A TRANSPORT COST-BASED OPTIMIZATION FOR ARABLE LAND APPLICATION OF MUNICIPAL SLUDGE IN ANKARA

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A TRANSPORT COST-BASED OPTIMIZATION FOR ARABLE LAND APPLICATION OF MUNICIPAL SLUDGE IN ANKARA

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ABSTRACT

A TRANSPORT COST-BASED OPTIMIZATION FOR ARABLE LAND APPLICATION OF MUNICIPAL SLUDGE IN ANKARA

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The agricultural use of sewage sludge is an alternative route for sewage sludge disposal which may also help to improve soil fertility by providing organic matter and nutrients. Yet, care should be taken to minimize soil contamination due to some constituents in sludge such as heavy metals, organic contaminants and pathogens. One approach may be selection of suitable lands. This study focuses on the determination of suitable arable lands for sewage sludge application on land in Ankara through a cost-based optimization model. In this model, it is aimed to minimize the transportation costs related to land application of municipal sewage sludge between 2013 and 2022. Lands suitable for sludge application were determined through spatial analysis using ArcGIS program. In the study, 75% of the total non-irrigated arable lands in Ankara were eliminated due to their non-conformity to land applications. According to results of optimization model developed with linear programming, 17.1% of the total suitable non-irrigated arable lands received sewage sludge. The minimum, maximum and average distances to these lands for which sludge application was feasible in a period of 10 years were 3.2, 71.6, and 50.7 km, respectively. The average transportation costs for transport of sewage sludge for 10 years were 184,983, 168,513, and 135,922 TL/yr when truck capacities of 10, 16 and 24 tonnes, respectively, were used. As the truck capacity increased, the total transportation costs decreased due to decreased numbers of round-trips required to transport sewage sludge to non-irrigated arable lands.

Keywords: Geographical Information Systems (GIS), Land Application, Optimization, Sewage Sludge

ÖZ

ANKARA’DAKİ KENTSEL ARITMA ÇAMURLARININ TARIMA ELVERİŞLİ ARAZİLERDE KULLANIMININ TAŞIMA MALİYETİ BAZLI OPTİMİZASYONU

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Arıtma çamurunun tarımsal kullanımı, organik madde ve besin maddeleri sağlayarak toprak veriminin artmasına yardımcı olabileceğinden arıtma çamuru bertarafı için alternatif bir yöntemdir. Ancak bu uygulamada, arıtma çamurunda bulunan ağır metaller, organik kirleticiler ve patojenler gibi bazı bileşenler sebebiyle oluşabilecek toprak kirliliğini en aza indirmek için özen gösterilmelidir. Uygun uygulama arazilerinin seçilmesi bir yaklaşım olabilir. Bu çalışma, arıtma çamurunun arazide kullanımı için Ankara’da uygun ekilebilir arazilerin maliyet-bazlı optimizasyon modeli vasıtasıyla belirlenmesine odaklanmaktadır. Bu modelde, kentsel arıtma çamurunun 2013 ve 2022 yılları arasında araziye uygulanmasıyla ilgili taşıma maliyetlerinin en aza indirgenmesi amaçlanmaktadır. Arıtma çamuru uygulaması için uygun araziler, ArcGIS programını kullanarak mekansal analiz vasıtasıyla belirlenmiştir. Bu çalışmada, Ankara’da bulunan toplam sulanmayan ekilebilir alanların %75’i arıtma çamuru arazi uygulamaları için uygun olmamaları sebebiyle çıkarılmıştır. Doğrusal programlama ile oluşturulan optimizasyon modeli sonuçlarına göre uygulama için uygun olan sulanmayan ekilebilir alanların toplamının %17,1’i arıtma çamuru almıştır. 10 yıl içinde, arıtma tesisi ile arıtma çamurunun uygulanabilir olduğu bu alanlar arasındaki mesafe en az 3,2, en fazla 71,6 ve ortalama 50,7 km olmuştur. 10 yıl içinde, arıtma çamurunun taşınması için 10, 16 ve 24 ton kapasiteli kamyonlar kullanıldığı zaman ortalama taşıma maliyetleri sırasıyla 184.983, 168.513 ve 135.922 TL/yıl olmaktadır. Kamyon kapasitesi arttıkça, arıtma çamurunu sulanmayan ekilebilir arazilere taşımak için gereken sefer sayıları düştüğünden toplam taşıma maliyetleri azalmıştır.

Anahtar Kelimeler: Arazi Uygulaması, Arıtma Çamuru, Coğrafi Bilgi Sistemleri (CBS), Optimizasyon

To My Dear Family

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TABLE OF CONTENTS

LIST OF TABLES

TABLES

LIST OF FIGURES

FIGURES

LIST OF ABBREVIATIONS

Al	Aluminum
AOX	Adsorbable organic halogen compound
As	Arsenic
B	Boron
^oC	Celcius degree
C	Carbon
Ca	Calcium
$CaCO_3$	Calcium Carbonate
CaO	Calcium Oxide
Cd	Cadmium
CEC	Cation Exchange Capacity
CFU	Colony-Forming Unit
Cl	Chlorine
CLC	CORINE Land Cover
cm	Centimeter
Co	Cobalt
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CO_3^{2-}	Carbonate
CORINE	Coordination of Information on the Environment
Cr	Chromium
Cu	Copper
da	Decare
DEHP	Di-2-(ethylhexyl)phthalate
DEM	Digital Elevation Model
DM	Dry Matter
DOM	Dissolved Organic Matter
EC	Electrical Conductivity
EU	European Union
Fe	Iron
g	Gram
GIS	Geographic Information Systems
H_2O	Water
h	Hour
ha	Hectare
HCB	Hexachlorobenzene
Hg	Mercury
hPa	Hectopascal
K	Potassium
kg	Kilogram
km	Kilometer
L	Liter
LAS	Linear alkylbenzene sulphonate
LP	Linear programming

m^2	Square Meter
m^3	Cubic Meter
mg	Miligram
Mg	Magnesium
Mn	Manganese
Mo	Molybdenum
MPN	Most Probable Number
N	Nitrogen
n.d.	No date
Na	Sodium
ng	Nanogram
NH_4^+	Ammonium Ion
Ni	Nickel
NO^-	Nitrogen Oxide
NO_3^-	Nitrate
NO_x	Mono-nitrogen oxides
NP	Nonylphenol
NPE	Nonylphenol polyethoxylate
OCDD	Octa-chlorinated Dioxin
OM	Organic Matter
P	Phosphorus
PAH	Polynuclear aromatic hydrocarbon
Pb	Lead
PBDE	Polybrominated diphenylethers
PCB	Polychlorinated biphenyles
PCDD	Polychlorinated dibenzo-p-dioxins
PCDF	Polychlorinated dibenzo-furans
ppm	Parts per million
S	Sulfur
Sb	Antimony
Se	Selenium
SO_2	Sulfur dioxide
SO_4^{2-}	Sulfate
t	Tonne (Metric Ton)
TCDD	Tetra-chlorinated Dioxin
THM	Trihalomethane
TL	Turkish Lira
TOC	Total Organic Carbon
U.S.	United States
U.S. EPA	United States Environmental Protection Agency
VOC	Volatile Organic Compound
VS	Volatile Solids
WWTP	Wastewater Treatment Plant
yr	Year
Zn	Zinc

CHAPTER 1

INTRODUCTION

In Turkey, as the wastewater treatment improved and the number of new wastewater treatment plants taken into operation increased, a significant increase in the amount of sludge occurred. That resulted in rising of concerns about wastewater sludge and biosolids management and the implementation of stricter regulatory limit values. In Turkey, landfilling of sludge is the most commonly used sludge disposal method (UNHSP, 2008). Today, agricultural use of sludge as a fertilizer or soil conditioner is attracting attention due to high nutrient concentrations of sludges (UNHSP, 2008).

Land application of sewage sludge can have many benefits for both soil and plants; however, it may also have disadvantages when it is not managed properly. High organic matter of sludge can enhance soil physico-chemical properties, microbial properties and soil enzymes. In addition, the macro and micronutrient contents of sewage sludge are essential for plant cultivation and improve the growth, dry matter accumulation and the yield of the plants. On the other hand, sludge may include undesirable organic contaminants, heavy metals and pathogenic bacteria that pose risks for human, animal and plant health. Leaching of heavy metals and nutrients to the lower layers of soil is another threat for the utilization of sludge on soil. In order to prevent adverse effects of land application, many countries put forward regulations limiting this application. In Turkey, "Regulation on the Use of Domestic and Urban Wastewater Sludges on Land" was put into action in 2010. Similar to European Union and U.S. legislation, Turkish regulation prohibits the use of untreated sewage sludge on soil.

The aim of this study is to determine the suitable arable lands for sludge land application through a spatial analysis and to develop a transport cost-based optimization model to minimize the transportation costs related to land application of sludge for the years between 2013 and 2022. An additional purpose of this study is to analyze land application as a sludge disposal method around a metropolitan city in terms of potential load that will be brought into the area and the required frequency of land application.

In this study, Ankara was used as the study area. Ankara Central Wastewater Treatment Plant as being the largest plant in Ankara and second largest plant in Turkey as well as producing stabilized sludge was determined as the plant to be studied. For determination of the best arable lands for sludge land application, some land use constraints related to the proximity of sludge land application site to residential areas, water courses and water bodies, railways and public areas, sand plains and inland marshes were defined to restrain the available arable lands. In addition to these constraints, further land elimination was conducted with slope constraint, land use capability constraints and some other constraints (e.g. salty and rock soils, and soils with bad drainage properties). Optimal sludge dose determination was done with the help of literature survey and expert opinions. The transport cost-based optimization model was built to figure out the arable lands to serve for the years between 2013 and 2022, and to determine the related minimum transportation costs of application. The study presents an approach for planning of the municipal sewage sludge land application in Ankara.

CHAPTER 2

LITERATURE SURVEY

2.1. Wastewater Sludge

Sewage sludge is the semi-solid residue generated during domestic wastewater treatment (U.S. EPA, 1993). “Biosolids” particularly refers to sewage sludge that has been stabilized and disinfected, meets the regulatory limitations and has potential beneficial uses such as fertilization or soil amendment (U.S. EPA, 1999a; UNHSP, 2008). Although “biosolids” term has been mainly taking the place of “sewage sludge” throughout the wastewater and sewage sludge works, “sewage sludge” or “sludge” term is used throughout this study.

2.2. Wastewater Sludge Generation Rates

With industrial development, improvements in human life and agricultural activities, more and more wastewater is produced. At the same time, concern about environmental protection is growing, thus strict and critical legislations are put into implementation (Wang, 1997).

An inevitable by-product of wastewater treatment is sludge. According to daily sludge production estimates made by Öztürk (2010), approximately 1,100,000 tonnes of dry sludge will be produced in Turkey in 2013 (Figure 2.1).

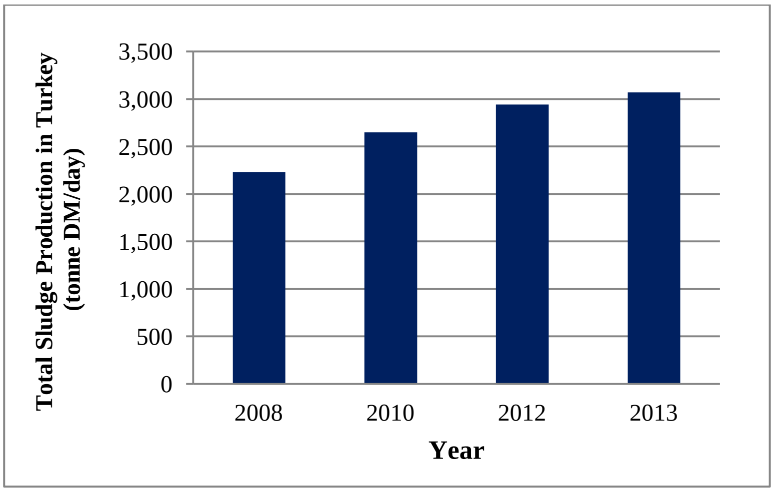

Figure 2.1: Total Sludge Production in Turkey (Öztürk, 2010)

About 10 millions tonnes of dry sludge was produced in the European Union Member States between the years 2003 and 2006 (European Commission, 2010). Annual sludge productions in some European Union Member States are given in Table 2.1. In U.S., nearly 6.2 million dry tonnes of sludge is produced annually in wastewater treatment plants (Kargbo, 2010).

Table 2.1: Annual sludge productions in some European Union Member States (European Commission, 2010)

Member State	**Year**	**Sludge Production (tonnes of dry solids)**
Austria	2005	266,100
Denmark	2002	140,021
Finland	2005	147,000
France	2002	910,255
Germany	2006	2,059,351
Greece	2006	125,977
Ireland	2003	42,147
Italy	2006	1,070,080
Luxemburg	2003	7,750
Netherlands	2003	550,000
Portugal	2002	408,710
Spain	2006	1,064,972
Sweden	2006	210,000
United Kingdom	2006	1,544,919

2.3. Treatment and Disposal Methods of Sludge

The large amounts of sludge generated from wastewater treatment plants must be treated to enhance its quality before using or disposing them. This treatment includes biological, chemical, physical and/or thermal processes basically designed for removing water, decreasing the pathogen level, stabilizing volatile solids and making a less attractive product for vectors (U.S. EPA, 1992). Sewage sludge treatment consists of several processes such as thickening, stabilization, dewatering and drying. For the ultimate disposal, treated sludge may be transported and disposed to landfills together with municipal solid wastes, applied onto the agricultural farmlands as organic fertilizer or soil conditioner, or incinerated specifically in large scale projects (Libhaber and Orozco-Jaramillo, 2012).

2.3.1. Treatment Methods of Sludge

2.3.1.1. Sludge Thickening

Sludge thickening eliminates water in concentrated liquid form from sludge to decrease the cost of further treatment or sludge disposal. Gravity thickening, lagoon thickening, gravity belt thickening and centrifuge thickening are the common processes involved in sludge thickening. *Gravity thickening* includes a settling tank. Thickened sludge is drawn from the bottom of the tank with the help of pump and sent to the stabilization unit or disposed as liquid sludge. It requires a small land, high operator attention and equipment maintenance. *Lagoon thickening* is also a gravity thickening using a basin made of earth. It is cheap but requires large area. *Gravity belt thickening* utilizes the gravity region of a belt press for thickening purpose. *Centrifuge thickening* uses a solid bowl centrifuge working at high frequencies. Both gravity belt thickening and centrifuge thickening require high operator attention and equipment maintenance (Libhaber and Orozco-Jaramillo, 2012).

2.3.1.2. Sludge Stabilization

According to U.S., European Union and Turkey legislations on sludge utilization on soil, sludge needs to be stabilized before land application. Stabilization methods mainly decrease the amount of organic matter, water content, stinky substances and pathogenic microorganisms (Arthurson, 2008). Common sludge stabilization methods are lime stabilization, anaerobic digestion (mesophilic or thermophilic), aerobic digestion, composting, and heat drying (Goldfarb et al., 1999).

In *alkaline stabilization process*, hydrated lime (calcium hydroxide) is mixed with liquid sewage sludge sufficiently in order to raise the pH to 12.0 for at least 2 hours. When pH reaches to 12.0, NH_4^+ ions in sludge remove their protons and produce ammonia gas (Arthurson, 2008). Ammonia is bactericidal and can diffuse through the cell membranes of durable organisms such as helminth ova (Mendez et al., 2004). Coliform indicator bacteria can be decreased by 2-7 orders of magnitude with the effects of both high pH and ammonia. In addition, the amount of fecal streptococci bacteria can be reduced to a minor level (Arthurson, 2008). If pH is maintained in the range of 10.0-11.0 during lime stabilization, odor production and vector attraction may occur in sludge due to biodegradation (Williford et al., 2007). Using quicklime (CaO) during alkaline stabilization brings about a substantial temperature increase in the system due to the reaction between quicklime and water to form hydrated lime (Tchobanoglous et al., 2003). Temperature of sludge generally rises up to 70°C during stabilization that provides pasteurization (Arthurson, 2008).

Anaerobic stabilization occurs in a biological system including considerable amount of anaerobic bacteria which convert organic matter into biogas (mixture of carbon dioxide and methane) in the environment with no oxygen. Digestion of the organic matter in the sludge results in a decrease in the amount of pathogens, odorous compounds, and the total solids/sludge quantity by transforming volatile solids (VS) into biogas. At the end of anaerobic stabilization process, the resultant product includes digested solids and some nutrients (e.g. ammonia nitrogen) that can be used readily (U.S. EPA, 2006a). The anaerobic stabilization can be carried out at either mesophilic (30 to 38°C) or thermophilic (50 to 60°C) conditions which are significant factors in pathogens removal (Arthurson, 2008). Mesophilic anaerobic stabilization provides virus inactivation by 50-99%. On the other hand, this ratio is 99.9999% for thermophilic anaerobic stabilization processes (Lepeuple et al., 2004).

Aerobic stabilization is the biochemical oxidative digestion of sludge and operates as the activated sludge process. When the food is consumed, the microorganisms shift to endogenous phase of metabolism. Their cell tissues are aerobically oxidized to CO_2, H_2O, NH_4^+, and NO^- . Autothermal thermophilic aerobic stabilization process is carried out in the thermophilic temperature range (>45°C) providing air as the source of oxygen to aerate the sludge. The high temperatures in the system may destroy all the pathogens and eliminate further disinfection requirement (Shammas and Wang, 2007). Thermophilic aerobic stabilization provides virus inactivation by 98% (Lepeuple et al., 2004).

In *composting* method, aerobic biodegradation of organic content in sludge occurs under controlled temperature, moisture, and oxygen levels. Wood chips, bark, saw dust, straw or previously produced compost products are used as bulking agents in order to absorb humidity, enhance porosity and provide carbon source. Windrows, static piles or enclosed tanks are used to store the sludge-bulking agent mixture for a time period in which temperature of the mixture can increase more than 55^0C during degradation. External aeration and periodic mixing may be applied to increase oxygen level. After this active stage is over, bulking agents may be removed with screening. Finally, composted sludge is maintained in a “curing stage” for an additional period (U.S. EPA, 2003a).

Heat drying is a stabilization method in which water is evaporated from sludge with the application heat from direct or indirect dryers (U.S. EPA, 2006b). Dryers provide hot gases (≥ 80°C) to the system to decrease the sludge moisture content below 10%. Since heat drying method does not eliminate the food content of sludge, an increase in sludge humidity may bring about unstable conditions (Acquisto et al., 2006).

2.3.1.3. Sludge Dewatering

Sludge dewatering is carried out to decrease the water content of sludge and ends with concentrated solid product. It reduces the cost of further treatment or sludge disposal. Although its processes are similar to the thickening processes, sludge dewatering results in higher solid content (Libhaber and Orozco-Jaramillo, 2012). Typical dewatering processes are centrifuges, belt filter presses, drying beds and lagoons. *Centrifuges* comprise of a solid-bowl rotating and separate sludge into a dense cake and a dilute stream (Tchobanoglous et al., 2003). *Belt filter presses* dewater the sludge with the application of pressure and squeeze out the water from the sludge (Libhaber and Orozco-Jaramillo, 2012). *Drying beds* are sand beds including an under drain system. After the sludge is spread onto the bed, excess water drains through the sand. The sun and wind help the dewatered product get drier. *Drying lagoons* include shallow earthen basins in which sludge is poured and is allowed to dry. The sludge cake is then removed mechanically (Garg, 2009).

2.3.1.4. Sludge Drying

Sludge drying is carried out to decrease the water content of sludge to less than 10% by evaporation. The product of this process is ready for incineration or utilization as fertilizer. Open air or mechanically supplied auxiliary heat can be applied for drying purpose. In open air drying process, large land area and high labor for discarding the dried sludge cake out of the bed are required. In addition, poor drying levels may be observed in overcast weathers and odor production may happen in the system (Garg, 2009).

2.3.2. Sludge Recycling and Disposal Methods

After treatment, sludge can either be recycled or disposed of with three major methods: incineration, landfilling, and recycling in agriculture (land application) (European Commission, 2001a). Detailed information about these main methods is given in this section. In addition to these disposal routes, some other disposal methods of sludge are utilization of sludge in silviculture, land reclamation, and other advancing combustion technologies such as wet oxidation, pyrolysis and gasification. Each of these methods has different inputs, outputs and impacts (European Commission, 2001a).

Figure 2.2 indicates the sludge disposal routes preferred by many countries. According to this figure, although agricultural use of sludge is the most common disposal, landfilling and composting are also highly preferred as disposal methods among the given countries. In Turkey, the sludge is mainly disposed into landfills (UNHSP, 2008).

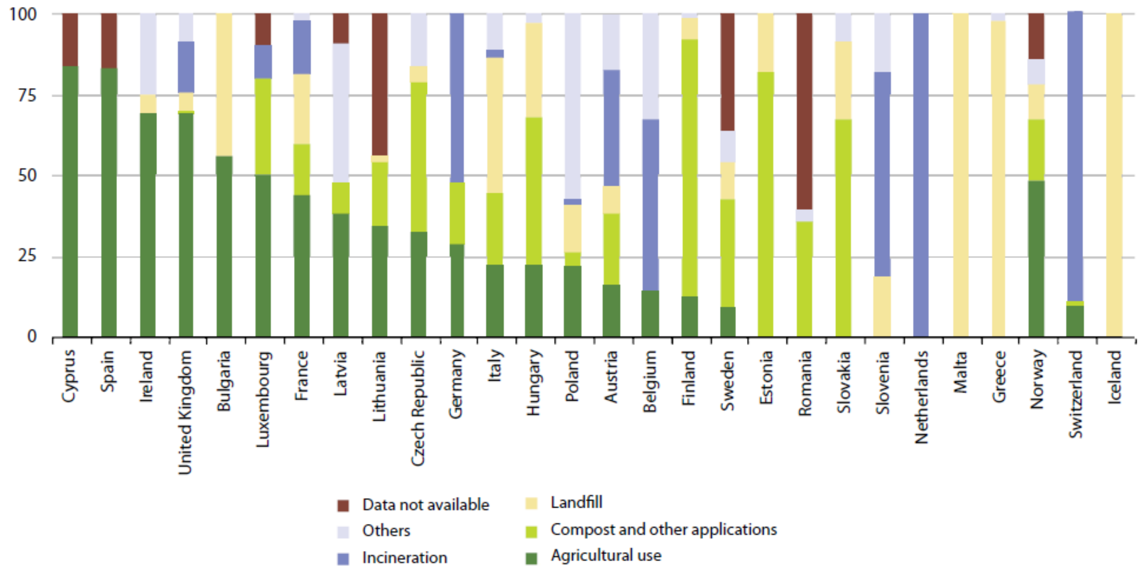

Figure 2.2: Sludge disposal methods from urban wastewater treatment (% of total sludge mass) (PURE, 2012)

2.3.2.1. Incineration

Incineration of sludge includes firing sludge at high temperatures in a combustor (U.S. EPA, 1999b). Mechanically dewatered sludge or dried sludge can be combusted in incinerators (Rulkens, 2008). Several methods such as mono-incineration (only sludge is incinerated), co-incineration (sludge is utilized as auxiliary fuel in energy or material production), wet oxidation and pyrolysis can be involved in incineration of sludge (European Commission, 2001a). While sludge is converted to a residue mainly including ash, sludge volume can decrease approximately to 20% of the original volume. All of the volatile solids and pathogens are reduced and toxic organic chemicals are degraded during the incineration process (U.S. EPA, 1999b). The products of incineration process are flue gases, ashes, wastewater, and energy produced in the system. As a result, incineration brings about emissions to the air, soil and water. These emissions may change depending on the incineration process and sludge characteristics. Particle emissions to the air can be decreased with flue gas treatment. The incineration plants may also generate dust, noise, odor and visual pollution (European Commission, 2001a).

Emission of dust, dioxins, heavy metals, volatile organic compounds (VOC), NO_x, CO and SO_2 to air may have negative health impacts. In addition to these pollutants, CO_2 can affect ecosystems and climate change adversely. If flue gas treatment is conducted by wet processes, water emission occurs. The wastewater produced during flue gas treatment process and leachate generated in landfills where the ashes are disposed of may result in groundwater or surface water pollution. The disposal of ashes or the flue gas treatment residues to landfill, and the use of ashes in road construction may cause soil pollution (European Commission, 2001a).

Despite the auxiliary fuel requirement of sludge incinerators, many sludge incineration plants involve energy recovery as part of their processes (U.S. EPA, 1999b). The energy produced in incineration process can be used to produce electricity or to dry the dewatered sludge cake before incineration process. Since the incineration processes emit large amounts of polluted exit gases, installations of efficient and sufficient gas treatment systems are very expensive (Rulkens, 2008). If the incineration plant does not include energy recovery, the temperature-based air quality requirements (i.e. the requirement of an afterburner to elevate the temperature of the exhaust gases to eliminate unburnt hydrocarbons) designated the operation of incinerator to some extent and cannot be covered in economical way. In U.S., numerous incineration plants terminated their operations in the past decade because other sludge disposal options were less costly and more acceptable by public despite recovering their own energy (U.S. EPA, 1999b).

Incineration of sludge is preferred worldwide especially with energy recovery systems and mainly utilized in large scale projects (Rulkens, 2008). According to Figure 2.2, incineration is the only sludge disposal option in Netherlands. Germany, Belgium, Switzerland and Slovenia mostly prefer sludge incineration as their sludge disposal methods. 33% of sludge produced in U.S. has been incinerated (Fericelli, 2011).

2.3.2.2. Landfilling

Landfilling is a sludge disposal method in which sludge is disposed to a specified area, either by itself (monofill) or together with solid waste (co-disposal), and covered up with soil layer. This disposal method has not any attempt for recycling nutrients and has only rare attempts to produce energy from the sludge (U.S. EPA, n.d).

Landfilling is mainly considered for sludge management when land application or other beneficial reuse options are not possible. Also, it can be a viable disposal option when there exists some restrictions due to land acquisition problems, odor producing materials in sludge or poor sludge quality due to high heavy metal or organic contaminant concentrations (U.S. EPA, 2003b).

Waste deposit in landfill firstly undergoes an initial aerobic phase about 14 days until the aerobic microorganisms consume all the oxygen in the system. During this step, the organic content of leachate increases. In acetogenesis step, acetogenic and fermentative bacteria degrade the readily degradable compounds in the system including little or no oxygen. In this step, the decreased pH brings about an increase in the solubility of inorganic compounds such as heavy metals, and high organic pollution of the leachate occurs. Finally, the organic materials in the system are consumed by methanogenic bacteria that generate methane in the landfill system (European Commission, 2001a).

The products of landfill systems include leachate, landfill gas and energy production when the gas is recovered. Therefore, landfill operation produces emissions to the air, soil and water. Emissions to air are dust particles and the gases generated in landfill if these gases are not recovered for energy production. The landfill gas consists of methane (about 50-60%), carbon dioxide (about 40-50%), and some trace gases including VOCs. Methane and carbon dioxide have adverse effects on the climate, and trace gases may be toxic and/or carcinogenic, with different threshold values. Soil and water emissions are due to leachate produced in the landfill system. The amount of leachate that is composed of many compounds (Ca^{2+}, K^+, Na^+, NH_4^+, CO_3^{2-}, SO_4^{2-}, Cl^-), heavy metals and organic contaminants (chlorinated organic compounds, phenol, benzene, pesticides) depends on weather conditions and landfill cover. If the leachate is not collected and treated properly, it may contaminate the soil, surface waters and groundwaters (European Commission, 2001a).

Dewatering of sludge is generally required to decrease the volume of sludge prior to transportation and to control the leachate production from the landfill. Solid content of sludge is an important parameter affecting the acceptability of sludge in landfills (Tchobanoglous et al., 2003).

Figure 2.2 shows that landfilling is the only sludge disposal method in Malta, Greece and Iceland. 38% of the U.S. sludge is sent to landfills (Fericelli, 2011). In Turkey, landfilling of the sludge to special areas or municipal solids waste disposal sites is the most preferred sludge disposal method (UNHSP, 2008). In Germany, however, sludge disposal to landfills was prohibited in 2005 (PURE, 2012).

In metropolitan cities, landfilling is becoming less attractive due to increasing sludge amounts and limited areas designated landfills in these highly populated residential areas (Wong et al., 2001). In addition, the restrictions on the amount of biodegradable wastes into landfills and dryness criteria limit the sludge disposal to landfills and lead to an increase in the requirement to utilize sludge for beneficial purposes in agriculture, landscaping, etc (PURE, 2012).

2.3.2.3. Land Application of Sludge on Agricultural Lands

U.S. Environmental Protection Agency (U.S. EPA) defines sludge land application as "spreading, spraying, injection, or incorporation of sewage sludge, including a material derived from sewage sludge (e.g., compost and pelletized sewage sludge), onto or below the surface of the land to take advantage of the soil enhancing qualities of the sewage sludge" (U.S. EPA, 1994, p.2). Sludge is applied to soil of agricultural lands to enhance soil structure, and ameliorate the nutrient content of soil for plant cultivation (U.S. EPA, 1994). Agricultural lands include the fields in which nonfood crops and food crops for both human and animal consumption are cultivated (National Research Council, 2002). In other words, agricultural lands are comprised of arable lands, permanent crops and permanent pastures (Environmental Indicators, 2010). This thesis study focuses on the land application of sludge on arable lands that are defined as "the lands under a crop rotation system and usually ploughed or tilled" by Eurostat (n.d.).

Agricultural use of municipal sludge has been practiced in many countries and is specifically common in Cyprus, Spain, Ireland and United Kingdom (Figure 2.2). According to Laturnus et al. (2007), 41% and 36.4% of sludge produced in U.S. and European Union member states, respectively, are used in agricultural activities. In recent years, agricultural use of sludge as a fertilizer or soil conditioner is taking attention in Turkey due to high nutrient contents of sludges and Turkey's poor soil quality (UNHSP, 2008).

Before sludge is applied on the agricultural lands, the agronomic rate which is the rate both supplies the nitrogen requirement of plants to be cultivated and minimizes the possible nitrogen leachate to the lower parts of plant roots must be determined. The amount of available nitrogen or phosphorus that should be supplied to the site depends on the plant species. The farmers meet the nitrogen requirement of their crops with commercial fertilizer. The effect of nitrogen loadings done depending on the agronomic rate with sludge land application on the groundwater is not expected to be different compared to commercial fertilizers (U.S. EPA, 1995).

Sludge includes readily available macronutrients (e.g. N and P) and micronutrients (e.g. B, Cu, Fe, Mn, Mo, Zn). Although the ratio of these constituents may not be equivalent to that of a commercial fertilizer, the sludge land application can be supported with additional fertilizer to meet nutrient requirements of cultivated crops (U.S. EPA, 1995).

There are some methods for sludge land applications. The type of the application site and compatibility of sludge determine the application method. Liquid sewage sludge (3-6% dry matter) can be injected with hoses into the soil or spread onto the soil with vehicles designed for these purposes. Decreasing the volume of sludge before transporting sludge to the application site is cost-effective. The dewatered or composted sludge can have dry matter content up to 30-40%. No specialized vehicle is required for their application into the site. Manure spreaders pulled with tractors can be used for sludge spreading as well (U.S. EPA, 2000). Transportation is the most expensive aspect of land application (U.S. EPA, 1999b).

Although the land application improves the yield of plants and substitutes commercial fertilizers, the nutrients, heavy metals, organic contaminants and pathogens in sludge may be transferred into the air and water, and introduced into the food chain through leaching, runoff, volatilization of these constituents. Moreover, exhaust gases of the vehicles used in transportation and application are emitted to air (U.S. EPA, 1999b).

In U.S., the application rate to agricultural lands differs between 0.2-7 t/da per year according to plant species, sludge characteristics, etc. Typical application rate is 1.0 t/da per year. Furthermore, the application is carried out each year between harvesting and planting of the crops (U.S. EPA, 1995).

2.4. Nutrient Value of Sludge

Sludge is a beneficial source of nutrients although it typically includes lower N (3.2%), P (2.3%), and K (0.3%) than those of typical commercial fertilizers that might contain 5% N, 10% P and 5-10% K. (Tchobanoglous et al., 2003). However, as the sludge utilization in agricultural lands conditions the soil and decreases the need for commercial fertilizers, the adverse affects of excessive nutrient entrance into the environment are reduced. Although sludge contains heavy metals, so do fertilizers, comprehensive data is not available on the heavy metal concentrations of fertilizers.

A study of nutrient levels analyzed during a year in 6 wastewater treatment plants in Turkey conducted by Terzi (2007). This study showed average total N, P and K contents of 3.7%, 0.6% and 0.3%, respectively. All the sludge samples analyzed in the study were aerobically or anaerobically stabilized.

50-90% of total N in sludge is in the form of organic compounds depending on the solids content of sludge (Sommers, 1977). Stabilization processes applied to the sludge decrease the organic portion of N due to the mineralization of the easily degradable organic matters during stabilization. For example, Tubail et al. (2008) detected a loss of N by 15.6% due to ammonia volatilization during composting of sludge.

Phosphorus mainly exists as inorganic phosphates of Fe, Al and Ca. Since the main portion of K is partitioned into the wastewater effluents at the end of treatment processes, sludge includes small amount of K. Sludge also contains many essential micronutrients for plants such as B, Cl, Cu, Fe, Mn, Mo, and Zn that are not included in most of the commercial fertilizers (Lu et al., 2012).

Nutrient contents of sludge may change depending on the sources of wastewater and wastewater treatment processes. Stabilization processes bring about the loss of organic matter due to degradation, increase P and metal concentrations, decrease ammonia nitrogen due to volatilization, and decrease K due to leaching. Alkaline-stabilized sludge includes lower N, P and metal concentrations, but high Ca concentrations due to the addition of lime during stabilization period (Lu et al., 2012). Nutrient contents of sludge and the rate of nutrient release (mineralization) depend on the stabilization processes. Mineralization of nitrogen from aerobically stabilized sludge (32.1%) was measured greater than that of anaerobically stabilized sludge (15.2%) (Garau et al., 1986; Wang et al., 2003). Furthermore, organic matter mineralization is also affected by soil type, temperature, soil humidity, aeration, species and amount of soil microorganisms (Garau et al., 1986; Zibilske, 1997; Lu et al., 2012).

The primary nutrients in sludge are in organic forms and less soluble than those in commercial fertilizers. In addition, since sludge nutrients are released to soil more slowly when compared to commercial fertilizers, sludge application can nourish the crops with slow rates and high utilization efficiency for a long time period (Lu et al., 2012).

2.5. Concerns Related to the Land Application of the Sludge

2.5.1. Heavy Metals

Heavy metals are the metals whose specific gravities are greater than five. They have various physical and chemical characteristics and have distinct effects within living organisms. Fundamental trace elements needed by the organisms such as plants and animals are only a small proportion of heavy metals. If their concentrations go beyond a certain level, they generate toxic impacts on the organisms. Due to their solubility, heavy metals are mostly unstable, hard to remove, thus resulting in a potential toxicity due to the easiness of accumulation in plant and animal tissues. Sludge can be a source of heavy metals depending on the wastewater characteristics. Heavy metal content of wastewater and hence the sludge changes depending on the wastewater sources, treatment processes and seasons. 70-90% of heavy metals precipitates or is absorbed to the sludge particles during wastewater treatment processes. Table 2.2 summarizes some heavy metal levels observed in 7 wastewater treatment plants during one-year period in Turkey. Application of sludge to the arable lands as fertilizer may cause heavy metal accumulation on the top layer of the soil. Although heavy metals cannot be degraded by microorganisms, they can be converted into more toxic constituents. Moreover, when heavy metals reach to the water bodies and soil with precipitation, they can bring about secondary contamination and serious pollution of resources (Xiao-Ying et al., 2012).

Table 2.2: Mean heavy metal concentrations in sludge samples collected from 7 wastewater treatment plants in Turkey

Heavy Metal	Mean Concentration (ppm dry weight)
Cu	119 - 1345
Zn	510 - 7451
Cd	0.53 - 4.43
Cr	19.7 - 4114
Ni	35.2 - 448
Pb	26.1 - 301

Total heavy metal concentrations do not mean much since each metal has different behavior in terms of bonding or bioavailability. To understand the level of their solubility and mobility in the environment, and their bioavailability, different physical and chemical forms of heavy metals can be examined. Sequential chemical extraction methods are used to determine the movement capability of heavy metals in sludge with respect to the degree of heavy metal release and potential adverse impacts on soil and plants. These procedures help to distinguish the proportion of water-soluble, exchangeable and easily soluble forms in the total metal concentrations in sludge. This data allows researchers to understand whether the concentration of that heavy metal is a possible source of the nutrient for plants, or a threat both for plants and the entire environment (Jakubus and Czekała, 2001). Heavy metal contents of unpolluted soils and agricultural plants can be seen in Table 2.3.

Table 2.3: Heavy metal contents of unpolluted soils and agricultural plants (Nagajyoti et al., 2010)

Heavy metals	Range in soil (ppm dry weight)	Range in agricultural plants (ppm dry weight)
Cd	0.01-0.7	0.2-0.8
Co	1-40	0.05-0.5
Cr	5-3,000	0.2-1.0
Cu	2-100	4-15
Fe	7,000-55,000	-
Mn	100-4,000	15-100
Mo	0.2-5	1-100
Ni	10-100	1.0
Pb	2-200	0.1-10
Zn	10-300	15-200

According to U.S. EPA (1976), heavy metals can be grouped into two categories based on whether they pose a hazard risk to plants, animals, or humans or not. Manganese (Mn), iron (Fe), aluminum (Al), chromium (Cr), arsenic (Ar), selenium (Se), antimony (Sb), lead (Pb) and mercury (Hg) are relatively less hazardous for plant production and plant accumulation with the land application of sludge. The reason is that these metals either have low solubility in slightly acidic/neutral, well-aerated soils or exist in soil with low concentrations. Therefore, plants' accessibility to these metals is quite low and plant accumulation is also low. High amounts of Fe and/or Al are present in the sludges of many treatment plants specifically those conducting tertiary treatment. If the site is managed properly, these metals will not incur a risk. Plants cannot use up Cr and Pb readily. That prevents food chain from the accumulation of these metals. Cr concentration in plant tissues was rarely increased with the utilization of sludge on arable lands; however, such low increase in Cr content should not be regarded as a warning since this might be an indication of a Cr deficiency in the diets of animals and humans. Hg concentrations are also low in most sludges, and low uptake of Hg by plants was observed due to sludge land application. Although high amounts of As are entered to the soils with sludge additions, many of the crops incline to refuse entrance of As to their aerial tissues (U.S. EPA, 1976).

Heavy metals which accumulate in plant tissues and pose a potential hazard to plants, animals and humans under many conditions are cadmium (Cd), copper (Cu), molybdenum (Mo), nickel (Ni) and zinc (Zn) (U.S. EPA, 1976).

Cadmium is not an essential metal for animals and humans, and high consumption of this metal can result in serious diseases. Therefore, Cd is the most important heavy metal to be considered in sludge land applications. The instability of Cd in soil is decreased by organic matter, clay, hydrous iron oxides, high pH, and reducing conditions. Cd content of a plant may vary depending on the sludge application rate, soil pH and the plant species. Soil temperature, nitrogen and phosphorus fertilization, addition of other heavy metals such as Zn and Cu also affect the tissue Cd concentration of the crops. Some plants may tend to accumulate Cd in high concentrations without being toxicated by Cd. According to the literature studies, Cd contents detected in corn grains were 3-15% of those measured in corn leaves. On the other hand, Cd concentrations in the grains of soybeans, wheats, oats and sorghum were 30-100% of those measured in their leaves (U.S. EPA, 1976).

Cu, Mo and Zn are essential metals which are responsible for some biochemical and physiological processes in plants and animals. Their two significant functions are involvement in redox reactions and direct involvement for many enzymes (Nagajyoti et al., 2010).

Unlike other heavy metals, *copper* is not readily bioaccumulated, and toxic effects of Cu is low for humans and animals (Fernandes and Henriques, 1991). Cu is a fundamental micronutrient for plant growth; however, it can be harmful for plants at high quantities (Mahmood and Islam, 2005; U.S. EPA, 1976). Excessive Cu uptake prevents the functions of enzymes and disrupts plant biochemistry (photosynthesis, pigment synthesis and membrane integrity) (Fernandes and Henriques, 1991). Cu concentrations in plant tissue normally vary between 5-20 ppm (U.S. EPA, 1976). In a study conducted by Walsh et al. (1972) indicated that Cu content in snap bean leaves and pods were measured in the range of 20-50 ppm under intense Cu toxicity conditions. In addition, most of Cu content was accumulated in the roots, and only a small portion of Cu was detected in the aerial parts of the snap beans. Cunningham et al. (1975) examined the phytotoxicity and metal uptake by land application of sludges having different metal contents. Cu was determined about twice as toxic as Zn.

Molybdenum is required by plants in small quantities. Although it exists as a few hundred ppm in plant tissues, this metal is not very toxic to crops. Acidic soils adsorb Mo depending on the level of iron oxide and phosphorus. If high amounts of phosphorus exist in soil, then some portion of Mo bonded to iron oxide will be replaced. Maximum Mo adsorption to soil occurs at pH value near 4.2. As the pH increases in the soil, Mo becomes more available. This attitude can be observed reversely for metals such as Cu, Ni and Zn (U.S. EPA, 1976).

Nickel is not an essential metal for crop production. Sludges include Ni in more readily available forms when compared to inorganic Ni sources. Ni can pose a risk of phytotoxicity only on acidic soils. As long as soil pH is greater than 6.5, toxicity and accumulation risk for food chain can be eliminated. The extractable Ni concentration is highly controlled by the surfaces of iron and manganese oxides, which behave as a “sink” for Ni, and by organic complexes. Phytotoxicity of plants with Ni depends on soil composition, quantity of Ni applied to the land, other metal concentration present in sludge (U.S. EPA, 1976).

Zinc is an essential metal for plants and animals since it involves in many enzyme systems. In acidic soils, Zn is found as Zn^{2+} in solution. In soil, Zn is either adsorbed by clay and hydrous iron oxide surfaces or chelated by organic matter. Plants use up Zn in Zn^{2+} form, high quantities of which is toxic for plants (U.S. EPA, 1976). Phytotoxicity of Zn is shown by a reduction in growth, development and metabolism of plants (Nagajyoti et al., 2010).

2.5.2. Pathogens

Utilization of sludge in agricultural land may cause pollution of plants’ leaf surfaces with sludge borne pathogens (Pahren et al., 1979). There are four main types of human pathogens that can survive in sludge: bacteria, enteric viruses, protozoa, and helminths (Lepeuple et al., 2004). Some researchers regard fungi as one of these types of pathogens (Straub et al., 1993; Gattie and Lewis, 2004). Human pathogens can be transmitted via air, soil and water. Moreover, vectors (e.g. flies) can also enable pathogen transmission from sludge (Jenkins et al., 2007).

Bacteria are the most susceptible sludge borne pathogens and are adversely affected from sunlight, drying and soil competition occurred with land spreading. Plants can be polluted with touching physically to soil and rain splashes (Pahren et al., 1979). Bacteria are poor competitors outside the host environment. In general, pathogenic bacteria can live in soil or water from a few days to 5-6 months. In contrast, their survival period may be decreased to 2-3 months depending on the temperature, inoculum degree, scheduling, sludge application rate and soil environment (Elliott and Ellis, 1977). If they are placed in cracked or split part of the plants, they can survive for a long time due to their protection from direct sunlight and desiccation (Pahren et al., 1979; Kowal, 1985). Treatment type, humidity, sunlight, pH, temperature, antibiotics, toxic substances, competitive microorganisms, nutrients, and organic matter are the important elements influencing the pathogenic bacteria survival in soil and sludge. Moreover, higher pH and low temperature environments are more hospitable for pathogenic bacteria (Elliott and Ellis, 1977). *Salmonella* spp., *Listeria* spp., *Escherichia coli* (enterotoxigenic and enteropathogenic variants), *Campylobacter* spp., *Clostridium* spp., and *Yersinia* spp. are some members of the enteric pathogenic bacteria (Table 2.4). Many of these bacteria can both infect humans and animals (Arthurson, 2008).

Table 2.4: Principal human pathogenic bacteria in municipal wastewater and sewage sludge (Arthurson, 2008)

Pathogen	**Disease(s) and/or symptoms**
Salmonella spp.	Salmonellosis, typhoid
Shigella spp.	Bacillary dysentery
Escherichia coli (enteropathogenic strains)	Gastroenteritis
Pseudomonas aeruginosa	Otitis externa, skin infections (opportunistic pathogen)
Yersinia enterocolitica	Acute gastroenteritis
Clostridium perfringens	Gastroenteritis (food poisoning)
Clostridium botulinum	Botulism
Bacillus anthracis	Anthrax
Listeria monocytogenes	Listeriosis
Vibrio cholera	Cholera
Mycobacterium spp.	Leprosy, tuberculosis
Leptospira spp.	Leptospirosis
Campylobacter spp.	Gastroenteritis
Staphylococcus	Impetigo, wound infections, food poisoning
Streptococcus	Sore throat, necrotizing fasciitis, scarlet fever

The usability of İZSU İzmir Wastewater Treatment Plant's sludge as organic fertilizer in agricultural plant production was determined by Altınbaş et al. (2004). Sludge application was done in the rate of 3 t/da dry weight to plant winter vegetables (cabbage, cauliflower, broccoli, leek and spinach). According to the microbiological analyses done on the plants, the total coliform counts found on leek, broccoli and cabbage were 240, 23, 75 number/g, respectively. 7 number/g E.Coli was found on leek. 10^5 CFU/g total bacteria were found on spinach.

Viruses continue to exist in soil and on the plants for a few weeks or months. Similar to pathogenic bacteria, they cannot live under direct sunlight and desiccated environments. Those conditions cause virus inactivation. Most enteric virus infections occur mildly in childhood. Hepatitis A is of utmost importance for humans since it is a very serious illness and may result in long term liver damage (Pahren et al., 1979). The human enteric viruses that may exist in wastewater and sewage sludge are listed in Table 2.5. The ranges of enteric viruses (in virus units/gram) were detected in US: 2-215 for untreated sludge, 0.04-17 for anaerobically stabilized sludge and 0-260 for aerobically stabilized sludge (Kowal, 1985). Soil nature, humidity, pH and temperature are the main parameters affecting the survival of the enteric viruses. Burge and Enkiri (1978)'s study indicated that as cation exchange capacity (CEC), specific surface area or organic carbon content increased, the adsorption capability of viruses to the soil particles reduced.

Table 2.5: Principal human enteric viruses in municipal wastewater and sewage sludge (U.S. EPA, 2003a)

Pathogen	Disease(s) and/or symptoms
Hepatitis A virus	Infectious hepatitis
Norwalk and Norwalk-like viruses	Epidemic gastroenteritis with severe diarrhea
Rotaviruses	Acute gastroenteritis with severe diarrhea
Enteroviruses	
Polioviruses	Poliomyelitis
Coxsackieviruses	Meningitis, pneumonia, hepatitis, fever, cold-like symptoms, etc.
Echoviruses	Meningitis, paralysis, encephalitis, fever, cold-like symptoms, diarrhea, etc.
Reovirus	Respiratory infections, gastroenteritis
Astroviruses	Epidemic gastroenteritis
Caliciviruses	Epidemic gastroenteritis

Consistence of Poliovirus 1 in soil and on crops cultivated under natural conditions was discovered by Tierney et al. (1977). First, experimental site was flooded to a depth of 2.54 cm with Poliovirus 1- introduced sewage sludge. Lettuce and radishes were grown as test plants. The virus survived for the most time (96 days) during the winter. However, the survival lasted mostly for 11 days during the summer. No Poliovirus 1 was detected on the mature vegetables 23 days after flooding event.

The protozoa exist as cysts in excreta material. Cysts are generally water borne and are more sensitive to negative environmental impacts such as desiccation, high temperatures than helminth eggs (Pahren et al., 1979). The protozoa that may survive in wastewater and sewage sludge are listed in Table 2.6.

Entamoeba histolytica cysts, a kind of the pathogenic protozoa, cannot live in anaerobic digestion process and at low temperatures. They cannot live on plant surfaces more than 3 days due to the exposure to air. Their survival period is 6-8 days even under optimum temperature and humidity (Pahren et al., 1979).

Table 2.6: Principal protozoa in municipal wastewater and sewage sludge (U.S. EPA, 2003a)

Pathogen	Disease(s) and/or symptoms
Cryptosporidium	Gastroenteritis
Entamoeba histolytica	Acute enteritis
Giardia lamblia	Giardiasis (including diarrhea, abdominal cramps, weight loss)
Balantidium coli	Diarrhea and dysentery
Toxoplasma gondii	Toxoplasmosis

Pathogenic helminths whose eggs are of great significance in municipal sludge and wastewater are given in Table 2.7. According to the taxonomic division, helminths are grouped as nematodes (roundworms) and cestodes (tapeworms). Intestinal nematodes do not need an intermediate host and generate huge amounts of eggs. For instance, a single female Ascaris can generate 200,000 eggs daily. The eggs of *Ascaris* and *Trichuris* are very durable under adverse environmental conditions (Pahren et al., 1979). A study conducted by Fitzgerald and Ashley (1977) showed that Ascaris roundworm eggs could survive during anaerobic stabilization process and convert themselves into embryon. Although the sludge hindered the development of Ascaris eggs, it also saved the eggs from the high temperature (38^{o}C) of anaerobic stabilization process. In other words, the eggs first appeared dead and embryoned, then they were able to infect pigs.

Table 2.7: Principal helminth worms in municipal wastewater and sewage sludge (U.S. EPA, 2003a)

Pathogen	Disease(s) and/or symptoms
Ascaris lumbricoides	Digestive and nutritional disturbances, abdominal pain, vomiting, restlessness
Ascaris suum	May produce symptoms such as coughing, chest pain, and fever
Trichuris trichiura	Abdominal pain, diarrhea, anemia, weight loss
Toxocara canis	Fever, abdominal discomfort, muscle aches, neurological symptoms
Taenia saginafa	Nervousness, insomnia, anorexia, abdominal pain, digestive disturbances
Taenia solium	Nervousness, insomnia, anorexia, abdominal pain, digestive disturbances
Necator americanus	Hookworm disease
Hymenolepis nana	Taeniasis

According to Hays (1977)'s study, primary and secondary treatment, anaerobic stabilization process, disinfection processes such as chlorination and ozonation do not successfully eliminate all pathogens. Since protozoa cysts and helminth eggs are relatively heavy, they exist in sludge. Documented land application-to-human illness transmissions were all related to the utilization of untreated sewage sludge on soil. Land application-to-animal illness transmissions happened due to raw and partially treated sludge. The most commonly documented protozoon is *Entamoeba histolytic;* and helminths are *Ascaris lumbricoides, Trichuris trichiura*, *Hymenolepis* spp, *Taenia saginafa* and *Necator americanus.* Elimination of these pathogens can be achieved with sufficient heating of sludge to more than 60°C for +30 minutes.

2.5.3. Organic Contaminants

Excessive use of household surfactants and their degradation products (linear alkylbenzene sulphonates (LAS), nonylphenols (NP), and nonylphenol ethoxylates (NPE)), plasticizers (phthalate esters, e.g. bis (diethylhexyl) phthalate (DEHP)), combustion by-products (polyaromatic hydrocarbons (PAH), polychlorinated dibenzo-p-dioxins and furans (PCDD/Fs)), substances for pest control (e.g. chlorobenzenes, such as hexachlorobenzene (HCB)), and flame retardants (polybrominated diphenylethers (PBDE)) have been detected in sludge (Laturnus et al., 2007; Aparicio et al., 2009).

The chemical properties of organic contaminants are given in Table 2.8. This table provides information about biodegradation (aerobic and anaerobic) periods in soil and adsorption capacities of the organic pollutants to humus and clay particles. LAS, DEHP and NP are not susceptible to adsorb to humus particles and are more readily decomposed than PAH, PCB or PCDD/F.

Table 2.8: The chemical properties of organic contaminants in soil (European Commission, 2001b)

	Solubility in Water at 20°C [mg/L]	**Vapor Pressure at 20°C [hPa]**	**Henry-Constant [9,8*10^{-4} hPa*m^{3} /mol]**	**Adsorption to Humus**	**Adsorption to Clay**	**Aerobic Degradation[1]**	**Anaerobic Degradation[1]**
LAS	62,5	0,0001	-	3 to 4	1	4	3
DEHP	40	6 x 10^{-4}	1,1 x 10^{-5}	4 to 5	3 to 4	3 to 4	2
NP	3.000	0,1	-	2 to 3	2	4	2 to 3
PAH							
Fluorene	1,8	9,6 x 10^{-4}	0,00021	4 to 5	3	3	1
Pyrene	150	0,8 x 10^{-5}	0,00002	5	3	2	1
Benzo[a]pyrene	0,004	0,7 x 10^{-8}	2,4 x 10^{-6}	5	3	2	1
PCBs							
4 to Chlorobiphenyl	1,65	2,0 x 10^{-2}	-	4 to 5	1 to 2	3	2
2,4,4 Tri-CB	0,085	1,1 x 10^{-3}	2.4 x10^{-2}	5	3	2 to 3	2
2,2,4,4,5,5 to Hexa-CB	0,001	1,1 x 10^{-5}	0.8	5	3 to 4	1	1
PCDD/Fs							
2,3,7,8 TCDD	4,7 x 10^{-5}	6,2 x 10^{-9}	5,4 x 10^{-23}	5	3	1	1
1,2,3,7,8 to PCDF	0,118 x 10^{-3}	5,8 x 10^{-10}		5	3	1	1
OCDD	0,004 x10^{-3}	4,1 x10^{-10}	0.14	5	3	1	1

[1]: time to 90% degradation: **1**: > 3 years, **2**: >1 years, **3**: >18 weeks, **4**: > 6 weeks

Similar to heavy metals, organic contaminants applied on land with sludge applications have risk for uptake by agricultural plants and entrance to the food chain. The physico-chemical characteristics of organic contaminants and the crop species determine the uptake rate of polar and non-polar organic contaminants by intact plants and various artificial environmental systems outside the living organisms (Laturnus et al., 2007).

Adsorbable organic halogen compounds (AOX) are formed with the holding of halogen-containing chemicals and activated carbon together. The formation of AOX can occur with various constituents in sludge and wastewater according to the sources of the samples. For example, in drinking water sanitation process, trihalomethanes (THM) are formed with chlorination and ozonation due to the presence of low concentrations of bromine in water (European Commission, 2001b).

Phthalates are participated into plastics as plasticisers, and commonly used in paints, glues, inks, etc. Although they can be decomposed in both aerobic and anaerobic environments, their factual decomposition rates decrease due to their high adsorption capacity. Di-2-(ethylhexyl)phthalates (DEHPs) are harmful for soil organisms and may have endocrine disrupting properties. Plants can uptake DEHPs (European Commission, 2001b). Due to their lipophilic characteristic, they accumulate in sludge (European Commission, 2001c).

Polynuclear aromatic hydrocarbons (PAH) are formed during incomplete combustion of fossil fuels. They are mostly known as carcinogenic/mutagenic compounds (European Commission, 2001b). PAHs accumulate in sludge because of their low biodegradability (European Commission, 2001c). The plant uptake of PAHs was investigated in a field experiment by Kacalkova and Tlustos (2011). Maize, sunflower, poplar, and willow were cultivated in a polluted land. PAH pollution was measured as 0.138 and 3.42 mg/kg of total PAHs (fluoranthene, benzo-b-fluoranthene, phenanthrene and pyrene). PAH contents in test crops were varied from 0.096 to 1.34 mg/kg. The greatest phenanthrene content was found in above ground biomass of sunflower, and the greatest pyrene content was measured in roots of maize.

Wild et al. (1990) monitored the long term (20 years) accumulation and decomposition of PAHs in sludge applied lands. Land application of sludge was carried out 25 times between the years 1942 and 1961 in an arable land in rural United Kingdom. The PAH content of soil increased during land application but decreased after the termination of the application. In 1984, the short-chain PAHs were detected at a level that had been measured before land application. However, the long-chain PAH concentration did not change after 1960. It was understood that natural characteristics of PAH substances had detrimental impact on the fate in the soil.

Linear alkylbenzene sulphonates (LAS) are commonly used anionic surfactants in cleaners and detergents. Except for some anaerobic environments, they are easily decomposed in aerobic environments. During wastewater treatment processes, LAS is adsorbed onto the sludge (European Commission, 2001b). If aerobic conditions are not provided during sludge storage before land application, LAS accumulation may occur in the soils (De Wolf and Feijtel, 1998).

The occurrence of LAS was discovered in two soils which were amended with sludge for 25 years by Carlsen et al. (2002). The first soil was amended with medium amounts of sludge for 25 years. The second soil was sludge applied with high amounts of sludge (1.75 t/da dry weight per year) for the same time period as the first soil. Very low concentrations of LAS (lower than 1 mg/kg) were detected in the first soil. However, high concentrations of LAS (approx. 20 mg/kg) were measured in the second soil. It exceeded the soil limit value determined by Denmark which was 5 mg/kg.

Nonylphenoles (+ethoxylate) (NPE) are commonly used in the formulations of detergents and pesticides; production of personal care products such as moisturizers, hair dyes, shampoos and deodorants and as wetting agents, emulsifiers, solubilizers and foaming agents. These compounds are discharged into wastewater treatment plants with large concentrations after their domestic and industrial uses (Ying et al., 2002). NPE compounds are biodegraded to lower-chain NPEs (e.g. NP) under aerobic and anaerobic environments and adsorbed to the sludge. Since the biodegradation occurs slowly under anaerobic conditions, their contents rise during anaerobic stabilization processes (European Commission, 2001b).

In their study, Patureau et al. (2007) examined the fate of organic contaminants (LAS, NP/NPE, PAH, DEHP) in a sandy soil after 30-year sludge land application in France. Maize was cultivated in the test field with 10 t/da sludge application each 2 years between the years 1974 and 1992. The experimental site was cultivated with maize without sludge application between the years 1992 and 2004. The field was monitored for 12 years after the termination of application. The organic contaminant concentrations were measured as 2-10 times greater than those of control soil. NP, NPE and LAS decreased less than 30% of the measured concentration during land application period. However, DEHP and PAH were measured in high concentrations. Except for NP, all organic pollutant concentrations increased after 12 years compared to the control plots.

Poly chlorinated biphenyles (PCB) are used as hydraulic oils, flame protection components, carrier components insecticides and in transformers and condensers. Other major sources of PCBs are incomplete combustion processes occurring in incineration facilities and fossil fuel burning. PCB compounds accumulate in sludge (European Commission, 2001c).

Polychlorinated dibenzo-p-dioxins (PCDD) and *polychlorinated dibenzo-furan (PCDF)* compounds are not produced deliberately. They are formed during production of chlorinated substances or combustion of chlorine containing substances (European Commission, 2001b).

Wilson et al. (1997) monitored the effects of PCBs, PCDDs and PCDFs on the arable land with stabilized sludge land application. This application increased the contents of all organic compounds in the experimental site. PCB concentration decreased to the value in the control soil in 128 days after sludge land application because of volatilization and biodegradation of PCB compounds. Since the sludge had not been applied directly onto the land, PCDD and PCDF concentrations did not change during the monitoring period (260 days) due to the sludge sticking onto the plants cultivated in the experimental field. No leachate containing PCDD/Fs occurred in the soil up to the depth 20 cm during monitoring period.

Eljarrat et al. (1997) studied the fate of PCDD, PCDF and PCB compounds in sludge after sludge application on arable lands. The organic contaminant concentrations were detected 1.2-11.6 times greater than those were measured in control plots. In the soils with low initial contamination, organic contaminant contents in final soil were below German regulatory limits. However, in the soils with high contamination, organic contaminant contents in final soil were detected beyond limits and restrained the plant production.

2.6. Application of Sludge on Arable Lands

2.6.1. The effects of Sludge Land Application on Soil Properties

2.6.1.1. Physico-chemical properties

Sludge applications on arable lands recycle the nutrients back to the soil and reduce the use of commercial fertilizers on these lands. The knowledge of chemical compositions (fertilizer value (N, P and K) and trace metal concentrations) of sludges to be applied onto the soil is of utmost importance prior to land application (Sommers, 1977). Sludge land applications may have negative impacts on the soil properties if the sludge includes high heavy metal contents and toxic substances (Singh and Agrawal, 2008).

The physical, chemical and biological features of soil can be improved by sludge land application. These changes differ depending on the soil and sludge characteristics (Epstein, 1975; Mitchell et al., 1978; Gupta et al., 1977; Angın and Yağanoğlu, 2009).

pH of the soil can also be altered with the land application of sludge (Silviera and Sommers, 1977). In some studies, it is reported that the addition of sludge to soil raised the soil pH (Tsadilas et al., 1995; Silviera and Sommers, 1977). Decrease in soil pH was also detected by some researchers (Silviera and Sommers, 1977; Ongun et al., 2010). The variability in soil pH may have been related to calcium carbonate concentration in the soil and the amount of acid produced during sludge decomposition (Silviera and Sommers, 1977). Soil pH is important considering heavy metal concentrations within sludge (Singh and Agrawal, 2008).

The influence of sludge application on soil physical properties mainly is dependent on the rate of sludge decomposition and its contribution to soil organic carbon content. Chemical characteristics of the sludge (carbon content, C/N ratio, etc.), temperature, soil humidity, waste application method (surface application, soil incorporation, etc.), land application rate are the main factors influencing the rate of sludge decomposition. Organic matter addition

increases aggregation capacity, hydraulic conductivity, water holding capacity and reduces bulk density. Bulk density of the soil decreases because of a dilution effect occurred due to the blending of the sludge organic matter with denser soil mineral portion. After the bulk density decreases, change in pore-size distribution and an increase in the number of small pores occur. The number of pores, pore-size distribution of soils and specific surface area restrain the water retention capacity of soils. Total pore sizes are enlarged with the increased aggregation capacity. As a result of sludge organic material addition into the soil, porosity enhances and the saturated hydraulic conductivity increases (Khaleel et al., 1981). Epstein (1975) set up a soil-sludge mixture incubation experiment in order to investigate the effects of raw and digested sludge addition into soil on water retention, hydraulic conductivity, and aggregate stability. Water holding capacity was improved with the application of raw and digested sludge. After day-27 of incubation, an important rise was observed in hydraulic conductivity. Then, it returned to its original soil value after 50 to 80 days of incubation. Aggregation stability percentage increased with the sludge addition. According to the analyses done after day-175, average stable aggregate percentage was 28-35% for the sludge added soils while the control sludge's aggregate percentage was 17%.
Heavy metals that seem especially concerning due to their accumulation in soils, uptake by plant tissues and groundwater contamination risk include Cd, Cr, Cu, Hg, Ni, Pb, and Zn (Dowdy and Volk, 1983). According to Chaney (1994), highly acidic soils enhance plant uptake of Zn, Cd, Ni, Mn, Co, and increase phytotoxicity possibility from Cu, Zn, and Ni. In addition, basic soils with high pH increased uptake of Mo and Se while Pb and Cr entering into the soil with sludge land application are not adsorbed to any reasonable extent at any pH. Hernandez et al. (1991) monitored the effects of sludge land application on calcareous soil whose organic content was low. Total N and extractable N and P concentrations rose. However, extractable K content did not change. Land application increased the concentrations of Cu, Zn and Pb while it decreased the Fe concentration. In addition, the extractabilities of Fe, Cu, Mn, Zn and Pb increased with respect to control soil.

Amendment of soils with high sludge application rates resulted in an increase in cation exchange capacity (CEC) of soils (Epstein et al., 1976; Lunt, 1959; Kladivko and Nelson, 1979; Antolin et al., 2005). The increased CEC in sludge applied soils is crucial since supplemental cation binding sites enable many essential nutrients existing in sludge (NH_4^+, Ca^{2+}, Mg^{2+}, K^+) to be kept in plant rooting zone rather than leaching with percolation water. Furthermore, the cation exchange sites (sludge organic functional groups) may help the complexation processes of heavy metal cations present in sludge. When they have complex structures, then they are not subject to leaching in soil and are considered to be largely unavailable to plants (Kladivko and Nelson, 1979).

Many short and long term field studies were conducted in Turkey and some other countries and revealed the effects of the use of sludge on arable lands and their potential effects on physico-chemical properties of soil, and nutrient content and heavy metal accumulation in soils. Table 2.9 presents a summary of these field studies. According to Table 2.9, different sludge application doses were applied to agricultural soils (i.e. 0.5-12 t/da dry weight). Organic matter content of soils increased with sludge application and mainly depended on the application doses. pH, mass and grain densities generally decreased. Salt content, cation exchange capacity (CEC), field capacity, aggregation capacity, porosity and permeability increased as the sludge application rates increased. Moreover, total and available heavy metal concentrations mostly increased depending on the increments in sludge land application rates and generally detected below regulatory limit values.

Table 2.9: Effects of sludge land application on physico-chemical properties of soils, and nutrient contents and heavy metal accumulations in soil

Soil / Plant	**Sludge Application Rate (t/da)**	**Effect on physico-chemical properties of soils**	**Effect on nutrient contents and heavy metal accumulation in soils**	**Reference**
Silty loam soil / winter wheat (*Triticum aestivum* L.), sugar beet (*Beta vulgaris* L.), and maize (*Zea mays* L.)	- 1.75 and 1.5 t/da dry weight for 7 years (1988-1994) - 0.5 and 1 t/da dry weight (every year after 1994)	- Increase in organic matter with increasing sludge dose - Decrease in alkalinity - Increase in soil fertility - Increase in electrical conductivity (EC)	- Increase in total N and available P with increasing sludge dose - Increase in total Zn and Cu concentrations in surface layer of the soil	Mantovi et al. (2005)
Alluvial soil / Wheat, potato and bean	0, 3 and 6 t/da dry weight for 1 year	- Decrease in soil pH in the application year - Increase in pH after the second year of the application - Increase in organic matter and salt content in the application year - Decrease in salt content after the second year of the application	- Increase in Cu, Zn, Mn, Fe, Ni, Cd and Pb concentrations with increasing application dose - Increase in P and K concentrations in the application year	Işık et al. (2005)
Meadow brown soil / Grass (*Zoysia japonica* and *Poa annua*)	0, 1.5, 3, 6, 12 and 15 t/da dry weight for 1 year	- Increase in organic matter content	- Significant increase in Cd concentration - Increase in Pb, Cu and Zn concentrations - Slight increase in N and P contents	Wang et al. (2008)
Calcerous soil / Tomato	0, 3 and 6 t/da dry weight	- Increase in EC and cation exchange capacity (CEC) - Decrease in pH		Perez-Espinoza et al. (2000)
Sandy loam soil	0 and 8 t/da dry weight for 1 year	- Increase in organic matter content	- Slight increase in exchangeable portions of Cd, Cu, Pb, Zn, Ni and Cr concentrations	Illera et al. (2000)
Saline-sodic soil / Barley (Tokak 157/37 type)	0, 4, 8 and 12 t/da dry weight for 1 year	- Increase in lime and organic matter contents, field capacity and aggregation capacity, and permeability with increasing application dose - Decrease in pH, EC, porosity, mass and grain density with increasing application dose	- Increase in Fe, Mn, Zn and Cu concentrations more than needed by plants	Angın and Yağanoğlu (2009)

Table 2.9: Effects of sludge land application on physico-chemical properties of soils, and nutrient contents and heavy metal accumulations in soil (Continued)

Soil / Plant	**Sludge Application Rate (t/da)**	**Effect on physico-chemical properties of soils**	**Effect on nutrient contents and heavy metal accumulation in soils**	**Reference**
Clay soil / wheat, white head cabbage, tomato	0, 1, 2, 3, 4 and 5 ton/da dry weight for 2 years	- Decrease in soil pH - Increase EC and organic matter with increasing sludge dose	- Increase in total N and available P concentrations and extractable Fe, Cu and Zn concentrations with increasing sludge dose	Özyazıcı et al. (2012), Özyazıcı and Özyazıcı (2012)
Typic Xerofluvent soil / Peanut (*Arachis hypogaea*), mixture of green barley (*Hordeum vulgare*) and common vetch (*Vicia Sativa L.*)	0, 0.6 , 1.3 and 1.9 t/da dry weight for 1 year	- Increase in total salt, organic matter content, total porosity, micro and macro porosity, field capacity, wilting point, available water content, structure stability index and aggregation percentage with increasing sludge dose -Decrease in particle and dry bulk density	- Increase in total N, Cu, Pb and Ni, and available P, K, Ca, Fe, Cu, Zn, Mn concentrations with increasing sludge dose - Decrease in available nutrient concentrations in the last sampling periods (in third year)	Delibacak et al. (2009a), Delibacak et al. (2009b)
Sandy loam soil / Smooth bromegrass (*Bromus inermis* Leyss)	0, 0.7, 1.4 and 2.1 t/da dry weight for 1 year		- Increase in Fe, Mn, Zn, Cu, Pb, Cr concentrations available to plants in the surface layer of the soil (0 – 20 cm depth)	Keskin et al. (2010)
Sandy loam soil / Sweet corn (Merit F1 type)	0, 1.2 , 2.5 and 3.7 t/da dry weight for 1 year	- Slight decrease in pH - Increase in organic matter content with increasing sludge dose -Decrease in pH at highest application dose	- No important change in Ni, Pb, Cd, Co and Cr concentrations	Ongun et al. (2010)
Alluvial soil / Sugar beet, wheat and corn	0, 1, 2, 3, 4 and 5 t/da dry weight for 1 year		- Increase in Cu, Zn, Ni, Cd, Cr, Pb concentrations with increasing sludge dose	Yalçın et al. (2011)
Calcicol clay-loamy soil / Vineyard site - perennial grape (*Vitis vinifera* cv.)	0, 0.7 , 2.0 , 5.9 t/da dry weight for 1 year	- Increase in organic matter content	- Increase in N in surface soil (for two years) - No change in total and available Cu, Zn, Ni and Pb concentrations	Korboulewsky et al. (2002)
Wheat (Cumhuriyet 75 type) and cotton (Nazilli 84 type)	1, 2, 3, 4 and 5 ton/da dry weight for 1 year	- Increase in pH, EC, organic matter content and CEC with increasing sludge dose	- Increase in total N, Fe, Cu, Zn, Mn, Pb and available P, K, Fe, Cu, Mn and Zn concentrations with increasing sludge dose	Göçmez (2006)

2.6.1.2. Leaching of nutrients and heavy metals

Application of sludge in the rates beyond plant requirements and the absorptive capacity of soil can bring about groundwater and surface water pollution (Warman and Termeer (2005). There are several studies conducted about the release of macro and micro nutrients, and heavy metals from sludge after the land application.

Ashworth and Alloway (2004) conducted a sandy soil column leaching study in which they determined the mobility and co-mobility extent of Cu, Ni, Zn and dissolved organic matter (DOM) resulted from anaerobically digested sludge land application (5 t/da dry matter). Slight retardation of DOM in soil column was observed due to the time period required for DOM in dry sludge to become dissolved. Since Ni migrated as organic complexes, it also leached easily from sludge. Both DOM and Ni had relatively high degrees of solubility from sludge. However, Cu leached with significant retardation. The mobility of inorganic forms of Ni and Cu was less than the mobility of them with the addition of sludge. DOM released from sludge favored the mobilization of heavy metals sorbed on soil or sludge. The existence of DOM did not prevent Zn from being completely adsorbed by the soil column.

Vu Tran (2008) reported the nutrient movement from sludge land applications in her Ph.D thesis. Lime-stabilized, aerobically stabilized and anaerobically stabilized sludge were applied to the experimental site with sandy loam soil in the rates of twenty times (20x), ten times (10x), five times (5x), and one time (1x) the anticipated nitrogen based agronomic rate. Nitrogen, phosphorus, heavy metals that were limited in the regulations, pH and electrical conductivity measurements were done from soil depths up to 1.5 m for 2 years after land application. NH_4-N at the surface layer (0.2 m) was mainly lost through ammonia volatilization and nitrification. The main proportion of total P and plant available P accumulation were detected in the surface soil layer (0.2 m). P leaching to groundwater was low. Aerobically stabilized sludge was decided to be the best sludge for the land application use since it reduced the risk of possible environmental pollution due to P leaching. As, Cd, Cu, Pb, Mo, Ni, Se, and Zn contents were detected below the regulatory limit values. It was concluded that nutrients and heavy metals did not pose any important risk for the environment when they were applied with sludge.

Ippolito and Barbarick (2008) investigated the fate of trace element released from long term sludge land application. Sludge was applied to the experimental site every 2 year between the years 1982 and 2002 (except 1998) in the rates of 0 (Control), 0.7, 1.3, 2.7 and 4 t/da. Cd, Cr, Cu, Mo, Ni, Pb, and Zn accumulated in the surface soil layer (0-20 cm). No important leaching to the bottom layer of soil was detected. It was understood that all detectable Cd was in relatively mobile forms while Cr, Cu, Mo, Ni, Pb, and Zn were in more resistant phases. Cd and Cr phases did not change with sludge land application. However, relatively immobile Cu, Mo, and Zn fractions, and relatively mobile Cu, Ni, and Pb fractions increased. The mobile fractions of the metals did not moved significantly through the bottom layers of the soil. Although the sludge was applied for a long time period in the rates several times greater than agronomic requirements, no groundwater pollution and/or metal leaching through soil layers were expected by the researchers under the same climatic conditions and agronomic applications.

2.6.2. The effects of Sludge Land Application on Plant Properties

According to Clapp et al. (1994)'s long term study (20 years) of sludge land application, using sludge as a nutrient source is beneficial for the plants. Previous studies showed that crop yields obtained with sludge land application were greater than those obtained in fertilized fields in the same watershed.

Antolin et al. (2005) studied the effects of sludge land application on growth, yield and solute content of barley for 3 years (1998-2001) with a field study under semiarid Mediterranean conditions of Spain. The treatments were conventional inorganic fertilizer, 1.5 t/da (dry weight) repeated application every year and control soil which did not receive any sludge. Sludge application enhanced barley grain yield importantly. Leaf protein contents and dry matter yields were increased from the beginning of development to ear emergence.

The influences of sludge on the phenology and growth of cotton plants were studied by Tsakou et al. (2001). According to phenological analyses, flowering and fruition began 2-3 weeks earlier than those plants received fertilizer. Sludge utilization resulted in high root biomass production and stronger plants that grew fast.

Dowdy et al. (1978) conducted a 4-year study to understand the effects of sludge land applications on the growth of snap beans. In the first part of the study, anaerobically stabilized sludge was applied in the total rates of 0 (Control), 35, 70 and 140 t/da in three equal applications. In the second part of the study, sludge was applied only once in the rates of 0 (Control), 11.2, 22.5 and 45 t/da. Crop production enhanced in both application systems as the application rates increased. The yields were often higher than those obtained with fertilizer control. Early growth stunting was inversely proportional to the sludge application rate. Crops growths and maturation periods were normal.

The increase of metal concentrations in plant tissues is an essential worry about the use of sludge on land applications and agricultural crop productions. Sludge may include higher trace element contents than are usually found naturally in arable lands. For this reason, sludge addition to soil may enhance the level of these heavy metal concentrations in both plant tissues and soil (Ham and Dowdy, 1978). The uptake pattern differs depending on the soil type, plant species, phenology, and complexation patterns of the metals (Mahler et al., 1980; Hernandez et al., 1991; Kidd et al., 2007).

The recycling of valuable constituents such as organic matter, N, P, K, and other plant macro and micro nutrients is possible with agricultural utilization of sludge (Warman and Termeer, 2005).

In a field experiment conducted by Mantovi et al. (2005), the effects of long term repeated sludge land application over 12 years on wheat + maize + sugar beet crop rotation in Italy. The experimental site received sludge every year in the fall in the rates of 1.75 and 1.5 t/da dry weight between 1988 and 1994. Then, these rates were changed to the rates of 0.5 and 1 t/da dry weight. As the sludge application rate increased, N, P, Zn and Cu concentrations in wheat grains, N and Cu concentrations in sugar beet roots and Cu concentration in maize grain also increased. Pb contents in wheat grain and sugar beet root, and Cu content in maize grain were lower than the detection limits. No obvious phytotoxicity effect was observed in the 12 years period.

The heavy metal uptake of seven vegetable crops was examined in a field study by Dowdy and Larson (1975). The seven vegetable crops grown were carrots, lettuce, peas, potatoes, radishes, sweet corn, and tomatoes. The sludge was applied to the experimental site's coarse and sandy soil with the rates of 0 (Control), 11.2, 22.5, 45 t/da. No undesirable influences on plant growth and no physiological instabilities were observed with sludge land application. In general, heavy metal contents of the vegetative tissue were greater than those of the fruit, root, and tuber tissue. Fe and Mn concentrations of edible root and tuber tissues did not change. Only Mn concentration in carrot tissue decreased. Zn concentration increased from 23 to 103 ppm, 37 to 98 ppm, and 24 to 53 ppm in carrot, radish, and potato tissue, respectively, with the addition of 45 t/da sludge. Carrots and radishes eliminated Cu from their edible tissues. Cd concentrations in the edible root and tuber tissues doubled with 45 t/da sludge application. In contrast, carrots gathered over 4 times more Cd (1.15 ppm) on the 45 t/da application when compared to radishes or potatoes. Despite adding 23 kg Pb/da, lead accumulation was not important in the root and tuber tissues. Similarly, B concentrations of the root and tuber tissues did not affected from sludge applications. No important increase was detected in the Fe, Mn, Cu, Pb, and B concentrations of the edible parts of the fruits. Nearly three-fold as much Zn was detected in pea vine tissue as in the edible fruit. According to the analyses done, it is understood that the accumulation rate have linear correlation with the sludge application rates.

Bilgin et al. (2003) investigated the influences of sludge land application on plant yield and quality in Ankara between the years 1997 and 2002. Düzce Wastewater Treatment Plant's sludge with 70% solid content (first trial), Turkey Electricity Institution (TEK) Wastewater Treatment Plant's sludge with 79% solid content (second trial), Ankara Central Wastewater Treatment Plant's sludge with 69% solid content (third trial) were used during the study in the rates of 1, 2, 3 and 4 t/da. All three sludges had different characteristics such s nitrogen, organic matter and heavy metal contents. Crop rotation was wheat + sugar beet + bean. The sludge only applied before wheat sowing. No sludge was applied before the cultivation of sugar beet and bean. Although different sludges were used in the second and third trials, except for Cu and Zn, no difference was detected in heavy metal contents of wheat grains. Germination and growth of the plants did not affect from sludge applications. However, wheat bending was observed after grain filling period only with 4 t/da application. Wheat stem yields and grain weights were influenced positively depending on the rate of sludge application. All sludges increased the protein proportion of the grains and grain qualities when they were applied in the rates of 2, 3 and 4 t/da.

Many researchers conducted short and long term experiments showing the effects of sludge land applications on growth, dry matter accumulation, nutrient content and heavy metal accumulations in plants. A number field experiments are summarized in Table 2.10. According to this table, application rates between 0.6-12 t/da were applied to cultivate a variety of crops in the given studies. Generally, yield, dry and organic matter content of crops increased as the sludge application dose increased. Similarly, heavy metal accumulation increased depending on the application rates. Some of these studies showed that the accumulation was higher in foliar parts of the plants than those detected in grains.

Table 2.10: Effects of sludge land application on growth, dry matter accumulation, yield, nutrient content and heavy metal accumulations in plants

Plants	**Sludge Application Rate (t/da)**	**Effect on growth, dry matter accumulation and yield**	**Effect on nutrient content and heavy metal accumulation in plants**	**Reference**
Peanut (*Arachis hypogaea* L.)	0, 0.6, 1.2 and 1.8 t/da dry weight for 1 year	- Increase in yield	- Increase in Fe, Cu and Ni concentrations of edible peanut parts	Delibacak et al. (2008)
Grass (*Zoysia japonica* and *Poa annua*)	0, 1.5, 3, 6, 12 and 15 t/da dry weight for 1 year	- Increase in dry matter - Increase in organic matter content	- Significant increase in Cd and Zn contents of *Z. japonica* only in 1.5 and 3 t/da applications - Increase in Pb and Cu contents of *P. annua* with increase in sludge dose	Wang et al. (2008)
Winter vegetables (cabbage, cauliflower, broccoli, leek and spinach)	3 t/da dry weight for 1 year	- Increase in yield of all the plants - Improvement in vegetative growth processes	- Fe, Mn, Cu, Zn, B, As, Cd, Cr, Hg, Co, Ni, Se, Mo and Pb concentrations of the plants considerably lower than the limit values	Altınbaş et al. (2004)
Smooth bromegrass (*Bromus inermis* Leyss)	0, 0.7, 1.4 and 2.1 t/da dry weight for 1 year	- Increase in dry matter yield (highest yield at 2.1 t/da application)	- Increase in N, K, Cu, Zn, Pb, Cr, Cd conc. of the plants - Increase in P and Mg in the second year of the study	Keskin et al. (2010)
Apple tree	0, 10, 20, 40 and 60 kg/tree (respectively 0, 1.3 , 2.5, 5.0, 7.5 ton/da) for 2 years	- Increase in fruit yield, shoot length, girth and cumulative yield efficiency	- Increase in foliar Mn and Zn concentrations (first year), and Fe, Mn and Zn (second year) - Increase in foliar N and Mg concentrations	Bozkurt and Yarılgaç (2003)
Sweet corn (Merit F1 type)	0, 1.2 , 2.5 and 3.7 ton/da dry weight for 1 year	- Increase in yield	- Increase in Ni, Pb, Cd, Co and Cr concentrations with increase in sludge dose - The least accumulation of heavy metals in corn grains - The highest accumulation in leaves	Ongun et al. (2010)

Table 2.10: Effects of sludge land application on growth, dry matter accumulation, yield, nutrient content and heavy metal accumulations in plants (Continued)

Plants	**Sludge Application Rate (t/da)**	**Effect on growth, dry matter accumulation and yield**	**Effect on nutrient content and heavy metal accumulation in plants**	**Reference**
Wheat, potato and bean	0, 3 and 6 t/da dry weight for 1 year	- Decrease in yield in the application year - Increase in yields of wheat and potato in second, third and forth years of the study - No increase in yield in fifth year	- Slight increase in Cu, Zn, Mn, Fe, Ni, Cd and Pb concentrations of leaves, grains and tubers	Işık et al. (2005)
Field corn	Application of liquid stabilized sludge (6% solids) in the rates of 0, 0.75 , 1.5 , 3 t/da in the first year and 0, 0.75 , 1.5 , 3, 6 t/da in second, third and forth years		- Slight increase in Total Cd, Cu, Ni and Zn concentrations - No metal concentration change in corn grains	Hyde and Page (1979)
Maize (*Zea mays* L.)	0, 6, 12 and 18 t/da for 3 years. Then, the application terminated for 6 years.		- Increase in Cd and Zn concentrations of stover with increasing application dose - Increase in Cr, Cu, Ni and Pb concentrations of stover and grain	Bidwell and Dowdy (1987)

2.7. Regulations for Sludge Land Application

In 1993, the U.S. Environmental Protection Agency (EPA) declared regulations in “40 CFR Part 503” and set numeric standards for specific metals in sludge to be applied on land (Table 2.13), for requirements to reduce vector attraction (e.g., reducing birds, rodents and insects), and for pathogens (U.S. EPA, 2012). This regulation does not allow the use of wastewater sludge on land without processing them with stabilization. Stabilization helps to reduce odor production, eliminate pathogens and decrease vector attraction potential of sludge. Alkaline stabilization, digestion, composting and heat drying are recommended methods for stabilization. 40 CFR Part 503 classifies treated sludge as Class A and Class B depending on the pathogen reduction levels and the degree of treatment received. Although both classes of sludges are secure in terms of land application, there are some additional requirements for Class B sludge applications (U.S. EPA, 2000). The regulation requires that the density of fecal coliforms in Class A sludge must be less than 1,000 Most Probable Number (MPN) per gram total solids (dry weight) or that Salmonella sp. bacteria be less than 3 per 4 grams total solids. On the other hand, the density of fecal coliforms in Class B sludge must be less than 2 million MPN or CFU per gram total solids (dry weight) (U.S. EPA, 1995).

European Union (EU) established the "Sewage Sludge Directive (86/278/EEC)" in 1986 to encourage correct use of sludge on agricultural lands in member states. The Directive determines the limitations for soil (Table 2.12, Table 2.15) and sludge (Table 2.13) heavy metal concentrations, and maximum allowable heavy metals loadings for land application. EU also prohibits the use of untreated sewage sludge in agricultural soils. However, Member States may authorize raw sludge utilization on land if it is incorporated into the soil. The Directive does not recommend specific attention about pathogenic microorganisms (Council Directive, 1986). After 86/278/EEC, Working Document on Sludge, 3rd Draft was prepared in 2000 to improve the current situation for European sludge management in agriculture. This draft document additionally includes sludge analysis methods, stricter limits for soil heavy metal concentrations and some limitations for organic contaminant concentrations (Table 2.14) (European Commission, 2000). However, this draft document is not a legal text and should only be used for consultation purposes. Today, only a few EU member states have limitations on pathogenic microorganisms (Table 2.11).

Table 2.11: Standards for maximum pathogen concentrations in sewage sludge of some EU member states (Inglezakis et al., 2011)

Country	Salmonella	Other Pathogens
Poland	No occurrence	Fecal streptococci: < 100/g
France	8 MPN/10g DM	Enterovirus: 3 MPN/10g of DM
Finland	Not detected in 25 g	Escherichia coli < 1000 CFU
Italy	1000 MPN/g DM	-
Luxembourg	-	Enterobacteria: 100/g no eggs of worm likely to be contagious
Hungary	-	Fecal coli and fecal streptococci decrease below 10% of original number
Poland	Sludge cannot be used in agriculture if contains salmonella	-

In Turkey, "Regulation on the Use of Domestic and Urban Wastewater Sludges on Land" was established in 2010. The objective of the regulation is taking necessary technical and administrative precautions for the utilization of sludge in soil in compliance with sustainable development aims. The use of untreated sewage sludge on soil is prohibited in this regulation. Similar to U.S. and EU sludge legislations, it includes limit values for soil (Table 2.12, Table 2.15) and sludge (Table 2.13) heavy metal concentrations, sludge organic contaminant concentrations (Table 2.14), and pathogens. Sludge is not allowed to be used for natural forests; for fruit and vegetable crops grown on the ground with the exception of fruit trees; for the cultivation of fruit and vegetable crops that have direct contact with soil or eaten raw; for grassland or forage crops if the grassland is to be grazed or the forage crops to be harvested before 4 weeks. In addition, the sludge cannot be applied on soil if soil texture is sandy; soil pH is less than 6 or soil organic matter content is greater than 5%. If organic matter content of sludge is greater than 40% or pH is not within the range of 6.0-8.5, that sludge is not allowed for the utilization on soil. Moreover, sludge application is prohibited for the saturated soils, wetlands, flood plains or snowfields; for the lands close to surface waters, protection areas, and drinking water basins less than 300 meters; and for the land having an inclination more than 12%. Moreover, after the stabilization application, the levels of E. Coli is required to be reduced by 2 logs (99%) (Regulation on the Use of Domestic and Urban Wastewater Sludges on Land, 2010).

Table 2.12 presents the comparison of heavy metal limits in soil allowed for land application in Europe and Turkey. This table indicates that heavy metal concentration limits in soils depend on the pH of the soils. EU Working Document includes stricter limitations when compared to 86/278/EEC. U.S. regulation does not include heavy metal limitation for soils in sludge land applications.

Table 2.12: Comparison of Heavy Metal Limits in Soil Allowed for Land Application (mg pollutant/kg dry soil)
(Council Directive, 1986; European Commission, 2000; Regulation on the Use of Domestic and Urban Wastewater Sludges on Land, 2010)

Element	**EU (86/278/EEC) (range)**	**EU Working Document on Sludge (3rd Draft)**			**Turkey**	
	6≤pH<7	**5≤pH<6**	**6≤pH<7**	**pH≥7**	**6≤pH<7**	**pH≥7**
Cd	1-3	0.5	1	1.5	1	1.5
Cr	-	30	60	100	60	100
Cu	50-140	20	50	100	50	100
Hg	1-1.5	0.1	0.5	1	0.5	1
Ni	30-75	15	50	70	50	70
Pb	50-300	70	70	100	70	100
Zn	150-300	60	150	200	150	200

- : Not included

Table 2.13 provides the comparison of heavy metal limits in sewage sludge that must be complied prior to sludge land application. According to the table, EU Working Document and Turkish regulation are stricter than 86/278/EEC and U.S. regulation. Only U.S. regulation includes As and Se limitations. Cr is only included in EU Working Document and Turkish regulation.

Table 2.13: Comparison of Heavy Metal Limits in Sewage Sludge Allowed for Land Application (mg pollutant/kg dry sludge)
(Council Directive, 1986; European Commission, 2000; U.S. EPA, 1995; Regulation on the Use of Domestic and Urban Wastewater Sludges on Land, 2010)

Element	**EU (86/278/EEC) (range)**	**EU Working Document on Sludge (3rd Draft)**	**U.S.**	**Turkey**
Cd	20-40	10	39	10
Cr	-	1,000	-	1,000
Cu	1,000-1,750	1,000	1,500	1,000
Hg	16-25	10	17	10
Ni	300-400	300	420	300
Pb	750-1,200	750	300	750
Zn	2,500-4,000	2,500	2,800	2,500
As	-	-	41	-
Se	-	-	100	-
Mo	-	-	-	-

- : Not included

Table 2.14 indicates the comparison of organic contaminant limits in sludge allowed for land application. This table shows that only EU Working Document and Turkish regulation involve limitations for organic pollutants in sludge.

Table 2.14: Comparison of Organic Contaminant Limits in Sewage Sludge Allowed for Land Application (mg pollutant/kg dry sludge)
(Council Directive, 1986; European Commission, 2000; U.S. EPA, 1995; Regulation on the Use of Domestic and Urban Wastewater Sludges on Land, 2010)

Organic Contaminant	**EU (86/278/EEC)**	**EU Working Document on Sludge (3rd Draft)**	**U.S.**	**Turkey**
AOX	-	500	-	500
LAS	-	2,600	-	2,600
DEHP	-	100	-	100
NPE[1]	-	50	-	50
PAH[2]	-	6	-	6
PCB[3]	-	0.8	-	0.8
PCDD/F	-	100 (ng toxic equivalent/kg dry sludge)	-	100 (ng toxic equivalent/kg dry sludge)

- : Not included
[1] : Nonylphenol and nonylphenol ethoxylates with 1 or 2 ethoxy groups
[2] : Sum of polycyclic aromatic hydrocarbons or poly aromatic hydrocarbons
[3] : Sum of congeners 28, 52,101,118,138,153 and 180

Comparison of limit values for yearly loads of heavy metals based on a 10-year average is given in Table 2.15. According to this table, EU Working Document and Turkish regulation have stricter limit values than 86/278/EEC regulation.

Table 2.15: Comparison of Limit Values for Yearly Loads of Heavy Metals Based on a 10-Year Average Allowed for Land Application (g/ha/yr DM)
(Council Directive, 1986; European Commission, 2000; Regulation on the Use of Domestic and Urban Wastewater Sludges on Land, 2010)

Element	EU (86/278/EEC)	EU Working Document on Sludge (3rd Draft)	Turkey
Cd	150	30	30
Cr	-	3,000	3,000
Cu	12,000	3,000	3,000
Hg	100	30	30
Ni	3,000	900	900
Pb	15,000	2,250	2,250
Zn	30,000	7,500	7,500

- : Not included

CHAPTER 3

METHODOLOGY

In this section, the framework of the optimization model and data used will be provided. The study is composed of a screening process in which suitable lands were selected for sludge land application, development and application of an optimization model to select among those to apply sludge with the least transportation costs. The sludge was transported from Ankara Central Wastewater Treatment Plant, which is the only plant producing stabilized sludge in Ankara. In screening out unsuitable arable lands, land use, soil slope, land use capability classes and other constraints were considered as will be described in further detail in following sections. The optimization model was developed to select the arable lands in which sludge could be applied with the minimum transportation costs. The management period was taken as 2013 to 2022. The framework of the study is provided in Figure 3.1.

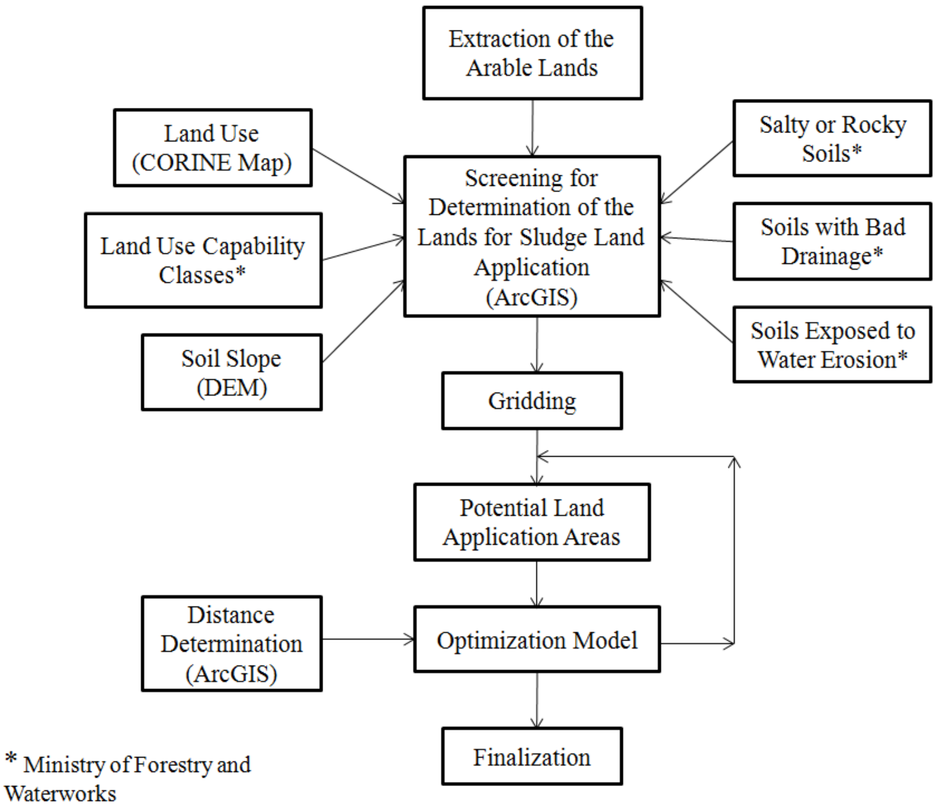

Figure 3.1: The framework of the transportation cost-based optimization model

3.1. Description of the Study Area

Ankara, the capital of Turkey, is the study area which is situated at 38° 44' - 40° 45' N and 30° 49' - 33° 52' E (Figure 3.2). Climate in Ankara is continental-Mediterranean type. In winter, it is very cold with little precipitation. In summer, it is hot with no or less rainfall (Karaca et al., 1995). Table 3.1 summarizes the long-term average climatic conditions in Ankara recorded in the period of 1960 - 2012. Average ambient temperatures vary in the range of 0.3-23.5^{0}C. The average total precipitation during May reaches to 51.2 kg/m^2, nearly five times greater than that for August (Table 3.1).

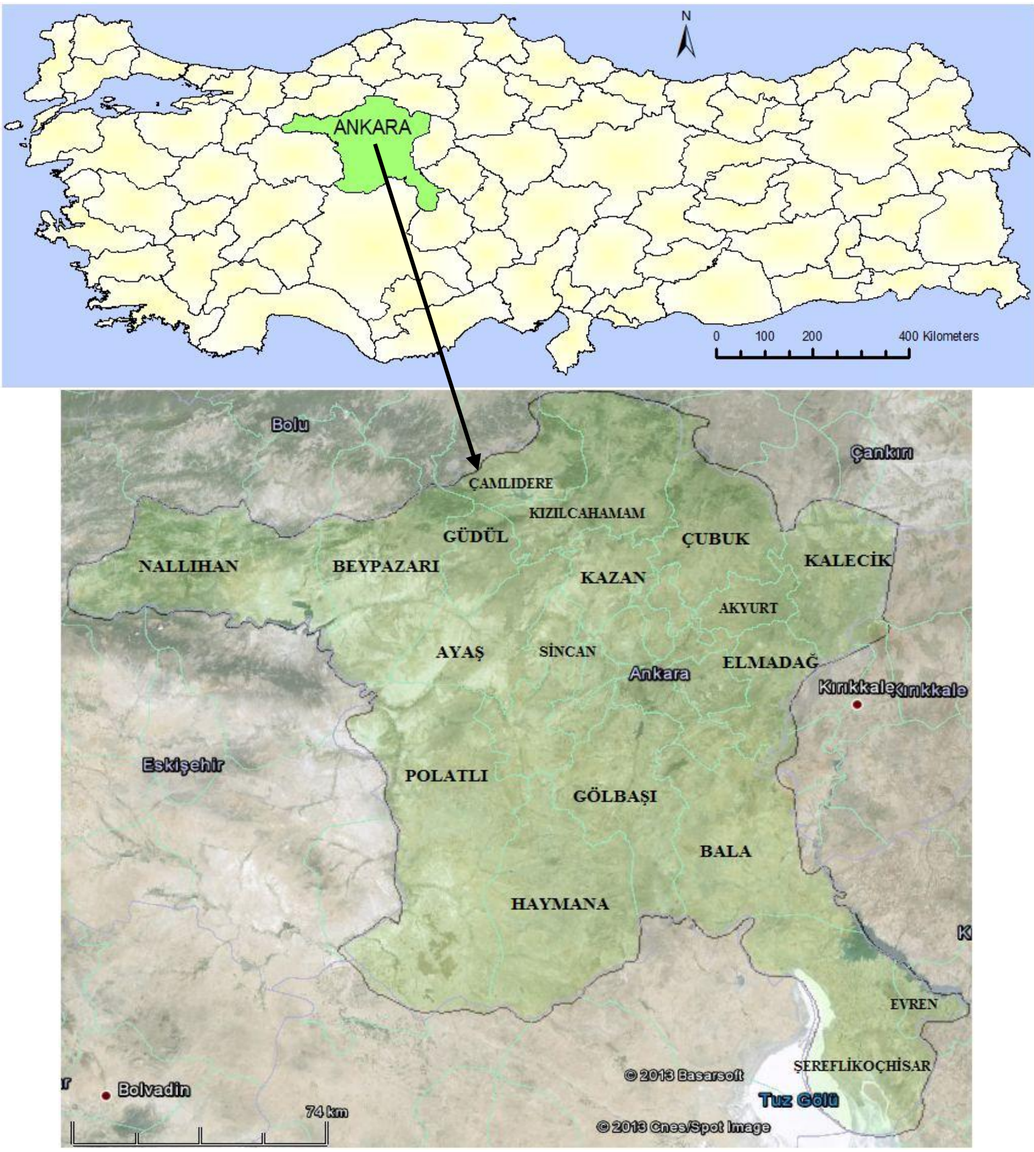

Figure 3.2: Map of the study area

Table 3.1: Data for Climatic Conditions in 1960-2012
(Resmi İstatistikler, n.d)

	January	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**
Average Temperature (°C)	**0.3**	**1.8**	**6.1**	**11.3**	**16.1**	**20.2**	**23.5**	**23.3**	**18.7**	**13.1**	**7.1**	**2.7**
Average Maximum Temperature (°C)	4.3	6.4	11.7	17.2	22.2	26.6	30.2	30.2	26.0	19.9	12.8	6.6
Average Minimum Temperature (°C)	**-3.0**	**-2.2**	**1.0**	**5.7**	**9.7**	**13.0**	**16.0**	**16.0**	**11.9**	**7.4**	**2.5**	**-0.6**
Average Number of Days with Precipitation	11.7	11.0	10.9	12.0	12.5	8.6	3.8	2.8	3.8	7.1	8.6	11.8
Average Monthly Total Amount of Precipitation (kg/m^2)	**41.8**	**36.9**	**38.7**	**49.0**	**51.2**	**35.4**	**14.5**	**10.9**	**18.5**	**30.2**	**33.9**	**46.9**

In 2012, the population of Ankara was 4,965,542 (TUIK, 2013a). In Ankara, 95% of the population was served by wastewater treatment plants in 2010 (TUIK, 2013b). Today, there are 10 wastewater treatment plants in Ankara (ASKİ, 2013). The only plant producing stabilized sludge in Ankara is Ankara Central Wastewater Treatment Plant (WWTP) which is the largest plant in Ankara, second largest plant in Turkey and forth largest plant in Europe in terms of daily flow of incoming wastewater (ASKİ, 2013).

Ankara Central WWTP is in operation since 1997 and it is a conventional biological system operating currently activated sludge process. The plant receives 765,000 m^3 of wastewater daily in dry conditions and 1,530,000 m^3 of wastewater daily in wet conditions (Gürgan, 2012). The treatment flow diagram of Ankara Central WWTP is presented in Figure 3.3. In the treatment scheme, the raw sludge settled down in primary clarifier is mixed with the wasted activated sludge from the secondary clarifier. The mixed sludge is firstly thickened before the anaerobic digestion unit. Following stabilization, the digested sludge is thickened and sent to the dewatering operation. According to ASKİ (General Directorate of Ankara Water & Sewage Administration), Ankara Central WWTP produces 300 tonnes of wet sludge daily with 28% dry matter content (Personal communication, May 24, 2013).

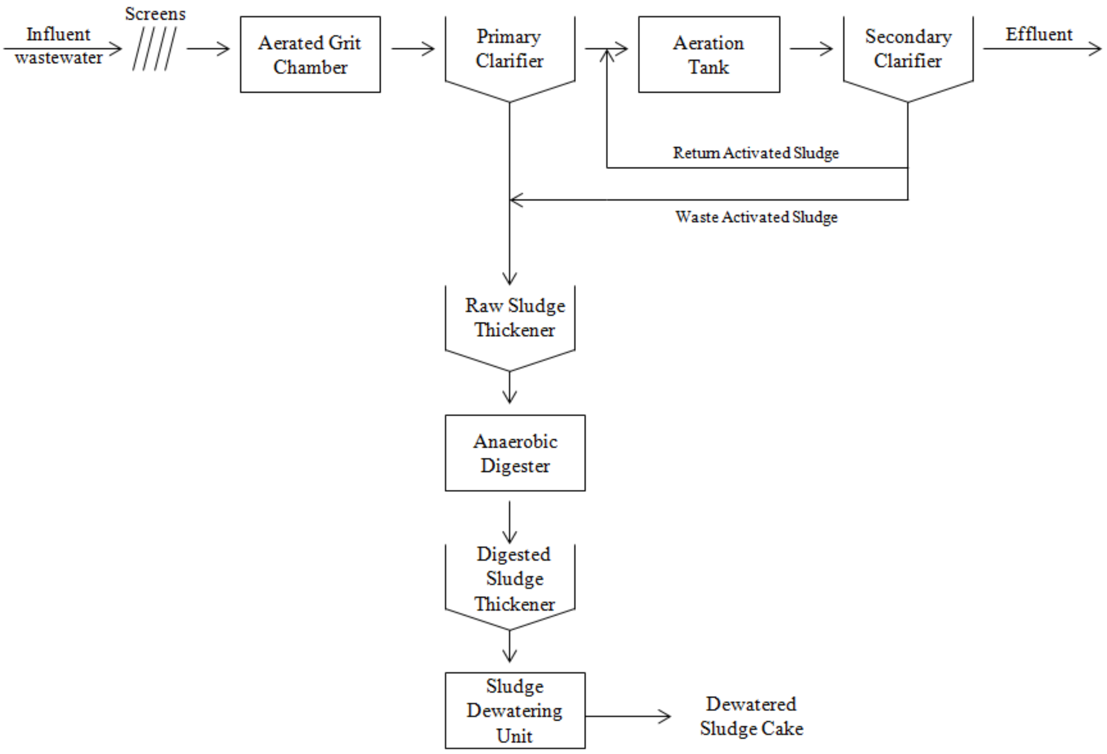

Figure 3.3: Treatment Process Flow Diagram of Ankara Central Wastewater Treatment Plant

Terzi (2007) monitored the monthly pH, dry matter and organic matter, N, P and K contents of the sludge produced in Ankara Central WWTP for 12 months between March-2005 and February-2006. The results obtained in that research are listed in Table 3.2. Since organic matter content is greater than 40%, average pH is greater than 6.0 and the sludge is stabilized, this sludge is suitable for agricultural land application with respect to the Regulation on the Use of Domestic and Urban Wastewater Sludges on Land (2010).

Table 3.2: pH, dry matter and organic matter, contents, and nutrient contents of the sludge produced in Ankara Central Wastewater Treatment Plant (Terzi, 2007)

Month	**Dry matter content** (%)	**Organic content** (%)	**pH**	**Nitrogen** (%)	**Phosphorus** (%)	**Potassium** (%)
March	23.9	54.4	5.93	3.87	0.66	0.20
April	23.3	54.9	5.77	4.03	0.67	0.21
May	23.0	55.1	6.11	4.03	0.71	0.22
June	24.7	50.6	5.97	3.25	0.71	0.23
July	22.9	56.0	6.09	4.11	0.62	0.26
August	23.0	57.3	6.12	4.20	0.66	0.29
September	23.2	56.5	5.82	3.91	0.75	0.25
October	20.7	58.2	6.04	4.01	0.74	0.20
November	21.3	58.8	6.65	4.20	0.88	0.19
December	21.7	57.7	6.11	3.20	0.92	0.18
January	23.9	52.4	6.19	3.31	0.75	0.18
February	26.8	50.9	6.18	2.64	0.65	0.26
Minimum	**20.7**	**50.6**	**5.77**	**2.64**	**0.62**	**0.18**
Maximum	**26.8**	**58.8**	**6.65**	**4.20**	**0.92**	**0.29**
Average	**23.2**	**55.2**	**6.08**	**3.73**	**0.72**	**0.22**

In a recent study, Kendir (2013) analyzed the heavy metal concentrations in the sludge produced in Ankara Central WWTP. Samples were taken monthly for 12 months between January-2012 and December-2012 (Table 3.3). The results of the analyses done on sludge samples are listed in Table 3.3 with their comparison to legislative limits. According to Table 3.3, recently measured heavy metal concentrations were all under the limits determined in the relevant Turkish regulation. Based on heavy metal concentrations in the sludge and regulations pertaining to sludge application on land (Table 3.3), the maximum sludge application rate can be 0.45 t/da in a year if Ankara Central WWTP sludge is to be applied onto land every year in a 10-year long period.

Table 3.3: Heavy Metal Concentrations in the sludge of Ankara Central WWTP in comparison to regulatory limits (Kendir, 2013; Regulation on the Use of Domestic and Urban Wastewater Sludges on Land, 2010)

Heavy Metal	**Minimum Concentration (mg/kg)**	**Average Concentration (mg/kg)**	**Maximum Concentration (mg/kg)**	**Standard Deviations**	**Limit Values (mg/kg)** [1]	**Limit Values for Yearly Loads (g/da/yr)** [1-2]	**The Amount of Sludge that can be applied to land in a year (t/da/yr)** [3]
Cd	2.3	**4.5**	6.9	0.7	**10**	**3**	**0.67**
Cr	144.0	**262.9**	356.1	47.6	**1000**	**300**	**1.14**
Cu	147.1	**188.8**	230.3	15.4	**1000**	**300**	**1.59**
Hg	0.4	**0.8**	1.3	0.1	**10**	**3**	**3.75**
Ni	69.7	**78.4**	89.9	5.0	**300**	**90**	**1.15**
Pb	35.1	**60.7**	85.2	15.6	**750**	**225**	**3.71**
Zn	1174.7	**1683.8**	2499.9	195.9	**2500**	**750**	**0.45**

[1] *Limit values according to Regulation on the Use of Domestic and Urban Wastewater Sludges on Land (2010) (dry sludge)*
[2] *Limit values for yearly loads of heavy metals based on a 10-year average (dry sludge)*
[3] *Yearly sludge application limits if the sludge is applied every year in a 10-year period*

NPE and PCB concentrations were also examined in samples taken in a 12-month long period by Kendir (2013). Monthly average NPE concentrations varied between 5.3 and 25.5 mg/kg dry sludge where the limit value in Turkish regulation is 50 mg/kg dry sludge. In addition, monthly average PCB concentrations were between 0.004 and 0.06 mg/kg dry sludge where the limit value in Turkish regulation is 0.8 mg/kg dry sludge.

To sum up, the sludge produced in Ankara Central WWTP is suitable for land application since it is stabilized anaerobically in the plant and complies with legislative limit values determined for organic content, pH, PCB, NPE and heavy metal concentrations in the Regulation on the Use of Domestic and Urban Wastewater Sludges on Land (2010).

As stated before, 300 tonnes of wet sludge is produced daily in Ankara Central Wastewater Treatment Plant with 28% dry matter. This value corresponds to 84 t/day dry sludge and 30,660 t/yr dry sludge.

During this study, it is assumed that the rate of increase in sludge amount is equal to the population growth rate of Turkey.

According to United Nations (2010), medium variant population growth indicates a continuous increase in world population between the years 2010 and 2100. In Turkey, population growth by medium variant is expected to decrease after 2050. High variant population growth assumes fertility more than a half-child greater than medium variant in the projection period and results in a sharp growth in the population. On the contrary, low variant population growth assumes fertility less than a half-child greater than medium variant in the projection period and brought about a significant decrease in world. Total population estimation depending on low, medium and high variant is given in Figure 3.4.

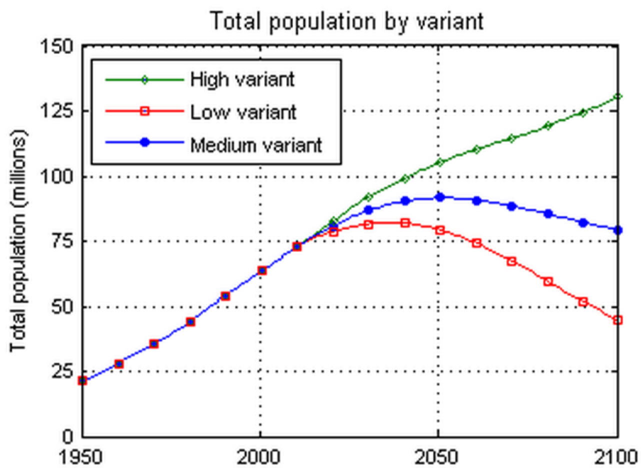

Figure 3.4: Total population estimations of Turkey by variant (United Nations, 2011)

Population growth of Turkey by medium variant was used to calculate the sludge projection. The population estimation between the years 2010 and 2025 is listed in Table 3.4. The graph showing the population versus year is provided in Section 4.1, Figure 4.1. The regression equation of this graph was used to determine the sludge projections between 2013 and 2022. The results of sludge projection calculations are presented in Section 4.1, Table 4.2.

Table 3.4: Estimated population of Turkey in different years (United Nations, 2010)

Year	Population
2010	72,752,000
2015	77,003,000
2020	80,753,000
2025	83,984,000

3.2. Optimization Model

Optimization is a mathematical method that can be used to allocate the resources deficient in quantity. Linear Programming (LP) is one of the optimization methods that can be practically utilized to solve transportation and aggregate production planning problems whose objective functions and constraints are linear (LINDO Systems, 2006). In addition, LP is applicable for linear surface fitting, load balancing, resource allocation, classification, minimum-cost network flow problems (Ferris et al., 2007). For the allocation of sludge produced in Ankara Central WWTP to non-irrigated arable lands with minimum transportation costs, LP was used. To solve the linear optimization problem, MATLAB program was employed, and script involving the use of “linprog” function was developed and executed.

The linear optimization model was structured to determine the most cost effective way to transport the sludge produced in Ankara Central WWTP to suitable non-irrigated arable lands (on annual basis) for a total management period of 10 years. This management period is selected based on the Regulation on the Use of Domestic and Urban Wastewater Sludges on Land (2010) which defines the cumulative loadings or yearly loads of heavy metals to soil within a 10-year period. In Ankara, both irrigated and non-irrigated agriculture are practiced. However, sludge application to irrigated lands may not be preferred due to higher potential for transport of sludge constituents to groundwaters or surface waters. Therefore, in this study, it was assumed that sludge application is feasible only for non-irrigated arable lands. In non-irrigated arable lands, cereals, legumes, feed crops, and root crops planting areas, fallow areas and flower, tree and vegetable planting lands are produced.

Sludge transportation cost is composed of fuel cost and other costs associated with maintenance and labor. It was assumed that a given area of non-irrigated arable land could receive sludge only once in 10-year period. This approach was used to minimize the risk of heavy metal build up in soil. Moreover, it was assumed that all sludge produced in Ankara Central Wastewater Treatment Plant was used for land application for agricultural purposes. Interest rate was assumed as 0% between 2013 and 2022. Given these assumptions, the optimization model is expressed as:

$$\text{Min Z} = \sum_{i=0}^{I} (\mathrm{CT_i} + \mathrm{CO_i}) \tag{3.1}$$

$$\mathrm{CT_i} = 2\, x_i\, round\_up\left(\frac{M_i}{T_k}\right)\, b_k\, f_A \tag{3.2}$$

$$\mathrm{CO_i} = 0.40\, \mathrm{CT_i} \tag{3.3}$$

Where

CT_i	Fuel cost for transportation of sludge to non-irrigated arable land from the Ankara Central WWTP to non-irrigated arable land (polygon) *i* in a given year (TL/yr)
CO_i	Other costs (truck tires, maintenance, personnel costs) required for transportation of sludge from the Ankara Central WWTP to non-irrigated arable land (polygon) *i* (TL/yr)
M_i	Amount of sludge that can be applied on non-irrigated arable land (polygon) *i* in a given year (t/yr)
x_i	The distance between the Ankara Central WWTP and the non-irrigated arable land (polygon) *i* (km)
T_k	The truck capacity *k* that is used for transporting sludge produced in Ankara Central WWTP to non-irrigated arable land (polygon) *i* (tonne)
b_k	Unit fuel consumption for the truck with capacity *k* (L/km)
f_A	Unit diesel fuel cost (TL/L)
I	Total number of non-irrigated arable land polygons available for potential sludge application in a given year assuming that area can receive sludge only once in 10 years.

The above objective function was subject to the following constraints:

- All sludge produced in a given year will be used in land application:

$$\sum_{i=0}^{I} \mathrm{M_i} = \mathrm{S} \tag{3.4}$$

- The amount of sludge applied on non-irrigated arable lands in a given year cannot exceed the amount of sludge that can be applied with the dosage of 1.0 t/da.

$$\mathrm{M_i} \leq \mathrm{B_i} \tag{3.5}$$

- Non-negativity:

$$\mathrm{M_i} \geq 0 \tag{3.6}$$

Where

S	Total sludge production of Ankara Central WWTP in a given year (t/yr)
B_i	The capacity of non-irrigated arable land *i* (t/yr)

Above optimization model was executed sequentially for each subsequent year in the management period of 10-years. The model was first run for 2013 and the selected non-irrigated arable lands were extracted from decision variable batch. Then, the model was run for 2014 and the process mentioned for 2013 was repeated for this year as well. Model runs were terminated after the results of 2022 were obtained. Therefore, sludge application was performed once in a given non-irrigated arable land. It must be emphasized that selection of arable lands on which sludge would be applied is dependent on both the distance and the area of relevant lands. Therefore, it is possible not to select the closest land based on the area. Moreover, optimization runs were conducted for trucks of three different capacities; 10 tonnes, 16 tonnes, and 24 tonnes. These capacities were retrieved from the study of Gül and Elevli (2006) in which trucks capacities of 10, 16 and 24 tonnes were used for cement transportation. The other costs of sludge transportation were taken as 40% of fuel costs as given in Equation 3.3. This percentage based on the study of Gül and Elevli (2006) as well. As given in Equation 3.1, round-trip distances were used while calculating fuel costs. Unit fuel consumptions and unit fuel costs used in the optimization model are listed in Table 3.5 for trucks of different capacities.

Table 3.5: Unit fuel consumption and unit fuel costs for trucks with different capacities (Gül and Elevli, 2006)

	24 ton	**16 ton**	**10 ton**
b_k fuel consumption (L/km)[1]	0,32	0,265	0,182
f_A, diesel fuel cost (TL/L)[2]	4,02	4,02	4,02
Unit fuel cost ($b_k f_A$) (TL/km)	1,376	1,140	0,783

[1] : The fuel consumption of corresponding truck loaded with full capacity, with 60 km/h average velocity on the road having average slope of 10% (98% of beltways in Turkey have a slope of 10%)

[2] : Diesel fuel's cost was taken as 4.02 TL/L (with VAT) (May 2, 2013)

According to Regulation on the Use of Domestic and Urban Wastewater Sludges on Land (2010), the sludge produced in wastewater treatment plants whose equivalent population capacity is greater than a million people must be dried until they have 90% dry matter content. Ankara Central WWTP was designed to serve for equivalent population of approximately 4 million people in 2002 (Tatlar Atıksu Arıtma Tesisi, 2013). For this reason, in this study, the dry matter content of the sludges which were transported to the non-irrigated arable lands for land application was determined as 90% dry matter. Each grid received sludge independently.

3.3. Land Cover

The land covers in Ankara and their distributions according to CORINE Land Cover-2006 (CLC) map are provided in Table 3.6. The standard CLC nomenclature includes forty four classes under five main land cover levels which are artificial surfaces, agricultural areas, forests and semi-natural areas, wetlands and water bodies (EEA, 2007). In this study, screening of suitable lands for sludge application according to different land uses is based on CLC-2006 map as will be described in Section 3.6. The percentage distributions of main land cover percentages in Ankara are depicted in Figure 3.5.

Table 3.6: CLC-2006 Ankara land cover distribution

Level	Level Name	Area (da)	Percentage (%)
1	**Artificial Surfaces**	**790,700**	**3.1**
1.1	*Urban Fabric*	*505,100*	*2.0*
1.1.1	Continuous urban fabric	40,600	0.2
1.1.2	Discontinuous urban fabric	464,500	1.8
1.2	*Industrial, commercial and transport units*	*176,300*	*0.7*
1.2.1	Industrial or commercial units	124,800	0.5
1.2.2	Road and rail networks and associated land	33,200	0.1
1.2.3	Port areas	-	-
1.2.4	Airports	18,300	0.1
1.3	*Mine, dump and construction sites*	*73,100*	*0.3*
1.3.1	Mineral extraction sites	31,000	0.1
1.3.2	Dump sites	-	-
1.3.3	Construction sites	42,100	0.2
1.4	*Artificial, non-agricultural vegetated areas*	*36,200*	*0.1*
1.4.1	Green urban areas	17,100	0.1
1.4.2	Sport and leisure facilities	19,100	0.1
2	**Agricultural areas**	**14,724,300**	**58.3**
2.1	*Arable land*	*9,748,500*	*38.6*
2.1.1	Non-irrigated arable land	7,425,600	29.4
2.1.2	Permanently irrigated land	2,317,400	9.2
2.1.3	Rice fields	5,500	0
2.2	*Permanent crops*	*5,200*	*0*
2.2.1	Vineyards	4,100	0
2.2.2	Fruit trees and berry plantations	1,100	0
2.2.3	Olive groves	-	-
2.3	*Pastures*	*748,700*	*3.0*
2.3.1	Pastures	748,700	3.0
2.4	*Heterogeneous agricultural areas*	*4,221,900*	*16.7*
2.4.1	Annual crops associated with permanent crops	-	-
2.4.2	Complex cultivation patterns	1,347,500	5.3
2.4.3	Land principally occupied by agriculture, with significant areas of natural vegetation	2,874,400	11.4
2.4.4	Agro-forestry areas	-	-
3	**Forest and semi-natural areas**	**9,101,800**	**36.0**
3.1	*Forests*	*1,271,400*	*5.0*
3.1.1	Broad-leaved forest	57,700	0.2
3.1.2	Coniferous forest	1,122,100	4.4
3.1.3	Mixed forest	91,600	0.4
3.2	*Scrub and/or herbaceous vegetation associations*	*4,502,900*	*17.8*
3.2.1	Natural grasslands	3,263,000	12.9
3.2.2	Moors and heathland	-	-
3.2.3	Sclerophyllous vegetation	-	-
3.2.4	Transitional woodland-shrub	1,239,900	4.9
3.3	*Open spaces with little or no vegetation*	*3,327,500*	*13.2*
3.3.1	Beaches, dunes, sands	11,200	0
3.3.2	Bare rocks	305,000	1.2
3.3.3	Sparsely vegetated areas	3,011,300	11.9
3.3.4	Burnt areas	-	-
3.3.5	Glaciers and perpetual snow	-	-
4	**Wetlands**	**90,400**	**0.4**
4.1	*Inland wetlands*	*63,300*	*0.3*
4.1.1	Inland marshes	63,300	0.4
4.1.2	Peat bogs	-	-
4.2	*Maritime wetlands*	*27,100*	*0.1*
4.2.1	Salt marshes	-	-
4.2.2	Salines	27,100	0.1
4.2.3	Intertidal flats	-	-
5	**Water bodies**	**555,900**	**2.2**
5.1	*Inland Waters*	*555,900*	*2.2*
5.1.1	Water courses	2,700	**0**
5.1.2	Water bodies	553,200	**2.2**
5.2	*Marine waters*	-	-
5.2.1	Coastal lagoons	-	-
5.2.2	Estuaries	-	-
5.2.3	Sea and ocean	-	-
	TOTAL	**25,263,100**	**100**

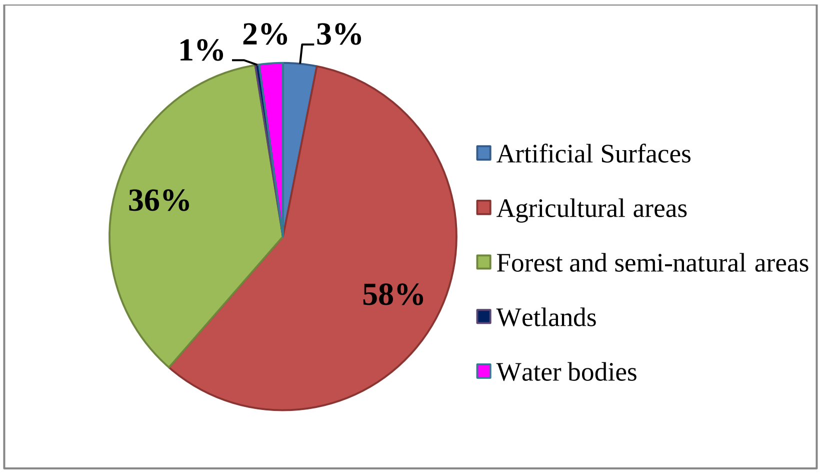

Figure 3.5: Land cover distribution in Ankara

3.4. Land Use Capability Classifications

In Turkey, land use capability classifications are defined under "Soil Protection and Land Use Law" (dated 3 July 2005) as "Land classification made depending on the climatic conditions and basic soil surveys by gathering the land use and soil protection data in order to determine the optimum land utilization without causing land degradation" (Soil Protection and Land Use Law, 2005). The classification is done by using land characteristics and sub-parameters including climatic conditions, soil, topography and drainage properties of the soil. In addition, the suitability of land for the cultivation of nearly all plant cultures is taken into consideration in grouping and classification of lands (Everest et al., 2011).

There are eight classes of land use capability which are defined under three groups. The groups and classes are given in Table 3.7. Class I, II, III and IV are arable lands that are used for crop cultivation. Classes V, VI and VII are not appropriate for crop production. Class VIII lands are not suitable for animal grazing or agricultural activities.

Table 3.7: Land use capability groups and classes
(Technical Directive for Soil and Land Classification Standards, 2008)

Land Use Capability Group	Land Use Capability Class
Lands Suitable for Cultivation	I
	II
	III
	IV
Lands not Suitable for Cultivation	V
	VI
	VII
Lands not Suitable for Agriculture	VIII

In Technical Directive for Soil and Land Classification Standards (2008) document, the land use capability classes are defined as the follows:

Class I Lands are the lands with very minor or no physical limitations crop cultivation with conventional agricultural applications. They are flat/nearly flat, deep, and fertile lands. Very little runoff and wind driven erosion may occur in these lands. The soils have good drainage and are not exposed to damage due to flooding. Crops planted with mattock and other intensive crops are suitable for cultivation in Class I lands.

Class II Lands can be cultivated easily by taking some specific precautions. Different from Class I lands, Class II lands have some restricting factors such as having a slight slope, moderate exposure to erosion, moderate thick soil, occasional exposure to floods and moderate moisture.

Class III Lands are moderately good for crops planted with mattock. In these lands revenue can be increased if good crop rotations are selected and applied using appropriate agricultural methods. These lands are moderately inclined, highly sensitive to erosion, contains high moisture; have shallow and stony, excessive sand content or low water holding capacity, and less fertility.

Class IV Lands are lands that can be assigned especially to continuous pastures and field crops. High inclination, erosion, bad soil characteristics (poor drainage to remedy, shallow and very stony structure but capable of being ploughed) and severe climate are the restricting factors for agricultural activities conducted in these lands. Lands with low inclination but poor drainage are also included in Class IV lands. Those areas are not exposed to erosion but they are not appropriate for cultivation of many crops due to sudden drying potential in spring and exhibiting less fertility.

Class V Lands are not very suitable to grow crops and can be allocated for long-term plants, meadows or forests. Class V lands include some restricting factors for cultivation such as having very poor drainage and very shallow or stony soils, etc. They are flat/nearly flat and not exposed to high runoff and wind driven erosion.

Class VI Lands require some moderate precautions even if they are used as forests and/or meadows. These lands are not suitable for cultivation because of high inclination and exposure to erosion, and being shallow or very arid.

Class VII Lands are highly inclined and exposed to erosion. They also include very shallow, arid and marshy areas. They may be utilized as forests or meadows with special care. If vegetation cover on these land decreases, exposure to erosion enhances significantly.

Class VIII Lands are not suitable for agricultural activities or usage as forests or meadows because of marshes, deserts, highlands, very deep hollows or stony land covers. In addition, this class of land includes natural environment and are protected as natural water catchment areas.

Distribution of land use capability classes in Ankara is presented in Figure 3.6. The occurrence of each land use capability classes in Ankara is given in Appendix A.

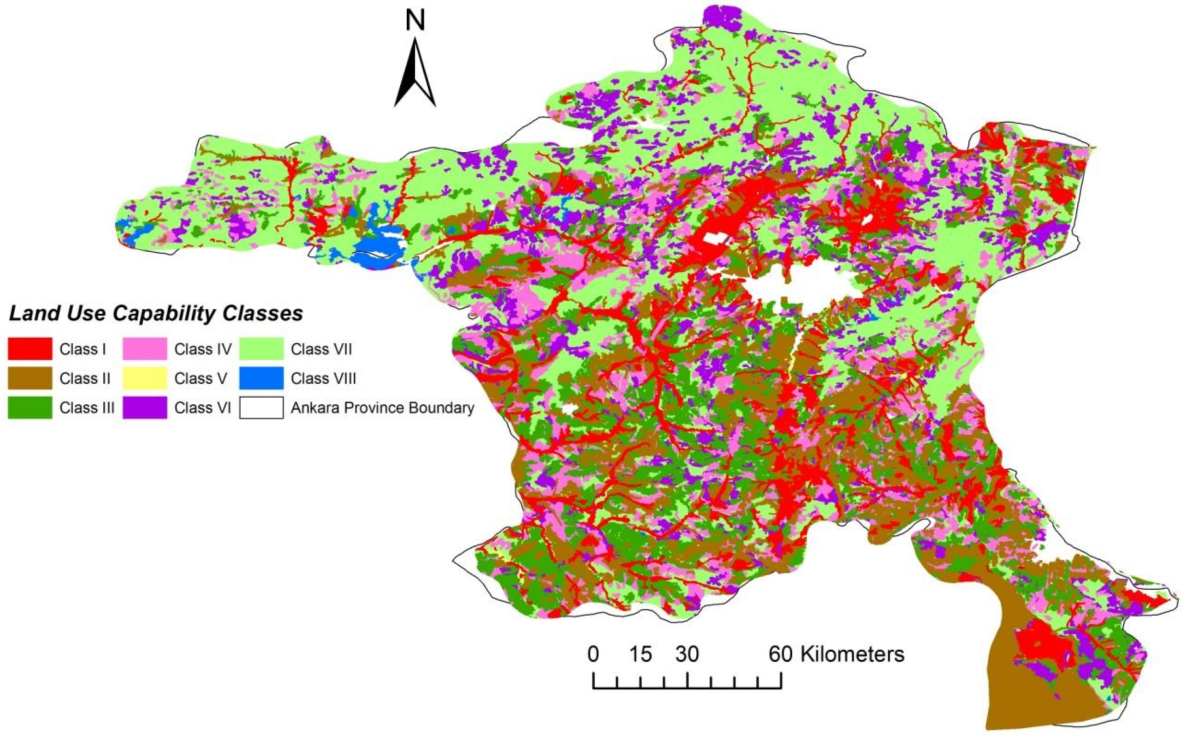

Figure 3.6: Distribution of land use capability classes in Ankara

3.5. Elevation in Ankara

The altitude of Ankara changes in between 245 and 2,067 m as can be seen in the Digital Elevation Model (DEM) in Figure 3.7. The DEM used is SRTM (The Shuttle Radar Topography Mission) - DEM with a resolution of 82*m*x82*m*. The shaded relief map of Ankara in Figure 3.8 is generated by using DEM. The altitude of the illumination is 45° and the azimuth of the illumination is 315°.

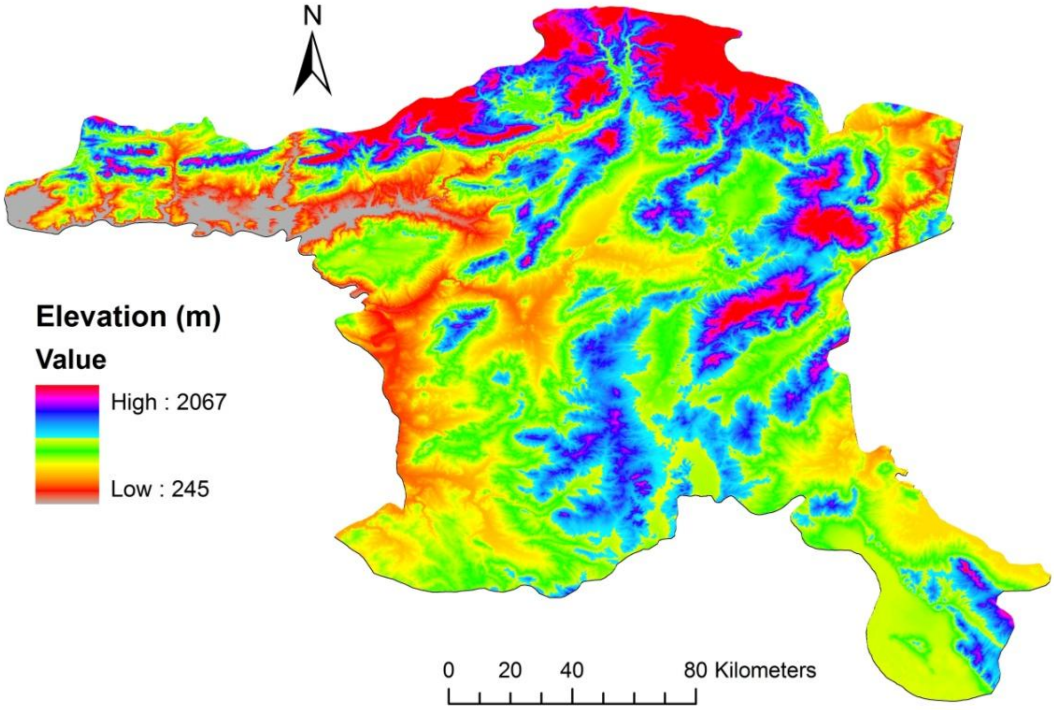

Figure 3.7: Digital Elevation Model of Ankara

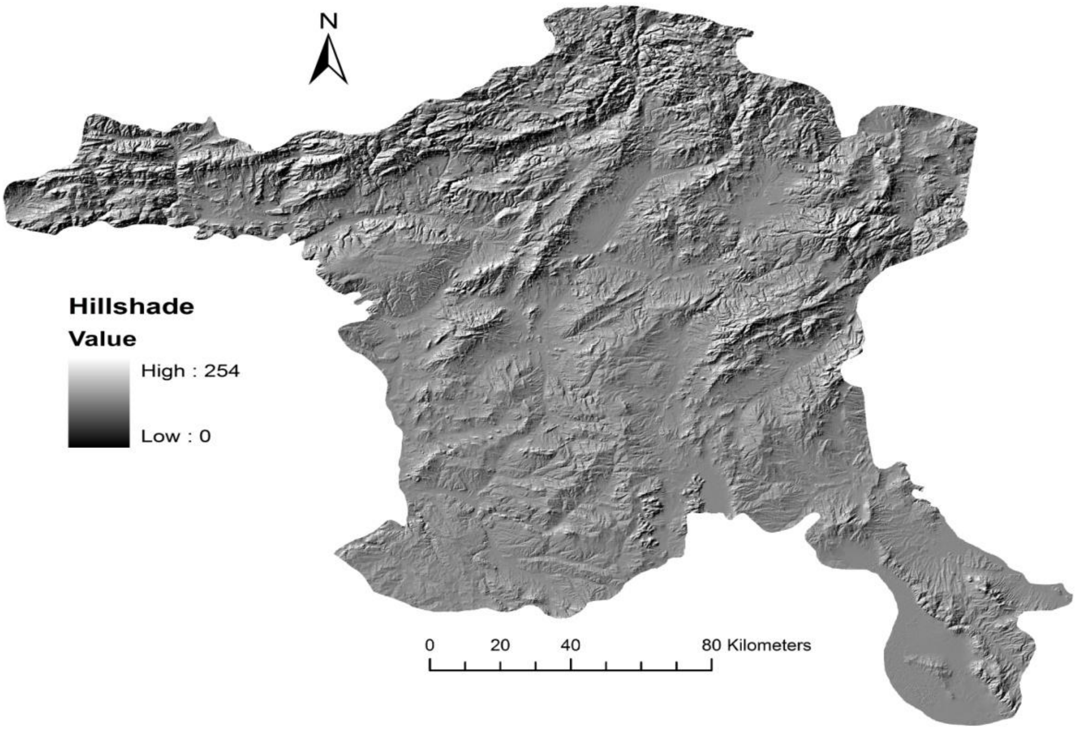

Figure 3.8: Hillshade Map of Ankara

3.6. Methods Used to Develop Transport Cost-Based Optimization Model

In this section, the methods used to construct the transport cost-based optimization model are discussed in detail. Geographical Information System (GIS) program ArcGIS 9.3 was used to determine the best agricultural lands for the sludge land application and to measure the distances between these lands and Ankara Central WWTP.

Determination of the location of Ankara Central WWTP was done using Google Earth program which was then incorporated into ArcGIS environment. The location of the plant can be seen in Section 4.1 in Figure 4.3.

Then, the determination of the arable lands was done using CLC-2006 map which is assumed to be error-free. CLC-2006 map includes 3 arable land classes that are non-irrigated arable lands, permanently irrigated lands and rice-fields. Since sludge land application has a risk for organic contaminant, N, P and heavy metal movement to groundwater in permanently irrigated lands and rice-fields due to regular flooding, the non-irrigated arable lands were chosen as the potential lands for this sludge land application study. Non-irrigated arable lands include cereals, legumes, feed crops, and root crops planting areas, fallow areas and flower, tree and vegetable planting lands. They do not include permanent pastures. The distribution of non-irrigated arable lands in Ankara is provided in Figure 4.3.

Since sludge land application may cause adverse health effects on people living near land application sites or contaminate the surface or groundwaters, some site restrictions and buffer zones (setback distances) were included in the study to eliminate sludge contact to humans and water resources.

Among 44 classes of CLC-2006 map, 7 classes under ‘artificial surfaces’ level were named as ‘*residential areas*’. Continuous and discontinuous urban fabric, industrial or commercial units, airports, green urban areas, sports and leisure facilities, and construction sites were included in residential areas. In addition to residential areas, road and rail networks and associated lands (were called as “Railways and Public Roads”), water courses, water bodies, beaches, dunes and sands (were called as “Sand Plains”), inland marshes were determined as sensitive areas that should not be in close proximity to sludge land application sites. The sensitive areas for sludge land utilization can be seen in Figure 4.4.

The sludge land application guidelines prepared by countries such as Australia, Canada, United States (Maine, Minnesota, Tennessee and Virginia states) do not recommend applying sludge to lands which are located within the minimum buffer zone distances. For example, Nova Scotia Canada Environment (2010) determined the minimum setback distances between lands and residential areas as 450 m, and between lands and public roads, railway lines as 30 m. In Turkish legislation, Regulation on the Use of Domestic and Urban Wastewater Sludges on Land (2010), the minimum buffer zone requirement between lands and surface waters was determined as 300 m. In this study, the buffer zones were determined as nearly 3.3 times of those setback distances mentioned above to eliminate the possible impacts of sludge land application (Table 3.8). Although no buffer zone is defined in any guidelines or regulations for sand plains and inland marshes, they were regarded as water resources throughout the study. The map after the addition of the buffer zones is presented in Figure 4.5. After buffer zones were applied to the map, the non-irrigated arable lands located within the buffer zones were discarded from the map. A closer look at buffer zone extraction process is given in Figure 4.6.

Table 3.8: Buffer zones applied to sensitive areas

Areas	**Setback Distances (m)**
Water Courses	1000
Water Bodies	1000
Railways and Public Roads	100
Inland Marshes	1000
Sand Plains	1000
Residential Areas	1500

Since the non-irrigated arable lands were big in size and not in unique forms, using their centroids would have been erroneous while calculating transportation costs. For this reason, first the study site was split into polygon grids that were 3*km* x 3*km* (a total of 3023 grids) in order to ease the transportation calculations. Then, the non-irrigated arable lands were split into *polygons* (Figure 4.7).

As previously mentioned in Section 2.7, according to Regulation on the Use of Domestic and Urban Wastewater Sludges on Land (2010), sludge land application cannot be conducted in the lands having a slope more than 12%. Slope of Ankara soils were calculated by using Digital Elevation Model of Ankara. The lands slopes of which are greater and lower than 11.8% are shown in Figure 3.9.

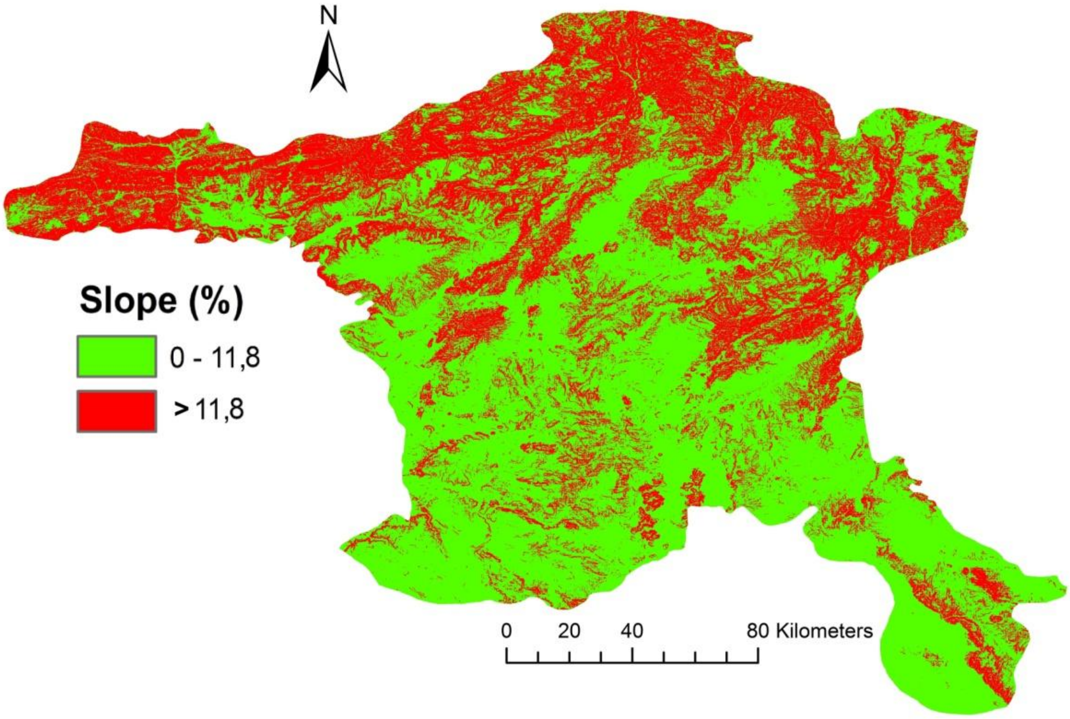

Figure 3.9: Soil surface slopes in Ankara

Non-irrigated arable lands which lied on the soils with slope greater than 11.8% were discarded from the map (Figure 4.8).

Among 8 land use capability classes (explained in Section 3.4), the lands suitable for cultivation (Class I-II-III-IV) were thought as potential sites for sludge land application. After close examination of these classes, Class III and Class IV were determined as the lands that would be appropriate to for sludge application. The reason for elimination of Class I and Class II was their being fertile lands and appropriate for all crops. However, Class III and Class IV lands need proper agricultural management and they have moderate limitations and less fertility compared to Class I and Class II lands. Due to their low water holding capacity, the crops that can be cultivated on the non-irrigated arable lands were thought as the best crop groups for these land classes. Furthermore, sludge land utilization on Class III and Class IV would improve the soil quality.

With the selection of Class III and Class IV lands as the suitable lands for sludge land application, all the non-irrigated arable lands belonging to classes I, II, V, VI, VII and VIII were eliminated from the map (Figure 4.9).

Since some lands whose soils belong to Class III and Class IV had still some unsuitable properties for sludge land application, the elimination of these lands was also conducted.

The non-irrigated arable lands lying on the soils which are salty or rocky, or having severe drainage properties were discarded from the map. In addition, the arable lands on the soils that are exposed to excessive water erosion were eliminated. All the non-irrigated arable lands remained after all the constraints can be seen in 3*km*x3*km* grid system in Figure 4.10. The placement of all the lands within the map including sensitive areas is given in Figure 4.11.

In order to calculate the distances between Ankara Central WWTP and the non-irrigated arable lands which remained after discarding those located on inappropriate soils, the centroids (center of gravity) of the arable lands were determined. If there existed any arable lands in a 3*km*x3*km* polygon, that polygon had only one center of gravity and was named with a polygon number (Figure 4.12). The distribution of centroids is shown in Figure 4.13. After the creation of centroids, the Euclidean distances between arable land centroids (1051 units) and Ankara Central Wastewater Treatment Plant were measured in ArcGIS program one by one in units of kilometers. The reason of using Euclidean distance measurements was the non-availability of road network between the non-irrigated arable lands.

CHAPTER 4

RESULTS AND DISCUSSION

4.1. Projected sludge quantities of Ankara Central Wastewater Treatment Plant

As previously mentioned in Section 3.1, the rate of increase in sludge amount is assumed as equal to the population growth rate of Turkey. Estimated population of Turkey for several years is given in Table 3.4. Since the study projection period is between 2013 and 2022 (10-year), the sludge production in 2013 was known (Section 3.1), the population in 2013 was determined by using linear regression equation of population versus year graph (Figure 4.1) as 75,253,000. The last 2 digits of year values in the x axis and population data were used to determine the regression equation in Figure 4.1.

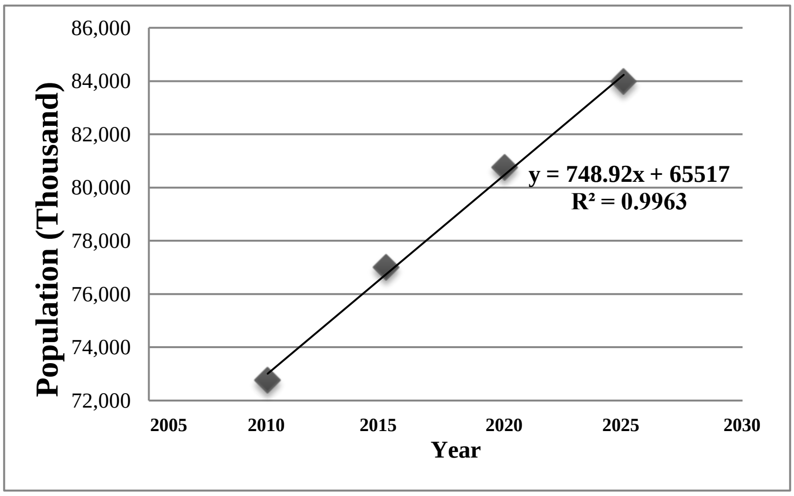

Figure 4.1: Population versus year graph of population estimation

The sludge amount in 2015, 2020 and 2025 was estimated by using proportional relationship of population data of these years (Table 4.1). By using sludge projection quantities versus year graph (Figure 4.2), all the sludge amounts produced between years 2013 and 2022 were calculated by using linear regression equation (Table 4.2). The last 2 digits of year values in the x axis and sludge projection data were used to determine the regression equation in Figure 4.2. As previously mentioned in Section 3.2, the dry matter content of the sludges which were considered for sludge land application was determined as 90% dry matter and their amounts are given in Table 4.2.

Table 4.1: Estimation of Sludge Projection Quantities

Year	Population	Amount of Sludge (t/yr)
2013	75,253,000	30,660
2015	77,003,000	31,373
2020	80,753,000	32,901
2025	83,984,000	34,217

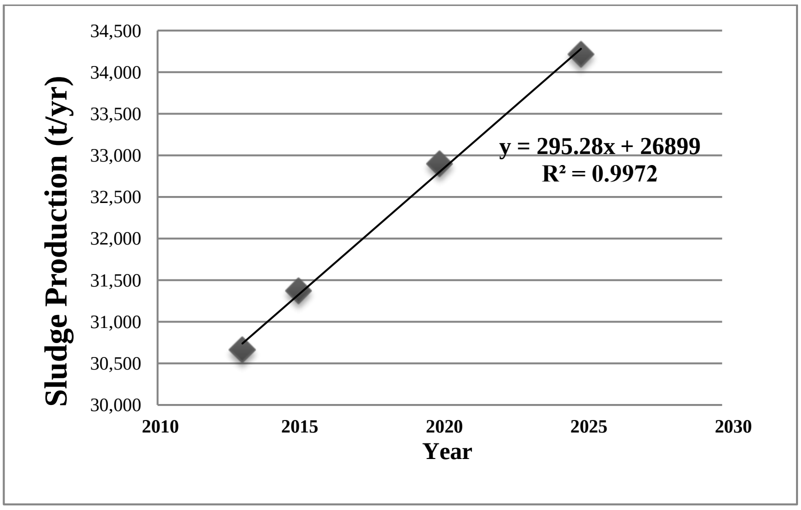

Figure 4.2: Sludge quantity projection

Table 4.2: Amount of estimated sludge production between the years 2013 and 2022 (according to regression equation in Figure 4.2)

Year	Amount of Sludge (t/yr) (100% dry matter)	Amount of Sludge (t/yr) (90% dry matter)
2013	30,738	34,153
2014	31,033	34,481
2015	31,328	34,809
2016	31,623	35,137
2017	31,919	35,465
2018	32,214	35,793
2019	32,509	36,121
2020	32,805	36,450
2021	33,100	36,778
2022	33,395	37,106

4.2. Determination of Optimal Sludge Dose to be Applied to Arable Lands

While determining the optimum sludge dose to be applied to arable lands, agronomic rate for nitrogen must be calculated. U.S. Environmental Protection Agency (U.S. EPA) defines agronomic rate as "the amount of biosolids needed in order to supply the recommended amount of nitrogen for a particular type of crop without allowing excess nitrogen to migrate below the root zone and into the groundwater" (U.S. EPA, 1999b). In U.S., the application rate to agricultural lands differs between 0.2-7 t/da per year according to plant species, sludge characteristics, etc. Typical application rate is 1.0 t/da per year (U.S. EPA, 1995). In Spain, 0.5-1.0 t/da dry weight of sludge is being used in agriculture per year (Eljarrat et al., 1997).

Soil nitrogen data or the data indicating the residual nitrogen content mineralized in soil after previous sludge land applications are needed during agronomic rate calculations in order to understand the nitrogen content available for crops (U.S. EPA, 1999c). However, there is no data available for soil nitrogen/nutrient analyzed in study area, Ankara. For this reason, an optimal dose was determined after getting the opinions of professors from Faculty of Agriculture in Ankara University and literature studies especially conducted in fields of Turkey.

As mentioned in Section 2.6, Yalçın et al. (2011), Delibacak et al. (2009b), Bilgin et al. (2003), Göçmez (2006) and Özyazıcı and Özyazıcı (2012) had research with sludge land application and determined the effects of the applications on plant (e.g. wheat, corn, sugar beet, peanut, bean, cotton, white head cabbage, tomato) and soil properties. These studies recommended the annual application dose of 1-3 t/da dry sludge depending on their crop rotation and soil characteristics. Specifically, Bilgin et al. (2003) suggested 1-2 t/da dry weight of sludge application for crop rotation that was wheat + sugar beet + bean in the *irrigated* areas of Middle Anatolian Region of Turkey in order to have the same yield performance with optimum fertilizer dose. In this thesis study, *1 t/da dry sludge* application dose was determined as the optimal dose to be applied to non-irrigated arable lands especially considering the studies conducted in Turkey.

4.3. Determination of the Suitable Non-irrigated Arable Lands for Sludge Application

The location of the Ankara Central WWTP and the distribution of total non-irrigated arable lands in Ankara are provided in Figure 4.3. According to this figure, the non-irrigated arable lands are uniformly distributed in Ankara. However, the northern parts of Ankara do not include non-irrigated arable lands since they are not very suitable for agricultural activities due to high altitude and mountainous structure.

Figure 4.4 presents the sensitive areas for sludge land utilization including water courses and water bodies, railways and public roads, inland marshes, sand plains, residential areas and their distribution among non-irrigated arable lands.

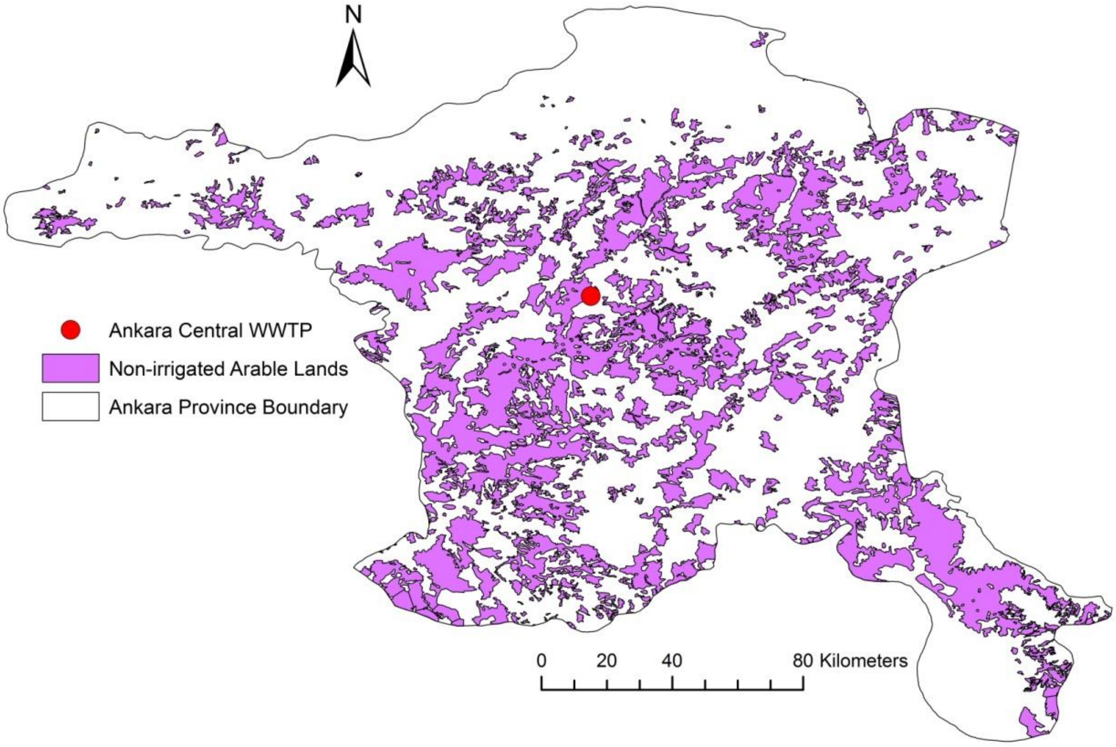

Figure 4.3: The distribution of non-irrigated arable lands in Ankara

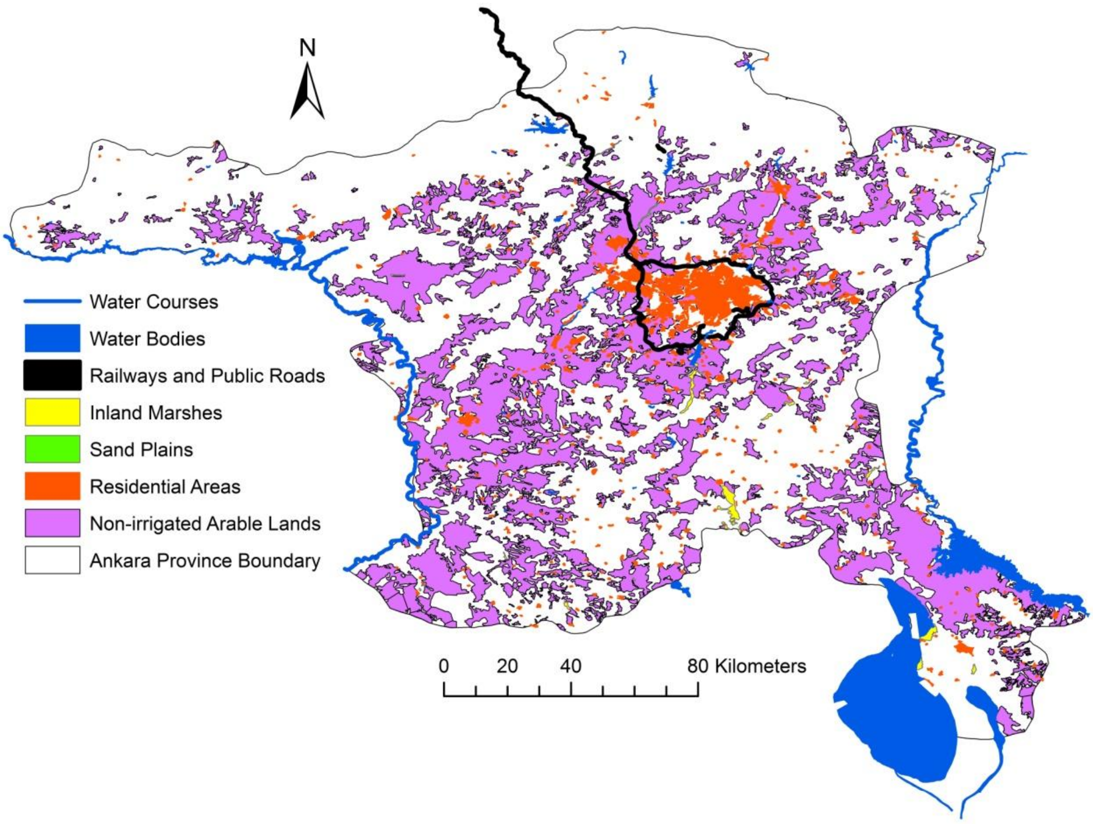

Figure 4.4: Sensitive areas in the study

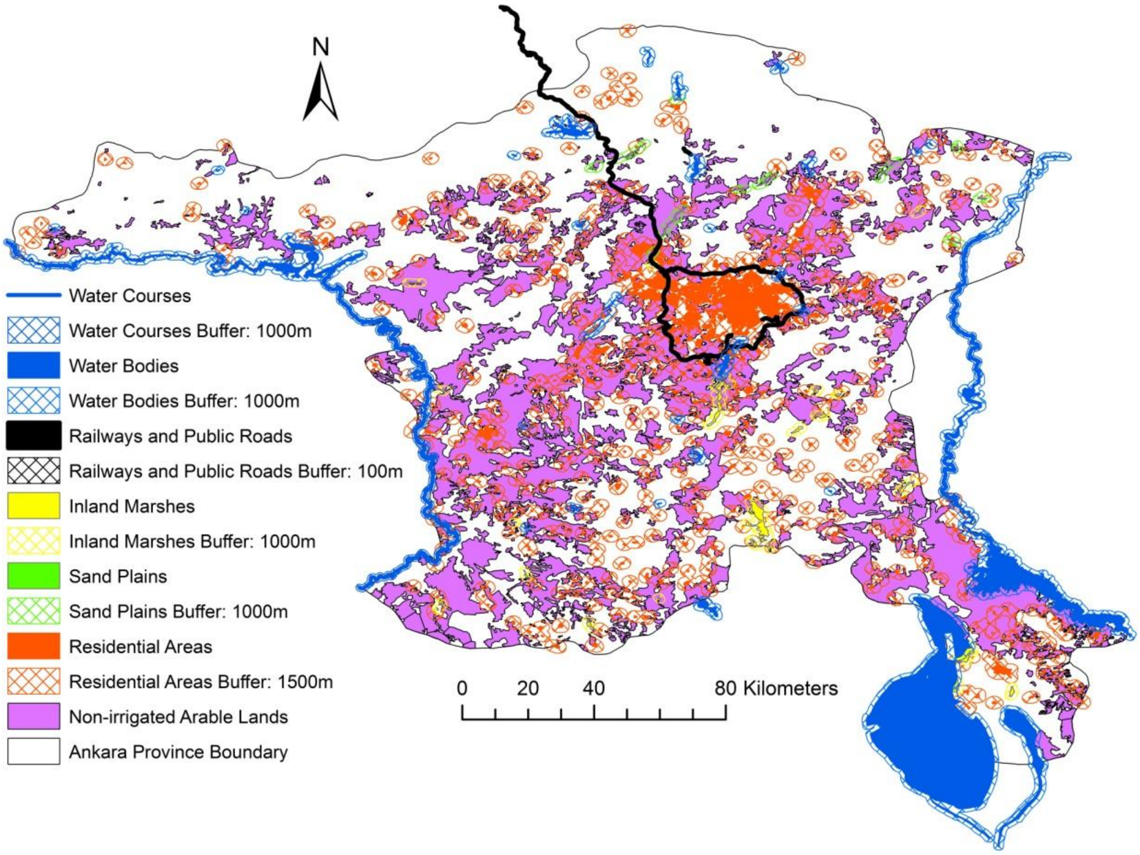

Figure 4.5: Buffer zone addition to sensitive areas

After buffer zones were applied to the map (Figure 4.5), the non-irrigated arable lands locating within the buffer zones were discarded from the map. Figure 4.6 presents a closer look at buffer zone extraction process. After eliminating lands placed in buffer zones which constituted 2,229,600 da of the non-irrigated arable lands, the remainder arable lands were calculated as 5,196,000 da.

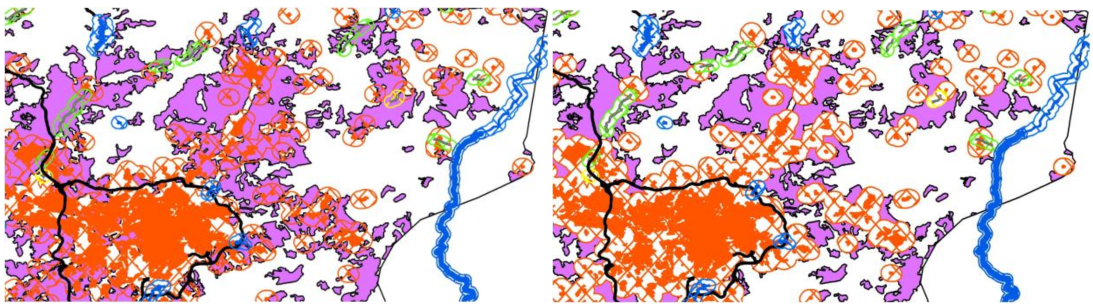

Figure 4.6: A closer look at buffer zone extraction process

The non-irrigated arable lands and the study area that were separated into grids (3*km* x 3*km*) in order to facilitate the transportation calculations is given in Figure 4.7.

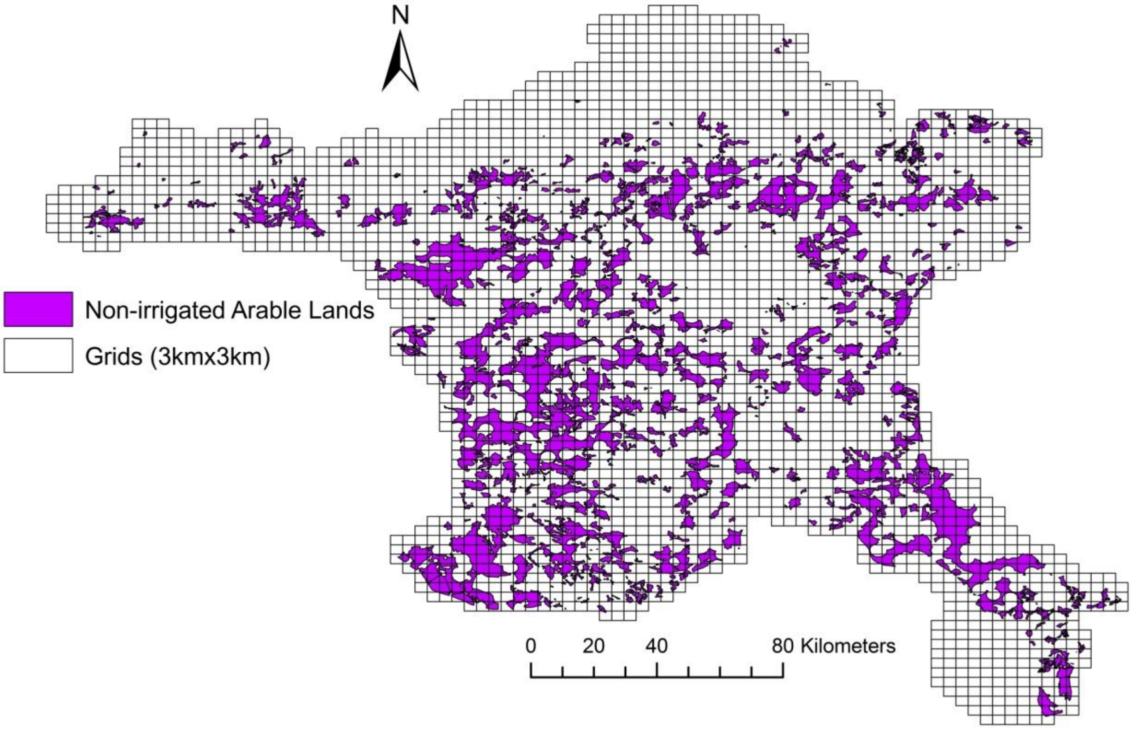

Figure 4.7: Construction of polygon grids (3*km*x3*km*) over the study site

According to the slope constraint, the non-irrigated arable lands which placed on the soils with slope greater than 11.8% were eliminated from the map. After discarding these lands whose total area was 923,250 da, total area of the remainder non-irrigated arable lands was measured as 4,272,750 da. The non-irrigated arable lands after slope constraint application is provided in Figure 4.8.

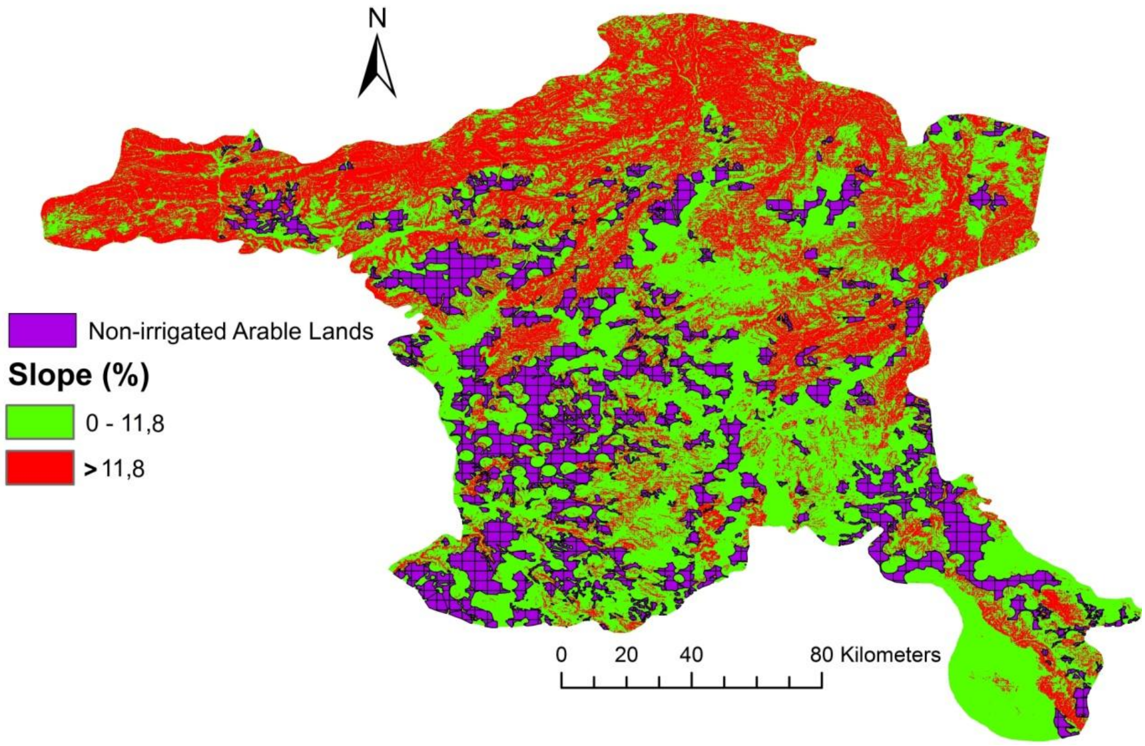

Figure 4.8: The non-irrigated arable lands after the application of slope constraint

Land use capability class constraint eliminated the Class I, II, V, VI, VII and VIII from the map. Suitable non-irrigated arable lands lying on Class III and Class IV lands are presented in Figure 4.9. After extracting these lands whose total area was 2,173,320 da, total area of the remainder non-irrigated arable lands was measured as 2,099,430 da.

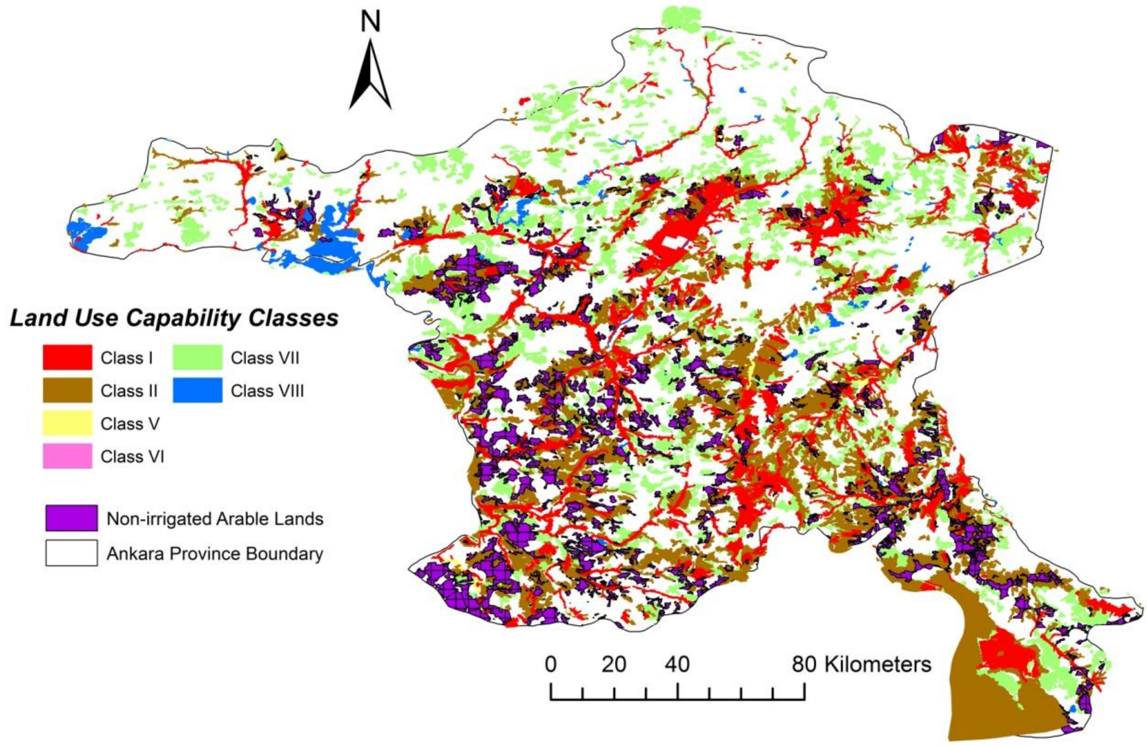

Figure 4.9: The non-irrigated arable lands after the application of land use capability classes constraint

After application of other constraints (salty or rocky soils, or soils with severe drainage properties), 227,900 da area was removed from the arable lands. The total area after this last constraint application was measured as 1,871,530 da.

All the non-irrigated arable lands remained after all the constraints can be seen in 3*km*x3*km* grid system in Figure 4.10. The placement of all the lands within the map including sensitive areas is given in Figure 4.11.

As a result, the non-irrigated arable lands presented in Figure 4.11 are close to sensitive areas in defined proximities, not placed on lands with slope greater than 12%, placed on Class III and Class IV soils, and not laid on salty or rocky soils or soils having bad drainage. The resultant areas in Figure 4.11 were considered as suitable for sludge land application.

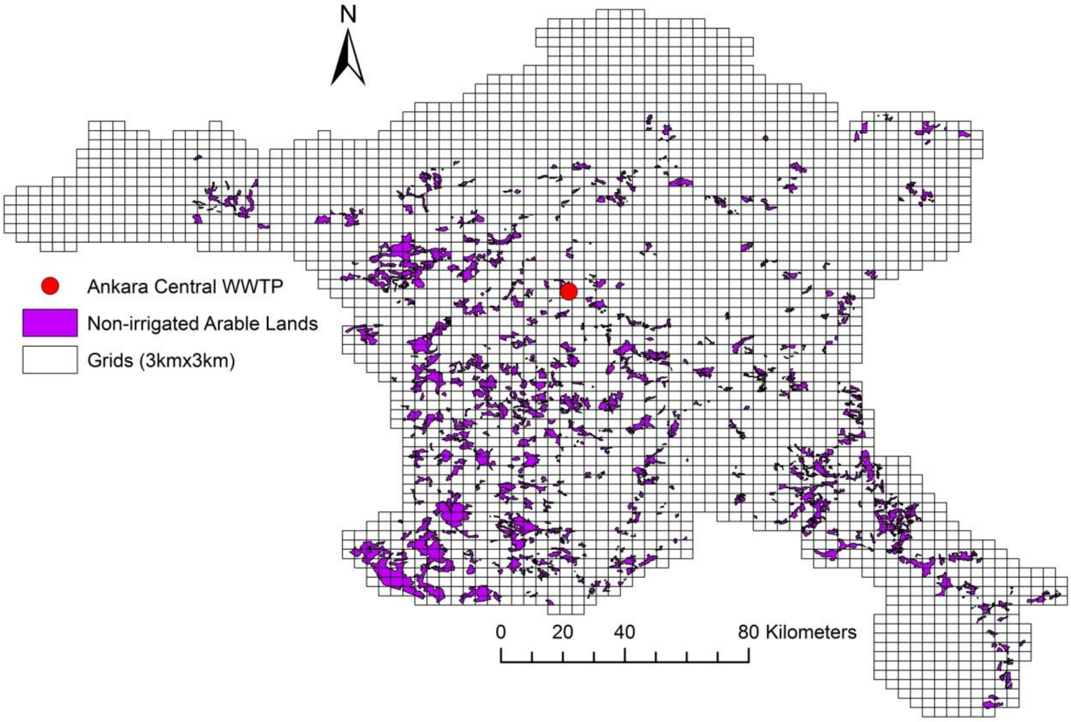

Figure 4.10: The non-irrigated arable lands in grid system after the application of all constraints

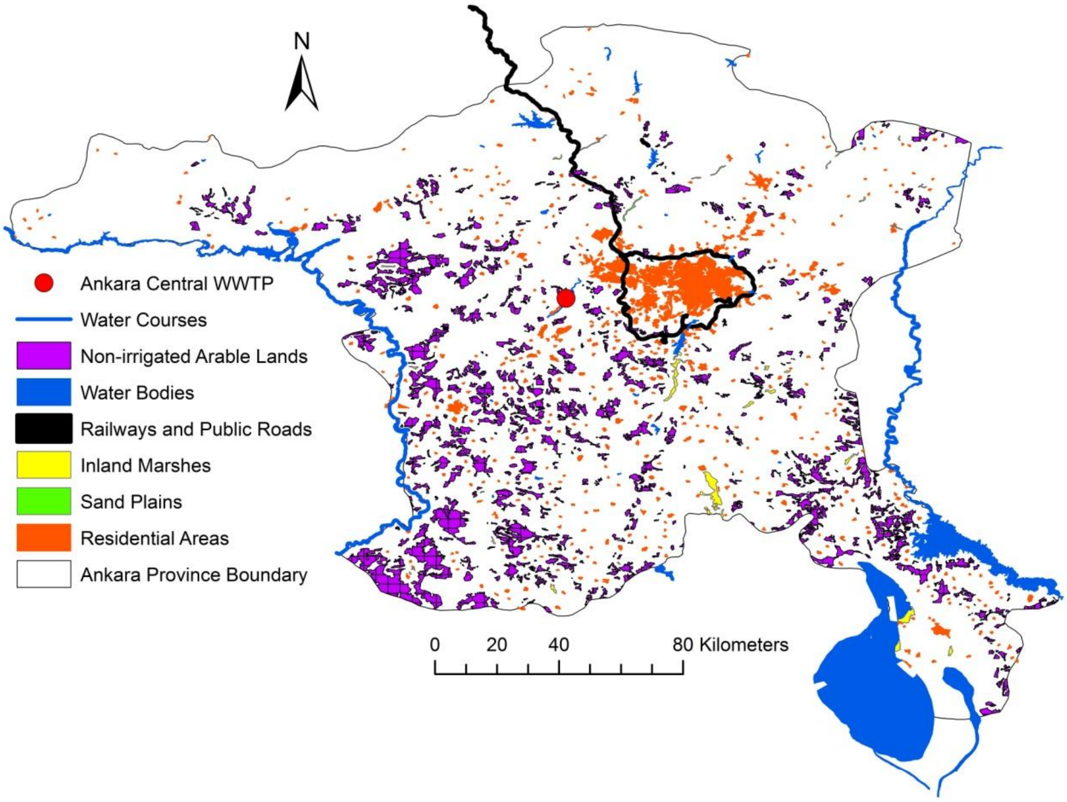

Figure 4.11: The non-irrigated arable lands with sensitive areas after the application of all constraints

The distance determination between Ankara Central WWTP and the suitable non-irrigated arable lands for sludge land application resulted in the statistical data of the non-irrigated arable land polygons given in Table 4.3. Figure 4.12 provides a closer look at the polygons and their centroids used in distance measurements.

Table 4.3: The statistical data of the non-irrigated arable land polygons

	Value
Number of polygons	1,051
Average area (da/grid)	1,781
Minimum area (da/grid)	6.3
Maximum area (da/grid)	9,000
Total area (da)	**1,871,530**

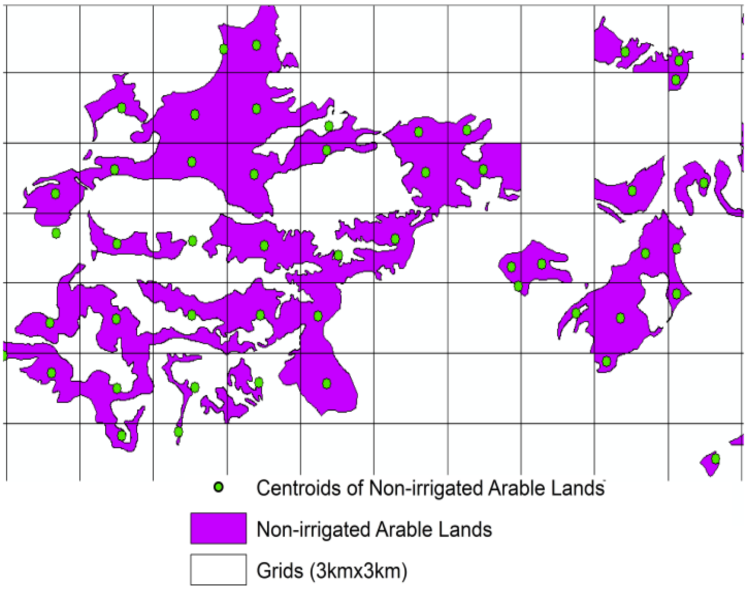

Figure 4.12: A closer look at the polygons and their centroids

Figure 4.13 shows the centroids of all suitable non-irrigated lands and Ankara Central WWTP.

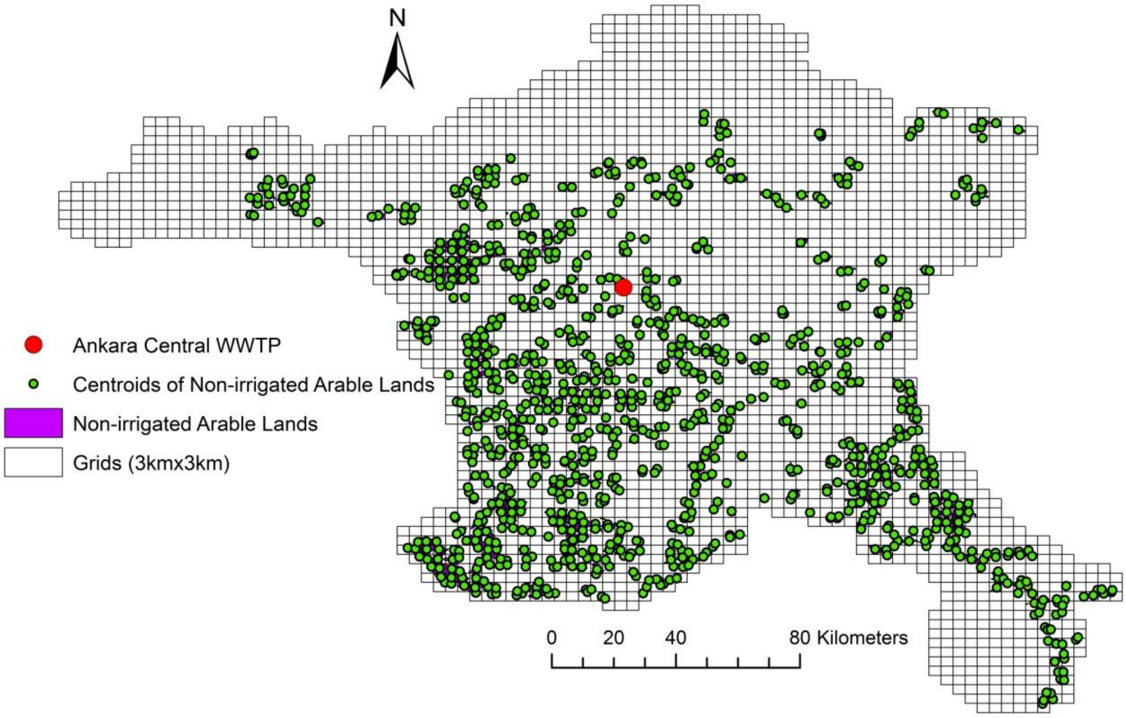

Figure 4.13: The centroids distribution of non-irrigated arable lands

4.4. Results of the Optimization Model

After the transport cost-based optimization model was run, the results obtained are presented in Table 4.4. This table shows the amount of sludge with 90% dry matter to be applied to suitable non-irrigated arable lands, minimum, average and maximum distances to be travelled in each year, and total transportation costs and number of round-trips for different capacity trucks required for sludge land application in each year.

Table 4.4: Optimization Model Results

Year	Amount of Sludge to be Applied (t)	Distance to be Travelled (km)			Total Transportation Cost (TL/yr) for Trucks with Different Capacities			Number of round-trips for Trucks with Different Capacities		
		Minimum	Average	Maximum	10 t	16 t	24 t	10 t	16 t	24 t
2013	34,153	3.2	9.1	13.2	61,211	55,825	45,025	3,427	2,148	1,435
2014	34,481	13.2	15.8	19.2	112,499	102,462	82,658	3,462	2,167	1,448
2015	34,809	19.2	21.0	22.6	146,943	134,136	108,204	3,347	2,100	1,403
2016	35,137	21.6	23.4	24.3	163,589	148,926	120,335	3,425	2,143	1,434
2017	35,465	23.8	25.2	26.0	184,535	167,858	135,554	3,554	2,222	1,486
2018	35,793	26.0	27.5	29.3	202,752	185,176	149,069	3,589	2,253	1,502
2019	36,121	29.3	30.3	31.2	213,373	194,352	156,961	3,463	2,168	1,450
2020	36,450	31.2	32.0	32.6	239,599	217,954	175,841	3,653	2,284	1,526
2021	36,778	32.6	33.9	34.6	255,579	232,732	187,473	3,686	2,307	1,539
2022	37,106	34.6	35.3	35.8	269,750	245,709	198,097	3,720	2,329	1,555

The graph showing the total transportation costs required for transportation of sludge with different truck capacities in years 2013-2022 is provided in Figure 4.14.

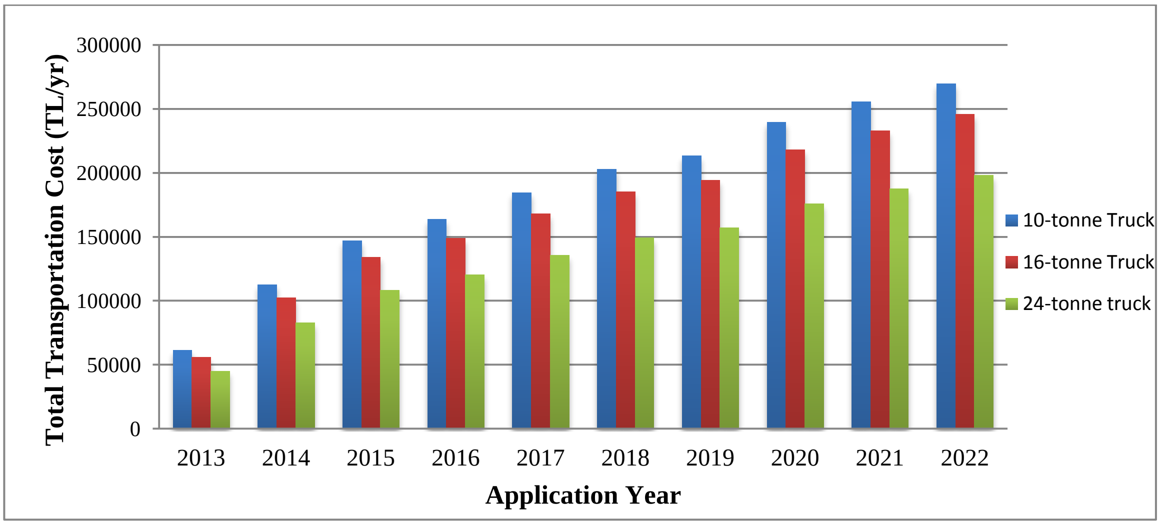

Figure 4.14: Total transportation costs for different truck capacities (2013-2022)

The percentages of the lands received sludge among total suitable non-irrigated arable lands are listed in Table 4.5. Figure 4.15 indicates the minimum, average and maximum distances to be travelled between 2013 and 2022.

Table 4.5: The percentages of lands received sludge among total suitable non-irrigated arable lands

Year	Percentage of the lands received sludge among total suitable non-irrigated arable lands (%)
2013	1.64
2014	1.66
2015	1.67
2016	1.69
2017	1.71
2018	1.72
2019	1.74
2020	1.75
2021	1.77
2022	1.78
TOTAL	**17.1**

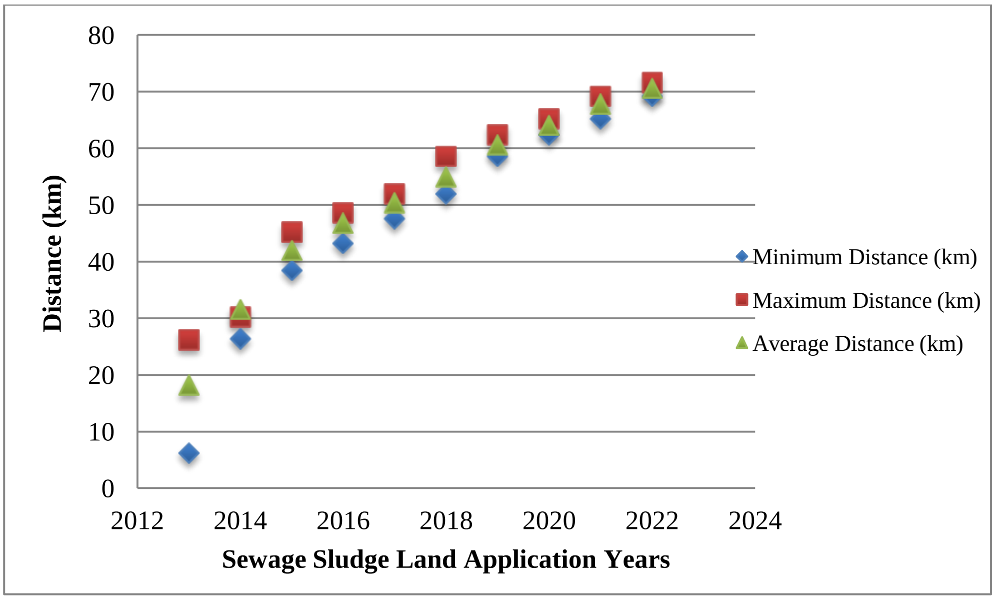

Figure 4.15: Round-trip distances to be travelled between 2013 and 2022

According to the ten-year model results, all the non-irrigated arable lands receiving sludge are given in Figure 4.16 and Figure 4.17 (closer view).

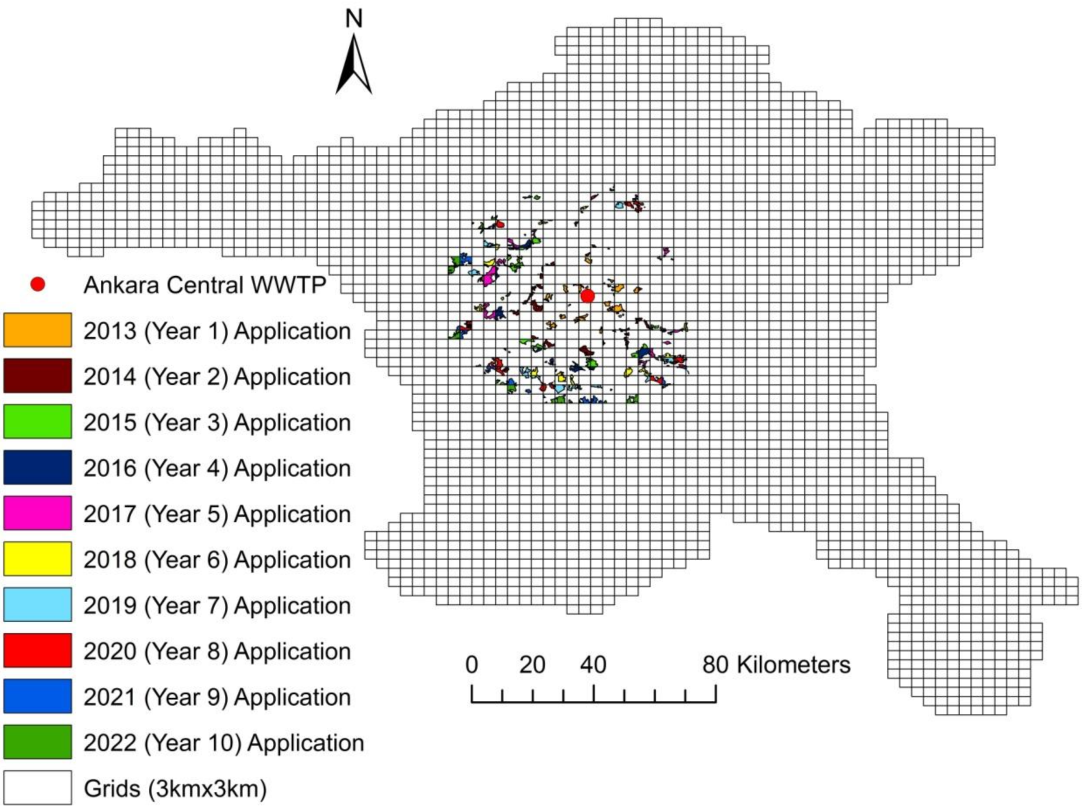

Figure 4.16: The placement of non-irrigated arable lands receiving sewage sludge between 2013 and 2022

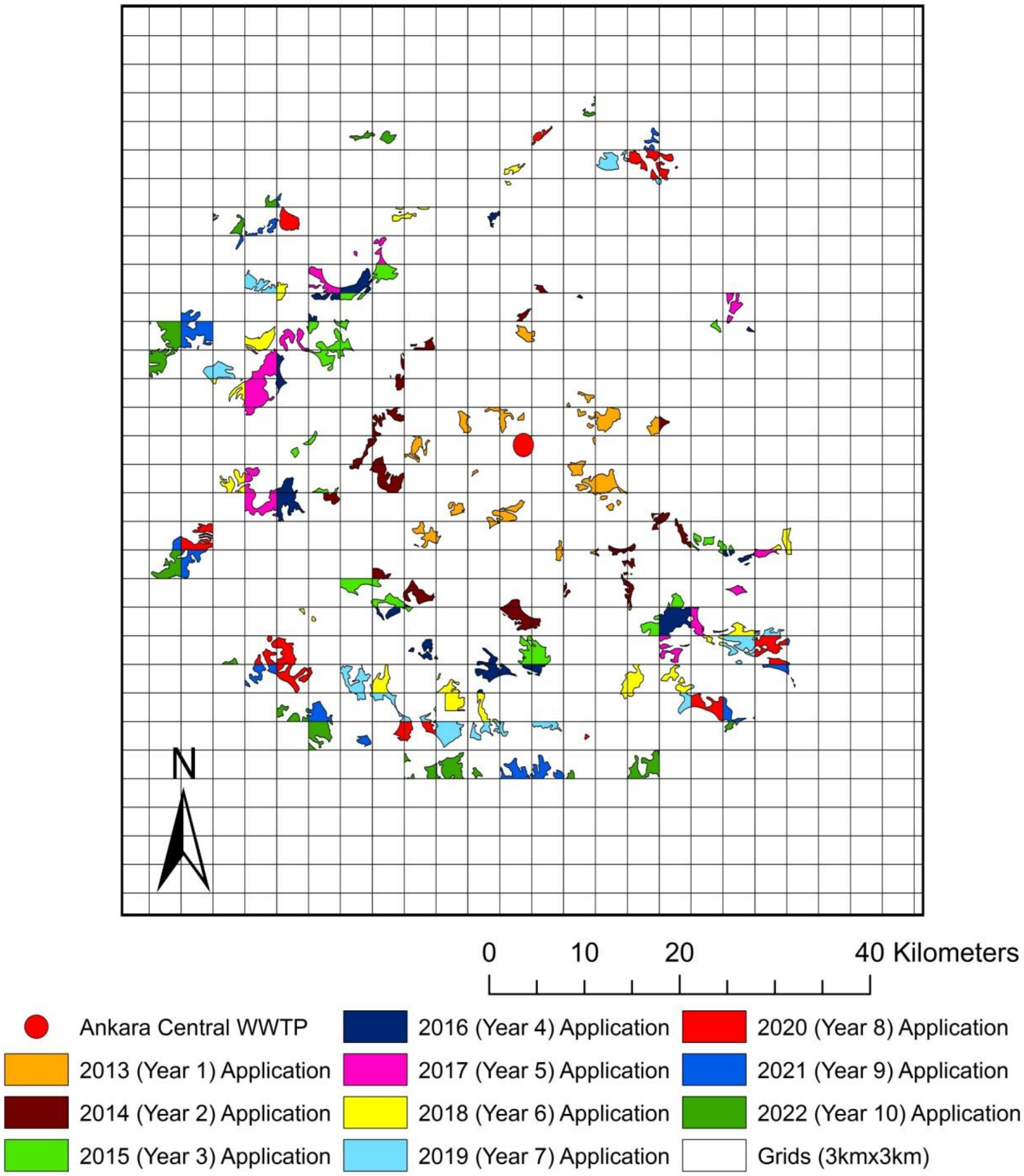

Figure 4.17: A closer look at the non-irrigated arable lands receiving sewage sludge between 2013 and 2022

The placement of the non-irrigated arable lands receiving sludge and their closer views can be seen in Figure 4.18 and Figure 4.19 (for 2013); Figure 4.20 and Figure 4.21 (for 2014); Figure 4.22 and Figure 4.23 (for 2015); Figure 4.24 and Figure 4.25 (for 2016); Figure 4.26 and Figure 4.27 (for 2017); Figure 4.28 and Figure 4.29 (for 2018); Figure 4.30 and Figure 4.31 (for 2019); Figure 4.32 and Figure 4.33 (for 2020); Figure 4.34 and Figure 4.35 (for 2021); Figure 4.36 and Figure 4.37 (for 2022).

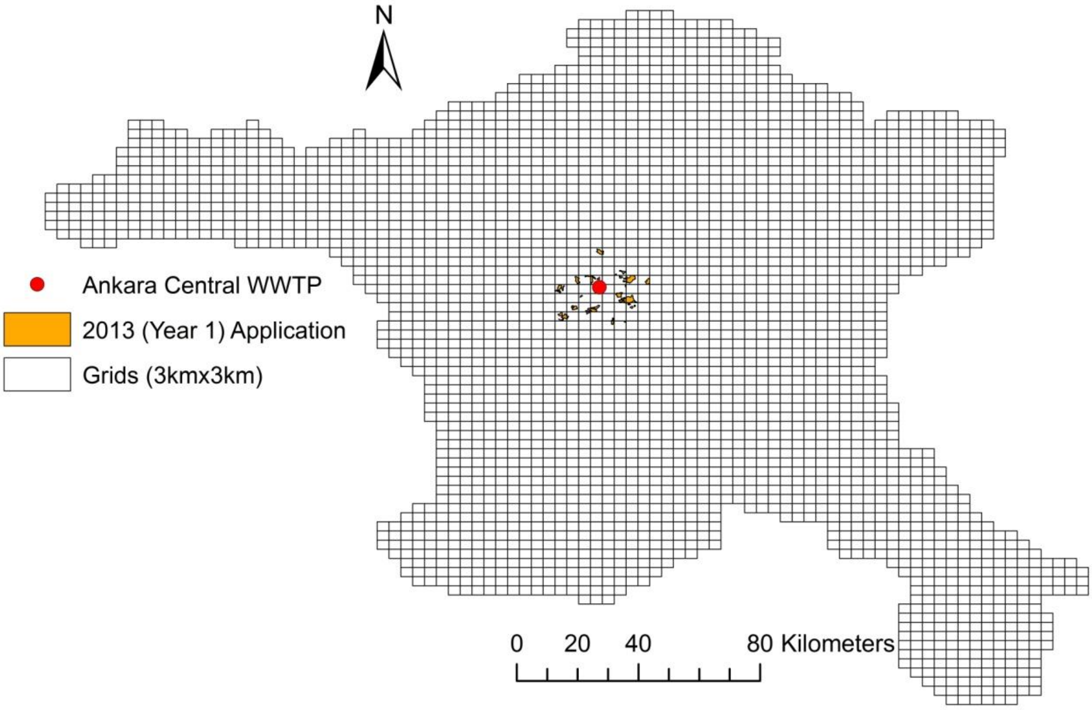

Figure 4.18: The placement of non-irrigated arable lands receiving sewage sludge in 2013

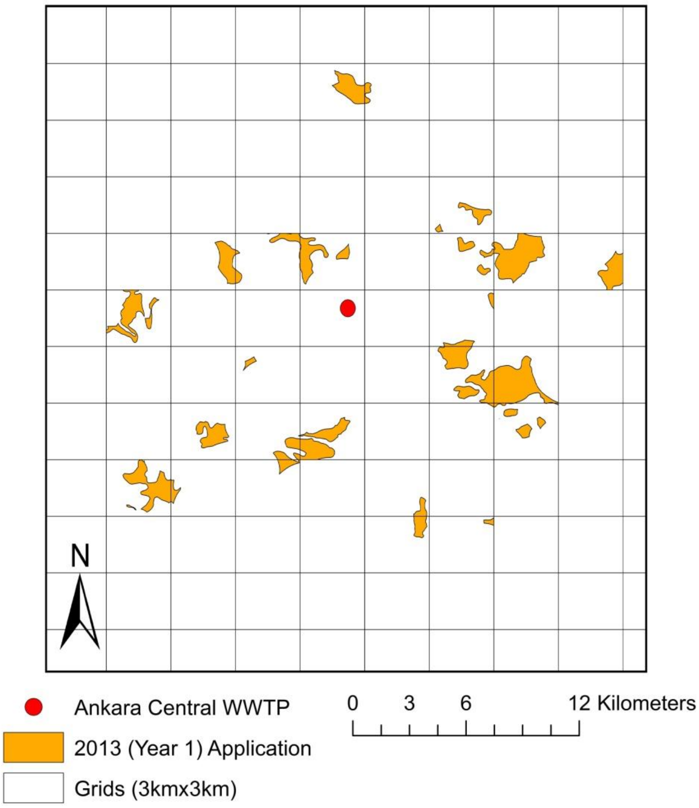

Figure 4.19: A closer look at the non-irrigated arable lands receiving sewage sludge in 2013

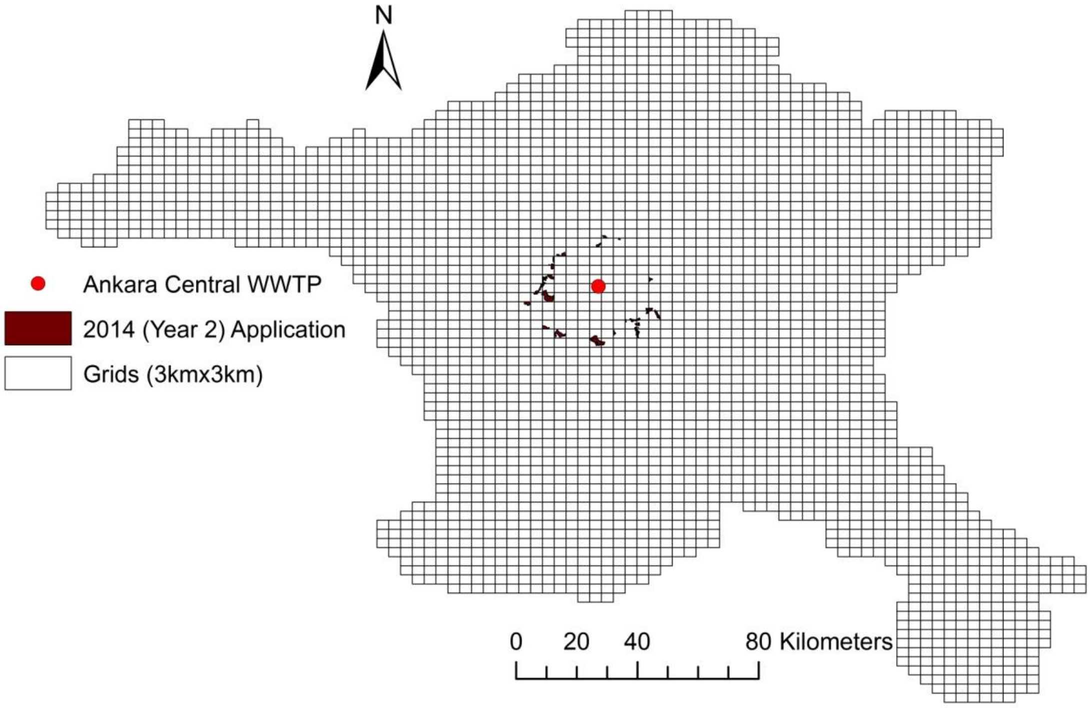

Figure 4.20: The placement of non-irrigated arable lands receiving sewage sludge in 2014

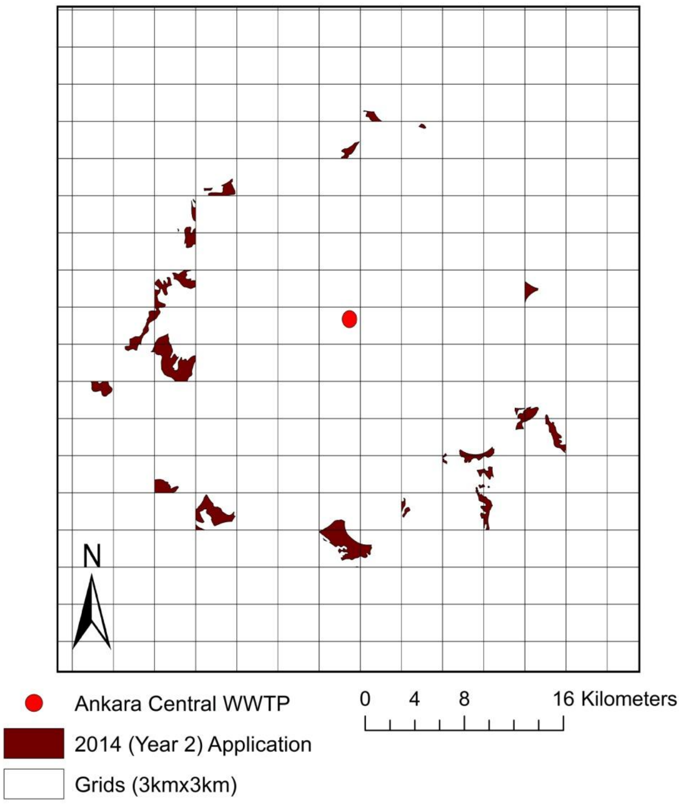

Figure 4.21: A closer look at the non-irrigated arable lands receiving sewage sludge in 2014

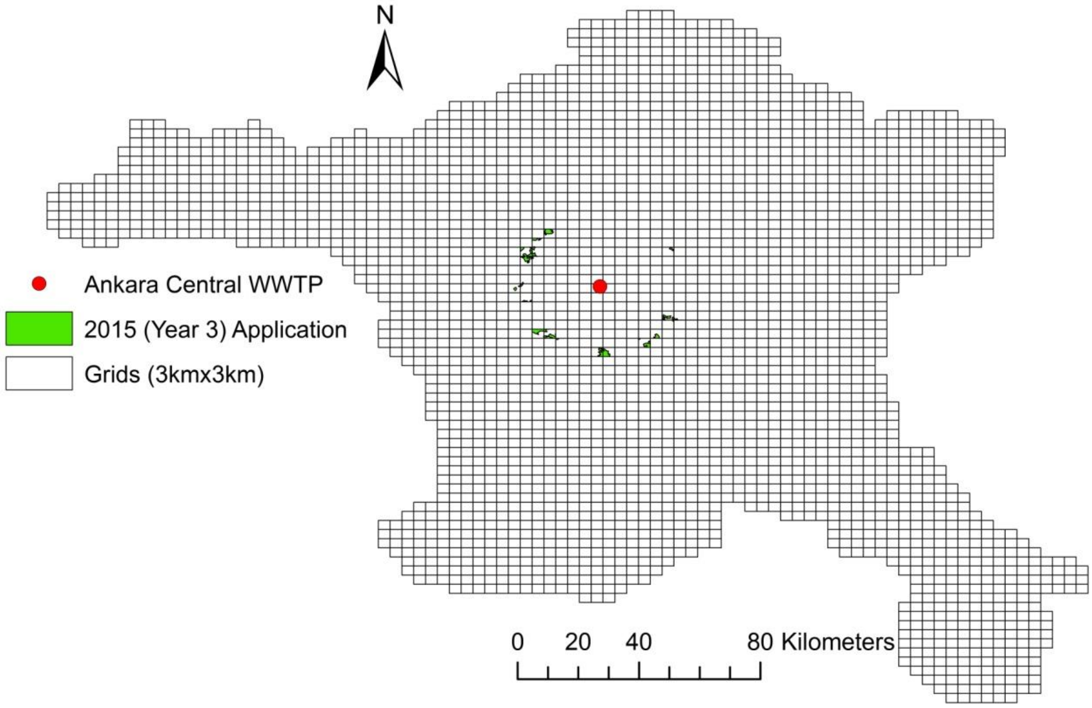

Figure 4.22: The placement of non-irrigated arable lands receiving sewage sludge in 2015

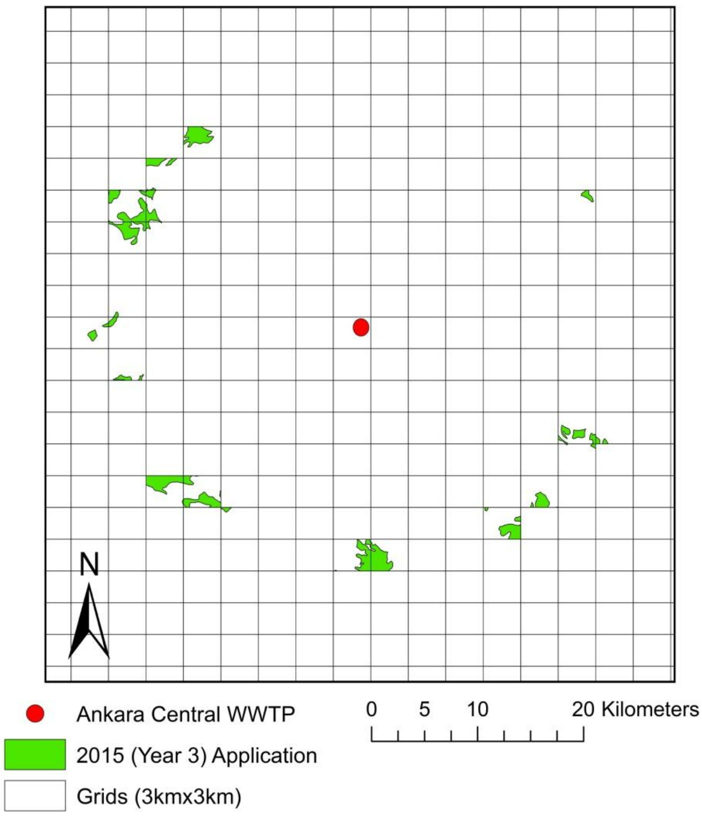

Figure 4.23: A closer look at the non-irrigated arable lands receiving sewage sludge in 2015

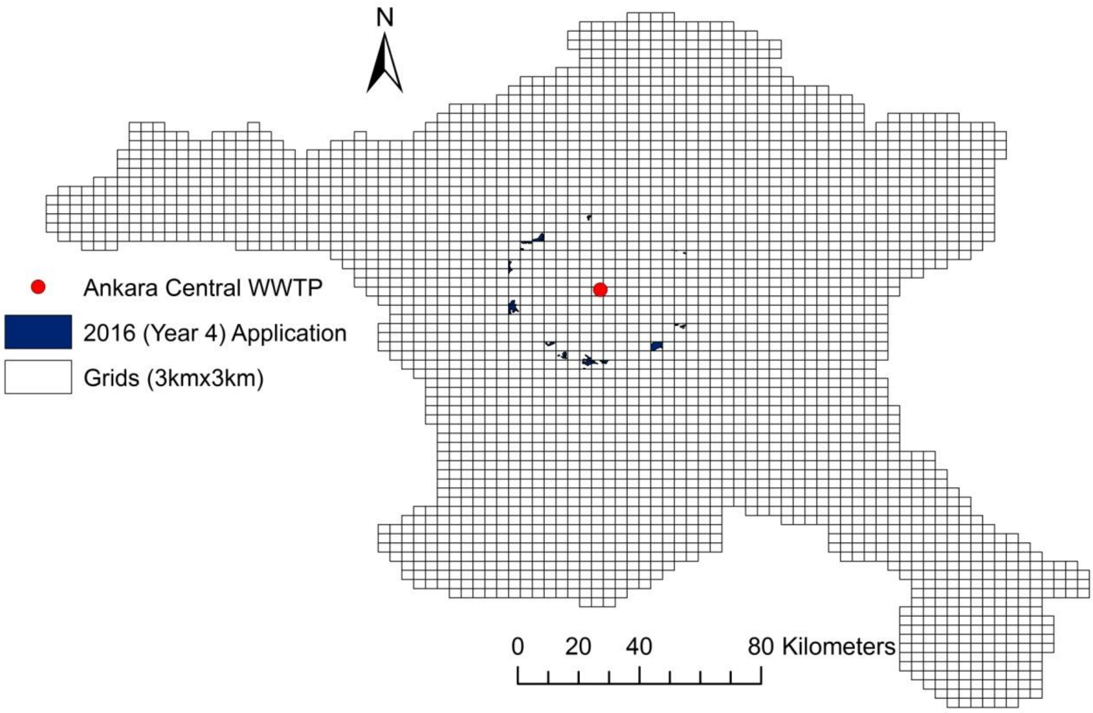

Figure 4.24: The placement of non-irrigated arable lands receiving sewage sludge in 2016

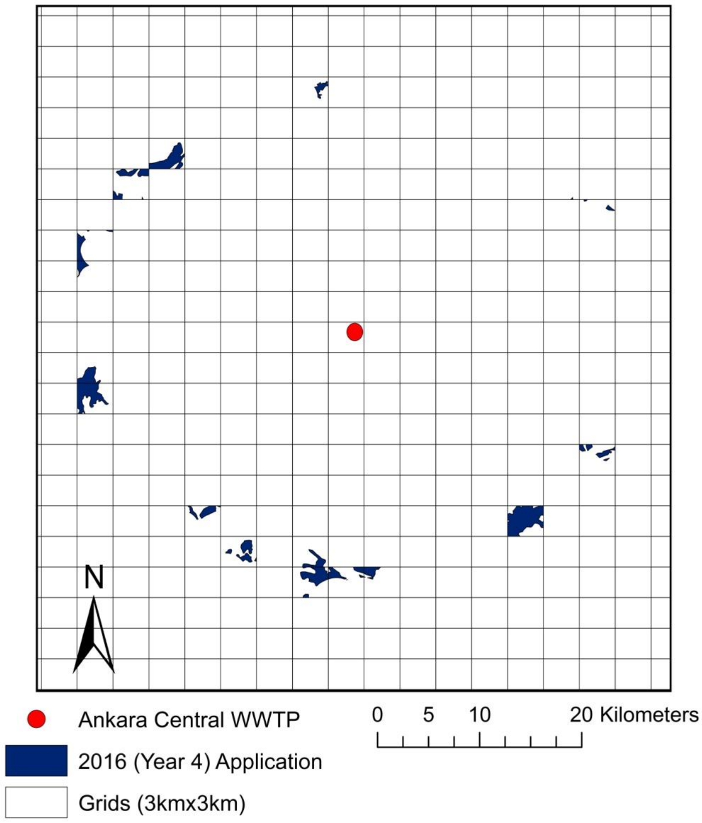

Figure 4.25: A closer look at the non-irrigated arable lands receiving sewage sludge in 2016

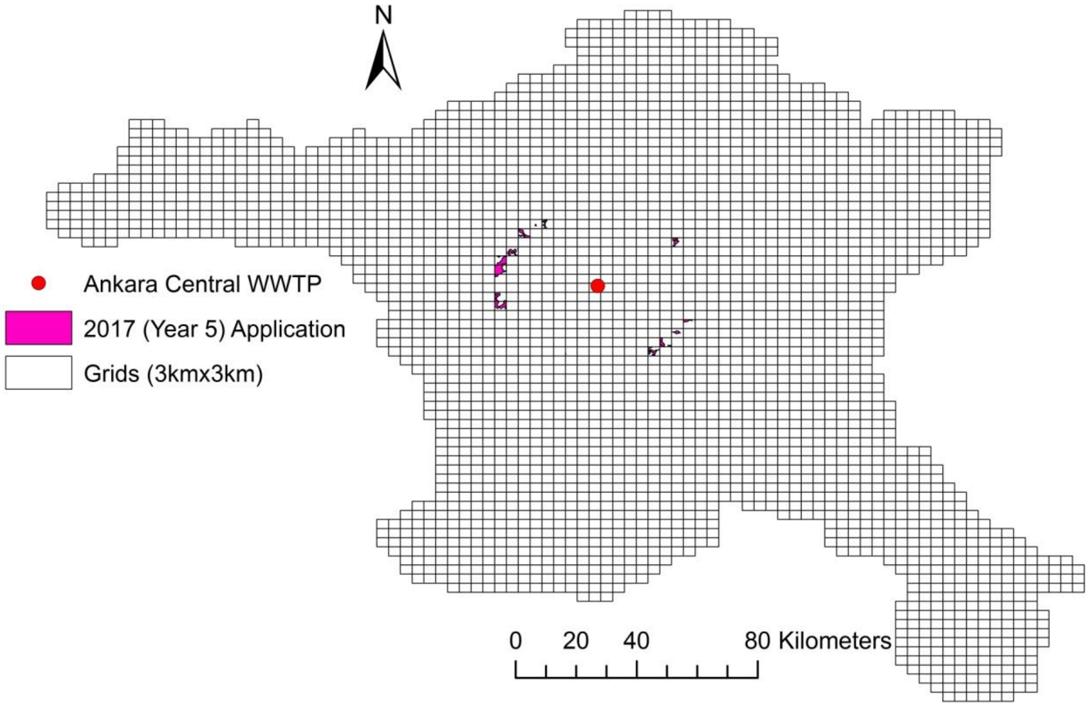

Figure 4.26: The placement of non-irrigated arable lands receiving sewage sludge in 2017

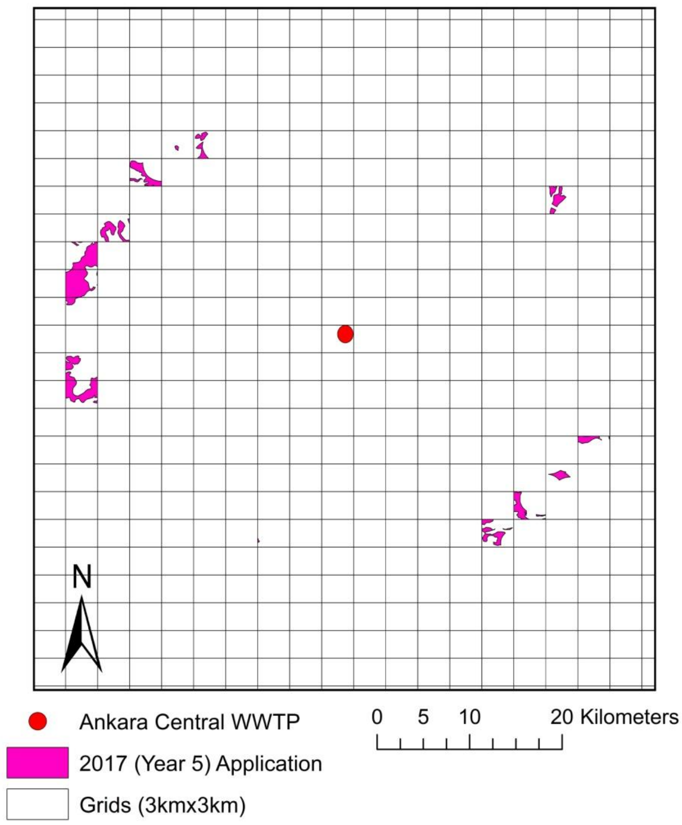

Figure 4.27: A closer look at the non-irrigated arable lands receiving sewage sludge in 2017

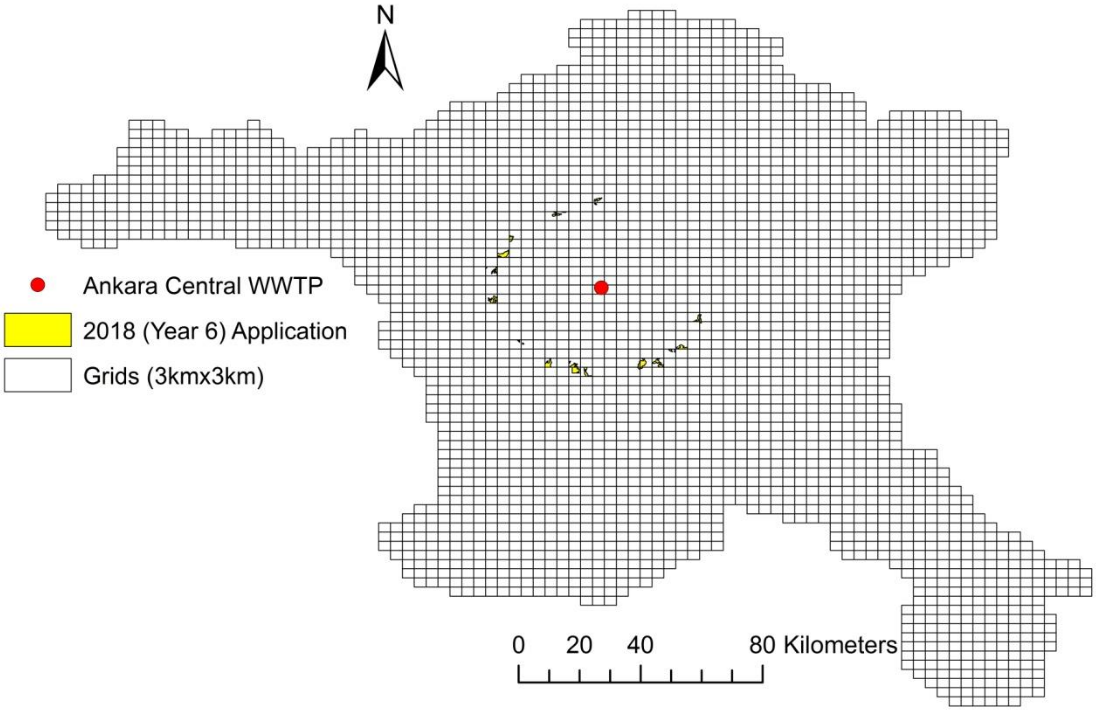

Figure 4.28: The placement of non-irrigated arable lands receiving sewage sludge in 2018

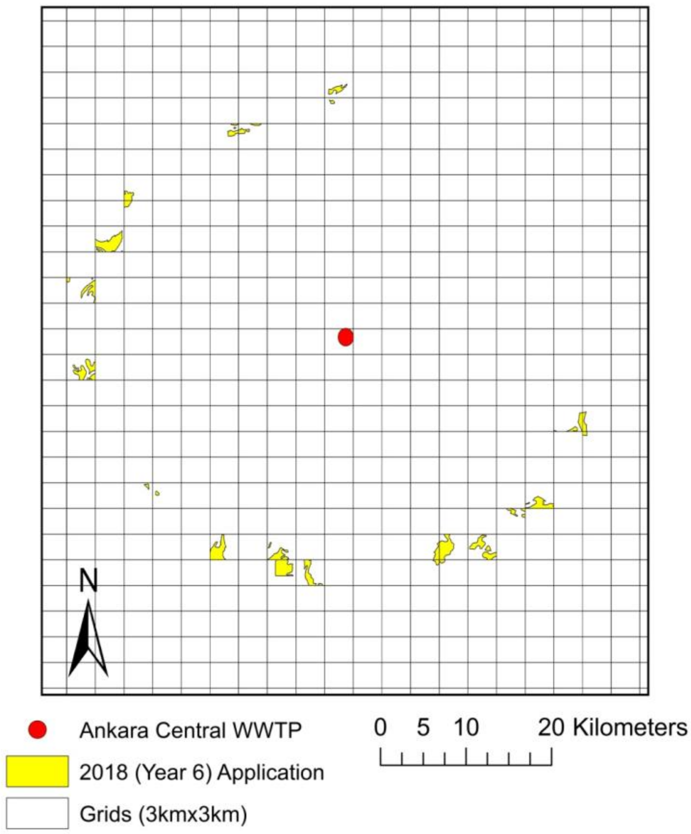

Figure 4.29: A closer look at the non-irrigated arable lands receiving sewage sludge in 2018

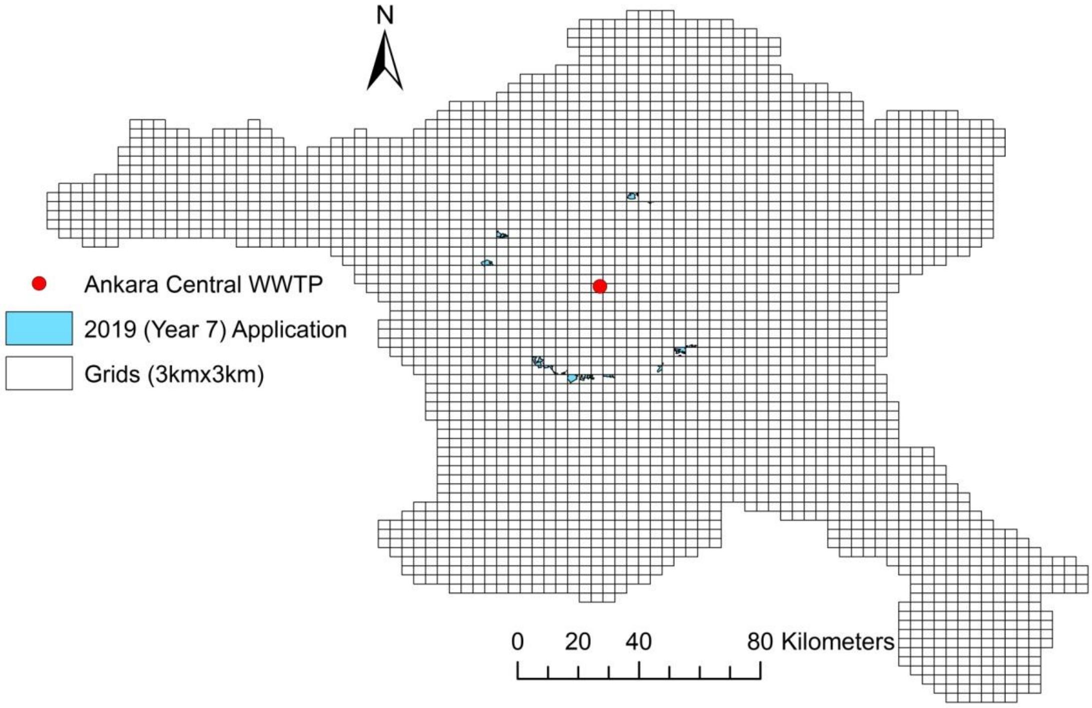

Figure 4.30: The placement of non-irrigated arable lands receiving sewage sludge in 2019

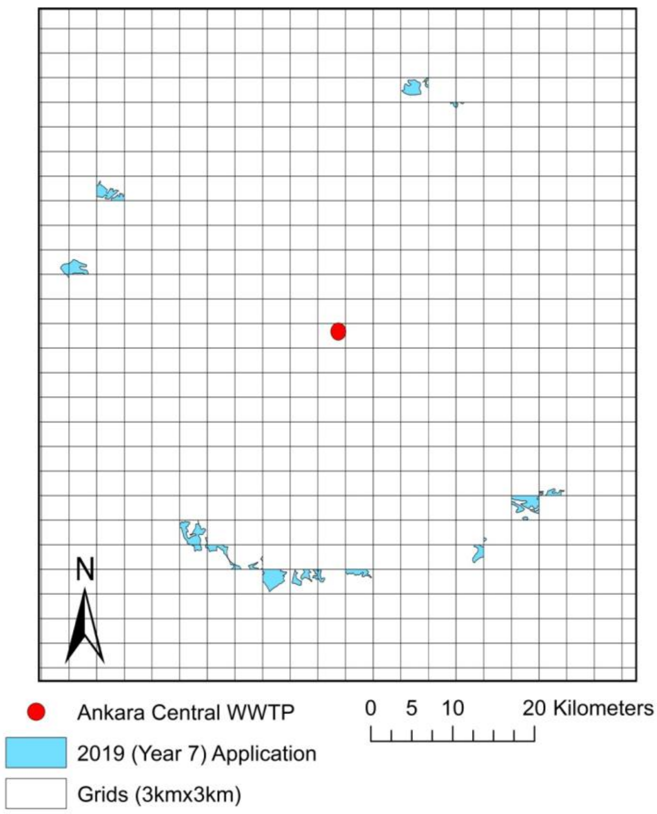

Figure 4.31: A closer look at the non-irrigated arable lands receiving sewage sludge in 2019

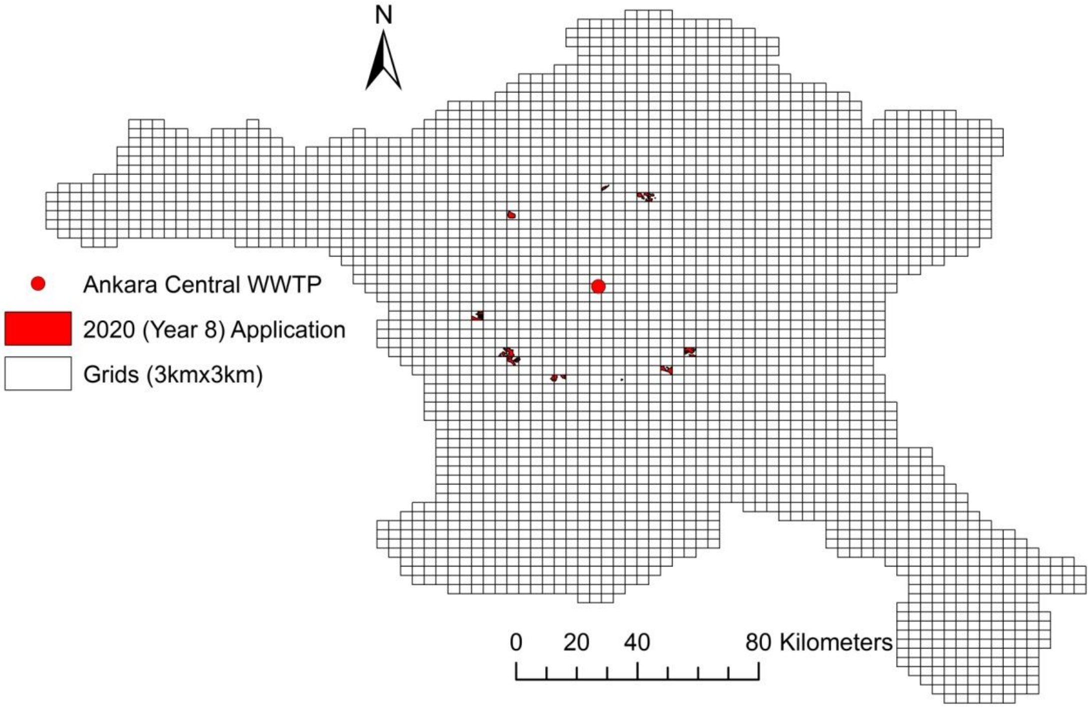

Figure 4.32: The placement of non-irrigated arable lands receiving sewage sludge in 2020

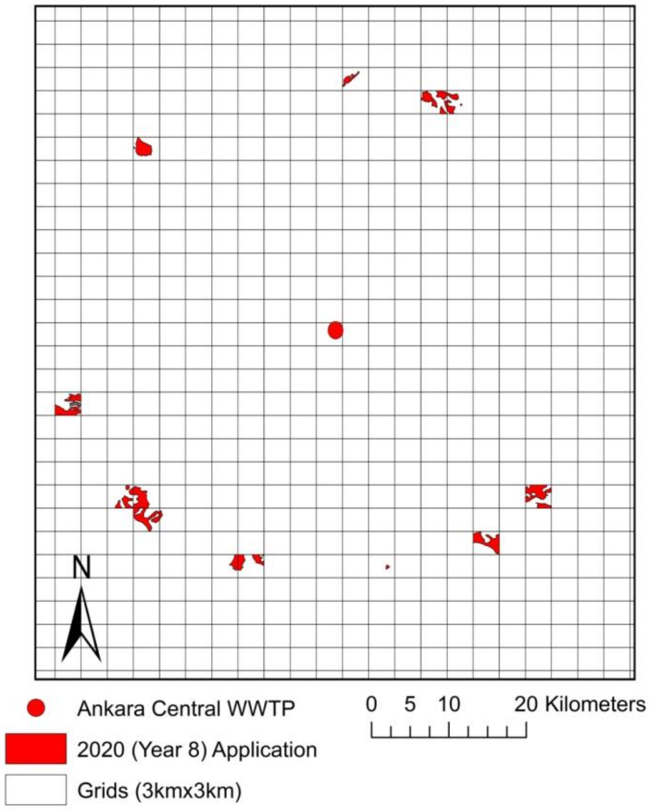

Figure 4.33: A closer look at the non-irrigated arable lands receiving sewage sludge in 2020

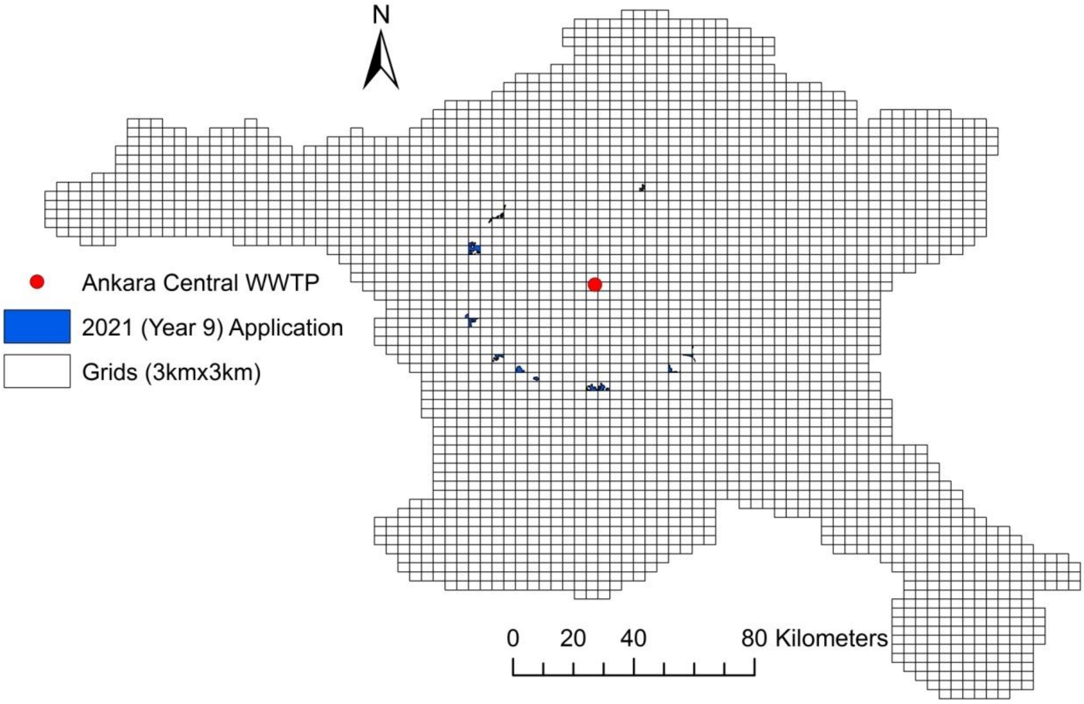

Figure 4.34: The placement of non-irrigated arable lands receiving sewage sludge in 2021

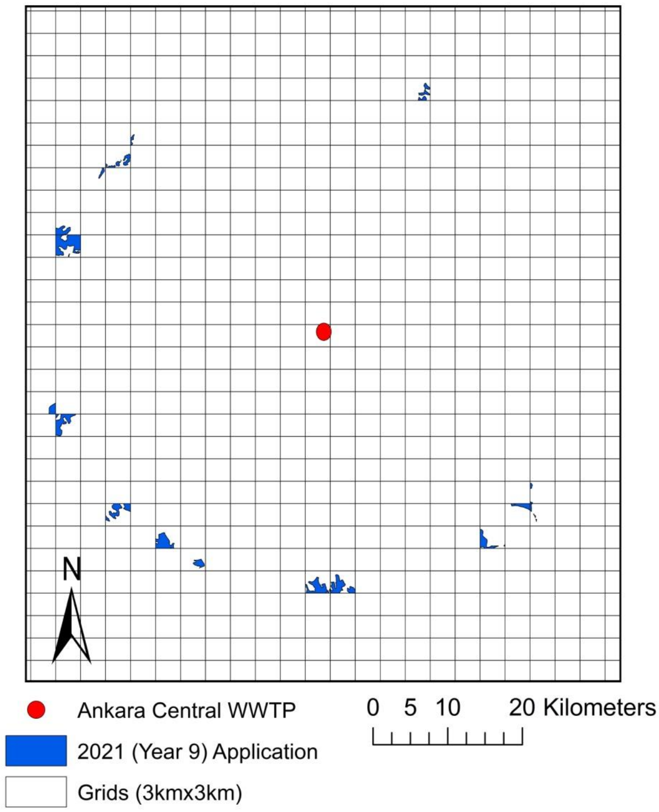

Figure 4.35: A closer look at the non-irrigated arable lands receiving sewage sludge in 2021

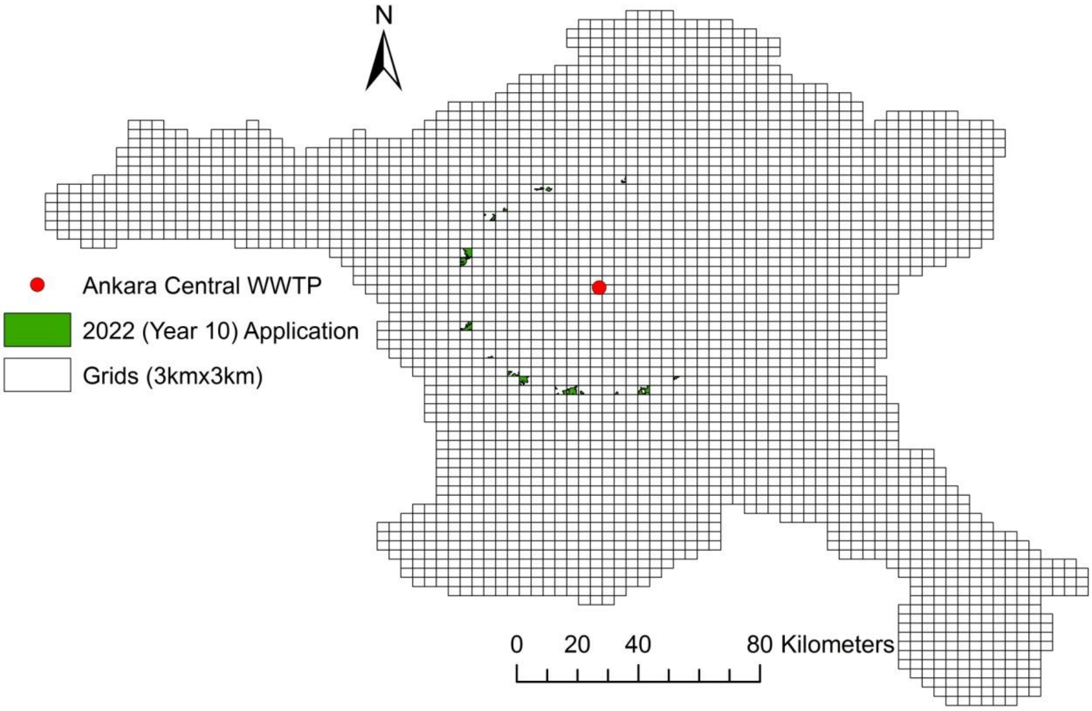

Figure 4.36: The placement of non-irrigated arable lands receiving sewage sludge in 2022

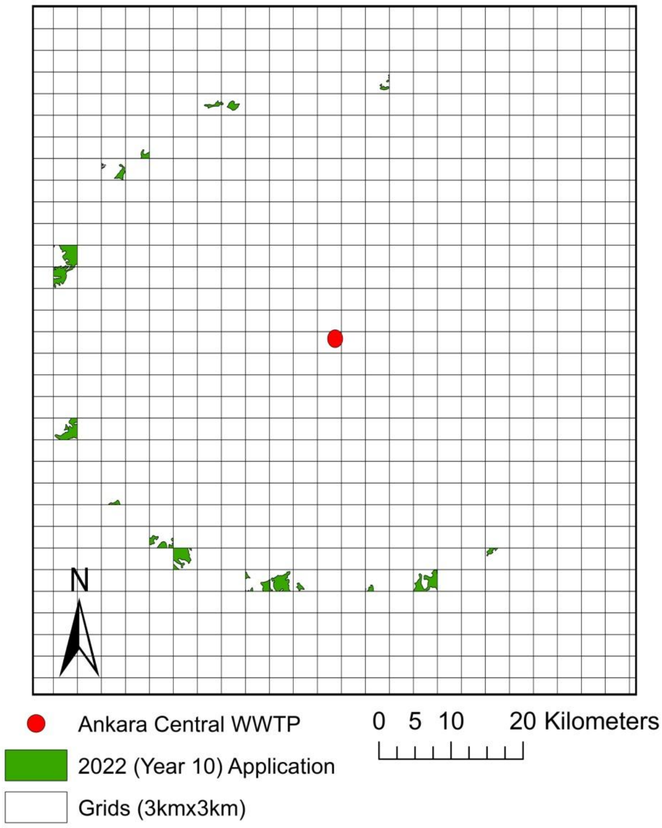

Figure 4.37: A closer look at the non-irrigated arable lands receiving sewage sludge in 2022

4.5. Discussion of the Optimization Model Results and Implications for Ankara

The constructed transport cost-based optimization model is able to simulate the optimization of sewage sludge flows to the appropriate non-irrigated arable lands in Ankara while considering the set of constraints.

The optimization model results showed that the sludge allocation to non-irrigated arable lands started from the lands closer to the Ankara Central WWTP. Since the non-irrigated arable lands that had received sludge would not receive any sludge within 10-year period, the model applied sludge to the latter closer lands of which received sludge in each year. For this reason, the overall lands receiving sludge in a year is round shaped. In this 10-year study, only 17.1% of the non-irrigated arable lands suitable for land application of sludge could get sewage sludge although 75% of the total arable lands were eliminated due to their improper locations or characteristics. This indicated that non-irrigated arable lands in Ankara have a significant potential for the agricultural use of sewage sludge. Ankara sludge is already stabilized, satisfying this criterion of Turkish regulations. Assuming that it also meets the heavy metal, organic pollutants and microbiological criteria of regulation, results of this study shows that in 10 years only 17.1% of the suitable non-irrigated arable lands is used for land application of sludge. With a very rough projection, it seems that for 50 years in Ankara the same land will not be used for 1 t/da dry sludge application. This is an important finding to assess the potential beneficial use of sludge in Turkey as well as to dispute different perceptions between different institutions and sectors for land application of sludge in Turkey.

In the study, as the truck capacity increased, the total transportation costs decreased due to diminishing numbers of round trips required to transport sludge to non-irrigated arable lands. 24 tonne-truck was resulted as the most cost-effective truck capacity among the other truck capacities. The number of trips was dependent on the amount of sludge to be transported, the rate of truck fullness was not an important criterion for their number. For example, a 10-tonne truck made a round trip whether it carried 10 tonnes of sludge or 1 tonne of sludge. For this reason, the number of round trips might not change as the amount of sludge increases depending on the years.

In this study, there were some deficient data. The knowledge of the nitrogen data of Ankara soils might have resulted in an accurate determination of optimal sewage sludge dose to be applied to arable lands. Therefore, more correct transportation costs could be obtained.

CHAPTER 5

SUMMARY & CONCLUSION

Since landfilling and incineration create environmental concerns, land application remains to be a sustainable and cost effective method for sludge disposal. For this purpose, this study aimed to estimate the land application possibility of sludge produced in a metropolitan city in Turkey, Ankara, to assess whether land available is sufficient for the land disposal of all sludge generated in Ankara.

This study is the first study carried out in Turkey that the suitability of the arable lands for sewage sludge land application through a spatial analysis were investigated and a transport cost-based optimization model to minimize the transportation costs related to land application of municipal sewage sludge was developed.

The non-irrigated arable lands were chosen as the agricultural areas to apply sludge due to their lower potential of heavy metal and nutrient leaching potential to the groundwaters. The land constraints including sensitive areas, slope, land use capability classes and other constraints (e.g. salty and rock soils, and soils with bad drainage properties) were evaluated by using Geographic Information Systems (GIS) program and were used to eliminate the non-irrigated arable lands that sewage sludge could not be applied because of health and contamination risks. After the distances between the remaining non-irrigated arable lands and Ankara Central WWTP were measured, they were used to build the transport cost-based optimization model minimizing the transportation costs related to the land application for 10-year period (2013-2022).

The main conclusions of the study are listed below.

- The developed transport cost-based optimization model is capable of simulating the optimization of sewage sludge flows to the appropriate non-irrigated arable lands in Ankara while considering the set of constraints.

- 75% of the total non-irrigated arable lands in Ankara was eliminated due to their non-conformity to sewage sludge land applications.

- According to the optimization model, 17.1% of the total non-irrigated arable lands suitable for application received sewage sludge.

- Minimum, maximum and average distances to the centroids of non-irrigated arable land polygons in ten years were 3.2, 71.6 and 50.7 km, respectively.

- The transportation of sewage sludge requires 184,983, 168,513, 135,922 TL/yr on average within 10-year for 10, 16 and 24 tonne-trucks, respectively.

- As the truck capacity increased, the total transportation costs decreased due to lessening numbers of round trips required to transport sewage sludge to non-irrigated arable lands.

- 24 tonne-truck resulted as the most cost-effective truck capacity among the other truck capacities.

- Even though Ankara Central WWTP is the second largest WWTP in Turkey, the sludges from this plant can be managed by beneficial use by land application.

All around the world there is a concern about the land application due to its possible environmental and public health effects. Additional concern is for the potential of land contamination especially for the applications constantly done on yearly basis over a long period of time.

The results obtained from this study states that year-after-year application is not required for Ankara; such that the sludge will be applied to the same land only after about 50 years. This is the result obtained with the remaining land after all the area deemed unsuitable by the regulation are extracted. Therefore, a long-term application seems to be not a significant problem if the application routine is managed properly.

CHAPTER 6

FUTURE WORK

The nitrogen data of Ankara soils is needed for sewage sludge land application studies to determine the optimum dose of sewage sludge to be applied on each parcel of soil. Due to the non-availability of nitrogen and phosphorus data of the soil, the most conservative and appropriate dose of sludge application was selected and used in this study. If this data and road network between non-irrigated arable lands are available, due to accurate calculation of the required sludge dose and application of the right dose better distribution and more accurate calculation of the transportation costs can be obtained.

In this study, the appropriate non-irrigated arable lands were applied sewage sludge in Ankara. The model may be modified to be used by decision makers on regional scales. A regional flow management of sewage sludge may eliminate the use of organic and inorganic fertilizers or animal manures in provinces where little animal farming occurs. In addition, environmental problems happening due to improper disposal of sludges or excessive use of commercial fertilizers may be reduced.

A similar model can also be used for a country-wide application of sludge. With the use of such approaches, the potential of sludge land application in Turkey can be correctly calculated. These results may help in the formation of country-wide policies towards the land application of sludge.

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APPENDIX A

DISTRIBUTION OF LAND USE CAPABILITY CLASSES IN ANKARA