \right) \Bigg) \Bigg)$$

$$+ \; C_i(3500 * (1+0{,}03) * S_i * 0{,}05))$$

$$+ \; (AD_i \Bigg(10\,000 * \; (1+0{,}03) * S_i * 0{,}05 - \left(\frac{65}{1+0{,}03} * S_i * 0{,}05 \right) \Bigg) \Bigg)$$

$$+ \; C_i(300 * (1+0{,}03) * S_i * 0{,}05) * 19 \Bigg) + \quad (1 - N_i) \Bigg)$$

Drying

$$* ((37 * (1+0{,}03) * S_i * 19 + 4 * S_i \;) * OSD_i$$

$$* \left[\sum_{m=1}^{4} (\; Y_{i,m} \; * \; 0{,}1 \; * \frac{S_{i,m}}{DM_i} * \left(SL_{i,m} \; + \; T_{i,m} \right) * 2 * 20 \right.$$

$$+ \left(SL_{i,m} \; * \; 40 * (1+0{,}03) + \; T_{i,m} \; * \; 50 * (1+0{,}03) \right)$$

$$* \left((0{,}5 \; * \; S_i \; * DM_i * \; C_i) \; + (0{,}8 \; * \; S_i \; * \; DM_i * AD_i) \right) * 20$$

Land Application

$$+ \sum_{k=1}^{119} (\Bigg(SL_{i,m} * \frac{1}{0{,}5} * [\, (0{,}5 \; * \; S_i \; * \; C_i) \; + (0{,}8 \; * \; S_i * \; AD_i)] \; + \; T_{i,m} * \frac{1}{0{,}8}$$

$$* [\, (0{,}5 \; * \; S_i \; \; * \; C_i) \; + (0{,}8 \; * \; S_i \; * \; AD_i)] \Bigg) * 0{,}1 \; * (1+0{,}03) * Z_{m,k} \; * \; 2 * 20 \;\;] + N_i$$

$$* \frac{S_{i,m}}{DM_i} * 0{,}1 * W_{i,k} \; * 2 * 20 \,) + (4 * (1+0{,}03) * \; (S_i/0{,}5\,) * X_{i,k} \; * \; 2 * 20) \;\; \Bigg)$$

Subject to;

Explanation: Solar drying plant will be selected based on the capacity of solar drying facility

$$0 < [\sum_{i=1}^{54}\sum_{m=1}^{3} S_i * SL_{i.m}] < 120 \ ton/day$$

For ***i*** *is number of WWTP/s and* ***m*** *is number of drying facilities*

Explanation: Solar drying plant will be selected based on track length of solar drying facility < 150 km

$0 < Y_{i,m}. * SL_{I,m} \leq 150 \ km$

Explanation: Thermal drying plant will be selected based on the capacity of thermal drying facility

$$0 < [\sum_{i=1}^{54}\sum_{m=4}^{4} S_i * T_{i.m}] < 600 \ ton/day$$

For ***i*** *is number of WWTP/s and* ***m*** *is number of drying facilities*

Explanation: Thermal drying plant will be selected based on track length of thermal drying facility < 150 km

$0 < Y_{i,m} * T_{i,m} \leq 150 \ km$ *For* ***i*** *is number of WWTP/s and* ***m*** *is number of drying facilities*

Explanation: Either solar or thermal can be selected for ith WWTP

$0 < SL_{i,m} + T_{i,m} \leq 1$ *for i is number of WWTP/s & m is number of drying facilities*

Explanation: Suitable area will be selected based on the capacity of the suitable area to hold sludge.

A_k *(da)* 0.5 (ton/da)= sludge capacity of area*

$$0 < [\sum_{i=1}^{54}\sum_{k=1}^{119} S_i * X_{i.k}] < A_k * 0.5$$

For ***i*** *is number of WWTP/s (51) and* ***k*** *is number of suitable area blocks (119)*

Explanation: Suitable area will be selected based on proximity < 150 km.

0 < $X_{i,k} * Z_{k,m} <$ *150 km for i is number of WWTPs & m is number of drying facilities & k is number of suitable area blocks*

C_i, AD_i, $SL_{i,m}$, N_i, $X_{i,k}$, $T_{i,m}$, OSD_i *binary integer*

where

C_i indicates compost stabilization for ith WWTP

AD_i indicates anaerobic digester for ith WWTP

S_i indicates sludge production amount for ith WWTP.Its unit is dry tonnes/ day

K_i indicates whether stabilization unit is absent for ith WWTP

(when unit is absent. $K_i = 1$; otherwise, $K_i = 0$)

SL_i indicates solar drying choice for ith WWTP

T_i indicates thermal drying choice for ith WWTP

N_i indicates no need for drying in terms of optimized total cost

DM_i indicates dry matter percentage of sludge after stabilization & dewatering (%)

$Y_{i,m}$ is track length between ith WWTPs and mth sludge drying facilities (km)

$Z_{m,k}$ is track length between mth drying facility and kth suitable area(km)

$W_{i,k}$ is track length between ith WWTP and kth suitable area(km)

$X_{i,k}$ is size of suitable area for ith WWTP and corresponding kth suitable are (da)

OSD_i indicates the on-site sludge drying scenario for ith WWTP

Capital, O&M and unit costs for cost items considered in the model are found through literature survey and personal communications with relevant municipalities. Stabilization option selection was made in accordance with the sludge amount that WWTP/s have. Specifically; composting method has been implemented for WWTP/s which have a sludge amount smaller than 1 tonne/day;

in the opposite case (sludge >1 tonnes/day). anaerobic digestion has been suggested as the stabilization method. Unit costs are provided in Table 4.1. In this table, the stabilization options and the operation costs for the scenario of installing the solar sludge drying unit on site are assumed to be 10% of the installation costs as a result of the literature review (Tetra Tech, 2016)

Table 4.1. Unit costs integrated into the cost model

	Capital cost ($)	**O& M cost ($/year)**	**Unit Cost**	**Source**
Anaerobic Digester	100,000	1000		(Hanum et al., 2019) (Tetra Tech, 2016)
Compost	3500	300		(Healy et al., 2015) (Hinds & Gamble, 2010)
Solar Drying On-Site Implementation	26,400	2640	For Cap: 37 $/ton .DM For O&M:4 $/ton.DM	(Kurt et al., 2015) (W20, 2016)
Solar Drying (Gate Fee)			40 $ /ton.DM	(CBS, 2017)
Thermal Drying (Gate Fee)			50 $/ton.DM	(CBS, 2017)
Transportation			0.1 $/ton.DM	(CBS, 2017)
Sludge Application			4 $/da	(CBS,2017)

For the WWTP/s for which stabilization with anaerobic digester is recommended. the electricity that can be obtained from biogas production is also included in the optimization model as income. The calculations in this context are given below in Table 4.2

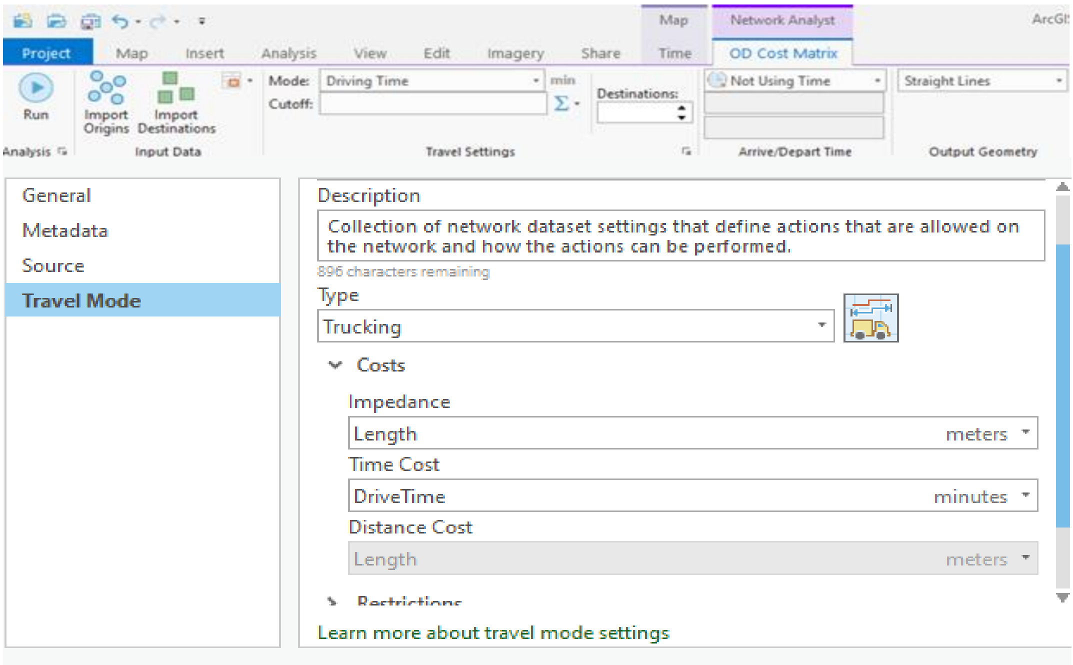
Table 4.2 : Income of electricity generation from biogas produced by anaerobic sludge digestion

Unit Cost Parameters	**Value**	**Unit**	**Source**
Electricity selling Price	13.3	Cent/Kwh	Turkish Law No. 5346 of 10/5/2005
Approximate Biogas Amount produced from wastewater treatment sludge	183	m^3/dry tonnes	(Abusoglu et al., 2019)
Electricity production value of biogas produced from wastewater treatment sludge	2.6	Kwh/m^3	(Abusoglu et al., 2019)
Electricity generation from unit dry tonnes of wastewater treatment sludge	2.6*183 = 476	Kwh/ dry tonnes	
Unit Income	476*13.3/100 =63	Euro/dry tonnes	

4.1. Model in Determination of Travel Distance for Transport Cost Estimation

Transportation cost is included in the optimization model for 3 different alternatives; which are from WWTP to sludge drying unit, from sludge drying unit to a suitable area for land application or directly from a WWTP to a suitable area for land application. For this reason, it is required to reveal the real track lengths in these stages. Origin-destination cost matrix tool of ArcGIS Pro software is utilized for determination of track length in all stages. The tool requires the network dataset on which all origins and destinations are operated. For this study, OSM-network dataset is utilized. This network dataset provides u-turn restrictions and one-way roads in addition to the roads in the model.

Figure 4.2 shows the interface of the origin-destination cost matrix. For this study, travel setting section is adjusted to a driving length with 150 km of cutoff value in addition with setting of trucking as a driving type. Although actual travel distances are used in calculations, straight lines are used to present the output geometry in order to display the path options in the map.



Mode: Driving Time

Cutoff: min

Destinations:

Not Using Time

Straight Lines

Description

Collection of network dataset settings that define actions that are allowed on the network and how the actions can be performed.

896 characters remaining

Type: Trucking

Impedance: Length meters

Time Cost: DriveTime minutes

Distance Cost: Length meters

Figure 4.2: Interface of origin-destination cost matrix

For the track length determination, origins and destinations are imported in accordance with the required starting and end point of the stage. As a result of the model run, lines layer with an attribute table containing the track lengths between each origin and destination options is created. In the optimization model, $\mathbf{Y_{i.m}}$, $\mathbf{Z_{m,k}}$, $\mathbf{W_{i,k}}$ are indicator for track lengths between origin and destination points in which ith indicates WWTP/s, mth indicates sludge drying facilities and kth indicates suitable area for sludge application.

CHAPTER 5

RESULTS AND DISCUSSION

5.1. Results of Model in Analysis of Suitable Areas for Sludge Application

5.1.1. Slope of Land

As it is mentioned in If the concentration of heavy metals is less than 50% of the limit values specified in Annex I-A, the use of stabilized sewage sludge in the soil heavy metal analyzes are not detected in the second and third years within the allowed period.

- If the stabilized sludge is applied to the soil every year based on a ten-year average, the maximum heavy metal amount that can be added to the soil cannot exceed the values given in Annex I-E of. In case of reaching the limit values, it is obligatory to stop the use in the soil.

Table 3.1, slope value is calculated from SRTM30 data. According to the Regulation on the Use of Domestic and Urban Sewage Sludge on Soil, land with slope value smaller than 12 % is allowable for sludge application; Thus; it is utilized in model as such. Map Figure 5.1 shows the suitable areas for sludge application in Gediz Basin regarding slope parameter Since the mountains in the Gediz basin are mostly located in the North-East part of the basin, that part of the basin is relatively less suitable for sludge application in accordance with map in Figure 5.1. Since the surrounding of the Gediz River is nearly at the water level, it is suitable for the application of sludge in terms of slope. Therefore; it can be concluded that the suitable areas with regard to slope parameter are compatible with the physical conditions of the basin.

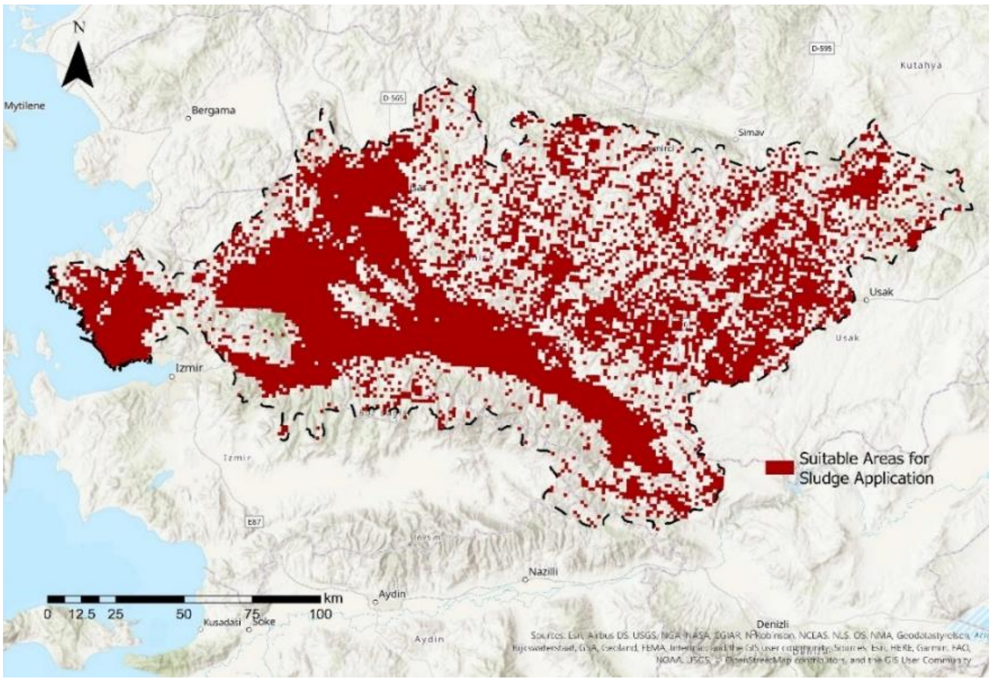


Figure 5.1: Map showing the suitable areas in terms of slope parameter.

5.1.2. Soil Organic Matter

Soil organic matter content is calculated from the soil organic carbon content as explained above. According to the Regulation on the Use of Domestic and Urban Sewage Sludge on Soil, soils with smaller than 5 % organic matter content is allowable for sludge application. Figure 5.2 shows the suitable areas for sludge application in terms of organic matter content of soil. As a result of this map, it can be concluded that the soil in a large part of the basin is rich in organic matter content of more than 5%.

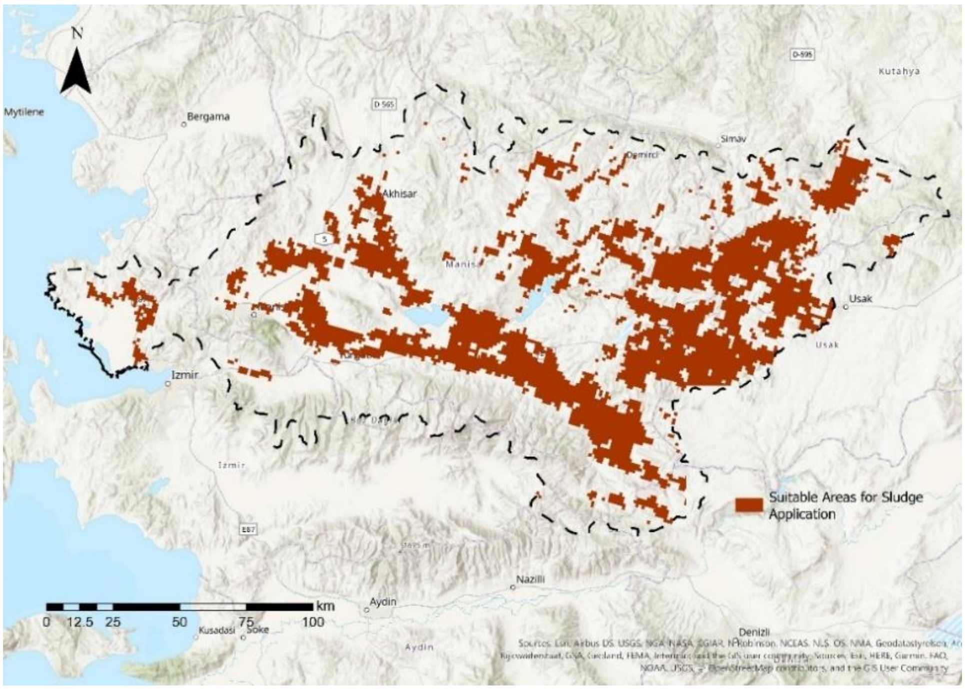


Figure 5.2: Map showing the suitable areas in terms of soil organic matter parameter.

5.1.3. Soil pH

Soils with pH greater than 6 is allowable for sludge application. The map shows the suitable areas for sludge application in terms of soil pH parameter in Figure 5.3. The map states that bigger part of the soil in Gediz Basin can be considered as non-acidic which can demonstrate the healthier conditions for cultivation and agriculture of plants.

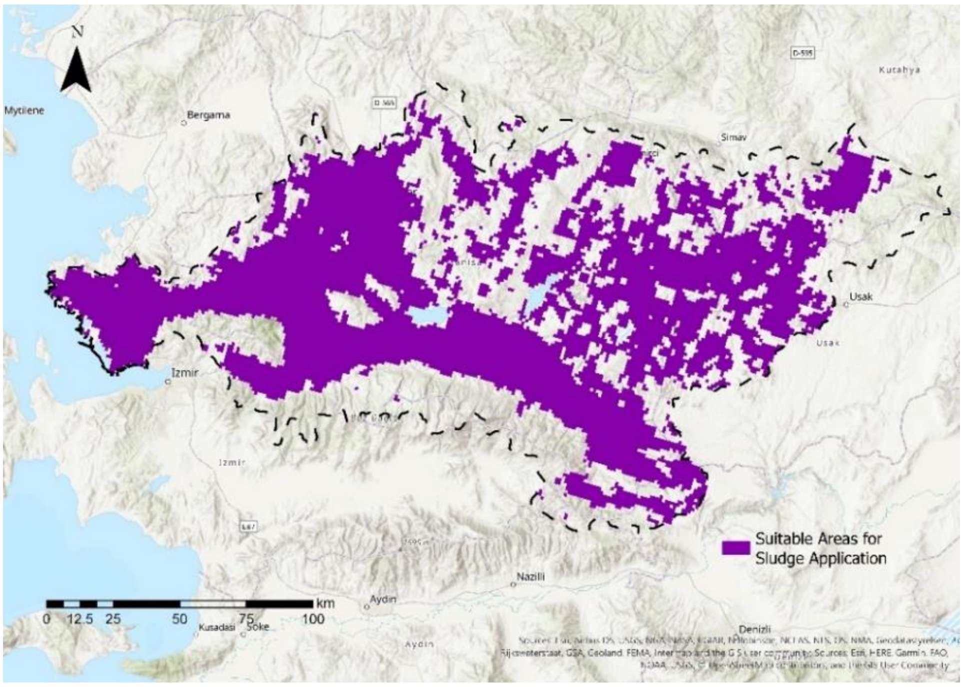


Figure 5.3: Map showing the suitable areas in terms of soil pH parameter

5.1.4. Groundwater Depth

As mentioned above, in order to create the continuous spatial groundwater depth distribution, spatial analysis was conducted. Figure 5.4 shows the results of spatial autocorrelation tool and its reference distribution statistics

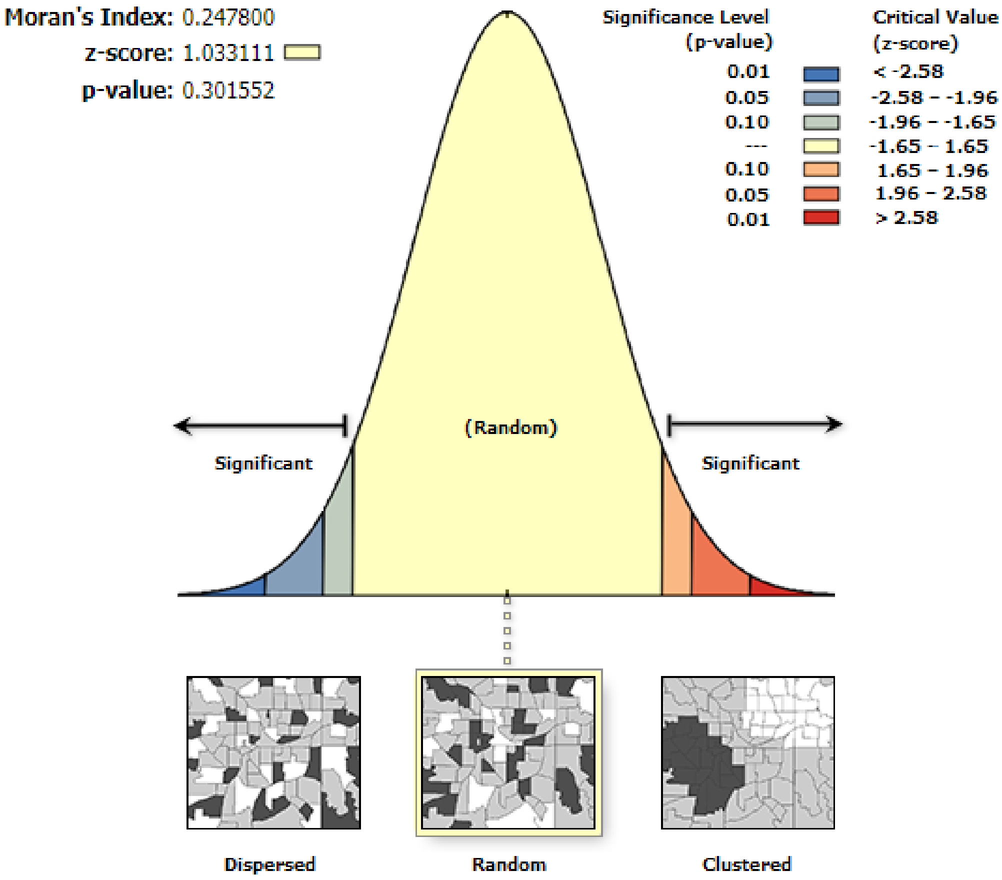


Figure 5.4: Reference distribution statistics (Global Moran's I)

As the result of the spatial autocorrelation tool which is shown in the upper left corner in Figure 5.4, raw data has 0.3015 as p-value and 1.03 as z-score. In accordance with the reference distribution statistics shown in Figure 5.4, Since these p and z-values of the raw data are located in the yellow range of the distribution graphic in Figure 5.4, it states that there is no spatial correlation between depth data of different groundwater well points. In accordance with Jie et.al (2013) and Ahmadi and Sedghamiz (2006); kriging interpolation method is more suitable for data of high spatial correlation, and IDW is for weak spatial correlation. For this reason, IDW is chosen as more suitable interpolation method for this kind of randomized distributed data. IDW interpolation provides the resulted map shown in Figure 5.5, As a result of IDW interpolation, no place below

1 meter as a groundwater depth was found in terms of correlative distribution. Therefore, the map in Figure 5.5 shows the interpolated distribution of whole basin in regards to groundwater depths from the surface.

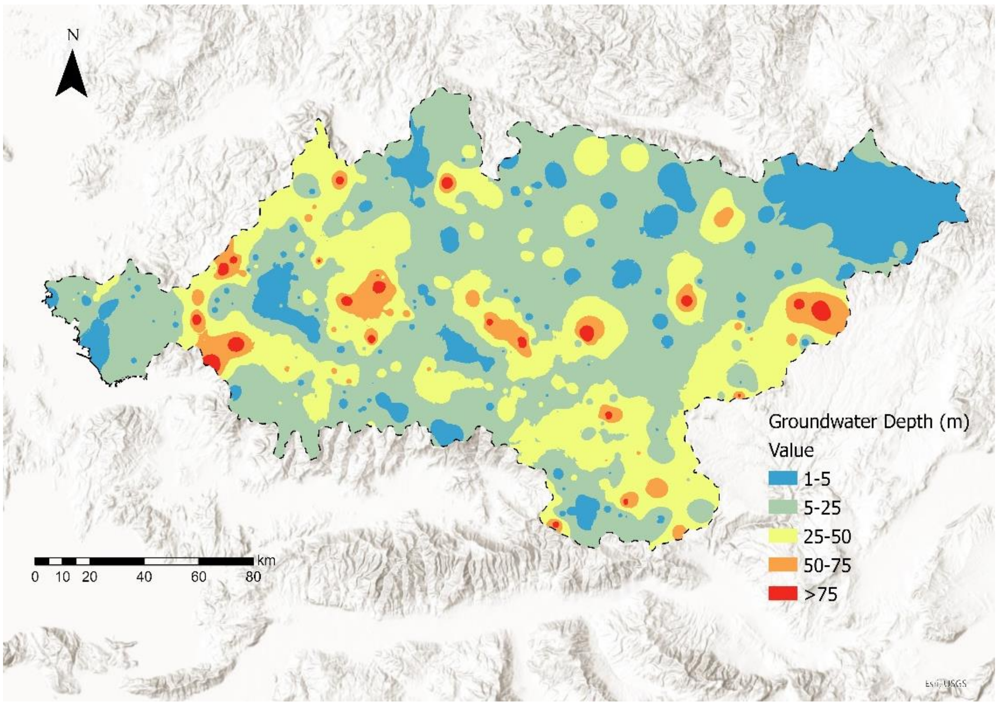


Figure 5.5: Interpolated distribution of groundwater depth in Gediz Basin

5.1.5. Sand Content of Soil

As it is mentioned previously, sand content of soil is calculated in accordance with the soil texture pyramid shown in Figure 3.5. According to soil texture pyramid, soil with 50% and more sand content is counted as sandy soil which is restricted for sludge application in compliance with the relevant regulation. Figure 5.6 shows the map showing the suitable areas in terms of sand content of soil.

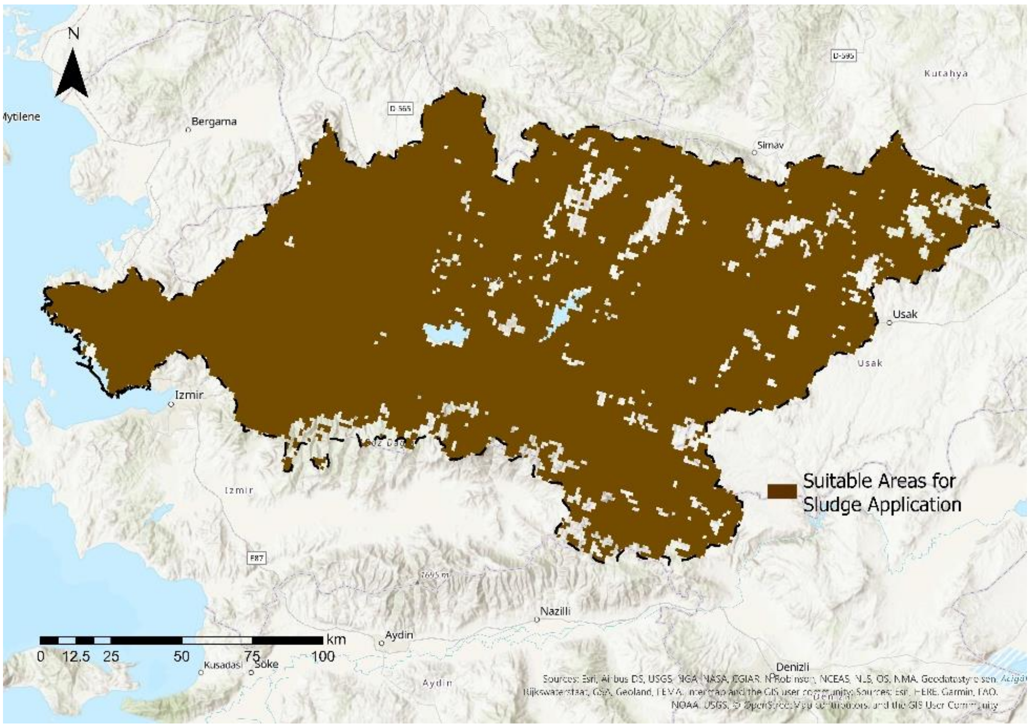
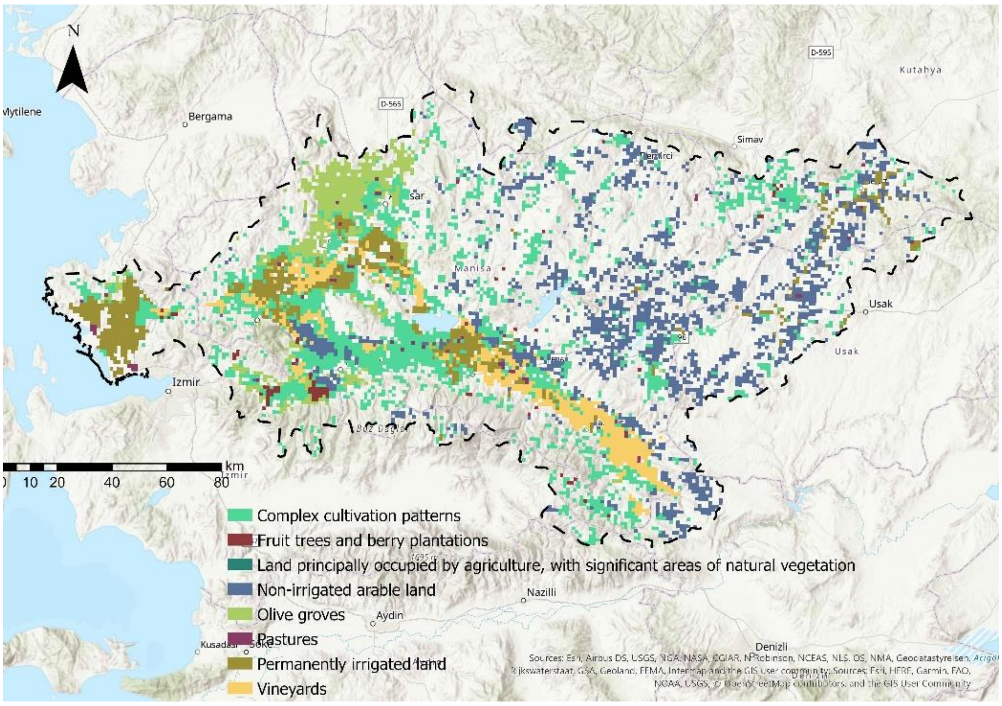


Figure 5.6: Map showing the suitable areas in terms of sand content of soil parameter

5.1.6. Land Use

The source of the data contains land use is Corine-2018. Corine data is classified into 5 main categories which are agricultural areas. artificial surfaces. forest and semi natural areas. wetlands and water bodies. Among these. because the class that may comply with the legislation is only agricultural areas. it is the only one included in the model. Map in Figure 5.7 shows the allowable sub-classes within the agricultural area class in Corine-2018 data.

When the map in Figure 5.7 analyzed together with the map in Figure 5.1, it can be concluded that agricultural lands are concentrated in areas with low slope of land. Also, with regard to suitable areas in terms of soil organic matter parameter in Figure 5.2, agricultural areas of Corine Land Use and soil with allowable soil organic matter content are overlapped with each other.



Sources: Esri, Airbus DS, USGS, NGA, NASA, CGIAR, N Robinson, NCEAS, NLS, OS, NMA, Geodatastyrelsen, Rijkswaterstaat, GSA, Geoland, FEMA, Intermap and the GIS user community, Sources: Esri, HERE, Garmin, FAO, NOAA, USGS, © OpenStreetMap contributors, and the GIS User Community

Figure 5.7: Allowable sub-classes within the agricultural area class in Corine-2018.

5.1.7. Water Resources and Protected Areas

According to the Regulation on the Use of Domestic and Urban Sewage Sludge on Soil, it is forbidden to apply sludge to areas which includes protected areas (including wetlands) and any area closer than 300 meters to water sources. The map in Figure 5.8 shows the water resources covered by a 300-meter buffer zone and protected areas in Gediz Basin.

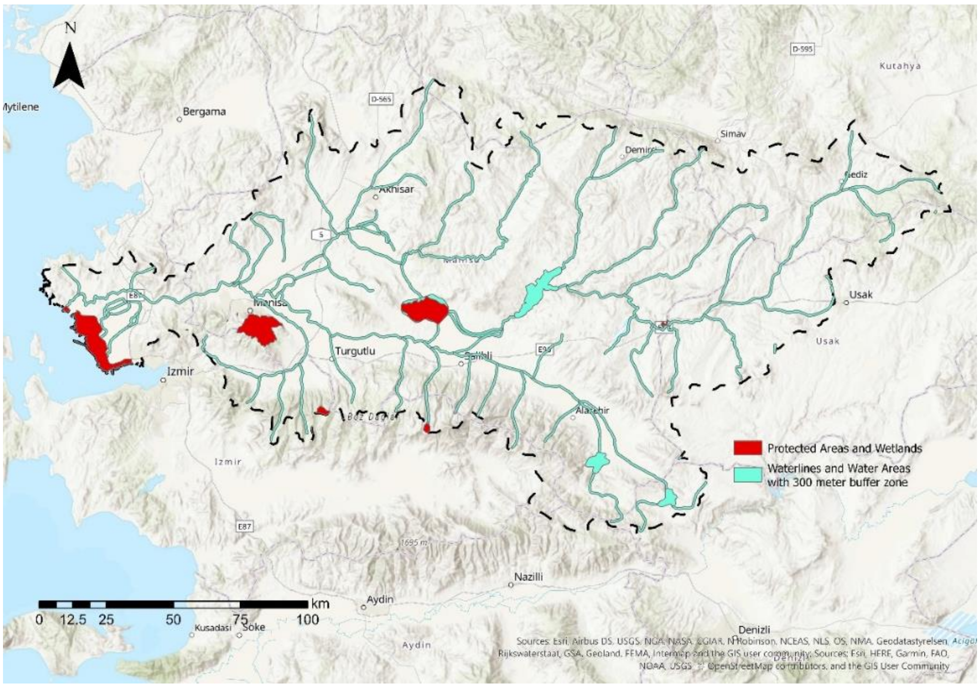
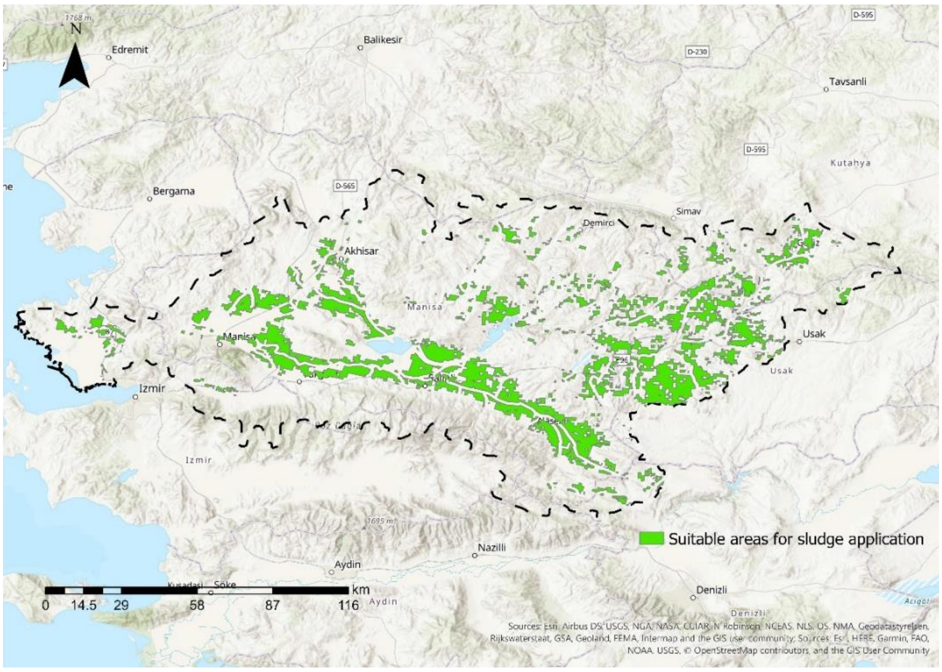


Figure 5.8: Water resources covered by a 300-meter buffer zone and protected areas in Gediz Basin

As given in Figure 3.6 and explained in the relevant paragraph there, all parameters were overlapped by overlay analysis on the ArcGIS platform, and the result in Figure 5.9 was obtained. As it can be seen from Figure 5.9, model resulted that, suitable areas for sludge application are frequently gathered at edge of water resources. As it can be seen on the land use map in Figure 5.7 this result is generally acceptable as the agricultural lands in the basin are also gathered near the water's edge. Another important point to be drawn from this model result is that soil organic matter content is an important parameter for the model. Therefore, the distribution of the areas on the map is similar to the soil organic matter map in Figure 5.2. The total size of suitable areas has been calculated as 2270 km^2. Therefore, it corresponds approximately to 13% of the 17 000 km^2 sized Gediz Basin area.



Sources: Esri, Airbus DS, USGS, NGA, NASA, CGIAR, N Robinson, NCEAS, NLS, OS, NMA, Geodatastyrelsen, Rijkswaterstaat, GSA, Geoland, FEMA, Intermap and the GIS user community; Sources: Esri, HERE, Garmin, FAO, NOAA, USGS, © OpenStreetMap contributors, and the GIS User Community

Figure 5.9 : Suitable Areas for Sludge Application in Gediz Basin

Figure 5.10 shows the suitable areas for sludge application within the 150 km^2 (15 x 10 km) sub-areas. The creation of sub-divided areas with 150 km^2 was made to facilitate the integration of the centroids of suitable areas for sludge application into the optimization model. Thus, suitable areas are included in the model within a certain distribution and suitable areas within the divided areas will be at a maximum distance of 18 km from each other.

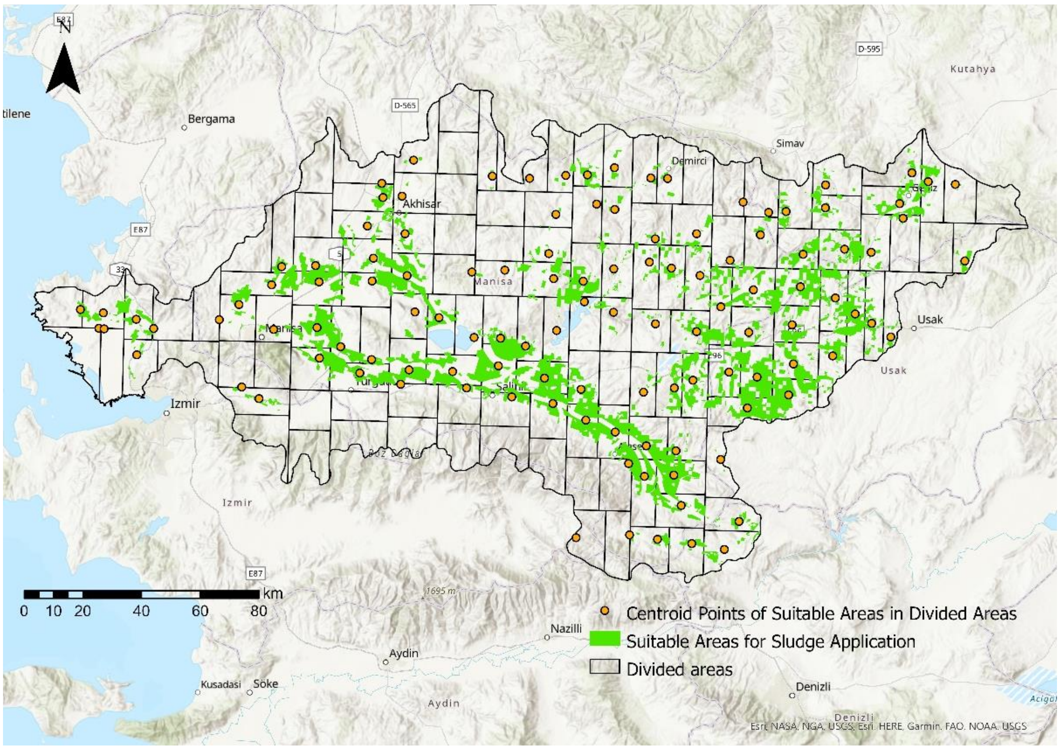


Figure 5.10: Suitable areas located in divided sub-areas of 150 km^2

In Figure 5.11, map showing which WWTPs can go to which drying plants within the capacity and distance constraints in the optimization model within the scope of Scenario 1. In addition, facilities that currently have their own sludge drying plan are also indicated in red on this map. Also, Map in Figure 5.12 shows the which drying plants can go to which suitable area centroid in accordance with the distance and capacity constraints under the concept of Scenario 1.

In Figure 5.13, it is shown that which WWTP can go to which appropriate centroid within the scope of optimization model constraints within the scope of Scenario 2. In this map, 3 different application periods are also demonstrated that in case of an undesirable result in soil control analyzes that should be done every 3 years according to the Regulation on the Use of Domestic and Urban Sewage Sludge on Soil. For this reason; potential suitable area options for the 2nd and 3rd Application period are also given.

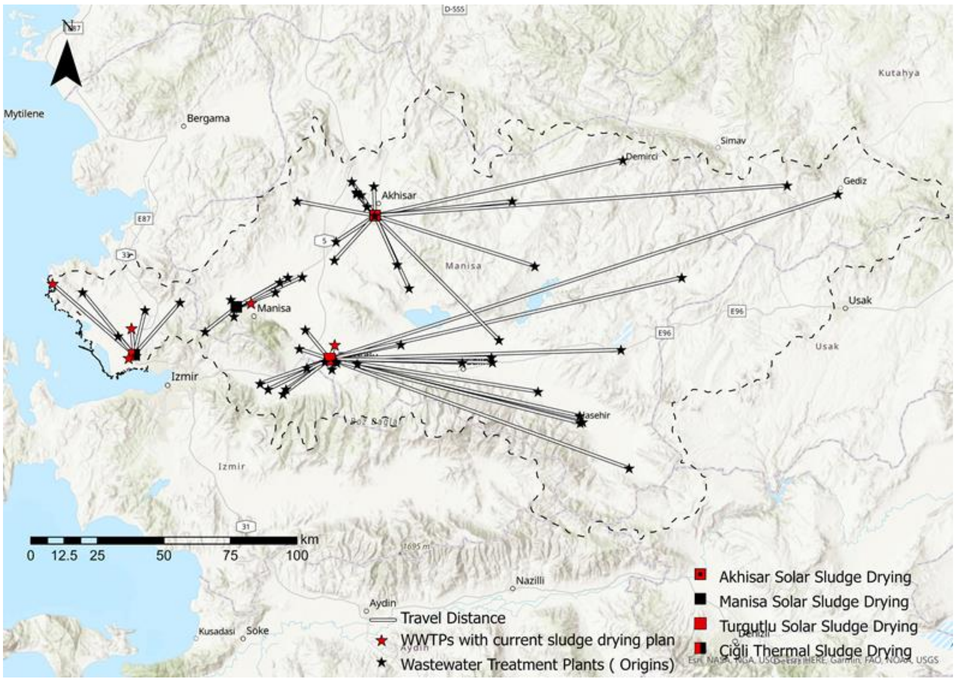


Figure 5.11: WWTPs (Origin) to Sludge Drying Plants (Destinations)

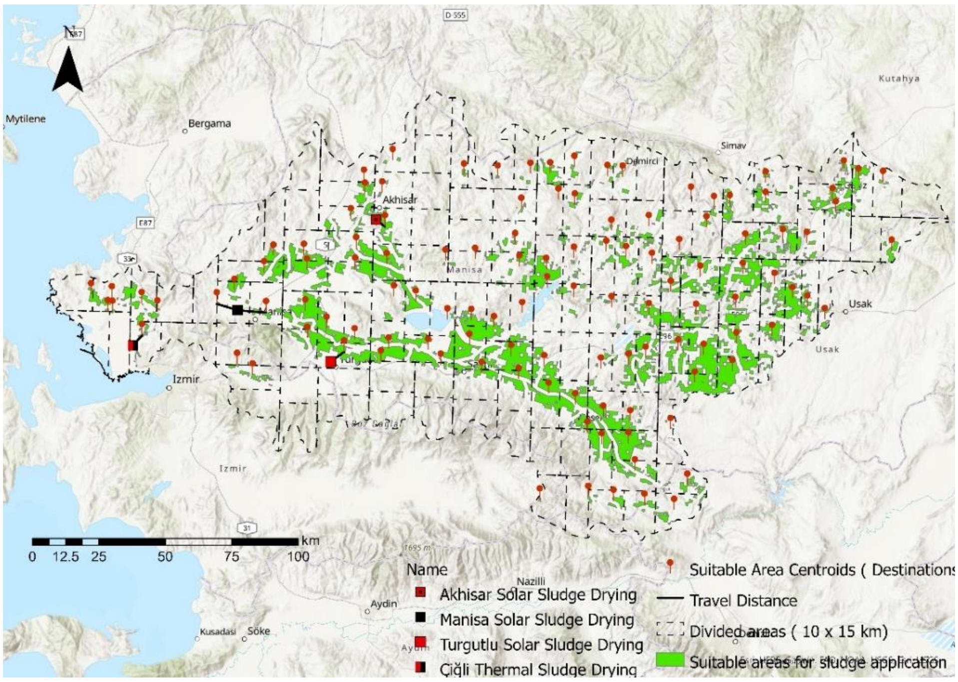


Figure 5.12 : Sludge Drying Plants (Origins) to Suitable Area centroids for sludge application (Destinations)

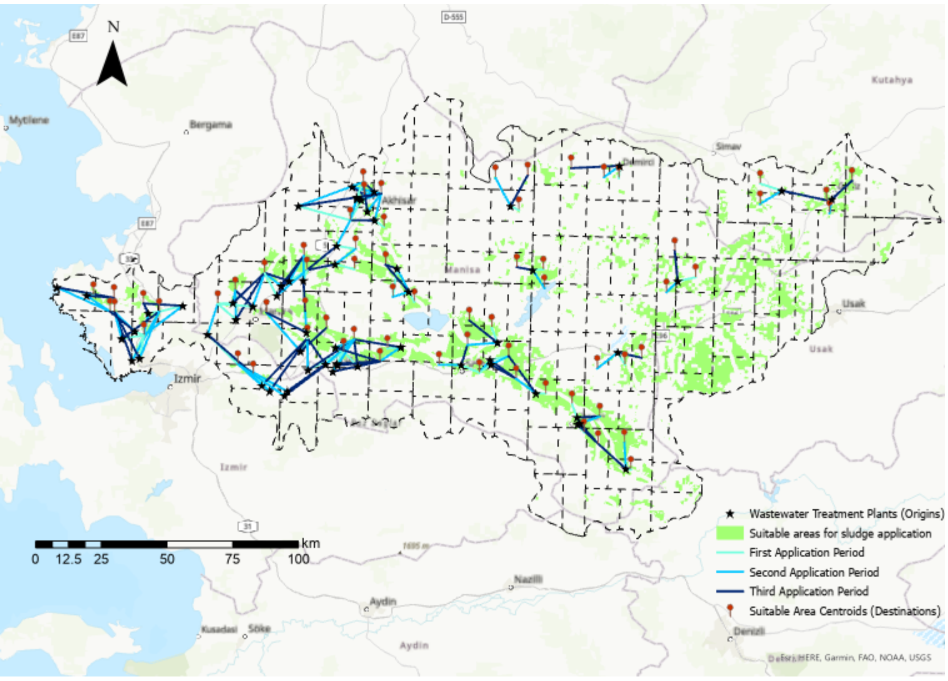


Figure 5.13 :WWTPs (Origins) to Suitable Area centroids (Destinations) for sludge application.

5.2. Results of the Optimization Model

As explained in the aim of the thesis, an optimization study was carried out in order to demonstrate the optimal sludge treatment and management pathway for each WWTP regarding stabilization, drying and land application by optimizing the total cost of sludge treatment and management processes. The results of this study are given in Table 5.1. In the table mentioned without specifying the names of the treatment plants, total sludge management costs are given as the results of the scenarios included in the optimization model together with the sludge quantities.

Table 5.1: Optimization Model Results

No	**Daily Wet Sludge Produced (tonnes/day)**	**Scenario 1-** Total Cost of sludge drying in off-site drying plant and Transportation and Land Application for stabilized sludge ($)	**Scenario -2**: Total Cost of sludge without drying. Transportation and Land Application for stabilized sludge ($)	**Scenario -3:** Total Cost of sludge drying in on-site plant. transportation and Land Application for stabilized sludge ($)	**Optimal Scenario #**
2	54	795,537	790,687	791,352	2
14	53	790,623	776,808	777,080	2
18	34.36	509,837	504,545	504,251	3
19	18	266,640	264,100	264,053	3
20	15	224,808	219,991	219,998	2
21	8.27	123,037	121,984	121,640	3
3	8	119,114	117,218	117,277	2
6	8	123,762	117,379	117,358	3

Table 5.1: continued

22	6.87	101,370	100,897	100,830	3
4	6	90,866	88,155	88,079	3
15	6	90,715	88,014	88,008	3
16	6	88,720	87,990	87,996	2
8	5	74,632	73,377	73,356	3
1	4	59,275	58,702	58,685	3
12	4	60,475	58,743	58,705	3
17	3	45,627	43,988	43,994	2
23	3	44,542	44,040	44,020	3
24	2.8	41,427	41,082	41,075	3
25	2.38	35,105	34,929	34,918	3
11	2	29,978	29,306	29,320	2
26	1.63	24,173	24,002	23,955	3
27	1.62	23,976	23,745	23,753	2
28	1.5	22,240	22,011	22,006	3
29	1.22	18,319	17,910	17,902	3

Table 5.1: continued

30	1.01	15,015	14,837	14,875	2
5	1	995	714	711	3
7	1	879	719	713	3
13	1	1.446	724	715	3
31	0.89	999	615	622	2
32	0.74	615	527	525	3
33	0.69	563	487	488	2
34	0.63	624	451	448	3
35	0.57	488	402	403	2
36	0.34	268	244	242	3
37	0.25	205	172	174	2
38	0.25	210	175	176	2
39	0.23	196	173	168	3
10	0.22	149	162	159	1
40	0.21	167	152	150	3
41	0.21	171	146	147	2

Table 5.1: continued

42	0.14	114	104	102	3
43	0.13	107	90	91	2
9	0.12	99	86	85	3
44	0.1	99	73	77	2
45	0.1	95	68	75	2
46	0.1	93	71	76	2
47	0.08	69	61	59	3
48	0.05	56	34	35	2
49	0.02	16	14	14	3
50	0.02	18	15	15	3
51	0.02	16	14	14	2

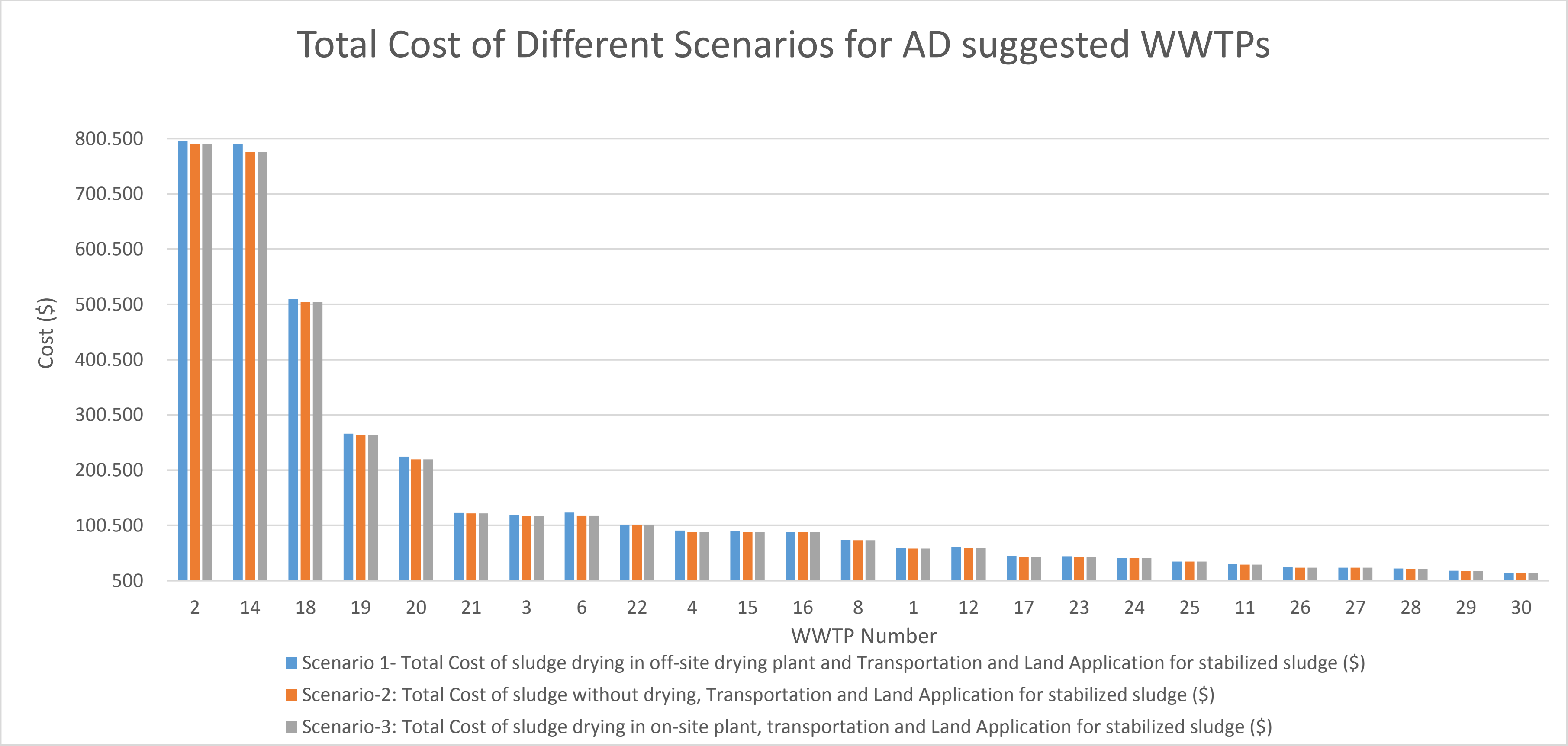


Figure 5.14: Total Cost of Different Scenarios for AD suggested WWTPs (from higher sludge amount to lower)

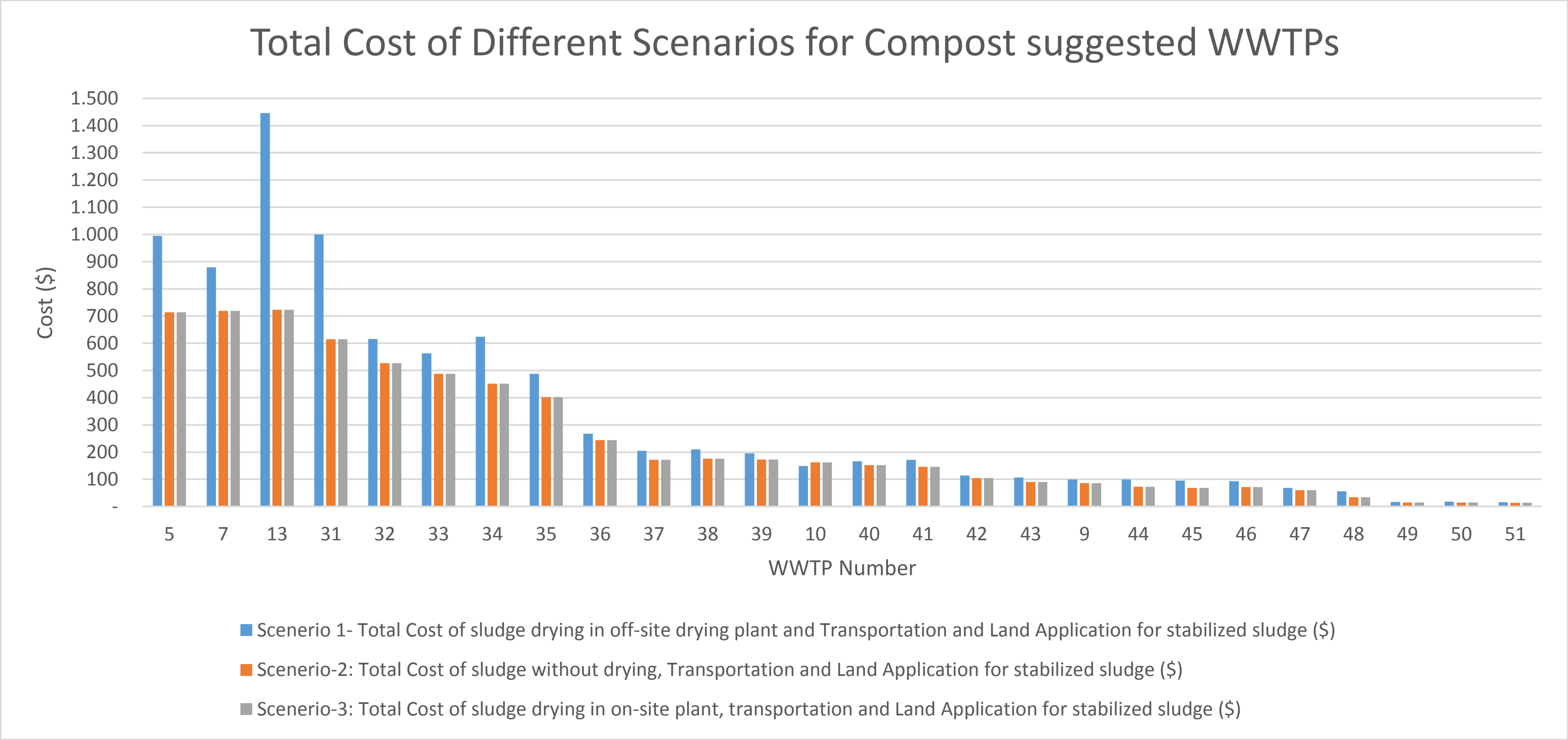


Figure 5.15: Total Cost of Different Scenarios for Compost suggested WWTPs (from higher sludge amount to lower)

5.3. Discussion of Optimization Model and Model in Analysis of Suitable Areas for Sludge Application Results

The main objective of this study is to decide on the most optimal way in terms of sludge management for each integrated WWTP in the Gediz Basin by integrating the main costs such as drying and stabilization costs and the management costs such as transportation and land application cost of the sludge into the optimization model within a period of 20 years under context of land application of sludge as the final sludge management method. In this study, three different model studies were carried out. Two of them were conducted to provide data to the original optimization model. These two studies are the model established to find suitable areas and the Origin-Destination Matrix study to find real distances

In the optimization model, the determination of suitable areas for the use of sludge on land is also included as a sub-model study. In that sub-model, one of the main parameters is depth of groundwater. Thus; the distribution in Figure 5.5 was obtained as a result of the calculation of the point well data by IDW interpolation method. As it can be understood from this distribution, the groundwater depths are considerably higher than 1 m which is a regulatory limit for sludge application on land. Therefore, groundwater depth did not affect the results as the other parameters considered.

The modeling of the depth of groundwater was used in the sub-model which was established for detecting the areas where the sludge application is allowed. As a result of the sub-model, suitable areas for land application does not exhibit a very wide distribution, and when examined together with the water resources map, it is seen that suitable areas are gathered around the branches of the main river Gediz. In addition, among all the parameters integrated into the sub-model, soil organic carbon and land use are parameters that affect the distribution of the result on the map at the highest level since they are the most constrained in terms of the values that must comply with the limits in the Regulation on the Use of Domestic and Urban Sewage Sludge on Soil.

Table 5.1 shows total costs of different scenarios and optimum scenario deduction for each WWTP resulted by model. As can be seen from this table, the off-site sludge drying option specified as scenario-1 was not found suitable for any WWTP.

The graph in Figure 5.14 gives the cost distribution of WWTPs with Anaerobic Digestion stabilization, sorted by sludge amount, on a scenario basis. As it can be seen from this figure, the total costs of the scenarios are very close to each other for WWTPs in this classification. Therefore, differences are expected in the case of sensitivity analysis on unit costs.

The chart in Figure 5.15 gives the cost distribution for the proposed WWTPs with compost stabilization, sorted from high sludge amount to low. The WWTP numbered 13 in this chart has a very high cost within the scope of scenario 1 is due to its approximately 200 km travel to the nearest drying plant. The distances of WWTPs numbered 5,7 and 31, are also more than 50 km to the nearest drying plant.

The potential reasons for the outcome of the model are listed below:

- Off-site sludge drying facilities do not show wide distribution in the Gediz basin. Therefore, this situation causes a high transportation cost for sludge drying in AATs within the scope of Scenario 1.
- Wide distribution of WWTPs and Suitable area centroids on a Basin basis. Thus; it causes the transportation cost to be comparatively low under Scenario 2.

General output of this study is that sludge can be used instead of chemical fertilizers. This idea, as mentioned in the literature section, can be established on a much more solid basis when it is supported by the result that the sludge which emerged as a result of many researches,provides the chemical and physical healing of the soil. According to what is written in the official "Fertilizer Recommendations" document of the Ministry of Agriculture and Forestry (TOB, 2020), it is recommended to use 50 kg of fertilizer per decare in order to meet the phosphorus and nitrogen needs of the soil. If a cost calculation is made within the scope of this amount of use. the lowest fertilizer purchase price of DAP fertilizer. which is the most commonly used fertilizer in Turkey according to the information announced by the Chamber of Agriculture in order to meet the phosphorus and nitrogen needs, is known as 19.9 US Dollars per 50 kg. Therefore, the use of sludge in the soil would enable the farmers to compensate the cost of chemical fertilizers.

Also, in terms of heavy metal accumulation in the soil, In the study conducted by Wei et al (2020), heavy metal accumulation in greenhouse soil have been analyzed when chemical fertilizer is used. As a conclusion of the study, chemical fertilizer application increased the availability of Cu, Ni, Pb, and Zn and the accumulation of Cd, Cu, and Zn. Moreover, there is an item in the relevant regulation says that “ If the stabilized sludge is applied to the soil every year based on a ten-year average, the maximum heavy metal amount that can be added to the soil cannot exceed the values given in Annex I-E. In case of reaching the limit values, it is obligatory to stop the use in the soil”. Since the application dosage of sludge in this study is much lower than the sublimit level which causes heavy metal accumulation stated in the literature studies and the application period is once in a three year, it would not cause any harmful situation for the soil it is applied on.

Within the scope of sensitivity analysis on Unit Costs, unit costs were increased by 5%, 15% and 25%, respectively. There was no change in the optimum scenario result that emerged from model in the increases of 5% and 15%; but the 25%

increase caused a change in the optimum scenario for some WWTPs. Sensitivity analysis result table with 25% increase is given in Appendix section. These increases have been made on the unit cost of transport, the unit cost of application of sludge and the gate fees of off-site drying. WWTPs that has different optimum scenario options are shown in bold.

CHAPTER 6

SUMMARY & CONCLUSION

Land application is one of the most efficient methods that contributes to the circular economy in terms of cost-effectiveness and it is a mechanism that supports the development of agricultural products grown in the land where it is applied. (Abreu-Junior et al. ,2017) (Aleisa et al., 2021) Therefore, the final sludge management method integrated into the optimization model made in this study is land application.

Among the facilities (WWTPs) in the Gediz basin, where this study was conducted. the WWTPs treating wastewater from municipalities as well as from industrial facilities belonging to food industries, which are in compliance with the Regulation on the Use of Domestic and Urban Sewage Sludge on Soil were included in the optimization model. In this context. stabilization methods have been proposed for the WWTPs according to the amount of sludge they produce and the cost of the specified method has been included in the optimization model. Afterwards, in case the sludge is taken to the drying facilities, the transportation cost up to the drying facility, the drying acceptance cost (gate fee), the transportation cost from the drying facility to the suitable area center and the sludge application cost are calculated. It was compared with the total cost of application of the sludge directly onto the soil without drying for agricultural purposes. In accordance with that, optimal pathway of sludge management for each WWTP is computed as a result of the cost-based optimization model.

In response to the main question of the study, "What is the most cost-effective management method considering that the sludge of WWTPs in the Gediz Basin which will ultimately be applied on soil", the appropriate method for each facility in terms of optimization of total sludge management costs has been determined under the concept of 3 different scenarios as a result of this study.

The general takeaway that can be made from this study is that WWTPs in the Gediz Basin will not encounter any problems in terms of the capacity of suitable areas in case they use their sludge on land. In addition, in accordance with the Table 5.1, it can be concluded that applying their sludge on land with on-site drying (scenario 3) or without drying (scenario 2) are chosen optimal scenarios for most of the WWTPs in this basin as a result of the optimization model.

One of the limitations of this study is the inability to find soil heavy metal data in the suitable areas of sludge application model. In addition, if the information about WWTPs in this basin can be obtained from official institutions in a complete and regular manner, there will be less need for modifications in the inputs in the model.

The main suggestion that can be drawn from the result of this study is to prioritize the choice of land use for WWTPs since it will not cause any problems in terms of capacity and distance, since the potential suitable areas in the Gediz basin have a wide distribution and mostly there are WWTPs that produce a small amount of sludge

In conclusion, As far as I am concerned, optimization studies that are generally found in the literature within the scope of ultimate management of sewage sludge as land application are generally on determining the appropriate dosage and its benefits and risks on the soil under pilot studies. In this context. my work presents a different concept. In my study, where the use of a in soil was chosen as the ultimate management method, it shows which of the scenario would be more appropriate for each WWTPs in terms of optimal cost of total sludge management expenditures. Thus, thanks to my study, I think that I contributed to the literature by presenting a study of the use of sludge on land, in which the cost optimization is also considered in addition to the studies in the literature regarding review of costs but without any optimization model. In addition, unlike the known optimization software systems, the platform on which I set up the optimization model is a GIS platform. Thus; it enables the optimization work to be visually supported by the created maps, flowcharts and thanks to the tools on this ArcGIS platform, it provides a user-friendly interface in designing the optimization model, allowing a faster flow of work.

CHAPTER 7

FUTURE WORK

As a research that can be done in the future of this study, the social and economic effect of the use of sewage sludge on the soil can be examined under the life cycle analysis. In addition, following the fact that off-site sludge drying is not a very optimum scenario as a result of this study, the locations of new central drying facilities can be determined by conducting a density analysis study to identify the regions where WWTPs are concentrated.

The data of the WWTPs used in this study were collected from many different sources. Therefore, in a situation where the data are collected from a single source, the basis of the model result will be considered to be more robust. In addition, it is thought that the optimization model and its sub-model will give more reliable results if the geographic information system-based data can be taken from open-source reliable and diverse platforms.

In addition, the model created in this study exhibits optimization study on a regional basis. However, with this optimization model designed in ArcGIS model builder, more comprehensive studies can be done by adding various data and constructs.

APPENDIX

Table 8.1: Information about sludge management of urban/domestic WWTPs

WWTP no	Province	Sludge production rate (tonnes/day)	Dry matter content (%)	Stabilization method	Sludge drying method	Current sludge management method
1	Manisa	4	20		0	Temporary storage
2	Manisa	54	25	Aerobic	0	Temporary storage
3	Manisa	8	2	Aerobic	0	Temporary storage
4	Manisa	6	20		0	Temporary storage
5	Manisa	1	25		0	Temporary storage
6	Kütahya	8	20		0	Temporary storage
7	Manisa	1	25		0	Temporary storage
8	Manisa	5	20		0	Temporary storage
9	Manisa	0.12	25		0	Temporary storage
10	Manisa	0.22	10		0	Temporary storage
11	Manisa	2	20		0	Temporary storage
12	Manisa	4	25		0	Temporary storage
13	Kütahya	1	20		0	
14	Manisa	53	25	Lime	0	
15	Manisa	6	20		0	Temporary storage
16	Manisa	6	20		0	Temporary storage
17	Manisa	3	20		0	Temporary storage

Table 8.2: Information about the industrial WWTPs considered in the study

WWTP No	Province	Industry Type	Sludge production rate (wet tonnes/day)	Treatment Type (P: Physical B: Biological)
18	Manisa	Food-Sauce	34.36	P+B
19	Manisa	Food-Canned	18	P+B
20	Manisa	Food-Canned	15	P+B
21	Manisa	Food-Grape	8.27	P+B
22	Manisa	Food-Canned	6.87	P+B
23	Manisa	Food-Canned	3	P+B
24	Manisa	Food-Sauce	2.8	P+B
25	Manisa	Food-Canned	2.38	P+B
26	İzmir	Food-Canned	1.63	P+B
27	Manisa	Food-Olive	1.62	P+B
28	Manisa	Food-Grape	1.5	P+B
29	Manisa	Food-Alcohol	1.22	P+B
30	İzmir	Food-Milk	1.01	P+B

Table 8.2: continued

31	Manisa	Food-Canned	0.89	P+B
32	Manisa	Food-Alcohol	0.74	P+B
33	Manisa	Food-Grape	0.69	P+B
34	Manisa	Food-Grape	0.63	P+B
35	Manisa	Food-Grape	0.57	P+B
36	Manisa	Food-Salt	0.34	P
37	Manisa	Food-Olive	0.25	P+B
38	Manisa	Food-Olive	0.25	P+B
39	Manisa	Food-Alcohol	0.23	P+B
40	Manisa	Food-sugar	0.21	P+B
41	Manisa	Food-Olive	0.21	P+B
42	Manisa	Food-Meat	0.14	P+B
43	Manisa	Food-Milk	0.13	P+B
44	İzmir	Food	0.1	P+B
45	İzmir	Food-Meat	0.1	B
46	Manisa	Food-Grape	0.1	P+B

Table 8.2: continued

47	İzmir	Food-Milk	0.08	B
48	Manisa	Food-Olive	0.05	P
49	İzmir	Food-Bread	0.02	B
50	İzmir	Food-Fickled	0.02	B
51	Manisa	Food-Olive	0.02	P

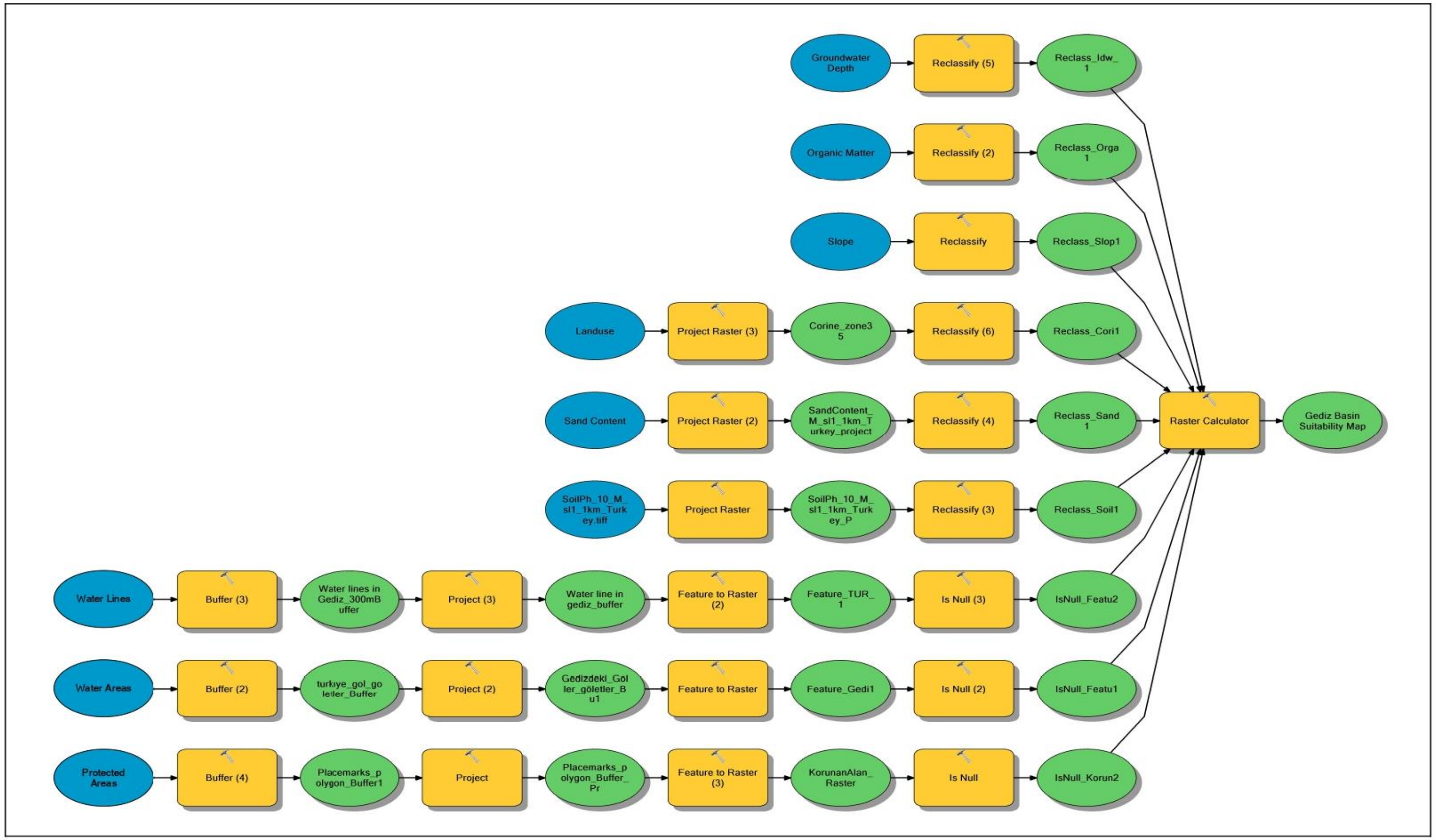


Figure 8.1. Sludge Suitability Model in The Model Builder Of Arcgıs (Figure 3.6)

Table 8.3: Optimization Model Table with % 25 rise on Unit Costs under the scope of Sensitivity Analysis

No	Daily Wet Sludge Produced (tonnes/day)	Scenario -1	Scenario-2	Scenario-3	Optimal Scenario in Base	Optimal Scenario with % 25 rise on Unit cost
2	54	797.301	792.366	793.758	2	2
14	53	793.828	778.571	779.498	2	2
18	34.36	511.506	505.828	505.890	3	2
19	18	267.447	264.740	264.895	3	2
20	15	225.872	220.511	220.693	2	2
21	8.27	123.488	122.375	122.075	3	3
3	8	119.652	117.479	117.640	2	2
6	**8**	**124.928**	**117.664**	**117.732**	**3**	**2**
22	6.87	101.619	101.156	101.159	3	2
4	6	91.447	88.387	88.368	3	3
15	**6**	**91.274**	**88.225**	**88.288**	**3**	**2**
16	6	88.979	88.196	88.273	2	2
8	**5**	**74.953**	**73.558**	**73.591**	**3**	**2**
1	**4**	**59.494**	**58.847**	**58.873**	**3**	**2**
12	4	60.837	58.893	58.897	3	2
17	3	45.947	44.090	44.133	2	2

Table 8.3: continued

23	**3**	**44.692**	**44.150**	**44.163**	**3**	**2**
24	**2.8**	**41.545**	**41.182**	**41.206**	**3**	**2**
25	**2.38**	**35.189**	**35.015**	**35.030**	**3**	**2**
11	2	30.125	29.371	29.411	2	2
26	1.63	24.250	24.073	24.038	3	3
27	1.62	24.045	23.799	23.827	2	2
28	**1.5**	**22.310**	**22.064**	**22.076**	**3**	**2**
29	**1.22**	**18.411**	**17.955**	**17.960**	**3**	**2**
30	1.01	15.066	14.876	14.931	2	2
5	**1**	**1.061**	**750**	**758**	**3**	**2**
7	**1**	**928**	**756**	**760**	**3**	**2**
13	**1**	**1.582**	**761**	**763**	**3**	**2**
31	0.89	1.075	644	662	2	2
32	**0.74**	**646**	**553**	**560**	**3**	**2**
33	0.69	590	511	520	2	2
34	**0.63**	**665**	**474**	**478**	**3**	**2**
35	0.57	514	422	429	2	2
36	**0.34**	**280**	**256**	**258**	**3**	**2**
37	**0.25**	**215**	**180**	**186**	**2**	**2**
38	0.25	220	184	188	2	2

Table 8.3: continued

39	0.23	206	182	179	3	3
10	0.22	154	171	169	1	1
40	**0.21**	**175**	**160**	**160**	**3**	**2**
41	0.21	180	153	157	2	2
42	0.14	119	110	108	3	3
43	0.13	112	94	97	2	2
9	**0.12**	**104**	**90**	**91**	**3**	**2**
44	0.1	106	76	82	2	2
45	0.1	101	72	80	2	2
46	0.1	98	75	81	2	2
47	0.08	73	64	63	3	3
48	0.05	60	36	37	2	2
49	**0.02**	**17**	**15**	**15**	**3**	**2**
50	0.02	19	16	16	3	3
51	0.02	17	14	15	2	2

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