Final Report

A STRATEGIC APPROACH FOR SITE SELECTION OF WASTE FACILITIES IN MEXICO

| SYNTHESIS PROJECT 2020 |

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Synthesis Project 2020
for the Master Geomatics and the Built Environment
at Delft University of Technology

23 June 2020

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Abstract

Open dumping, open burning and burying of municipal solid waste (MSW) can be the cause environmental and public health issues. These practices are more prevalent in developing countries such as Mexico, where proper waste management systems are not present. Considering the environmental and health issues, it is therefore important to minimise the number of open dumps in Mexico. The construction of sanitary landfills is regarded as the best alternative to open dumping since it is the a cost-effective and environmentally friendly solution.

An important part of constructing sanitary landfills is the selection of potential locations for these waste facilities where investment will be made to build them. In order to select these locations first the weak spots need to be located. Weak spots are areas that do not have enough (proper) waste management services. Since Mexico does not have a national solid waste information system, a method to locate these weak spots needs to be developed. With the use of the weak spots a method can be developed to select the potential locations for sanitary landfills that also takes the social, economical and legal constraints into account. The following research question is formulated: What are the weak spots in the current waste infrastructure network in Mexico and, based on this, where should strategic investment be made to improve waste disposal? By answering this question, information will be provided on the issues with the management of waste in Mexico with a focus on the areas of the weak spots and the locations where investment can be made to develop new sanitary landfills.

To detect the weak spots, a set of factors of different scenarios were developed, scored, overlaid, and visualised in maps. Regions that have the lowest score were detected as weak spots. To select the potential locations for investment in new sanitary landfills a spatial decision support system (SDSS) was developed and implemented as a QGIS plugin. The weak spots that corresponded to urban areas were used for analysis in the SDSS. This is due to the fact that it is more economically beneficial to construct sanitary landfills in urban areas.

The weak spot analysis showed that the southern region of Mexico, especially the state of Oaxaca, had the highest deficiencies in waste infrastructure. With the output from the QGIS SDSS plugin we are able to determine potential areas for new sanitary landfills in an automated manner.

This research has resulted in the visualisation of the weak spots in the Mexican waste infrastructure and the selection of potential locations where investment can be made for the construction of new sanitary landfills. The approach for locating the weak spots of the waste infrastructure can be used to find the weak spots in other types of infrastructure on a state and country scale in Mexico. The QGIS SDSS plugin could also be used to locate sanitary landfills in Mexico that violate the standards and regulations. The approach used to develop methods to detect the weak spots in the waste infrastructure and select potential locations for investment into new sanitary landfills could be used as a model for other countries to develop their specific approaches.

Acknowledgements

A strategic approach for site selection of waste facilities in Mexico was written within the context of our Synthesis project. The Synthesis project is executed by students at the end of the first year of the Master Geomatics and the Built Environment at the Delft University of Technology. In this project, Master students work for 10 weeks together on a task, given by a client, that concerns a Geomatics related problem. During this project, the students will incorporate and use the knowledge gained and skills developed in the first year of the Master Geomatics. In our case, we worked in a group of six students on the task given by our client, which is the Rotterdam-based company 52impact.

This report could not have been made without the help of the supervisors and clients. We want express our gratitude to Bastiaan van Loenen and Edward Verbree for their support, guidance and feedback during the project. We also want to thank our clients from 52impact, Maurits Kruisheer and Thijs Perenboom, for providing us with feedback, interesting insights and for giving us the opportunity to work on this project.

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Chapter 1

Introduction

1.1 Motivation

Around the world more than two billion tonnes of municipal solid waste (MSW) is produced every year, one third of which ends up in an uncontrolled open dumps (Kaza et al., 2018). Open dumps are locations where waste is dumped without any or limited management (A. Mavropoulos, 2016). The occurrence of open dumping is more prevalent in developing countries where proper waste management systems are not present (Kaza et al., 2018). If MSW is not collected or citizens do not have access to proper waste facilities, this may result in the open dumping, open burning and burying of waste (Ferronato & Torretta, 2019; Ferronato et al., 2017; Reyna-Bensusan et al., 2018). These practices pollute the soil, rivers and water bodies through the leaching of solid, liquid and gaseous pollutants from the open dump or burial site, which consequently affects the environment and public health (Ferronato & Torretta, 2019; T.Subramani et al., 2017). Open dumps contribute to an increase in greenhouse gas emissions of methane and carbon dioxide. (Ferronato & Torretta, 2019; Triassi et al., 2015). Open dumping and burying can increase the spread of diseases through contact with animals visiting or originating from these places (ISWA, n.d.).

The problems with waste management that many developing countries face are also present in Mexico. In Mexico, waste management services are not equally administered and organised among different states and municipalities (Kaza et al., 2018; SEMARNAT, 2019). States and municipalities with no or inadequate waste management services might also have more open dumps. Percentages on the amount of open dumping in Mexico vary. The World Bank estimates that 21 % of all MSW in Mexico ends up in open dump sites (Kaza et al., 2018). However, the former Mexican Secretary of Environment suggests that this percentage is closer to 70 % (MexicoNewsDaily, 2017).

Considering the health and environmental issues, it is therefore important that the amount of open dumps in Mexico is minimised. Disposing waste in any kind of landfills is globally the most common option of waste disposal and is preferred by governments since these facilities are the most cost-effective (Kaza et al., 2018; Sánchez-Arias et al., 2019). A sanitary landfill is a type of landfill where waste is disposed of in an manner that is not harmful to the public health and environment (Hossain et al., 2011; MIT, n.d.). This is done by isolating the waste from the environment and waiting for it to be completely biologically and chemically degraded (Hossain et al., 2011; MIT, n.d.). In order to reduce the health and environmental issues caused by open dumps, we present a strategic approach for site selection of sanitary landfills in Mexico.

1.2 Problem definition

Areas that currently do not have (proper) waste management services are seen as the weak spots in the waste infrastructure. Mexico does not have a national solid waste information system (Marín et al., 2012).

It is therefore not clear where these weak spots in the waste infrastructure of Mexico are. If the weak spots were located, then they could be used as a starting point for site selection of sanitary landfills. Furthermore, when selecting potential locations for new sanitary landfills social, economical and legal constraints need to be taken into account as well.

To contribute to tackling the problem of open dumps the company 52impact wants to develop a strategy in order to achieve this. 52impact is a Rotterdam-based company specialised in using geospatial data to visualise and model applications with a focus on sustainability. They want maps to be created that visualise the weak spots of the waste infrastructure in Mexico. With these maps potential locations for strategic investment into waste facilities can be visualised (52impact, n.d.).

To fulfil the task of developing a strategic approach for site selection for waste facilities in Mexico, the following research question is formulated:

What are the weak spots in the current waste infrastructure network in Mexico and, based on this, where should strategic investment be made to improve waste disposal?

The aim of our Synthesis project is to provide the reader with information on the issues with the management of waste in Mexico where the focus will lie on the weak spots in the waste infrastructure and selecting sites for strategic investment of new sanitary landfills.

1.3 Research approach

Our research approach consists of two parts: an analysis to locate the weak spots in the Mexican waste infrastructure and developing a spatial decision support system to select potential locations for new sanitary landfills (Figure 1.1).

To locate the weak spots the collected data was divided into factors that are directly and indirectly related to waste management. Spatial analysis was applied to generate the data-sets of the direct factors. Statistical analysis was done to explore the dependent relationship between the indirect factors and waste management. The data-sets of the direct and indirect factors were checked for redundancy and dependency, and were normalised to the same range. If two factors had a strong correlation, also known as multicollinearity, one of them was removed from further analysis. Then, factors were selected for three scenarios, their values were overlaid to get the total score on waste infrastructure, and the areas with lowest score were detected as weak spots. With scenario one, only the directly related factors were used, with the exception of factors that favoured landfills. With scenario two, only indirectly related factors of socioeconomic nature were used. With scenario three, all the directly related factors and one indirectly related factor concerning the ratio of the footprint of urban areas to the total footprint was used. The weight of the difference between the supply and demand of waste (the gap in landfill capacity) was also doubled to emphasise the need for new sanitary landfills. From these three scenarios maps were made to visualise the weak spots.

To select the potential locations for investment in new sanitary landfills a spatial decision support system (SDSS) was developed and implemented as a QGIS plugin. The weak spots that corresponded to urban areas were used for further analysis. This is due to the fact that it is more economically beneficial to construct sanitary landfills in urban areas. From a literature study, the official Mexican criteria for site selection of new sanitary landfills were found. They were classified into constraints that specify if a location is suitable and decision criteria that specify the level of suitability. Then the zones for which the criteria would be applied were defined. Hereafter, the weighting of the criteria was determined with the use of two methods: the equal weighting method that assigns equal weights to all criteria and the analytic hierarchy process (AHP) method that assigns weights to the criteria based on their relative importance with respect to each other. Within the QGIS plugin, suitability maps based on the decision criteria and within a certain zone of weak spots were made and rasterised. Based on these maps a mask layer was made that combined the zones with the weak spots corresponding to the constraints. With the use of the raster calculator and Boolean queries, the suitability score of each pixel was determined. The last step was to classify suitability into four categories, each with a certain range of suitability scores. With this classification the most suitable location for investment into new sanitary landfills could be selected.

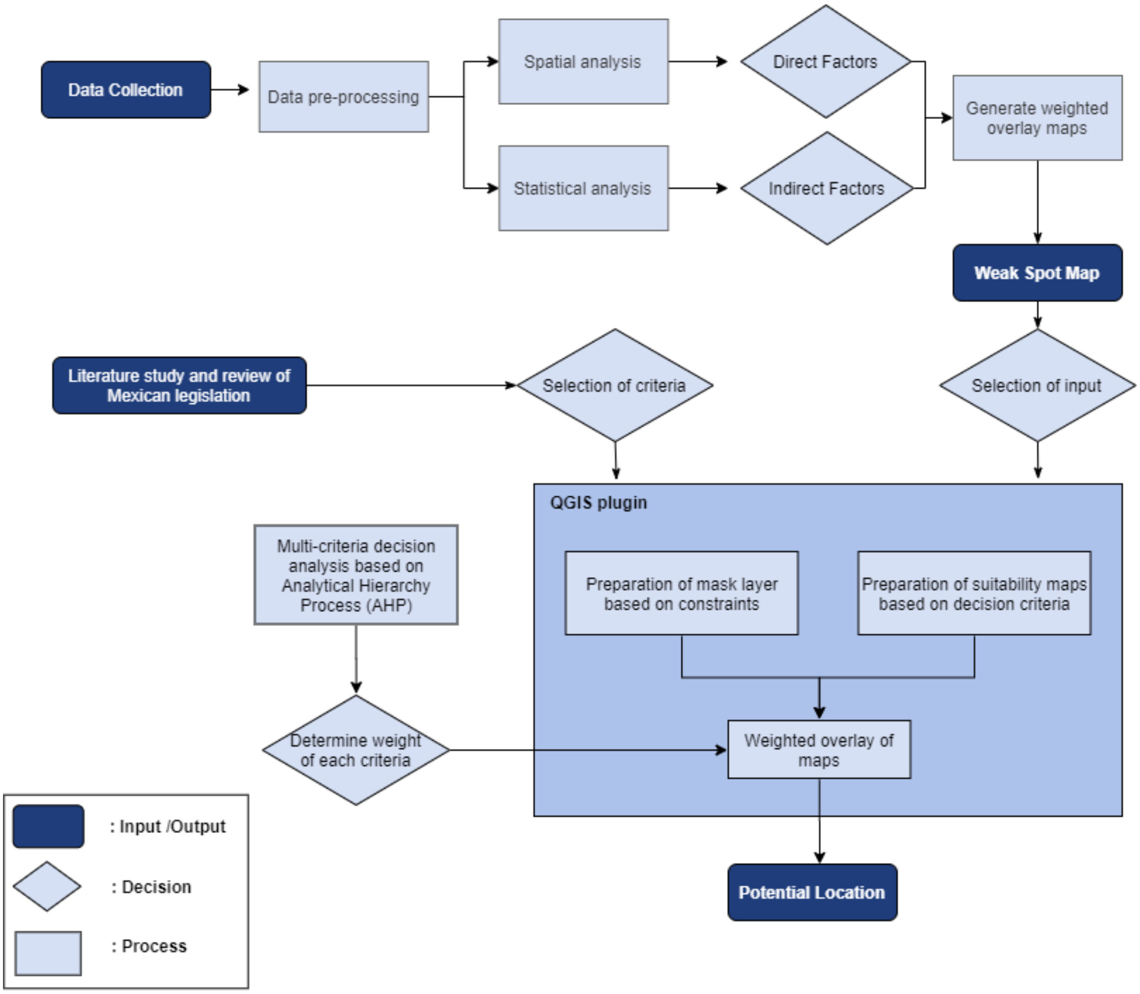


Figure 1.1. Flowchart of the research approach

1.4 Reading guide

The report is structured as follows: Chapter two provides the results from a literature study where a background on waste management in Mexico, mismanagement of waste and methods to improve this are given. The third chapter presents the methodology to detect the weak spots in the waste infrastructure of Mexico and how to select potential locations for new sanitary landfills using a spatial decision support system (SDSS). The results of the methodology are provided and visualised in Chapter four. The fifth chapter presents a discussion of the results, where the focus lies on the significance, implications and limitations. Conclusions and recommendations for future work are provided in Chapter six.

Chapter 2

Background on waste management

This chapter is divided into three sections: Waste management in Mexico, Waste mismanagement: causes, effects and improvements and Waste management in rural areas: issues and improvements. The first section provides insight into the current situation of municipal solid waste (MSW) management in Mexico. First, the governance of MSW management in Mexico is presented with information on the responsibilities and rights of the municipal, state and federal governments. Hereafter, information on the management of MSW in practice is provided, where the waste collection services and mechanism and final disposal sites are discussed. The second section presents information on waste mismanagement, where the causes, effects and improvements of this problem are given. The third and final section provides information on specific issues and improvements of waste management in rural areas.

2.1 Waste management in Mexico

2.1.1 Governance of MSW management

Municipal solid waste management involves the collecting, transporting and disposing of municipal solid waste (MSW). MSW is defined as waste generated by households, offices, markets, other institutions and public roads and places in a municipality (Diputados et al., 2007; Hoornweg et al., 2015). The responsibilities with regards to the management of MSW in Mexico depend on the level of government. In Mexico there are three levels of government: federal, state and municipal. The federal government is divided into three branches: legislative, executive and judicial. The legislative branch is represented by a bicameral Congress. The Congress has the power to issue laws in order to protect the environment (Secrataría de Gobernación, 2019).

Municipal governments

One of these laws is the General Law for the Prevention and Integral Management of Waste (Spanish: Ley General para la Prevención y Gestión Integral de los Residuos) (LGPGIR). The objective of this law is to promote comprehensive management of waste (Diputados et al., 2007). According to the constitution of Mexico (Spanish: Constitución Política de los Estados Unidos Mexicanos) municipal governments are responsible for the cleaning, collection, transport, treatment and final disposal of waste, which is reiterated by the LGPGIR (Diputados et al., 2007; Secrataría de Gobernación, 2019).

The LGPGIR states that municipal governments can issue local regulations with regards to waste management within the context of federal and state laws and standards . Municipal governments are allowed to classify the MSW into organic and non-organic waste to facilitate its separation. They can directly organise the comprehensive management of waste or grant concessions to companies to provide waste management services in the municipality. Municipal governments can charge residents for the payment of waste management services (Diputados et al., 2007).

State governments

The state governments are primarily responsible for the management of waste that is not MSW (Diputados et al., 2007). They issue state programs and policies for the prevention and integral management of waste that must be adhered to by all the municipalities in a state (Diputados et al., 2007; SEMARNAT, 2020b). They also promote and work together with municipal governments on programs for the prevention and comprehensive management of waste (Diputados et al., 2007).

Federal government

The federal government is responsible for creating, conducting and evaluating policies, regulations and standards with regards to comprehensive waste management. They exercise their powers given by the law mainly through the Ministry of Environment and Natural Resources (Spanish: Secretaría del Medio Ambiente y Recursos Naturales) (SEMARNAT) (Diputados et al., 2007).
In evaluating policies on waste management, the National Institute of Statistics and Geography (Spanish: Instituto Nacional de Estadística y Geografía) (INEGI) is of assistance. This autonomous national agency is responsible for collecting and publishing statistical and geographical information of Mexico (INEGI, n.d.). INEGI collects information by conducting censuses on various topics at different levels of government. One of these censuses is the National Institute of Statistics and Geography (Spanish: Censo Nacional de Gobiernos Municipales y Delegacionales). In this census INEGI asks municipalities questions on a wide range of subjects such as the collection and final disposal of waste (INEGI, 2018). The census provides information for the federal government which is used in publications on national waste policies (SEMARNAT, 2020a).
The federal government supports the development of the waste infrastructure together with the states and the municipalities by providing technical and financial assistance(Diputados et al., 2007). Two federal programs that financially support states and municipalities are the Municipal Solid Waste Program (Spanish: Programa de Residuos Sólidos Municipales) (PRORESOL) from the National Infrastructure Fund (Spanish: Fondo Nacional de Infraestructura) (FONADIN) and the program for the prevention and comprehensive management of waste (Spanish: Programa para la prevención y gestión integral de residuos) from SEMARNAT (PRORESOL, 2016; SEMARNAT, 2018). PRORESOL provides up to 50 % of the total cost for studies, consultancy and infrastructure projects with respect to waste management (PRORESOL, 2016).The program from SEMARNAT provides up to 20 % of the total cost of projects for the development of waste management infrastructure. For non-infrastructure projects related to waste management they provide up to 100 % of the total amount (SEMARNAT, 2018).
During the period of 2013-2018 2.37 billion MXN (€ 94.5 million) of federal resources was allocated for the funding of 346 projects related to comprehensive waste management. 44.6 % of these resources went to construction, expansion, sanitation and closure of landfills. 24.6 % went to equipment to organise waste collection services. 16.7 % went to installations that can utilise the waste through recycling or composting. 7.2 % went to machinery for different waste facilities (SEMARNAT, 2020a). It is not clear how much of the federal resources were allocated for non-infrastructure projects. PRORESOL and SEMARNAT only approve funding for waste infrastructure projects if the facility complies with the federal standard of NOS-083-SEMARNAT-2003 (PRORESOL, 2016; SEMARNAT, 2018).

NOM-083-SEMARNAT-2003 standard

NOM-083-SEMARNAT-2003 is an official standard that provides environmental protections specifications with regards to the site selection, design, construction, operation, monitoring, closure and complementary works of a final disposal site of municipal solid waste (MSW) and special waste. The standard is mandatory for all public and private organisations that are involved in processes with respect to all final disposal sites. The standard provides definitions on waste, waste management and waste facilities. Restrictions for the site selection of waste disposal sites are given in the standard. NOM-083-SEMARNAT-2003 also provides the requirements for the construction and operation of waste disposal sites (SEMARNAT, 2004).

2.1.2 MSW management in practice

MSW management in Mexico is characterised by the composition and separation of waste, the presence and coverage of waste collection services, the collection mechanism, and the final disposal of waste.

Waste coverage rate

The waste coverage rate is defined as the percentage of people who have access to waste collection services. The waste coverage rate in Mexico is 84 % (Gob.mx, 2015). Figure 2.1 shows the percentage of the population with access to waste facilities per state. The waste coverage is the lowest in the southern states of Chiapas, Oaxaca and Guerrero and the highest in the central states of Aguascalientes and Mexico City.

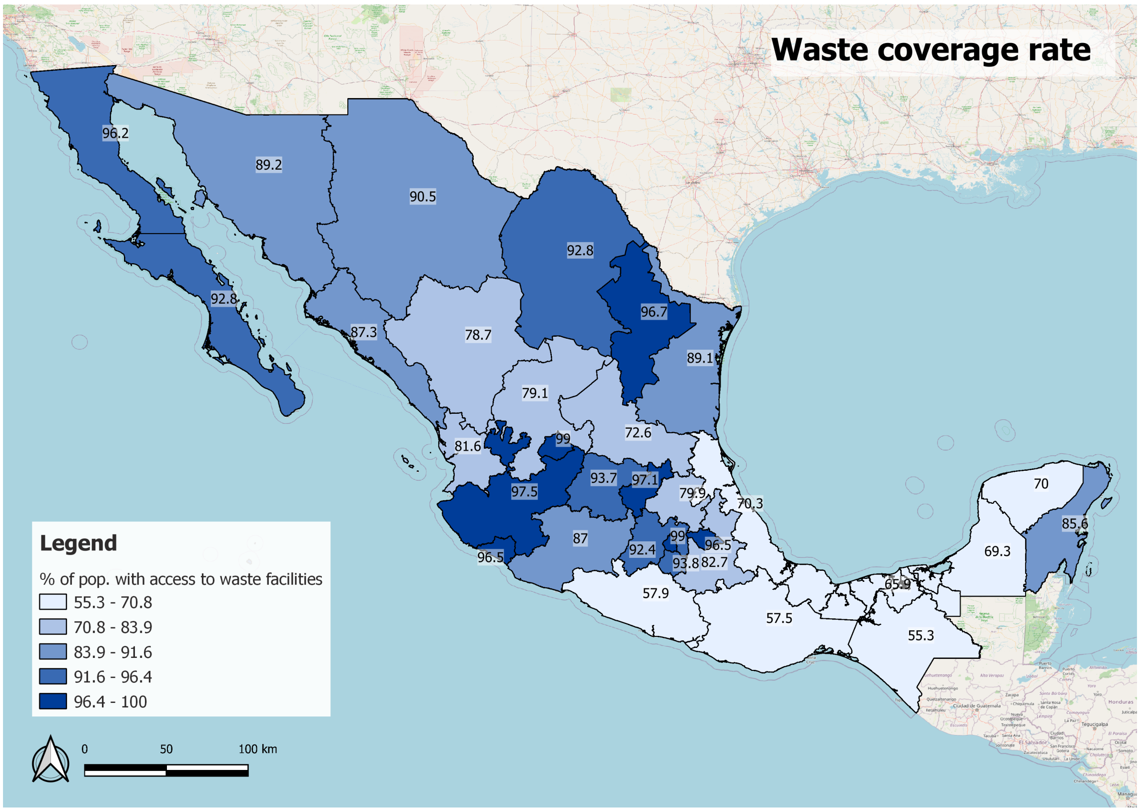


Figure 2.1. Percentage of population with access to waste facilities per state

Waste collection services

Waste collection services are present in 92.1 % of all municipalities in Mexico. 97.3 % of these municipalities run their own waste management service, while the rest may outsource it to private companies, non-profit organisations or a combination of both. It is possible that there is more than one organisation providing waste collection services in a municipality (INEGI, 2019).

Waste collection mechanism

Figure 2.3 shows a flowchart of the waste collection mechanism of MSW in Mexico. If there are waste collection services present in a municipality then the MSW can be collected house to house, deposited in a container, at a collection point or a combination of these three systems. From the waste that is collected 41.7 % is collected house to house, 7.5 % through collection points, 2.2 % through a system of containers and 48.6 % through a combination of systems (INEGI, 2019).

Only 5 % of the total amount of waste that is collected is separated beforehand by citizens into organic and non-organic components. Organic waste consists of five main categories: food, garden, wood, organic fibers and leather and accounts 46.4 % of all MSW. Non-organic waste refers to all other types of MSW and can be classified into eight main categories: plastic, carton, paper, glass, textile, metal, rubber and synthetic fibers and accounts for 34,3 % of all MSW. 19,3 % of MSW consists of other types of waste, such as ceramics, construction materials and disposable diapers. Figure 2.2 shows the composition of MSW in Mexico. Waste separation is practised by waste collection services in 6.1 % of all municipalities (INEGI, 2019; SEMARNAT, 2020a).

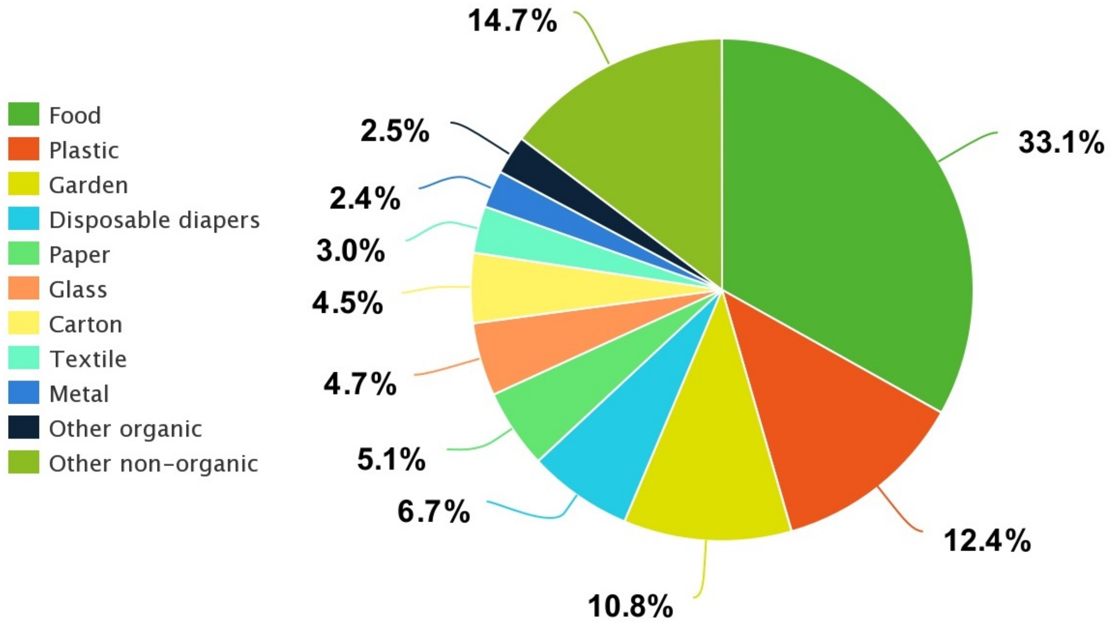


Figure 2.2. Waste composition of MSW in Mexico

Final disposal of waste

After collection, the municipal collection vehicles deposit the waste at the final disposal site (see Figure 2.3 of Appendix B). There are two types of final disposal sites: sanitary landfills and controlled open dumps (Figure 3). A sanitary landfill is a waste facility that adheres to the standards set by the Mexican government for a final disposal site of which NOM-083-SEMARNAT-2003 is the most important. A controlled open dump is a waste facility that operates and functions as a landfill but does not comply with all of the requirements in the NOM-083-SEMARNAT-2003 standard, especially the one with regards to waterproofing. An uncontrolled dump is a site that does not comply with any of the requirements in the NOM-083-SEMARNAT-2003 standard (SEMARNAT, 2004). Data from INEGI shows that from the 2203 waste facilities registered in Mexico there are currently 489 sanitary landfills that comply with the NOM-083-SEMARNAT-2003 standard (INEGI, 2018). From the waste that is collected in Mexico, 74.0 % is deposited in landfills and controlled open dumps, 21 % in uncontrolled open dumps and 5.0 % is recycled (De Medina Salas, 2018; Kaza et al., 2018). However, data on the presence of uncontrolled open dumps is not complete, making it difficult to estimate their true amount (INEGI, 2018).

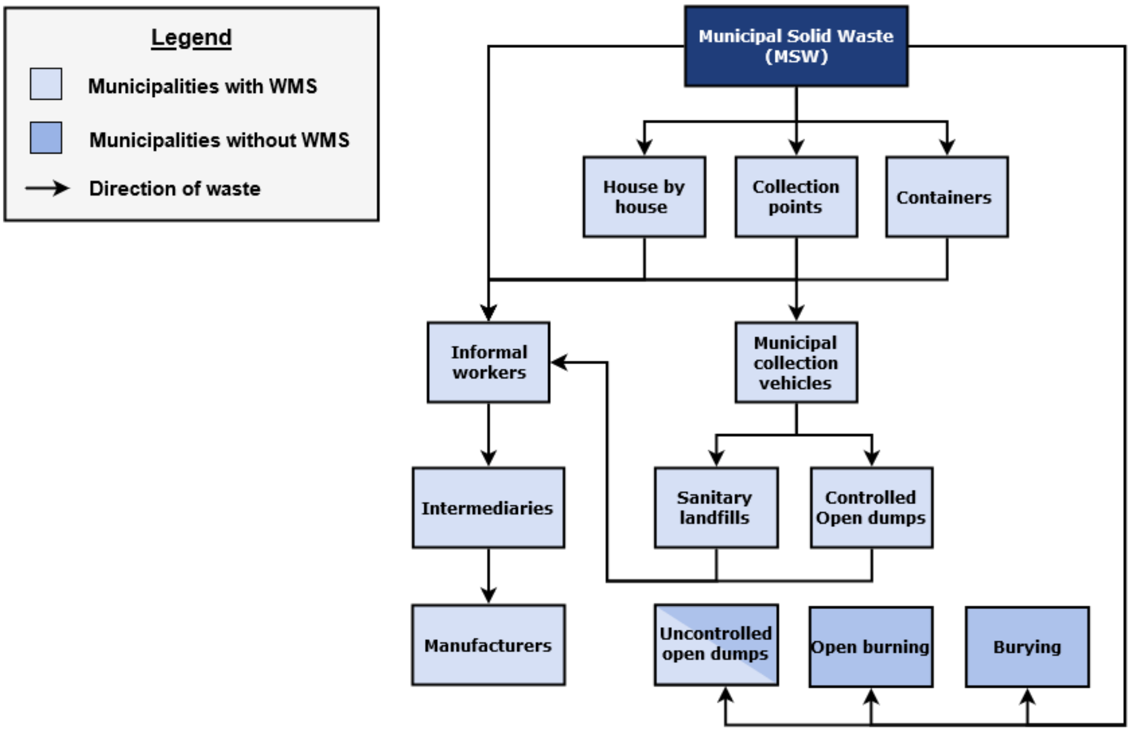


Figure 2.3. Waste collection mechanism in Mexico

31.5 % of the MSW has the potential to be recycled. These are all the types of non-organic waste with the exception of textiles. Although textiles cannot be recycled, they can be reused. In Mexico there are 26 official recycling centres (SEMARNAT, 2020a). The non-regulated informal system plays an important part in recycling of waste in Mexico (see figure 2.3). The informal workers, also known as waste pickers or scavengers collect items that can be recycled from waste of households, collection points, containers, sanitary landfills and open dumps (McCubbin, 2012). Collecting waste from households is usually done for a fee. After collection, they transport the waste with donkey or horse carts to privately operated transfer stations, where after paying a fee, they deposit the waste (McCubbin, 2012; Mihai, 2017). Hereafter, they select the recyclable items and sell them to intermediary traders (Espitia, 2015; McCubbin, 2012; Mihai, 2017). These intermediaries transport and sell the recyclable items to manufacturers who use the items as materials for their products (Espitia, 2015; McCubbin, 2012). If the waste pickers collect recyclable items on the landfill or open dump, then they will also sell them to intermediaries who are present at these sites (Espitia, 2015; Mihai, 2017; Schneider et al., 2017).
Waste treatment methods are an alternative to recycling or disposing waste in landfills. One example of these methods is the composting of organic waste. There are currently 24 composting plants in Mexico (SEMARNAT, 2020a). Waste treatment methods in general however, do not play a large role in the management of MSW in Mexico. Only 6 % of the municipalities with waste management service treat their waste (De Medina Salas, 2018).

MSW management in Mexico is primarily organised by the municipalities but the state and federal governments can provide financial and technical support (Diputados et al., 2007). Although most people in Mexico have access to waste collection services and most municipalities provide these services there is still a considerable percentage of waste openly dumped (Gob.mx, 2015; INEGI, 2019; Kaza et al., 2018).

2.2 Waste mismanagement: causes, effects and improvements

Waste mismanagement occurs when the system for collecting, transporting and disposing of waste is not organised well enough to prevent environmental and public health problems (Ferronato & Torretta, 2019). First, information on the causes and effects of waste mismanagement is given to help understand this problem. Then, improvements to waste management are presented to solve the mismanagement of waste.

2.2.1 Causes of waste mismanagement

One of the causes of mismanagement of waste in developing countries is the lack of waste management services due to insufficient financial resources (Khatib, 2011; Lavagnolo, 2018) . If municipalities do not have any waste management services other methods of waste disposal occur (see figure 2.3) (Ferronato & Torretta, 2019; Reyna-Bensusan et al., 2018). In 75.5 % of these municipalities in Mexico part of the MSW is illegally burned by the citizens. In 63.3 % of the municipalities the MSW is openly dumped. Uncontrolled open dumping could also take place in municipalities with waste collection services since none of them have a coverage rate of 100 %. In 37.8 % of the municipalities the MSW is buried (INEGI, 2019).

Economic and population growth will lead to an increase of waste in Mexico (Kaza et al., 2018; Lavagnolo, 2018). Urbanisation, which is a result of economic and population growth will also lead to an increase of waste since urban areas in Mexico generate a higher amount of waste per capita than their rural counterparts (Lavagnolo, 2018; SEMARNAT, 2020a). If there are no or inefficient waste management services, then the increase in the amount waste will lead to an increase in open dumping, open burning and burying of waste (Ferronato & Torretta, 2019; Reyna-Bensusan et al., 2018).

Inefficient waste management in developing countries is caused by low financial & insufficient administrative resources (Khatib, 2011; Zurbrügg & Schertenleib, 1998). The problem with low financial resources could be solved by increasing the fees for waste management services (Khatib, 2011; Zurbrügg & Schertenleib, 1998). However, it might occur that higher fees lead to an increase in open dumping (Khatib, 2011). This is due to the fact people do not want to pay these (higher) fees and then dispose their waste in open dumps(Ichinose & Yamamoto, 2011).

Insufficient administrative resources can be interpreted as not having a legal framework consisting of laws, regulations and standards that waste management services must adhere to (Khatib, 2011). Although Mexico does have a legal framework on waste management, not all of these laws, regulation and standards are comprehensive enough to achieve an efficient waste management system. The NOS-083-SEMARNAT-2003 standard only states requirements that relate to the environmental aspects of selecting locations for new sanitary landfills and not the social and economical components (SEMARNAT, 2004). Another aspect of insufficient administrative resources is the absence of data on the status of MSW (Khatib, 2011). This data could be used to develop waste management systems if not present and if they are, to improve them (Khatib, 2011). Although Mexico does have data on MSW from INEGI, this data is not always complete and accurate (INEGI, 2018).

2.2.2 Effects of waste mismanagement

Practices resulting from the mismanagement of MSW have a negative effect on the environment and public health. Waste that is openly dumped or buried will decompose into several solid, liquid and gaseous pollutants (Jayawardhana et al., 2016).

Leachates are liquids that originate from rainwater and flow through the waste of a landfill, dump or burial site absorbing the solid, liquid and gaseous pollutants (Jayawardhana et al., 2016; T.Subramani et al., 2017). In sanitary landfills, the leachate is isolated from the soil with the use of multiple ground layers. Leachates and gaseous pollutants can be collected and treated to reduce the environmental impact (Jayawardhana et al., 2016). With open dumps and burial sites this does not apply. The leachates will end up in the soil and contaminate it which could lead to a decrease in the amount and diversity of vegetation

(Ali et al., 2014). The leachates can end up in rivers and water bodies, polluting them and negatively affecting the environment (Ferronato & Torretta, 2019; T.Subramani et al., 2017). The contamination of surface & groundwater has a detrimental effect on the public health since these water sources are used for drinking and irrigation (T.Subramani et al., 2017). The pollution of rivers and seas has a negative effect on the amount of flora and fauna and is toxic to people that swim there (Ali et al., 2014; Ferronato & Torretta, 2019).

Gases emanating from open dumps, open burning and burial sites such as methane and carbon dioxide contribute to an increase in greenhouse gas emissions. Other gases resulting from these places are toxic to people if they are exposed to them (ISWA, n.d.).

Examples of the toxic effects of exposure to solid, liquid and gaseous pollutants are nausea, headache, cancer and respiratory & cardiovascular diseases (Triassi et al., 2015).

Open dumps and burial sites can increase the spread of infectious diseases, which is mainly done through contact with animals visiting or originating from these places such as flies, mosquitoes, rodents and birds (ISWA, n.d.).

Since open dumps are not well organised, accidents might happen affecting the informal workers. In most cases these accidents are cuts resulting in wounds that could become infected. In some cases fires, explosions and landslides of the waste mass occur (ISWA, n.d.).

The odour emanating from open dumps can also have an effect on the lives of people. People that live close to a landfill may have problems performing their daily activities due to the exposure to the odour of the open dump (Nuraiti et al., 2007).

2.2.3 Improvements to waste management

To solve the mismanagement of waste, methods to better the legal framework, formalise the informal sector, close open dumps and invest in new sanitary landfills can be applied.

Improve the legal framework

Although waste can be burned on and buried in open dumps, most of these practices occur in the backyards of citizens of a municipality. The burning of waste (in backyards) is illegal in Mexico (Reyna-Bensusan et al., 2018). No information could be found on the legality of the burying of waste. If governments want to decrease the open burning and the burying of waste they must improve and enforce current laws, regulations and standards to guarantee that not only the environmental aspects are considered in waste management but also the social and economical components. Governments must also improve their methods of collecting data on waste management, by making it mandatory by law for all levels of government to supply all information that is needed for better understanding of waste and associated problems in the country (Khatib, 2011).

Formalise the informal sector

Formalising the informal sector, consisting of waste pickers, can lead to an improvement of waste collection and recycling services (Kaza et al., 2018). There are three methods of formalising the informal sector. The first method is when waste pickers are organised in cooperatives and associations. The municipality has a cooperation agreement with these organisations to provide collection and recycling services. The income of the waste pickers is partially fixed through the fees paid by the municipality for the collection services. The rest of their income however, is not fixed since this depends on the quality and quantity of the recycled items that is sold by them (Aparcana, 2017).

The second method is when waste pickers are contracted by community based organisations that pay them a fee for waste collection and recycling services (Aparcana, 2017; Kaza et al., 2018). The municipality supports the formalisation of the waste pickers through regulations, providing equipment and establishing the infrastructure to perform their tasks (Aparcana, 2017). The waste pickers could also form micro- and small enterprises (MSEs) to provide waste collection, street sweeping and recycling services (Aparcana, 2017; Kaza et al., 2018). Then the municipality will pay them a fee for performing these services (Aparcana, 2017). These methods however are not beneficial to the waste pickers because the fees for their services are not regularly paid by the municipalities (Aparcana, 2017).

The third method of formalising the informal sector is when the municipal governments and companies cooperate with the waste pickers and even hire them to work in their organisations (Aparcana, 2017; Kaza et al., 2018). This method is the most beneficial to waste pickers since it provides them with a fixed income and other work-related benefits (Aparcana, 2017).

Waste pickers are a socially marginalised group in Mexico and other developing countries. Waste pickers work in conditions that are damaging to their health. Children who are waste pickers are subject to child labour and are not able to attend school. Regardless of the method chosen to formalise the informal sector, municipal and national governments must issue laws and regulations legally recognising waste pickers and eventual organisations, companies and cooperatives established by them. The laws and regulations must also promote better working conditions and prohibit child labour in this informal sector (Aparcana, 2017; Kaza et al., 2018).

Other alternatives for waste collection services can be organised in a community or a region (Hidalgo et al., 2016; Zurbrügg & Schertenleib, 1998). With community-based waste collection services, the collection and transport of the waste is done by the members of the community (Zurbrügg & Schertenleib, 1998). Regional waste collection services are organised by multiple municipal governments to cover the region in which the municipalities are located. Collection and transport of waste is done by a regional organisation (Hidalgo et al., 2016).

Close open dumps

Open dumps cause environmental and health problems. It is therefore important that they must be closed (A. Mavropoulos, 2016). There are three methods to close an open dump. The first method is to remove the waste from the open dump and transporting it to a sanitary landfill. The second method is to 'close' the open dump by upgrading it to a sanitary landfill. This method is only possible if the pollution of the groundwater is not too high. The third method is to close the open dump by covering it with a layer of local soil or clay. This is known as in-place closure and is the most applied method (ISWA, n.d.).

Invest in new sanitary landfills

When a open dump is closed by in-place closure, there is still waste generation from nearby sources. In order to cope with the waste and reduce the impact on the environment and public health, sanitary landfills should be developed. An important aspect of developing a sanitary landfill is selecting the most suitable site for constructing the waste facility (Zurbrügg & Schertenleib, 1998). The costs of constructing sanitary landfills and developing other aspects of waste management can be high (Khatib, 2011). Municipalities can apply for funding for projects related to the construction of sanitary landfills and other aspects of MSW management with SEMARNAT and FONEDIN. The projects must however comply with the NOS-083-SEMARNAT-2003 standard (PRORESOL, 2016; SEMARNAT, 2018).

2.3 Waste management in rural areas: issues and improvements

Rural municipalities are in general poorer than their urban counterparts, making it more difficult for them to improve their MSW management (Oakley & Jimenez, 2012; Zurbrügg & Schertenleib, 1998). Sanitary landfills are also seen to be more beneficial in urban areas since they have a higher population and settlement density. Therefore, alternative improvements for waste management in rural areas are given in this section. First, information on the current situation of MSW management in rural areas is provided to understand the magnitude of the problem in these places. Then, we elaborate on what the motives are for not investing in sanitary landfills in rural areas. Hereafter, two solutions to reduce the municipal solid waste in rural areas are given, since less waste generated also means less waste that needs to be disposed of. Finally, the semi-trench method is explained which could serve as an alternative to sanitary landfills in rural areas.

2.3.1 Current situation of MSW management in rural areas

In rural areas the waste collection rates vary between 30 % and 80 %. Many households are not part of a formal service for waste collection (Friesen-Pankratz et al., 2011). From the current state of waste management in Mexico, we know that in the absence of any waste management service provided by the municipality, waste disposal methods such as open dumping, open burning or burying will occur. 92 % of households in rural municipalities say that they dispose part of their waste through open dumping, open burning or burying (Reyna-Bensusan et al., 2018).
Rural communities in Mexico are separated by economic and social barriers and lack incentives to carry out integrated waste management. In addition to these factors, inadequate road infrastructure makes it unable for waste collection vehicle to reach certain areas. This has caused a low frequency and coverage of waste collection services in rural areas. These reasons together limit the comprehensive management of MSW in rural municipalities. (Buenrostro et al., 2009).

2.3.2 Motives for not investing in sanitary landfills in rural areas

The motives and reasons for not investing in sanitary landfills in rural areas are mainly due to the financial resources of rural municipalities and the spatial patterns of urban and rural areas.

Financial resources

Rural municipalities in general do not have the financial resources to construct a sanitary landfill (Oakley & Jimenez, 2012). Urban areas often receive more attention and budget allocation in infrastructure development than their rural counterparts. The financial assistance from FONADIN and SEMARNAT would not be enough for rural areas since it only applies to studies, consultancy, equipment, machinery and construction or closure of waste facilities. It does not apply to the day-to-day operations of the waste management services (PRORESOL, 2016; SEMARNAT, 2018). Being unable to construct and operate a sanitary landfill due to low financial resources is the main motive for rural municipalities to not invest in these waste facilities (Oakley & Jimenez, 2012).

Spatial patterns

The distribution of human settlements in Mexico varies per region. As per initial observations (Figure 2.4), we noticed that the settlements are highly concentrated in the middle of the country; whereas in the northern and southern part, they are rather dispersed. Furthermore, the size of the settlements, and the ratios between urban and rural settlements also differ between regions.

The concentration of the settlements reflects the development status of different regions of the country. Areas with a higher concentration of settlements are likely to have higher concentration of population, employment, and economic activities. The size of the settlement, on the other hand, reflects the administrative characteristic of the area, where large settlements are usually metropolitan or large cities, and small settlements are small cities or villages. When looking at settlements per administrative boundaries, the ratio between urban and rural areas also pointed out if an area is highly developed or not. Thus, studying the spatial characteristics of human settlements shows the whole picture of the development status within the regions.

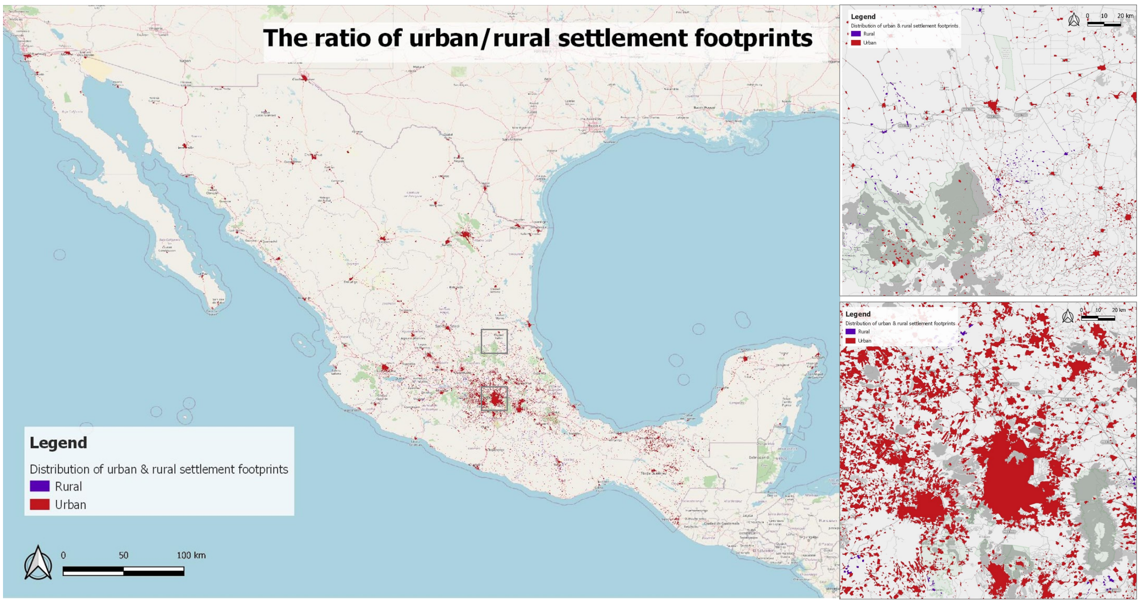


Figure 2.4. Human settlement footprints - classified as urban / rural

Furthermore, it is acknowledged that there is a relationship between spatial patterns and the development of the infrastructure networks. On one hand, compact spatial development allows a more cost-effective infrastructure network to be installed (United Nation ESCAP, 2012), which is also true for the waste infrastructure. Investment in sanitary landfills is therefore only beneficial when they are placed near dense and populated areas. In fact, large landfills require more effort in improving standards during their lifespan than smaller sites. However, the unit cost of these improvements will decrease with increasing site size. Thus, in the long term, large landfills sites serving two or more cities could be more economically beneficial, while the distance to large cities is not too long. (Thurgood et al., 1998).

It can be concluded that with regards to the spatial patterns, investment in sanitary landfills in rural areas would not be economically viable.

2.3.3 Methods to reduce the amount of waste

Two methods in rural areas could reduce the amount of waste generated: composting and establishing food banks.

Composting

46.4 % of all MSW is organic waste which could be used for composting (SEMARNAT, 2020a). Composting is the process where microorganisms in the soil convert the organic matter into a stable dark brown material called humus. Compost can be used to improve the soil for better crop yield (U.S. EPA, 2018; Q. Wang et al., 2019). Composting reduces the amount of waste that needs to be disposed of and has environmental benefits such as a reduction in methane emissions (Vigneswaran et al., 2016). An economic benefit of composting is that it can replace part of the fertilisers which are more expensive than compost (Couth & Trois, 2012; Q. Wang et al., 2019).

Open windrow composting is a method where rows of composting piles are situated next to each other and turned frequently to stimulate the process of composting (Vigneswaran et al., 2016). Open windrow composting is the most used method for managing organic MSW (De Silva & Yatawara, 2017). The method is easy to implement, operate and construct with minimal equipment, infrastructure and financial resources making it therefore suitable for rural areas (Vigneswaran et al., 2016).

Food banks

In Mexico 33.6 % of the MSW consists of food remains (SEMARNAT, 2020a). Part of this food waste is consumable food that is thrown away. 11 million people in Mexico suffer from malnutrition. The amount of food waste that was consumable is more than the amount of food needed for the people suffering from malnutrition. Food waste is also a large contributor to greenhouse gas emissions. It is therefore important that consumable food is not wasted. The network of Food Banks of Mexico (Spanish: Bancos de Alimentos de México) (BAMX) is the overarching organisation for food banks. Most food banks of Mexico are in urban areas (BAMX, n.d.). In cooperation with this network, food banks in rural areas can be established, thereby reducing waste, malnutrition and greenhouse gas emissions (Kaza et al., 2018).

2.3.4 Alternative to sanitary landfills in rural areas

An alternative to sanitary landfills in rural areas is disposal of waste using the semi-mechanised trench method.

Semi-mechanised trench method

The semi-mechanised trench method is easy to implement and requires less equipment and construction than a conventional sanitary landfill. With the semi-mechanised trench method hydraulic excavators dig trenches that are filled with waste (see Figure 2.5). The waste then degrades naturally. If the trench is full, it is covered with the soil that was removed during the excavation. Semi-mechanised landfills have less problems with animals that spread the diseases, odours and leachates than open dumps. Natural attenuation of the leachates results in minimal pollution of the groundwater. If leachate generation however is a problem, then soil or tarp could (temporarily) be used to cover the trench in order to prevent rainwater from flowing through the waste thereby generating leachates. Semi-mechanised landfills are low in cost due to the fact that they need less personnel to operate the facility. Less energy is also used for the operation of these type of landfills since most of the waste management processes are biological (Oakley & Jimenez, 2012).

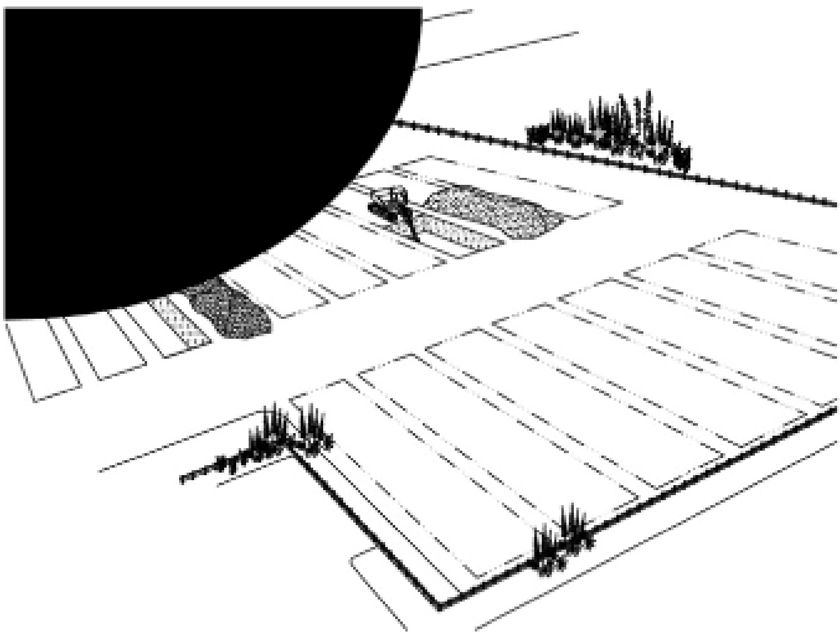


Figure 2.5. Semi-mechanised trench method (Oakley & Jimenez, 2012)

Chapter 3

Methodology

Investments in waste infrastructure should be the main focus of the area that needs the facilities the most. For that, we employed a strategic approach to first find the weak spots with ranking in the current waste infrastructure in Mexico. Then we chose the weakest spots to find new locations to invest in sanitary landfills. Hence, the methodology for this research project consists of two main parts, which are "Detecting weak spots" and "Selecting potential locations for new landfills". The result from the first part is the input for the second part.

3.1 Detecting weak spots

3.1.1 General research approach

Weak spots are generally defined as the areas that need improvements or investments in waste infrastructure. As waste management is a multidisciplinary topic (Nehrenheim, 2014), we need to take various aspects into account to detect weak spots in the waste infrastructure of a country. In this part, we present an overview on the steps for weak spots detection.

Firstly, based on the previous literature review on the background on waste management, we collected the relevant data-sets and reviewed them in terms of correctness, completeness, reliability, and usability, or if it is necessary to further processing the data. (section 3.1.2).

Secondly, we split these data-sets into two groups:

- **Direct factors:** factors directly related to waste management and the waste problem; intermediate steps to prove their level of relevance are not needed. For example, the capacity of open dumps and landfills, the amount of waste generated by the population, the average distance to waste facilities and the ratio of waste that is collected (Section 3.1.3).
- **Indirect Factors:** factors indirectly related to waste management and the waste problem; we need to conduct analysis to prove their level of relevance. These are mostly socioeconomic factors. For example, the density of population, the GDP and poverty rate. These do not show direct impact on the waste infrastructure but can indirectly be part of the cause of the waste problem. (Section 3.1.4).

Where most of the data- sets are available at the municipality level, some are at the state level or at the human settlements level, and some data needs to be processed. We chose the municipality level as the base scale for data processing and weak spots detection, because they are not too vague nor too detailed. Moreover, the output of weak spots at the municipality level would be an appropriate input for the next steps in selecting new locations for landfills. Selecting an entire state as a weak spot is too broad for a strategic approach, and weak spot as human settlement is too specific when conducting the research for the whole country.

In the third step, we generated the data-sets for the direct factors and indirect factors. For the direct factors, apart from ready to use data-sets, spatial analysis and basic calculation were employed to generate the data. For the indirect factors, statistical analysis was used to find relevant factors, spatial analysis and other calculation tools were also used to generate the data-sets for the factors. Then, we checked if the set of factors satisfied the following qualities: completeness, redundancy, mutual dependence of references. For that, we first refined the two sets of factors based on our understanding towards the similarities of the factors.

In the fourth step, we determined if the factor is a benefit factor or a cost factor:

- **Benefit**: a factor that makes a place better in regards of waste management. The higher the value of the factor, the stronger the place.
- **Cost**: a factor that makes a place worse in regards of waste management. The higher the value of the factor, the weaker the place.

We then normalised the value of data-sets to the range of 0 to 1 using Linear Max-Min normalisation (Vafaei et al., 2016) . If the factor is a benefit, the max value of the data-set is scored as 1, and the min value is 0. If the factor is a cost, the max value of the data-set is scored as 0, and the min value is 1.

After that, to further refine the two set of factors based on their normalised values we used the variance inflation factor (VIF) to check for multicollinearity between the factors (Miles & Shevlin, 2001). Multicollinearity ocus when there is a high degree of correlation between two independent variables such that the contribution of each independent variable to variation in the dependent variable cannot be determined (Merriam-Webster, n.d.). If a pair of factors shows high correlation, we remove one of the two factors from the set.

Lastly, we used both groups of factors to create maps implementing the weighted overlay method. The maps were created using three scenarios:

- **Scenario 1:** A map using only the direct factors, without the direct factors that favour the investment in landfills. This will be a general overview, the weights of the layers are all equal.
- **Scenario 2:** A map using only the indirect factors. This could be of use if there was little data about waste management available, furthermore it could tell us more about the characteristics of the weak spots. The weights of the layers are again all equal.
- **Scenario 3:** A map that shows us the weak spots for the locations of landfills specifically. Since the aim of this project is to select sites for new landfills we will take these factors into account and weigh them accordingly.

The general approach is visualised in figure 3.1. Furthermore, it should be noted that we used QGIS for most of the data processing and analysing. Only when some tools were not available in QGIS, we used ArcGIS instead.

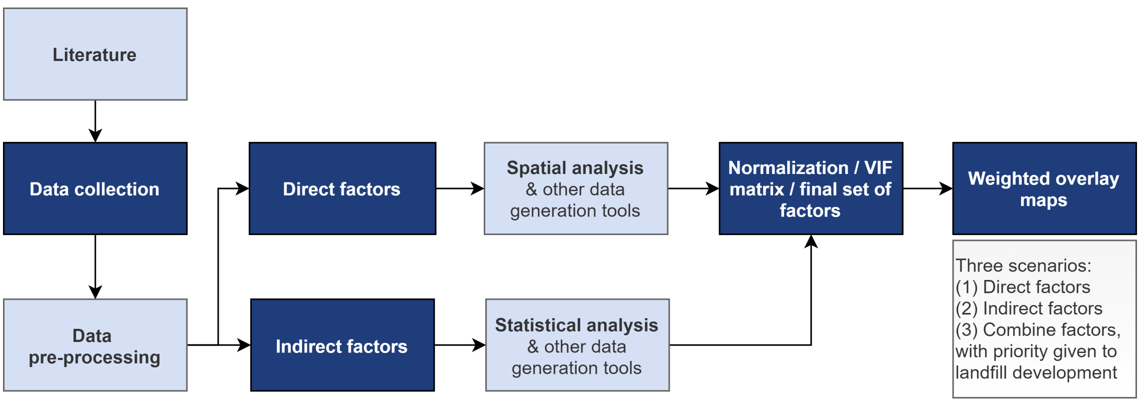


Figure 3.1. Flowchart methodology

3.1.2 Data collection and review

As waste management is a multidisciplinary topic (Nehrenheim, 2014), it involves various organisational, institutional, social, economic and environmental aspects. Therefore, in order to understand the problem and look for the factors that relate to the waste management of Mexico, we first collected the information and data regarding these aspects. The topics for data collection are not only based on literature, but also the group brainstorming process, as findings might come from the data that has not been mentioned in the literature.

We were given two data-sets by our client, one containing the registered sanitary landfills and one containing the registered open dumps of Mexico. These two were generated from a INEGI data-set using keywords. When inspecting the original data-set, we realised some unclassified waste facilities were missing. To make sure we were in fact taking all the registered facilities into account, we classified the remaining facilities using mainly visual inspection (full methodology in appendix B). We were able to classify almost all waste facilities, which resulted in the following numbers: 416 sanitary landfills, 1773 open dumps, 5 recycling centres and 12 unknown facilities (see Figure 3.2). The full results are visible in appendix B.

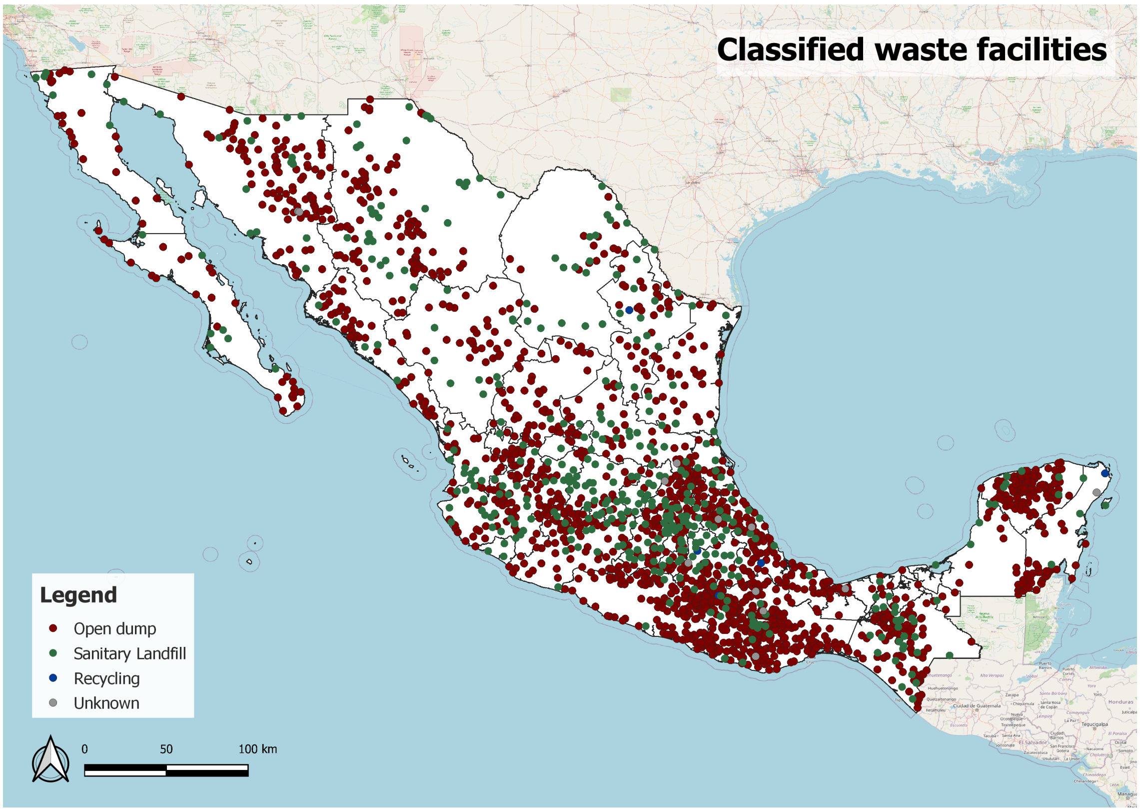


Figure 3.2. Classified waste facilities

All other data sets were found using open data sources on the Internet. A full table of the raw data and its sources is visible in Appendix A, table 1. The main sources for our data were from INEGI which is the National Institute of Statistics and Geography of Mexico (INEGI, n.d.) and the geoportal created by CONABIO which the National Commission for the Knowledge and Use of Biodiversity of Mexico (CONABIO, 2020). The scale of the data-sets differs from locality to state level, so further processing was needed. We also checked the data in terms of temporal compatibility, relevant and completeness.

3.1.3 Selection of direct factors

The set of direct factors can be divided into three fields: the waste disposal sources (the demand side), the provided waste infrastructure (the supply side), and the relationship between them. For each factor, we had different approaches to generate the data at the municipality level, in some exceptional cases we generated the data at the state level and assigned the same value for all municipalities within one state. The most common approach is spatial analysis. We started with a complete list of direct factors grouped into three fields (see Table3.1).

Table 3.1. List of original direct factors

DIRECT FACTORS	ORIGINAL DATASET	DATA GENERATION METHOD
	The waste disposal sources - the demand side	
Daily waste disposal per municipality	Shapefile of municipality (Table 1), Data on population per municipality in 2020	Field calculator, join datasets
Density of human settlement footprint per municipality	Shapefile of human settlements (Table 1)	Field calculator (calculate area)
Percentage of rural area per municipality	Shapefile of human settlements	Field calculator (calculate area)
Spatial distribution of human settlement footprint per state	Shapefile of human settlements	ArcGIS average nearest neighbour
	The provided waste infrastructure - the supply side	
Daily waste collection - capacity (kg) - by landfills per municipality - by waste facilities (both landfills and open dumps) per municipality	Data on waste facilities (Appendix B)	Calculation using Excel
Density of waste facilities (open dumps and sanitary landfills accordingly) per municipality	Data on waste facilities	Field calculator
Percentage of waste being illegally disposed per state	Data on illegal disposal (Appendix A)	Use data directly from source
Municipalities with or without waste collection service per municipality	Data on waste collection service (Appendix A)	Use data directly from source
Percentage of population having access to the waste collection service per state	Data on waste collection service (Appendix A)	Use data directly from source
Waste collection rate per municipality	Data on waste collection service (Appendix A)	Use data directly from source
	The relationship between demand and supply	
Total gap capacity (both open dumps and sanitary landfills) per municipality	Data on waste facilities	Calculation using Excel
Gap capacity of sanitary landfills per municipality	Data on waste facilities	Calculation using Excel

Table 3.1 continued from previous page

DIRECT FACTORS	ORIGINAL DATASET	DATA GENERATION METHOD
Average distance from human settlements to the closest waste facilities	Shapefile of human settlements and waste facilities	ArcGIS generate near table, Field calculator

Direct factors - The waste disposal sources (the demand side)
As mentioned in the previous chapter (Section 2.3.2), spatial characteristics of human settlement is an important aspect of the waste problem. Therefore, apart from the waste disposal demand, we also took the spatial distribution of human settlement footprints into account as direct factors related to the waste disposal sources.

Daily waste disposal per municipality
We first joined the data on municipal population in 2020 to the shapefile of municipalities based on the municipal code. Then, using the Field calculator from QGIS, we multiplied the data on municipal population in 2020 with the average waste disposal per person per day to get the total waste disposal per municipality per day.

The waste disposal demands are different for urban and rural areas in Mexico, the per capita waste generation per day was 0.958 kg for the urban community and 0.631 kg for the rural (Taboada-González et al., 2011). Since we did not have the data on urban/rural population at the municipality level, we used the percentage of the country wide urban population in 2018 for calculation, which is 80.5% (World Bank, 2018). We calculated the daily waste disposal per municipality as follows:

$$daily\ waste\ disposal\ per\ person = \frac{0.958x0.805 + 0.631x0.2}{2} \approx 0.9\ kg/person/day \tag{3.1}$$

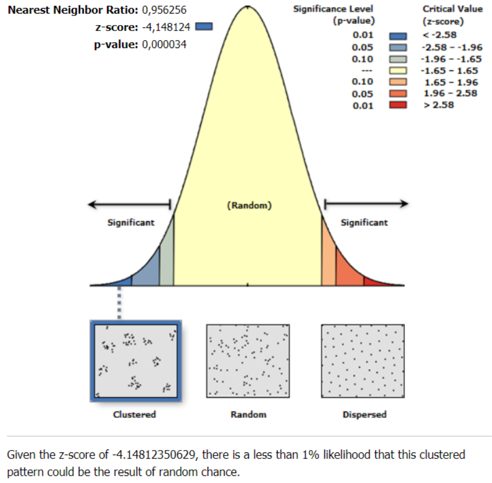
Density of human settlement footprint per municipality
We first used QGIS Field calculator to calculate the total areas of footprints belonged to one municipality and the area of that municipality accordingly. We then calculated the density of human settlement footprint per municipality as:

$$footprint\ density = \frac{total\ area\ of\ footprints}{area\ of\ municipality} \tag{3.2}$$

Percentage of rural area per municipality
Using the urban/rural attribute of the shapefile human settlements, we calculated the total area of rural footprint per municipality, then divided it through the total footprint area per municipality.

$$rural\ ftpt\ area = \frac{area\ (rural\ footprints\ in\ municipality)}{area\ (all\ footprints\ in\ municipality)} \tag{3.3}$$

Spatial distribution of human settlement footprint per state
Using the average nearest neighbour tool in ArcGIS, the shapefile human settlements, and the shapefile of state boundaries, we investigated if the distribution of the settlements in a state is clustered, sparse, or random (see figure 3.3). We first extracted the human settlements according to each state, and ran the average nearest neighbour tool for each shapefile.



Average Nearest Neighbor Summary	
Observed Mean Distance:	13553,9430 Meters
Expected Mean Distance:	14173,9687 Meters
Nearest Neighbor Ratio:	0,956256
z-score:	-4,148124
p-value:	0,000034
Dataset Information	
Input Feature Class:	Settlement_footprint_pop_UR_Area_MunLevel
Distance Method:	EUCLIDEAN
Study Area:	1974458845190,000000
Selection Set:	False

Figure 3.3. Example of the result of Nearest neighbour analysis of one state

The clustered type indicates that the footprints are close by and it would be easier for them to share (waste) infrastructure. Whereas the sparse type indicates that they are far away from each other, and investment in waste infrastructure would be more local, since transportation time and distance from the source to the facilities is an important economic aspect.

Direct factors - The provided waste infrastructure (the supply side)

Apart from the capacity of the waste facilities, the spatial distribution of the waste facilities is an equally important factor and needs to be considered in weak spots analysis, as capacity alone does not fully reflect the accessibility to the waste facilities.

Moreover, we also explored other measurements on the service side of the waste infrastructure, including the percentage of waste being illegally disposed per state, municipalities with or without waste collection service, the percentage of population having access to the waste collection service per state, and the waste collection rate per municipality. We used the data from source and joined them to the shapefile of municipalities.

Daily waste collection amount by waste facilities - capacity

We calculated the supply of the open dumps and the sanitary landfills separately, and then summed them up to have the total quantity of collected waste per municipality per day. The process of calculating the supply, which is the same for both waste facilities since the format and structure of the data-sets are similar, is as follows:

- By exploring the data sets of the waste facilities, we detected two important attributes: the ID of the municipality and the amount of daily waste that the waste facility receives from that municipality. Each waste facility corresponds with more than one municipal ID. This shows that waste facilities serve more than one municipality, and one municipality can be served by many waste facilities.
- Using Excel, we retrieved the list of unique records of municipality's ID. Then we calculated the total daily amount of waste that each municipality sends to the waste facilities.

Density of waste facilities

Using QGIS Field calculator, We first counted the number of open dumps and sanitary landfills per municipality using the shapefile of municipality and the shapefile of open dumps and sanitary landfills. Then we got the density of open dumps and the density of sanitary landfills per municipality as:

$$density\ of\ waste\ facilities = \frac{count\ (waste\ facilities)}{area\ (municipality)} \tag{3.4}$$

Direct factors - The relationship between the demand and supply

Total gap capacity per municipality

We generated this data by taking the difference between the daily waste disposal per municipality and the daily amount of waste collection by waste facilities using the Field calculator in QGIS.

$$total\ gap\ capacity = waste\ disposal\ per\ day - waste\ collection\ per\ day \tag{3.5}$$

$$ratio\ between\ disposal\ and\ capacity = \frac{waste\ disposal\ per\ day}{waste\ collection\ per\ day} \tag{3.6}$$

Gap capacity of sanitary landfills per municipality

This step employs the same approach as the total gap capacity per municipality (section 3.1.3). We only replace the daily waste collection amount by landfills instead of waste facilities in general.

$$total\ gap\ capacity = waste\ disposal\ per\ day - landfill\ waste\ collection\ per\ day \tag{3.7}$$

$$ratio\ between\ disposal\ and\ capacity = \frac{waste\ disposal\ per\ day}{landfill\ waste\ collection\ per\ day} \tag{3.8}$$

Average distance from human settlements to the closest waste facilities

For this part, we first computed the distance from the human settlement to the closest open dumps /sanitary landfill using an ArcGIS tool generate near table. The output is a table with three columns, the first one is the id of the settlement footprints, the second one is the id of the nearest open dumps / landfills, and the last one is the Euclidean distance between those two.

Then, we joined the output table to the footprint shapefile, so we had a new attribute as the distance to the nearest open dumps / landfills. We further generalised the dataset to the municipality level by calculating the average distance to the nearest waste facilities of all the footprints belonged to the municipality.

3.1.4 Selection of indirect factors

Apart from the factors directly related to the waste problem, there are also many socioeconomic factors that might be indirectly related to the current state of the waste management and problems linked to this. This includes factors such as poverty rate, population density and GDP. To find the factors that show the highest correlation with waste management we used statistical analysis (Longley et al., 2015). These factors could tell us more about the characteristics of the weak spots.

First of all we had a list of all the indirect factors and a list of direct factors, that resulted from the previous section, 3.1.3. All data is on state level, which is less computationally expensive and more complete than some data-sets on municipality level. Furthermore there are multiple data-sets for which municipality level data was not available or reliable.

Secondly, when calculating the correlation matrices we left out the state "Mexico city" (or sometimes called "Distrito Federal") as that showed to be an outlier in terms of waste management and population density (figure 3.4). Since the density of population here is a lot higher than any other part of the country and there are no waste facilities in this state itself according to our data-sets, the state mainly uses waste facilities from neighbouring states.

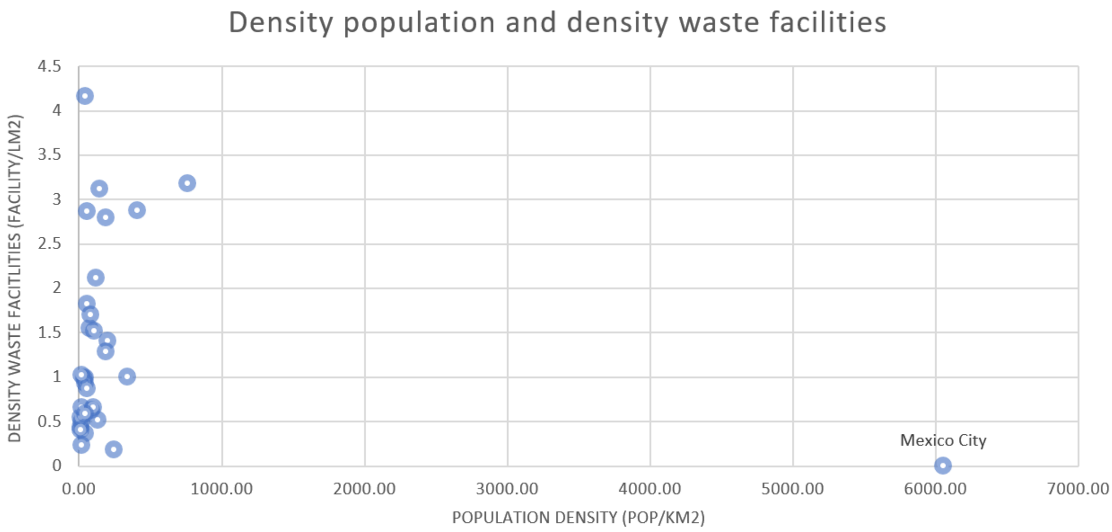


Figure 3.4. Scatterplot density population and density waste facilities per state

In order to find the indirect factors that showed the highest correlation with the general waste management we first normalised all the data-sets. Then we calculated pearson's correlation coefficient r between each of the normalised indirect factors and the direct factors.

$$r = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}} \tag{3.9}$$

The formula for r is shown in equation 3.9, where n is the amount of states, x is one of the direct factors and y is one of the indirect factors. These r values between all these factors can be visualised using a correlation matrix. Since there is such a high number of indirect factors to test we decided to split the correlation matrices into five sections: Economic factors, population factors, social factors, settlement distribution and waste management and distribution. (full list is visible in appendix D)

Whether a certain r-value indicates a strong relationship is largely dependent on the field of study in which it is used and highly sensitive to outliers (Akoglu, 2018). For this project we assumed any correlation with a r-value stronger than +/- 0.5 is considered a strong correlation, and any r-value stronger than +/- 0.7 to be very strong which is in line with standards used in multiple scientific fields (Mukaka, 2012).
Using these indications of strength we selected the indirect factors that showed the highest correlation with the direct waste management factors. Furthermore we defined the selected indirect factors as being a "cost" or a "benefit" factor based on the correlations they have with the directly related cost and benefit factors. If an indirect factor for example has a strong positive correlation with a direct-benefit-factor and a strong negative correlation with a direct-cost-factor, this indirect factor is assumed to be a benefit factor itself, and vice versa.

3.1.5 Normalisation, VIF matrix, and final factors

The set of factors need to be checked in terms of completeness, non-redundancy, and non-dependency. Regarding completeness, we already covered every possible aspects of the waste problems by grouping and elaborating the factors. Regarding non-redundancy and non-dependency, we first refined the factors based on our understanding towards the similarities of the factors.

Firstly, the total gap capacity already covers the factors on the waste disposal demand and the amount of waste that is collected, so we only kept the two factors on total gap capacity and gap in landfill capacity.

Secondly, human settlement density or distribution of human settlements alone do not represent the spatial distribution status of the human settlements. Hence, we tried to combine these factors and introduced six types of spatial patterns as follows: (1) sparse - low density, (2) random - low density, (3) clustered - low density, (4) sparse high density, (5) random - high density, and (6) cluster - high density. To define if the density is low or high, we used the threshold of 0.1 based on the normal distribution of the values of all municipalities. The ascending order of the types indicates the level of appropriateness of investment in sanitary landfills; whereas the reverse order indicates the level of appropriateness of investment in remotely solution for waste treatment.

After refining the list of factors, we assigned the label of cost factor or benefit factor for the factors. These labels are explained in the general approach (section 3.1.1).

Then, we normalised the values of the factors into one range (from 0 to 1) using the approach of Linear Max-Min normalisation (Vafaei et al., 2016). This step was to make all the factors comparable and could be added up with the overlay method to determine weak spots. The formulas are different for cost and benefit factors.

Benefit factors:

$$normalisedx = \frac{x - xmin}{xmax - xmin} \tag{3.10}$$

Cost factors:

$$normalisedx = \frac{xmax - x}{xmax - xmin} \tag{3.11}$$

Then, we checked the multicollinearity between the factors of each of the sets among themselves by calculating the variance inflation factor (equation 3.12).

$$VIF = \frac{1}{1 - r^2} \tag{3.12}$$

If the VIF value between two factors is higher than 4.0, we considered the two factors as multicollinear (Miles & Shevlin, 2001). We then remove one of the factors. If we were not sure which factor to remove we added up all the VIF values of the two factors, and selected the one that showed the lowest multicollinearity with all other factors. We chose to use the VIF method at this point because the values are normalised to cost and benefit, so factors that are accidentally correlated before the normalisation might not stay the same. For the sake of simplicity, the normalisation and the VIF matrix were conducted in Excel. Finally, we obtained a list of final factors.

Then, we joined the normalised values of the final factors to the shapefile of municipality.

3.1.6 Generate weighted overlay maps

For this step, we classified the factors for the three scenarios. For each of the scenario, we performed a (weighted) overlay of the normalised values of the factors to get the final scores at the municipal level (using the Field calculator in QGIS). The areas that have the lowest scores are considered the weak spots that require investment in waste infrastructure. Finally, we produced the maps of weak spots for the three scenarios.

3.2 Selecting potential locations for new landfills

In the second part of the methodology, we developed a spatial decision support system (SDSS) to select suitable locations for new sanitary landfills within the proximity of the detected weak spots. A flow chart of the steps involved in this process is shown in figure 3.5. Each step is explained in further detail in the following sub-sections.

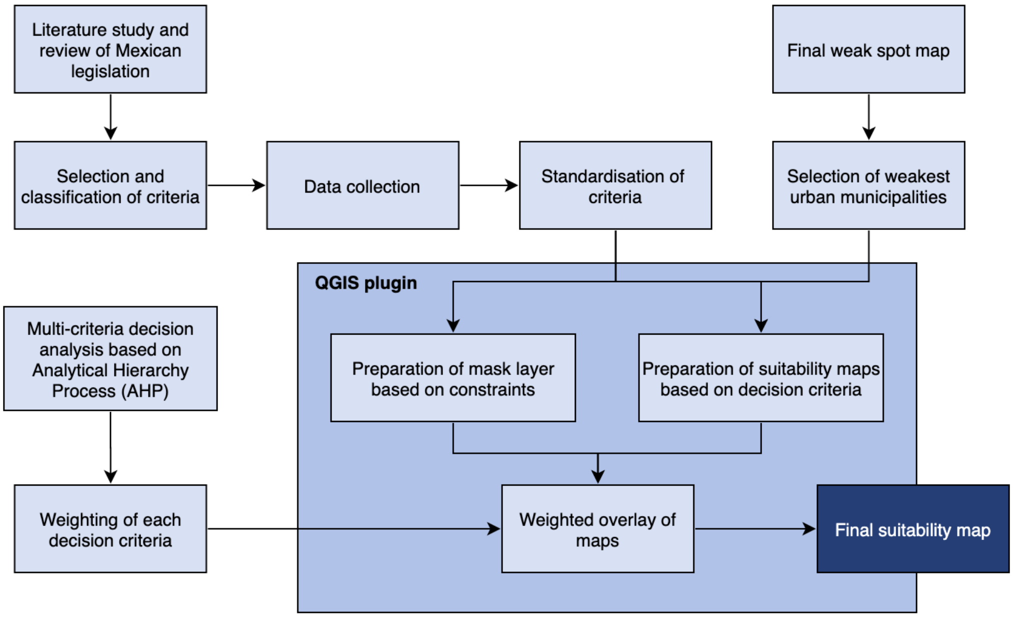


Figure 3.5. Flow chart of landfill site selection process

3.2.1 Selection of weak spots

As described in section 2.3.1, the siting of new sanitary landfills is only appropriate for more densely populated areas. Therefore, this part of the analysis only focuses on weak spots corresponding to urban municipalities. The selection process was done by categorising the weak spot municipalities into urban, sub-urban, and rural based on the settlement footprint data set used in the weak spot analysis, which described the type of settlement, and an additional data set on urban cities in Mexico from the World Bank. If the majority of settlements in a municipality were urban, then we classified the municipality as urban and selected it for the site selection suitability analysis. Furthermore, we only considered weak spots with the relatively lowest score.

3.2.2 Selection and classification of criteria

Firstly, in order to determine the appropriate site selection criteria, we performed a literature study and reviewed Mexican legislation. In total we collected over 30 relevant criteria, which we split into four main themes: social, economic, environmental and institutional. A complete overview is provided in table 3 of appendix C. From this overview, we chose to select seven criteria for the final SDSS (outlined in table 3.2). This selection was made in order to reduce the complexity of our SDSS and due to limitations related to the availability of data. Our selection mostly focused on the criteria that were derived from Mexican legislation. We focused on these criteria to ensure that our SDSS would comply with national standards. In addition, we chose to include two extra criteria related to the proximity of the road network and land use (in terms of agricultural and industrial areas). These extra criteria were added as they were frequently cited in literature (Demesouka et al., 2014) and allowed our SDSS to cover economic factors, as well as social and environmental factors.

We classified the criteria into two main types: constraints (C) and decision criteria (DC). Constraints are criteria which specify whether a site is suitable or unsuitable for landfill placement. They can be seen as a mask operation to exclude unsuitable sites. In contrast, decision criteria specify the level of suitability of different sites. Some criteria are both constraints and decision criteria, simultaneously excluding areas unsuitable for landfill placement as well as specifying different levels of suitability for the remaining sites. The classification of constraints and decision criteria was based on the literature study and review of Mexican legislation.

Table 3.2. Final selection criteria

Category	Criteria	C/DC	Zones	Scale Value
Social	Proximity to settlement footprints	C	<500 m >10 km	0
		DC	500 m - 6 km	10
			6 km - 8 km	5
			8 km - 10 km	2
	Proximity to airports	C	<15 km	0
Economic	Proximity to main road network	DC	<500 m	10
			>500 m	2
	Proximity to industry and agriculture	C	*located on site*	0
		DC	0 - 0.5 km	2
			0.5 - 1.5 km	5
			1.5 - 2.5 km	10
Environmental	Proximity to natural (protected) areas	C	*located on site*	0
	Proximity to surface water bodies	C	<0.5 km	0
		DC	0.5 - 1.5 km	2
			1.5 - 2.5 km	5
			>2.5 km	10
	Proximity to flood zones	C	*located on site*	0

3.2.3 Data collection

Next, we collected the input data for all selected criteria. An overview of the data sources is provided in table 2 in appendix A. The data was mainly collected from Mexican government sources via the INEGI data platform and CONABIO Geoportal. However, we noticed that the national data sets for the road and river networks contained multiple gaps and lacked detail. Therefore, we decided to use OpenStreetMap as the source for these two criteria. Furthermore, during the data collection process, we noticed that the available data related to natural areas and natural protected lands contained significant overlaps. For this reason, we decided to merge these two criteria into one.

In order to obtain the final data sets for the road network and agricultural and industrial areas, we had to filter the original data. For the road network, we selected only the primary, secondary and tertiary roads in order to simplify the input data and focus on main roads. For the agricultural and industrial areas, we determine those areas based on a land use and vegetation data set and filter only for features that have "agricultura" and "industria" as attribute name.

Since the datasets were from different sources, their coordinate reference systems were not consistent. Therefore, we chose to reproject all datasets to Mexico ITRF2008 / LCC (EPSG:6372) using QGIS. We chose this coordinate system because it is applicable to the whole of Mexico and ensured that all datasets would have units of meters, making it easier to implement the site selection criteria.

3.2.4 Zoning and standardisation of criteria

Once the data had been collected, we defined the zones for which the criteria were applicable and assigned discrete values to each of these zones. These discrete values were standardised to a suitability scale of 0-10, where 0 represents unsuitable areas for landfill siting and 10 represents areas with the highest suitability. For example, as shown in table 3.2 and figure 3.6, areas less than 500 meters and more than 10 kilometres from a settlement were assigned a scale value of 0. The remaining area between these two constraint zones was split into three zones with scale value decreasing with distance from the settlement footprint. The constraint zones were based on regulations from Mexican legislation, whereas the decision criteria zones were based on the literature study. However, we decided to simplify the zoning found from literature in order to reduce the complexity of our SDSS. Therefore, we only defined a maximum of three buffer zones, with scale values of 10, 5 and 2.

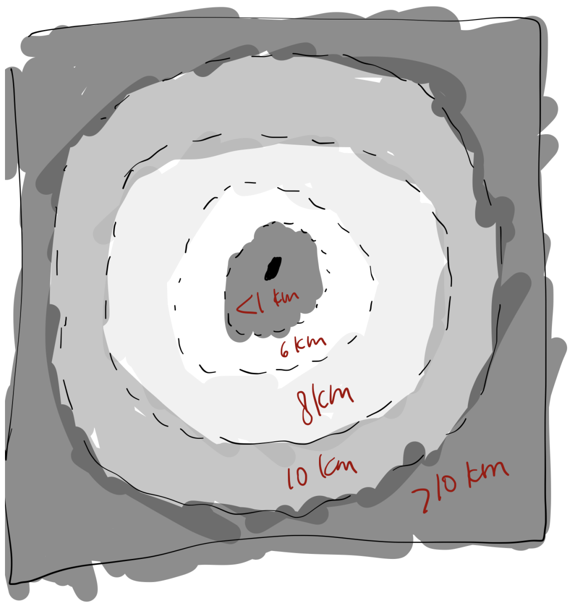


Figure 3.6. Suitability zones based on proximity to settlement footprints

3.2.5 Weighting of criteria

After the standardisation step, we assigned weights to the four decision criteria in order to specify their importance. We chose to implement two weighting schemes for the analysis: equal weighting and the analytic hierarchy process (AHP). AHP was selected among other multi-criteria decision-making processes because it is one of the most commonly used weighting methods, cited in 47% of papers reviewed in a recent comparison of multi-criteria spatial decision support systems for landfill site selection (Demesouka et al., 2014). Equal weighting is mainly cited in older literature (Demesouka et al., 2014), but was implemented in order to allow comparison of the results.

AHP was developed by Saaty and provides the possibility to formulate the relative importance of criteria with the respect to one another (Saaty, 1987). It is based on the pairwise comparison of criteria using a scale of importance ranging from 1-9 (see table 3.3). In this way, a complex decision problem is simplified to form a hierarchy of smaller decision problems. AHP checks the consistency ratio of the pairwise comparisons and ratings through the use of a consistency ratio (CR). A CR of < 0.1 indicates a reasonable rating of criteria (Ohri & Singh, 2013). The pairwise comparison of the four decision criteria is shown in table 3.4. The rating of each criterion with respect to another is based on the evaluation of each criterion's contribution in the regulations of Mexico. The final weights were calculated by normalising the eigenvector associated with the maximum eigenvalue of the comparison matrix (Ohri & Singh, 2013). The sum of the final weights equals 1. The consistency ratio of the ratings was 0.07.

Table 3.3. Scale of importance (Saaty, 1987)

INTENSITY OF IMPORTANCE	DEFINITION
1	Equal importance
3	Weak importance of one over another
5	Essential or strong importance
7	Demonstrated importance
9	Absolute importance
2, 4, 6, 8	Intermediate values between the two adjacent judgements

Table 3.4. Pairwise comparison of decision criteria and weight calculation using AHP

	Proximity to settlement footprints	Proximity to road network	Proximity to agriculture & industry	Proximity to surface water bodies	Weight
Proximity to settlement footprints	1	1/3	6	4	0.30
Proximity to main road network	3	1	8	3	0.50
Proximity to agriculture & industry	1/6	1/8	1	1/5	0.05
Proximity to surface water bodies	1/4	1/3	5	1	0.15

Notes: All entries in diagonal are equal to 1; Entries below diagonal are reprirocal of entries above diagonal

3.2.6 Map preparation and overlay analysis

The next step was to prepare suitability maps for all criteria based on the zones and scale values outlined in table 3.2. The different zones were implemented using basic GIS functions (buffer, difference and dissolve). In addition, the input data was clipped to a 10-kilometre bounding box centred on the weak spot to limit the analysis to areas within a close proximity to the weak spot. Then, the suitability maps were rasterised so that we could perform an overlay analysis. We chose a horizontal and vertical resolution of 2500 for all maps, corresponding to a pixel size of approximately 5 m^2.

Based on the rasterised maps, a mask layer was prepared by combining the zones corresponding to the constraints (scale value = 0). This was done by using the raster calculator to perform a Boolean conditional statement on each rasterised suitability map, which assessed whether a pixel was not equal to 0 (!=0). The output was either 0 (False, meaning the pixel was equal to 0) or 1 (True, meaning the pixel was not equal to zero). The Boolean query results of each suitability map were multiplied together, meaning that if any of the criteria maps had a pixel value of 0 then the mask layer would also equal 0. Otherwise, the mask layer would equal 1.

For areas that were suitable for landfill siting, we used the weighted linear combination (WLC) method to overlay the suitability maps of the decision criteria to determine the level of suitability of each pixel. The weighted overlay was multiplied by the mask layer to ensure that areas unsuitable for landfill placement were excluded in the final result. This procedure is summarised by equation 3.13, where S is the final suitability score, x_{ij} is the scale value of each decision criteria zone and w_i is the weight of that decision criteria.

$$S = mask \times \sum(w_i \times x_{ij}) \tag{3.13}$$

3.2.7 Classification of suitability

We classified the final overlay map into four suitability categories based on the score ranges shown in table 3.5. These categories were based on a landfill site selection SDSS implemented by Ohri and Singh (2013). We chose to subdivide the output into 4 categories in order to generalise the results, making it easier to understand the output of the SDSS.

Table 3.5. Suitability categories based on scale values

SUITABILITY CATEGORY	SUITABILITY SCORE RANGE
Unsuitable	0
Less preferable	1-5
Suitable	5-8
Most suitable	8-10

3.2.8 Development of SDSS plugin

After we had determined the research approach, we developed a basic SDSS plugin in QGIS to perform the map preparation and overlay analysis steps. The plugin was implemented using custom functions in Python and we built a Graphical User Interface (GUI) using Qt Creator. The output of this plugin is the final suitability map for landfill site selection within a 10 km proximity of a weak spot. In this sub-section we will provide an overview of the plugin's properties, functionality and workflow.

GUI of the plugin

The GUI of the plugin is shown in figure 3.7. After the users open QGIS and unzips our plugin package into the plugin directory of QGIS, then they can click and use it. When the users enter our interface, they can select the input layers for 'INPUT' and different criteria. Here, the 'INPUT' refers to the shapefile of the weak spots location which will be used to determine the extents of the site suitability analysis. In the GUI, the criteria are divided into three categories: 'SOCIAL', 'ECONOMY' and 'ENVIRONMENTAL', as mentioned in table 3.2. Users need to provide the initial shapefile that contains these contents.

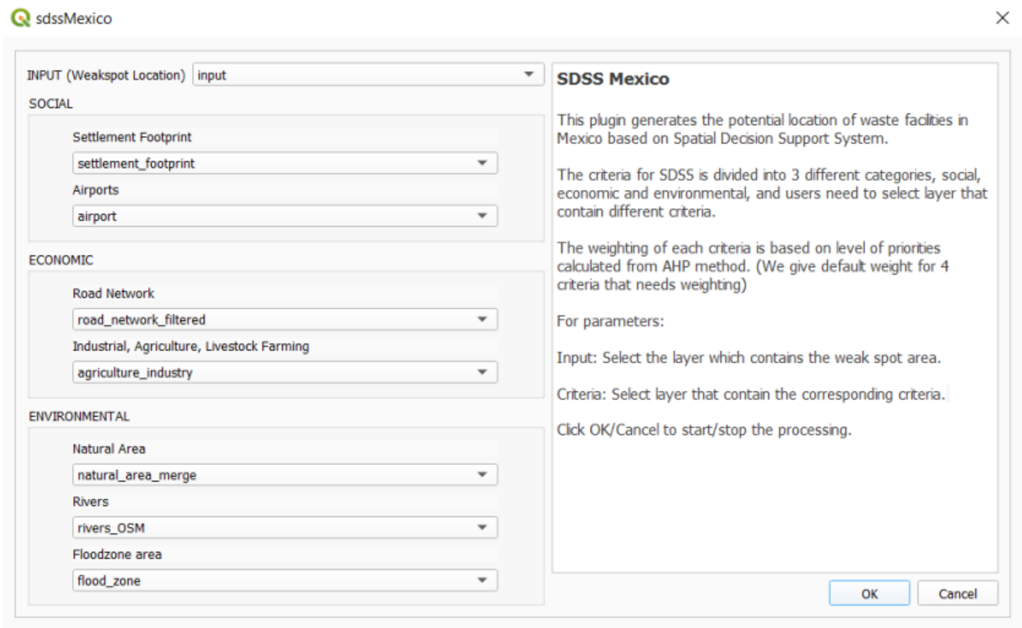


Figure 3.7. GUI of plugin

Workflow of the plugin

The workflow of the plugin is shown in figure 3.7. In our plugin we wrote different functions for each step. For each criterion, we called the functions in the order of the workflow. Once we determined the criterion for each file, we needed to clip the criterion based on the extent of the input weak spot. Then we called multiple buffer analysis functions to get buffers on different suitability levels. The 'difference' function is used to create the buffer ring. Next, we determined the parameters for rasterisation to get the raster layer. Then we gave weights for each layer and used raster calculator to get the result. Finally, we got to the final result of the potential location after rendering and styling.

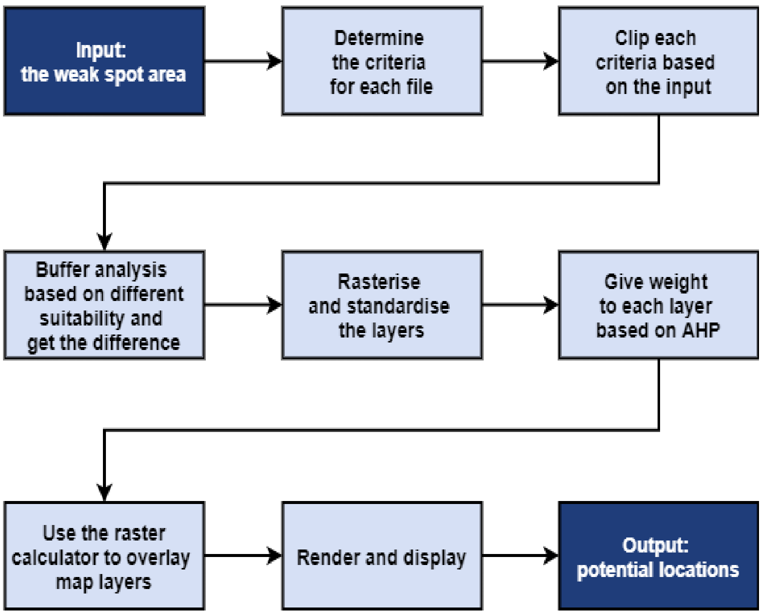


Figure 3.8. Workflow of SDSS plugin

Chapter 4

Results and findings

This chapter presents the results from the weak spot detection and the spatial decision support system for the selection of potential locations for new sanitary landfills. Maps that were produced based on the spatial analysis are shown first. Primary findings of the statistical analysis and correlation matrices are then given. Hereafter, we present the maps with the weak spots of the waste infrastructure in Mexico. This is followed by providing information on the characteristics of the weak spots. The chapter concludes with the results from the spatial decision support plugin that was used to determine potential locations for new sanitary landfills.

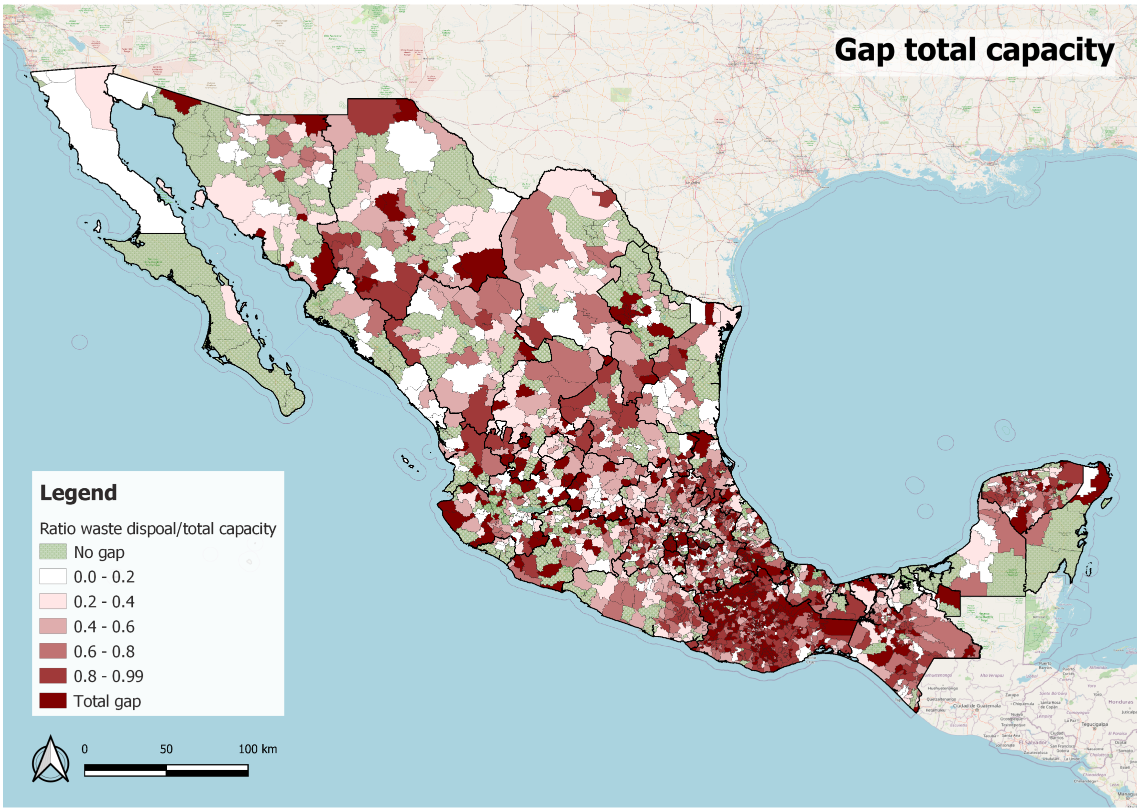
4.1 Detecting weak spots

4.1.1 Direct factors

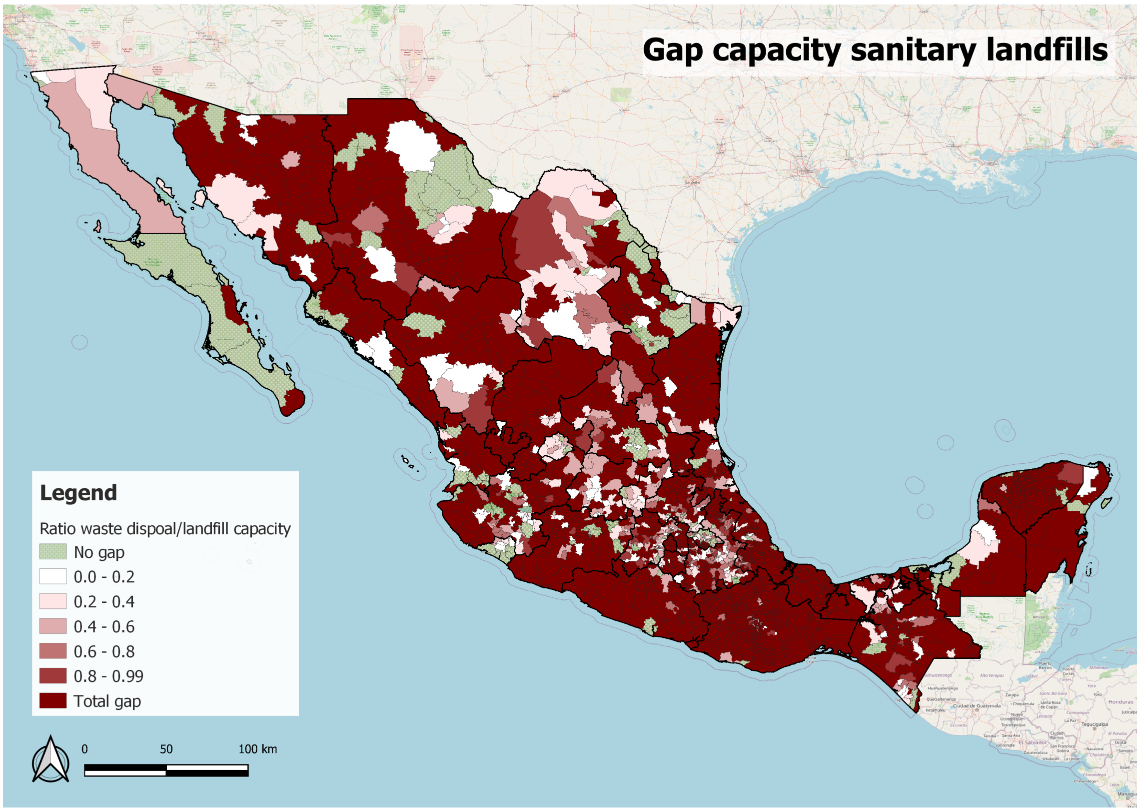
After conducting the spatial (data) analysis for the direct factors, we produced maps as results that can be found in the Appendix F. We only present here some intermediate results that we find important in order to understand the context of waste management in Mexico.

Firstly, the result on the total gap capacity Figure 4.1a shows that even with the supply of open dumps, only a small portion of the regions are receiving sufficient provision of waste collection and treatment. Areas with high shortage in waste infrastructure concentrate in the southern part of the country. On the other hand, by exploring the gap capacity of sanitary landfills alone Figure 4.1b, a large portion of the regions that spread throughout the country are lacking of appropriate waste infrastructure. It is also noticed that using the gap capacity in sanitary landfill alone cannot strategically point out the place that need the investment in the shortcoming period, as most of the regions are as weak. Hence, more factors should be taken into account.

Secondly, the average distance from the human settlements to the closest waste facilities Figure 4.2 at the municipality level also shows interesting results. On the one hand, the smaller the size of the municipality, the closer it is to open dumps. It could be that states with a great number of municipal divisions have more settlements and population. On the other hand, the municipality that have less gap capacity in sanitary landfill does not necessarily have a short average distance to the landfills. Therefore, the combining of different factors on spatial distribution of human settlements and waste facilities is important to comprehensively assess the waste problem.

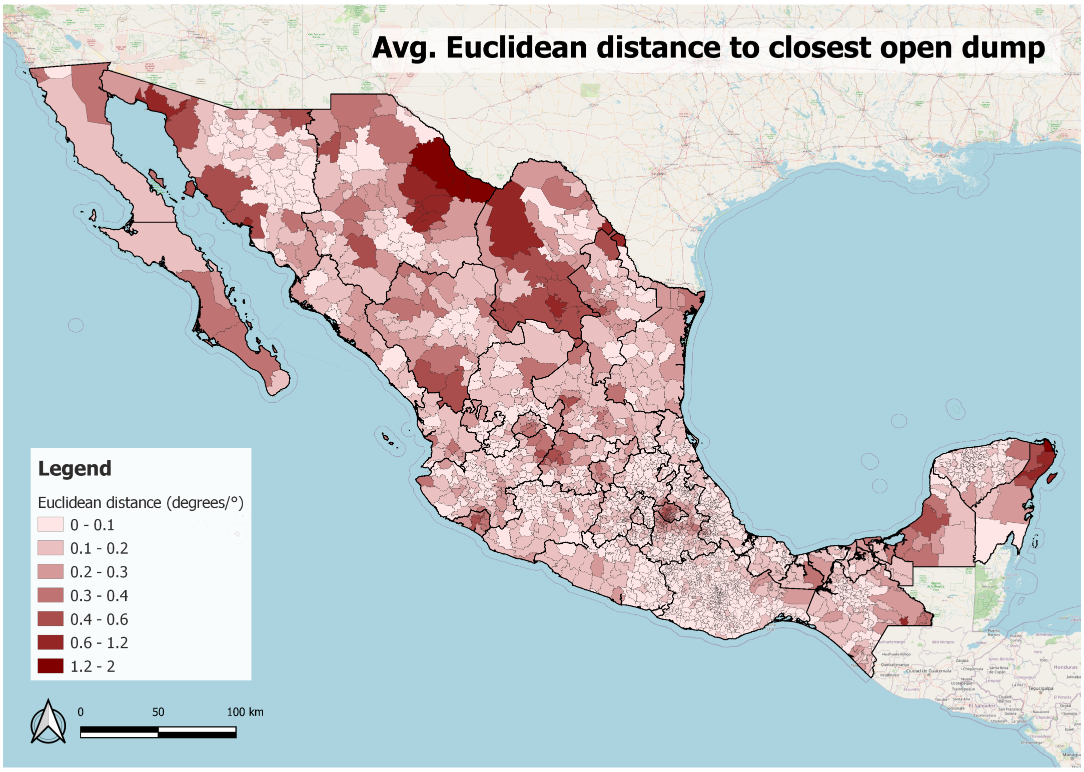


(a) Total gap capacity (taking into account both open dumps and sanitary landfills)

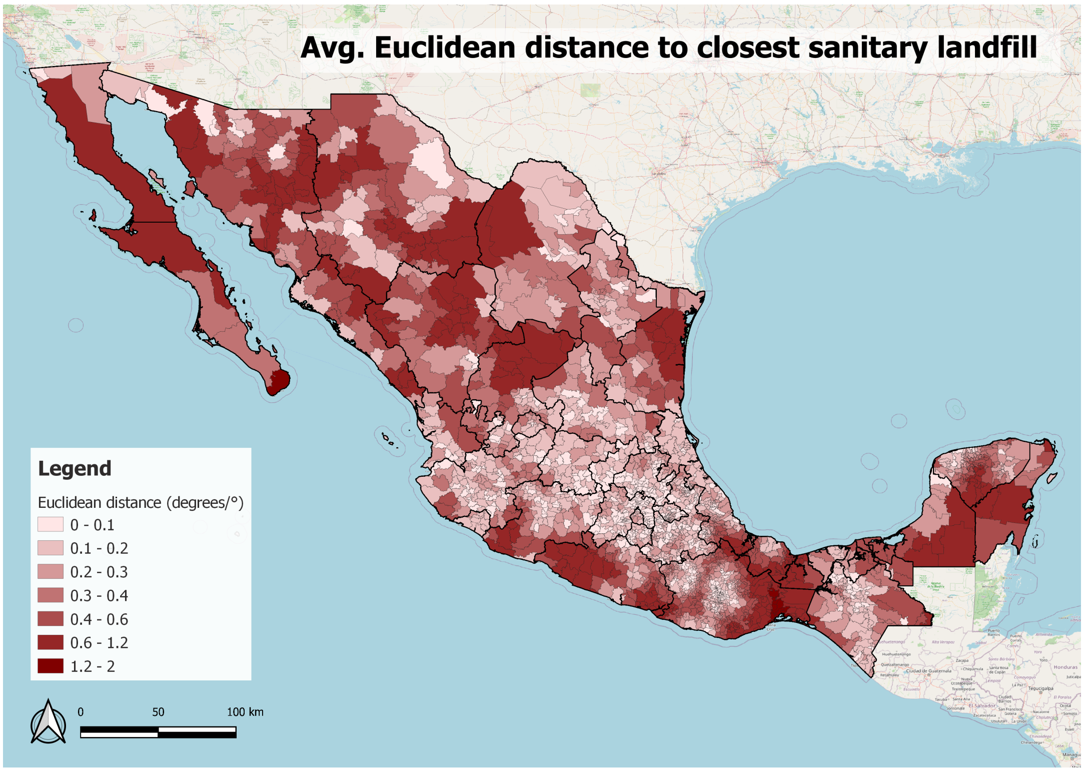


(b) Gap capacity regarding Sanitary Landfills

Figure 4.1. Total and landfill gap capacity



(a) Average distance from human settlements to the nearest open dump



(b) Average distance from human settlements to the nearest landfill

Figure 4.2. Average euclidean distance to nearest waste facilities

Direct factors classified as cost - benefit

We assign the cost and benefit label to the selected direct factors as in Table 4.1. It is noted that the last two factors are labelled according to the priority in landfill investment (Section 4.1.1).

Table 4.1. Selected direct factors

ABV. NAME	DESCRIPTION	SCALE	YEAR	Cost/Benefit
Dens. dumps (c.)	Density of open dumps	Mun.	2017	C.
Dens. landfills (b.)	Density of sanitary landfills	Mun.	2017	B.
% illegal disposal (c.)	% of waste being illegally disposed	State	2010	C.
No service (c.)	Municipalities with or without waste collection service	Mun.	2016	C.
% pop. with access (b.)	% of pop. with access to the waste collection service	State	2015	B.
Waste collection rate (b.)	% of total MSW that is collected	Mun	2010	B.
R. total gap capacity (c.)	gap in total capacity (ratio disposal/capacity)	Mun.	2017	C.
R. landfill gap capacity (c.)	gap in landfill capacity (ratio disposal/capacity)	Mun.	2017	C.
Avg. dist. landfills (c.)	Average euclidean distance to the closest open dumps	Mun.	2017	B.
Avg. dist. dumps (b.)	Average euclidean distance to the closest landfills	Mun.	2017	C.
Spatial ftpt distribution (b.)	Spatial distribution of human settlements/footprints	Mun.	2015	B.
% rural ftpt area (c.)	% of the rural footprint area out of total footprint area	Mun.	2015	C.

As explained in the methodology 3.1.1, we labelled the factors as cost or benefit as follows: :

- Density of open dumps: the main aim of the waste management in Mexico is to closing down open dumps and invest in environmental friendly solution. So the higher the density of open dumps, the weaker the place with regards to the waste infrastructure.
- Density of landfills: the opposite of the density of open dumps. In order words, high density of landfills is advantageous.
- Percentage of waste being illegally disposed: high rate of illegal disposed reveals the need for a more proper waste infrastructure system. Therefore, the factor is a cost.
- Municipalities with or without waste collection service: since "with service" is scored as 0, and "without service" 1, the factor is a cost.
- Percentage of population having access to the waste collection service: the higher the value, the better the waste infrastructure provided, so the factor is labelled as benefit.
- Waste collection rate: the higher the value, the better the waste infrastructure provided, so the factor is labelled as benefit.
- Total gap capacity (ratio disposal/capacity): the higher the value, the larger the gap between demand and supply, the more important it is to invest in waste infrastructure. So, the factor is labelled as cost.
- Gap capacity in sanitary landfills (ratio disposal/capacity): the same as total gap capacity.
- Average distance from human settlements to the closest open dumps: the higher the value, the farther it is from the open dumps, the better the situation within the area, so the factor is a benefit.
- Average distance from human settlements to the closest landfills: the opposite of the distance to the closest landfills, so the factor is a cost.
- Spatial distribution of human settlement footprint per state: (1) sparse - low density, (2) random - low density, (3) clustered - low density, (4) sparse high density, (5) random - high density, and (6) cluster - high density; they order from low to high value if investment in sanitary landfills is a priority. So, the factor is a benefit one if we are looking for locations for landfills.
- Ratio of rural footprints compared to total footprints: the higher the value, the less important it is to invest in landfills. So the factor is a cost.

4.1.2 Indirect factors

The selection of the relevant indirect factors is done with statistical analysis where we made correlation matrices to calculate the strength of the correlation between direct and indirect factors, grouped in five different themes. The full list of data-sets is visible in appendix D. One of the correlation matrices is shown in figure 4.3, the complete overview of matrices is visible in appendix E.

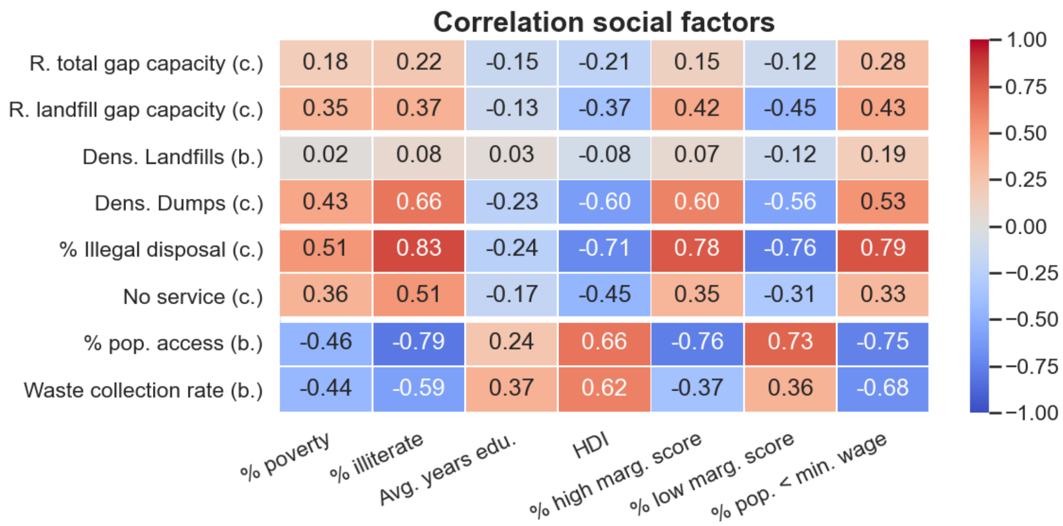


Figure 4.3. Correlation matrix of social factors. Horizontal: indirect factors, vertical: direct factors

Selection and classification of indirect factors

To get the relevant indirect factors we selected only those factors with strong (+/- 0.5) or very strong (+/- 0.7) correlation with multiple direct factors. Furthermore we can assign these indirect factors to being a 'cost' or a 'benefit'. If we use figure 4.3 as an example, we select the following indirect factors:"R. poverty '18", "R. Illiterate '10", "HDI '10", "R. high marg. score", "R. low marg. score" and "R. pop > Min. wage". This means the factor "avg. years edu '10" is discarded. When looking at the "R. illiterate '10" factor, we see that it has a strong positive correlation with the density of open dumps and the percentage of illegal disposal, these last two are both "cost" factors. The factor has a strong negative correlation with the percentage of the population with access to the waste facilities and the percentage of waste that is collected, these two are both benefits. This results into us defining the "R. illiterate '10" factor as a cost. This can be done for all the factors that show strong correlation.

Doing these selections on all correlation matrices leads to the following indirect factors (which are also visualised separately in appendix F):

Table 4.2. Selected indirect factors

ABV. NAME	DESCRIPTION	SCALE	YEAR	COST/BENEFIT
Pop density	Population density	Mun.	2018	B.
% Rural pop	% of rural pop.	Mun	2010	C.
% pop in 1st sector	% of working pop. in primary economical sector	State	2010	C
% pop in 2nd sector	% of working pop. in secondary economical sector	State	2010	B.
% pop in 3rd sector	% of working pop. in tertiary economical sector	State	2010	B.
HDI	Human development index	Mun	2010	B.
% poverty	% of pop. Living in moderate poverty	Mun	2018	C.
% illiterate	% of pop. Above 15 that is illiterate	Mun	2010	C.
% pop <min. wage	% of working pop. That earns less than min. wage	Mun	2010	C
Marg. Score	Marginalisation score	Mun	2010	C
% rural ftpt area	% of rural footprint area/total footprint area	Mun	2015	C

4.1.3 Normalisation, VIF calculations and final factors

Normalisation and VIF calculations

After we assign the cost and benefit label to the set of factors, we normalise the data-sets accordingly, as shown in equation 3.1.5. Then, we further refine both the lists of direct and of indirect factors by checking for multicollinearity between the factors. The check we use the variance inflation factor (VIF), any two factors between which the VIF is higher than 4 are considered to have multicollinearity.

Direct factors- VIF matrix

Table 4.3. VIF matrix for direct factors

	R. landfill gap capacity (c.)	R. total gap capacity (c.)	Dens dumps (c.)	Dens landfills (b)	R. rural ftpt area (c.)	% pop. with access (b.)	No service (c.)	% illegal disposal (c.)	Spatial ftpt distribution (c.)	Avg dist landfills (c.)	Avg dist. Dumps (b.)	N.Waste collection rate (b.)
R. landfill gap capacity (c.)												
R. total gap capacity (c.)	1.23											
Dens dumps (c.)	1.02	1.00										
Dens landfills (b)	1.04	1.00	1.00									
% rural ftpt area (c.)	1.01	1.00	1.03	1.00								
% pop. with access (b.)	1.12	1.10	1.05	1.00	1.00							
No service (c.)	1.02	1.07	1.01	1.00	1.00	1.10						
% illegal disposal (c.)	1.11	1.11	1.05	1.00	1.00	47.73	1.10					
Spatial ftpt distribution (c.)	1.00	1.01	1.01	1.01	1.00	1.00	1.00	1.01				
Avg dist landfills (c.)	1.10	1.00	1.00	1.04	1.00	1.05	1.00	1.04	1.05			
Avg dist. Dumps (b.)	1.19	1.01	1.05	1.00	1.00	1.15	1.01	1.16	1.01	1.01		
Waste collection rate (b.)	1.00	1.01	1.03	1.00	1.02	1.01	1.37	1.01	1.02	1.03	1.00	

According to the VIF matrix of direct factor Table 4.3, there is severe multicollinearity between the factors '% illegal disposal' and '% pop with access'. To decide which of these two to keep we add up all the VIF values for each of the two factors to see which of the two shows the least correlation with any of the other factors. This gives:

- Sum VIF '% illegal disposal' = 58.32
- Sum VIF '% pop with access' = 58.31

Since they show very similar values, we remove the factor on percentage of population having access to the waste collection service per state ('% pop with access') from the set as this factor contains less information and the data-set is less detailed.

Indirect factors - VIF matrix

Similar to the direct factors we calculate the VIF to check for multicollinearity between the different indirect factors.

Table 4.4. VIF matrix for indirect factors

	Pop density (b.)	% rural pop (c.)	% primary sect. (c.)	% secondary sect. (b.)	% tertiary sec. (b.)	Human Dev. Index (b.)	% poverty (c.)	% illiterate (c.)	% less min. Wage (c.)	Marginalization (c.)	% rural ftpt area (c.)
Pop density (b.)											
% rural pop (c.)	1.10										
% primary sect. (c.)	1.03	1.03									
% secondary sect. (b.)	1.00	1.01	2.58								
% tertiary sec. (b.)	1.07	1.04	5.01	1.22							
Human Dev. Index (b.)	1.12	1.58	1.04	1.01	1.05						
% poverty (c.)	1.04	1.11	1.02	1.01	1.03	1.59					
% illiterate (c.)	1.05	1.23	1.04	1.01	1.05	3.10	1.36				
% less min. Wage (c.)	1.06	1.64	1.07	1.02	1.08	2.96	1.49	2.24			
Marginalization (c.)	1.10	1.58	1.04	1.01	1.06	4.77	1.55	4.27	3.57		
% rural ftpt area (c.)	1.06	1.20	1.00	1.01	1.00	1.10	1.03	1.05	1.04	1.14	

As visible in table 4.4 there are multiple cases of multicollinearity among the indirect factors. Again we add up all the VIF values for these factors and select the one with the lowest sum.

The factors '%tertiary sect. (b.)' and '%primary sect. (c.)':

- Sum VIF '%tertiary sect. (b.)' = 14.61
- Sum VIF '%primary sect. (c.)' = 15.867

We select the tertiary sector factor and discard the primary and secondary sector factor. The secondary factor is discarded too because it wouldn't make sense to keep two of these factors.

The factors 'Marginalization (c.)', 'Human Dev. Index (b.)' and '% illiterate (c.)':

- Sum VIF 'Marginalization (c.)' = 21.10
- Sum VIF 'Human Dev. Index (b.)' = 19.33
- Sum VIF '% illiterate (c.)' = 17.40

Here we select the percentage illiterate factor and discard the other two.

Final factors for different scenarios

After refining the list of direct and indirect factors, we arrange them according to the three scenarios introduced in the general approach to weak spot detection (Section 3.1.1) in Table 4.5.

Table 4.5. Overview of factors used for weak spots maps

Factor name	Direct factor map	Indirect factor map	Landfill related map	Figure
R. total gap capacity	x (Cost)		x (Cost)	4.1a
R. landfill gap capacity	x (Cost)		x2 (Cost)	4.1b
Density open dumps	x (Cost)		x (Cost)	6c
Density sanitary landfills	x (Benefit)		x (Benefit)	6d
Avg. distance open dumps	x (Benefit)		x (Benefit)	4.2a
Avg. distance sanitary landfill	x (Cost)		x (Cost)	4.2b
% illegal waste disposal	x (Cost)		x (Cost)	6a
No service	x (Cost)		x (Cost)	6e
Waste collection rate	x (Benefit)		x (Benefit)	6b
Pop. density		x (Benefit)		8c
% illiterate		x (Cost)		8e
% poverty		x (Cost)		8a
% rural pop.		x (Cost)		8d
% tertiary sect.		x (Benefit)		8f
% <min. wage		x (Cost)		8b
% rural ftpt area		x (Cost)	x (Benefit)	7b
Spatial ftpt distribution			x (Benefit)	7a

x Cost

x Benefit

4.1.4 Generating weighted overlay maps

Scenario 1: Using direct factors

For this scenario, we use the direct factors from Table 4.5, except for the factors on spatial distribution and the ratio of rural footprints compared to total footprints, as they favour the investment in landfills. The overlaying of the set of factors (same weight) result in the map of the first scenario (Figure 4.4). It should be noted here that the values of the overlay score are relative. Meaning that a municipality with a very high score might look good, but is only a good place in comparison with the rest of Mexico and might still need investment. The map shows that the southern part of the country need the most attention in waste infrastructure development since the overlay score is generally lowest there. However, the pattern of areas that are considerably weak does spread within the country. Hence, the map is valuable both nationwide (where strategic investment should focus in the Southern part) and statewide (where development should focus in some particular municipalities).

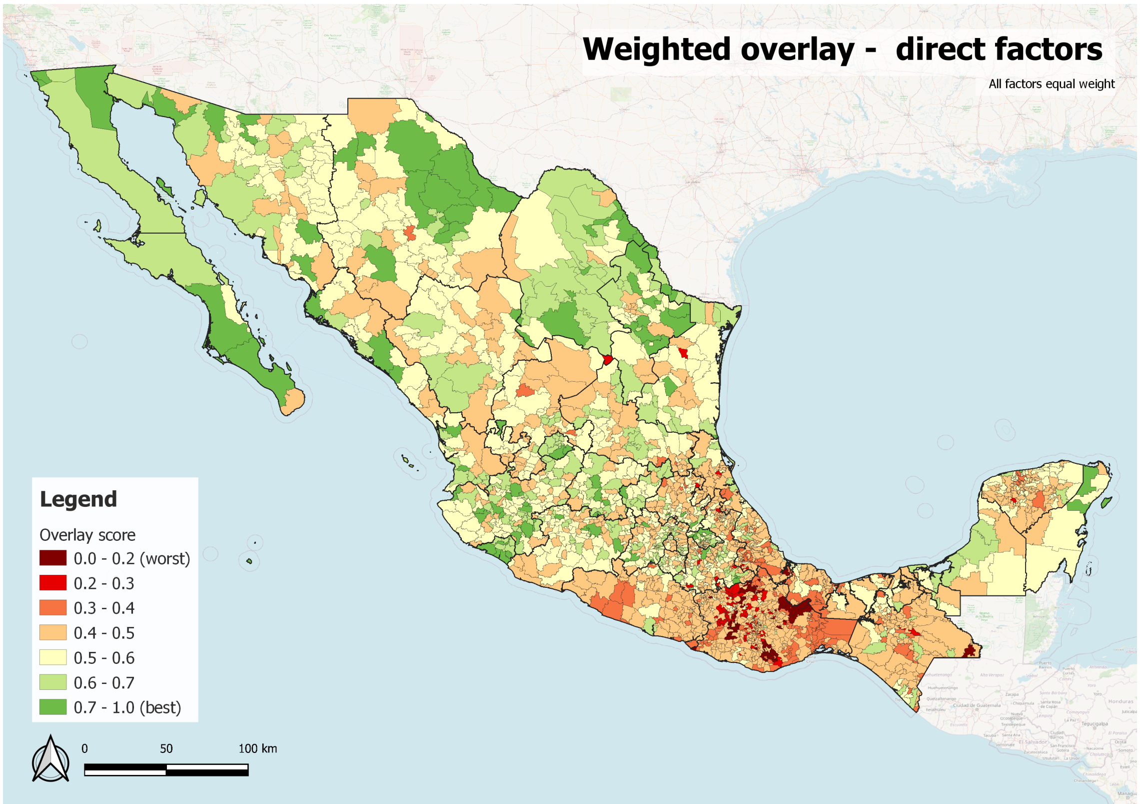


Figure 4.4. Weighted overlay map - Scenario 1: Using direct factors that do not favour landfill

Scenario 2: Using indirect factors

For this scenario, we use the indirect factors visible in table 4.5. As the statistical analysis provides a set of factors that show the highest correlation with the direct factors. Thus, we produce a weak spots map that only use those indirect factors to see if it shows a similar result with the first map. The overlaying of the set of factors (equal weight) result in the map of the second scenario (Figure 4.5). The map shows that the weak spots appear quite dense and the total scores are relatively higher than the first scenario using directly related factors. The correlation coëfficient between the total score of the first and second scenarios is r = 0.47, and by plotting the two set of score, the trend is sometimes not the same. By comparing the patterns of the two maps (scenario), the locations of weak spots have a lot in common, except for the big cities. It is because big cities are still lacking of waste facilities when looking from the direct factors, but they are highly developed in terms of economic and social aspects. Hence, we come to a conclusion that solely using indirect socio-economic factors can also applicable to determine weak spots in case other direct measurements are not available; but it is not always true for big cities. However, such an approach might only be true with countries that have the same development context as Mexico.

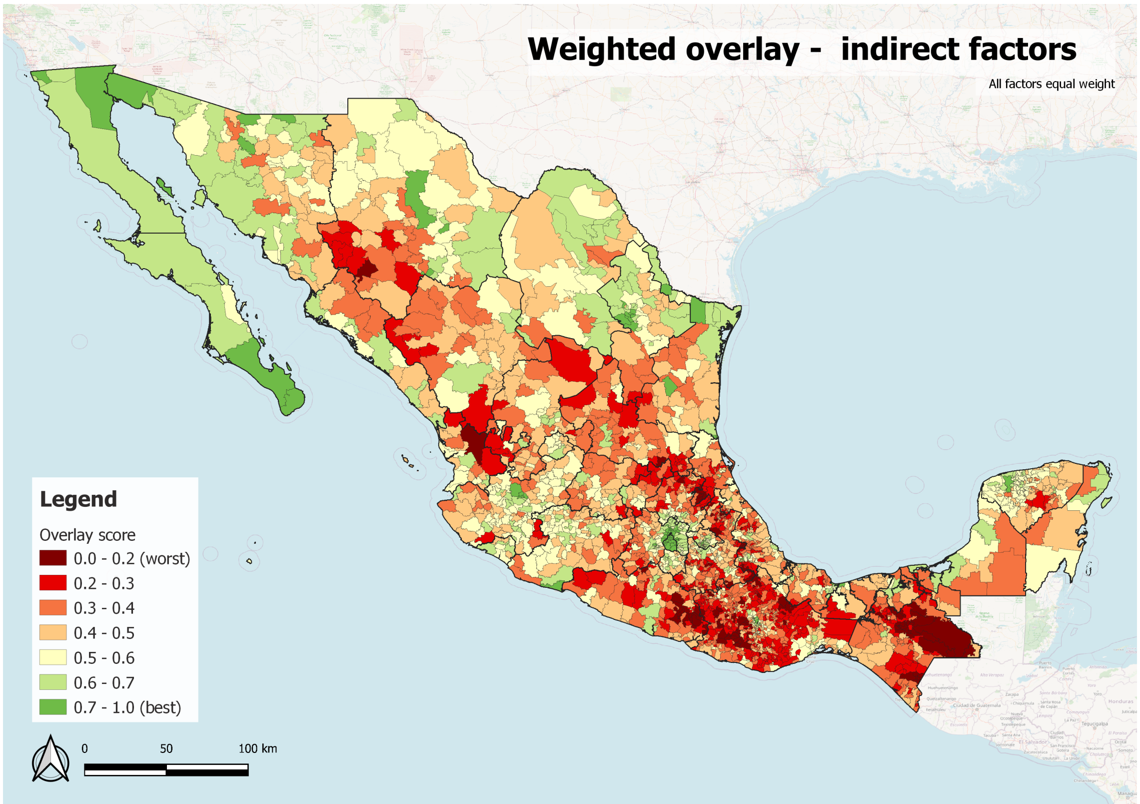


Figure 4.5. Weighted overlay map - Scenario 2: Using indirect factors

Scenario 3: Using factors and weights that favour the investment in landfills

For this scenario, we use all the direct factors from table 4.5, they include the factor on spatial distribution that favours clustered and dense footprint and the factor on ratio of rural footprint area/total footprint area. Moreover, we also double the weight of the factor of gap in landfill capacity to emphasise the need for sanitary landfills. The map product of the third scenario (Figure 4.6) points out the municipalities in need of investment in landfills.

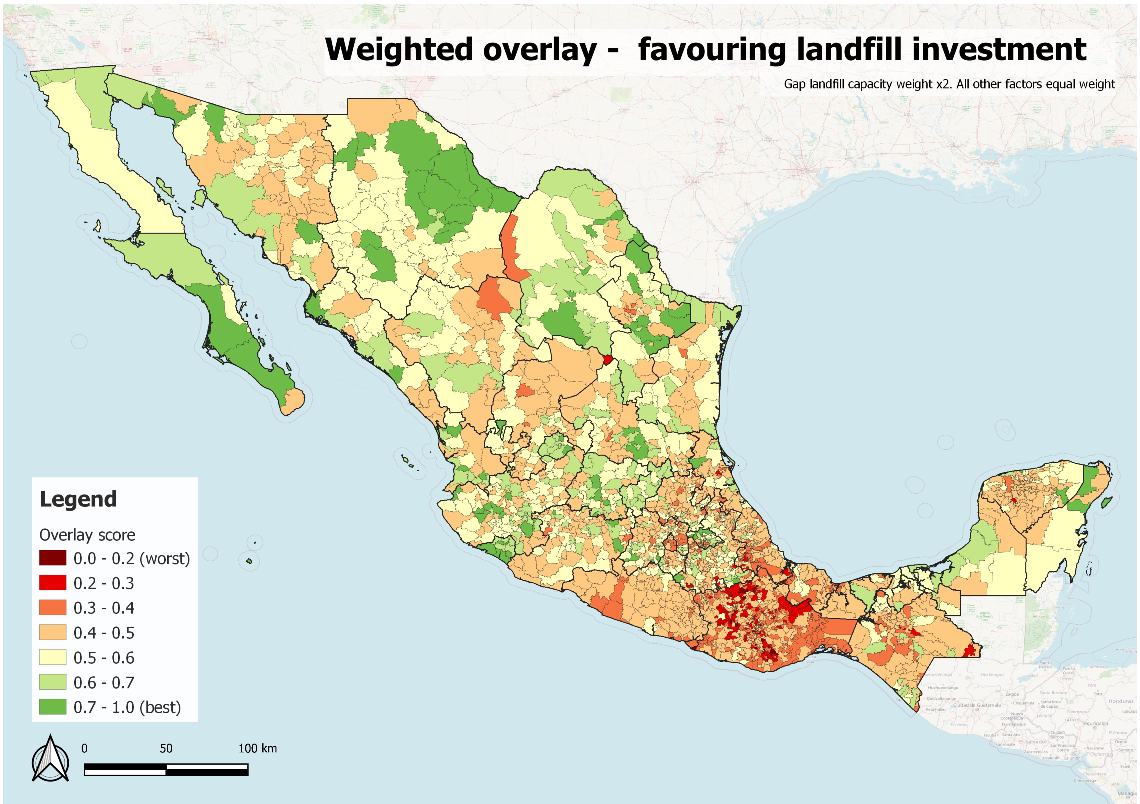


Figure 4.6. Weighted overlay map - Scenario 3: Using factors and weights favouring landfill investment

Since the map of scenario 3 uses factors and weight favouring landfills we used this to determine the weakest spots, which can be used as the input for the next step of finding potential locations for new landfills. We therefore zoom in the weakest regions and select the municipalities with an overlay score lower than 0.3 as the weak spots most in need of investment (Figure 4.7).

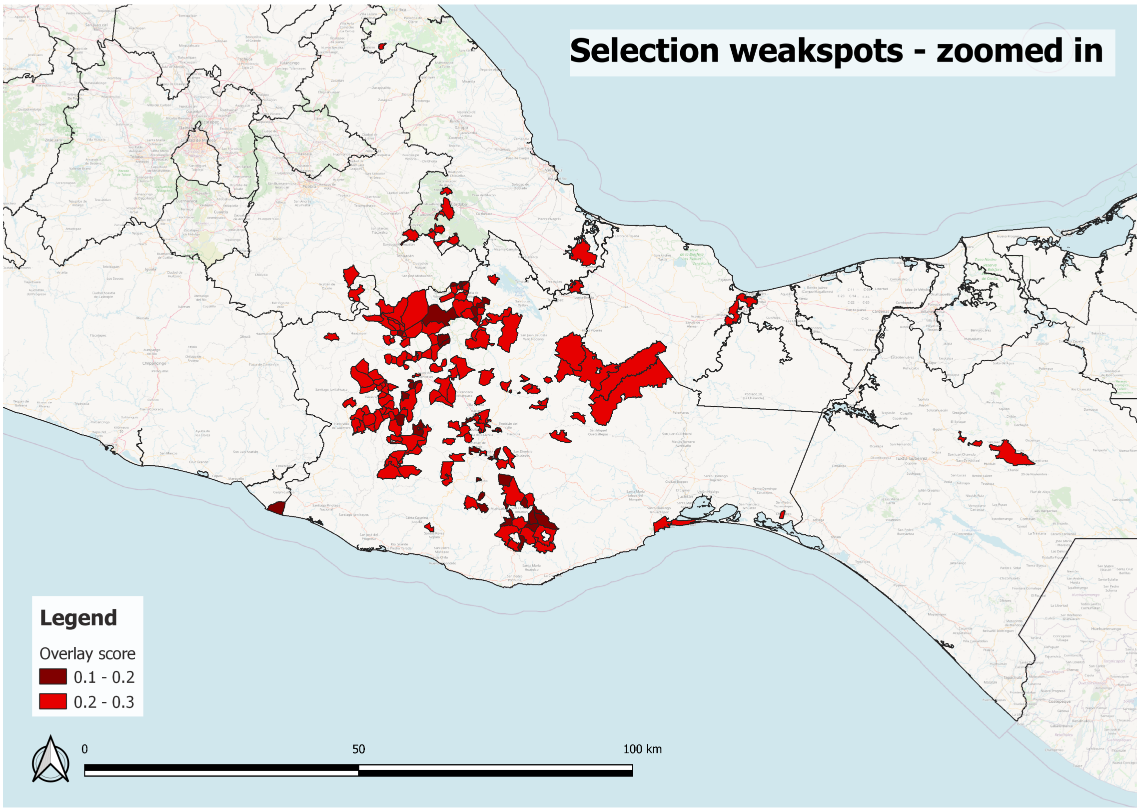


Figure 4.7. Selection of weakest spots

Characteristics of weak spots

Looking at map 4.7 the area where the weak spots are most prevalent is in the south of Mexico, specifically in the state of Oaxaca. Looking at the indirect factors can tell us more about the characteristics of most of the weak spots we found. Table 4.6 shows the average value of the indirect factors throughout the whole country, and the average factor for the waste facilities only.

Table 4.6. comparison indirect factors

	% rural ftpt	pop dens.	% illiterate	% pop rural	%. pop terr sec	% pop poverty	% pop <min wage
Country avg.	44.7	311.554	14.0	59.4	54.8	61.3	39.0
Weakspot avg.	36.6	131.349	21.4	92.6	52.2	76.2	67.2

The weak spots have a slightly higher percentage (76.2%) of poverty than average (61.3 %) and have significantly higher percentage of people earning less than minimum wage (67.2% compared to 39%). The population density is considerable lower in the weak spots (131.349 pp/km2) than the average of the country (311.554 pp/km2), even when taking factors into account that favour landfills, which are generally densely populated urban areas. This is confirmed by looking at the percentage of rural population which is on average almost twice as high in the weak spots as it is in the rest of the country. Generally speaking rural, thinly populated and relatively poor areas show up as the main weak spots. For the selection of sanitary landfill locations however it makes more sense to select the most densely populated urban areas of these weak spots (see section 2.3.2). The improvements of the thinnest populated rural areas need a different approach, which is described in section 2.3).

4.2 Selecting potential locations for new landfills

Based on weak spot analysis, there are 189 municipalities that have overlay score below 0.3. As stated on previous section 2.3.2, we chose sanitary landfill as the focus of waste facilities investment. Therefore, the potential locations are recommended to be located on dense urban areas. To find the investment locations, we categorise these municipalities into three categories: urban, sub-urban, and rural.

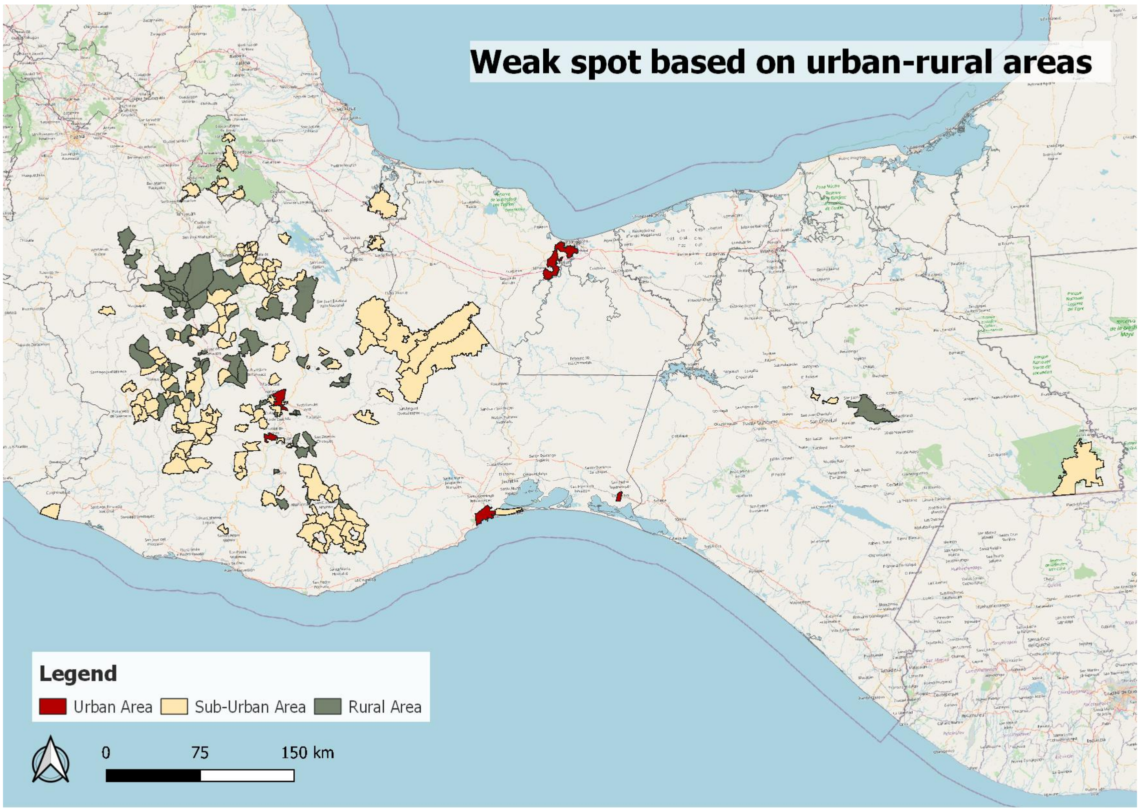


Figure 4.8. Weak spot based on urban-rural areas

In order to determine the input layer for SDSS plugin, we only selected the input (investment location) based on weak spot areas which are located on urban area. As stated on (Figure 4.8), we found that there are five municipalities that are located in an urban area, which are: San Antonio de la Cal, San Pablo Huixtepec, Oaxaca de Juorez, Salina Cruz, and Cosoleacaque. Based on this, we set the input layer into as follow:

- Input 1: Oaxaca de Juorez, San Antonio de la Cal
- Input 2: San Pablo Huixtepec
- Input 3: Cosoleacaque
- Input 4: Salina Cruz

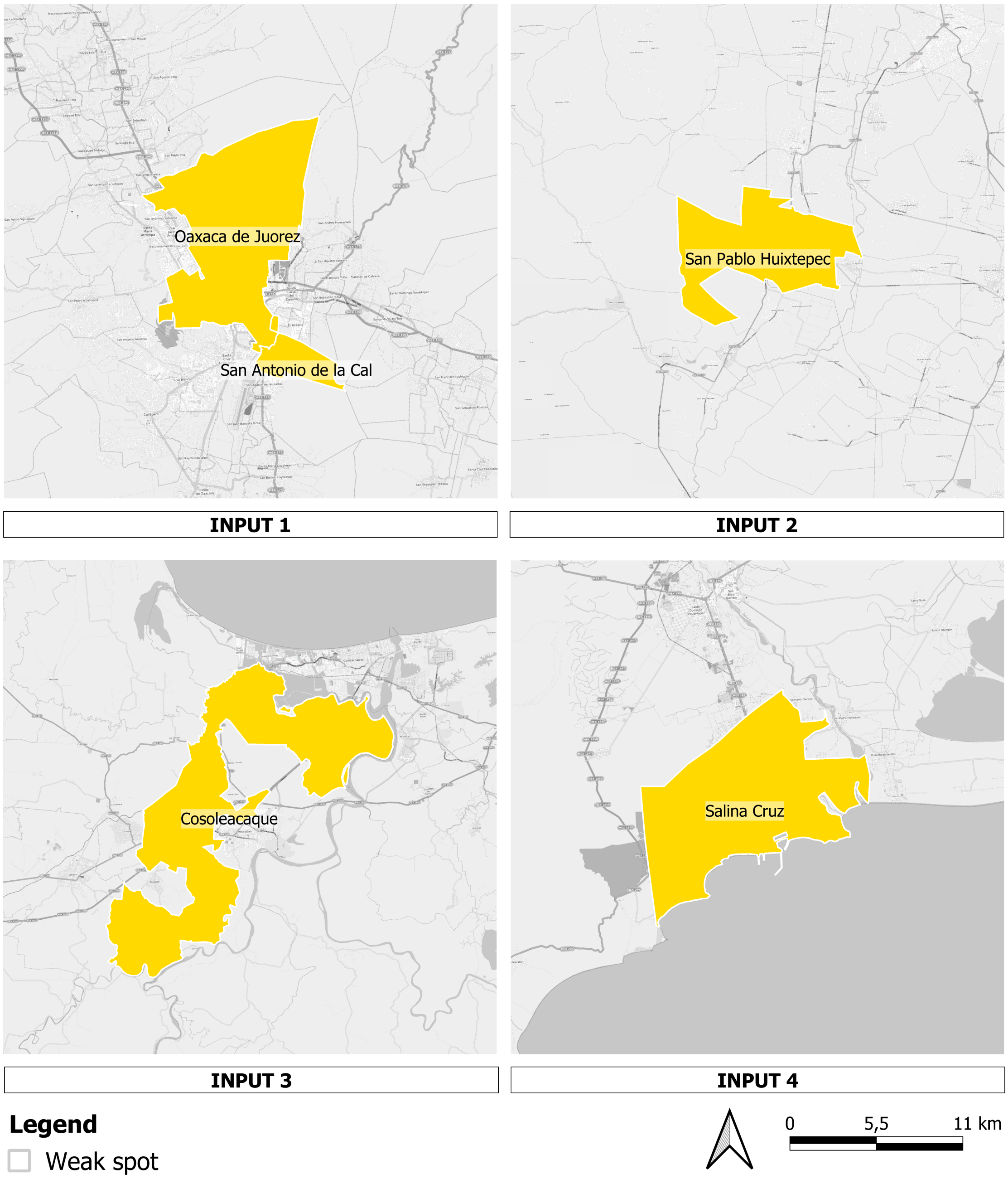


Figure 4.9. Selected 4 input layers

We processed these input layers (Figure 4.9) in the spatial decision support system (SDSS) plugin by overlaying them with all criteria layers. We ran the SDSS plugin based on two different weighting scenarios: equal weighting and AHP weighting. At the end, the plugin gave a raster map as the output with range of value based on total overlay score starting from 0 to 10.

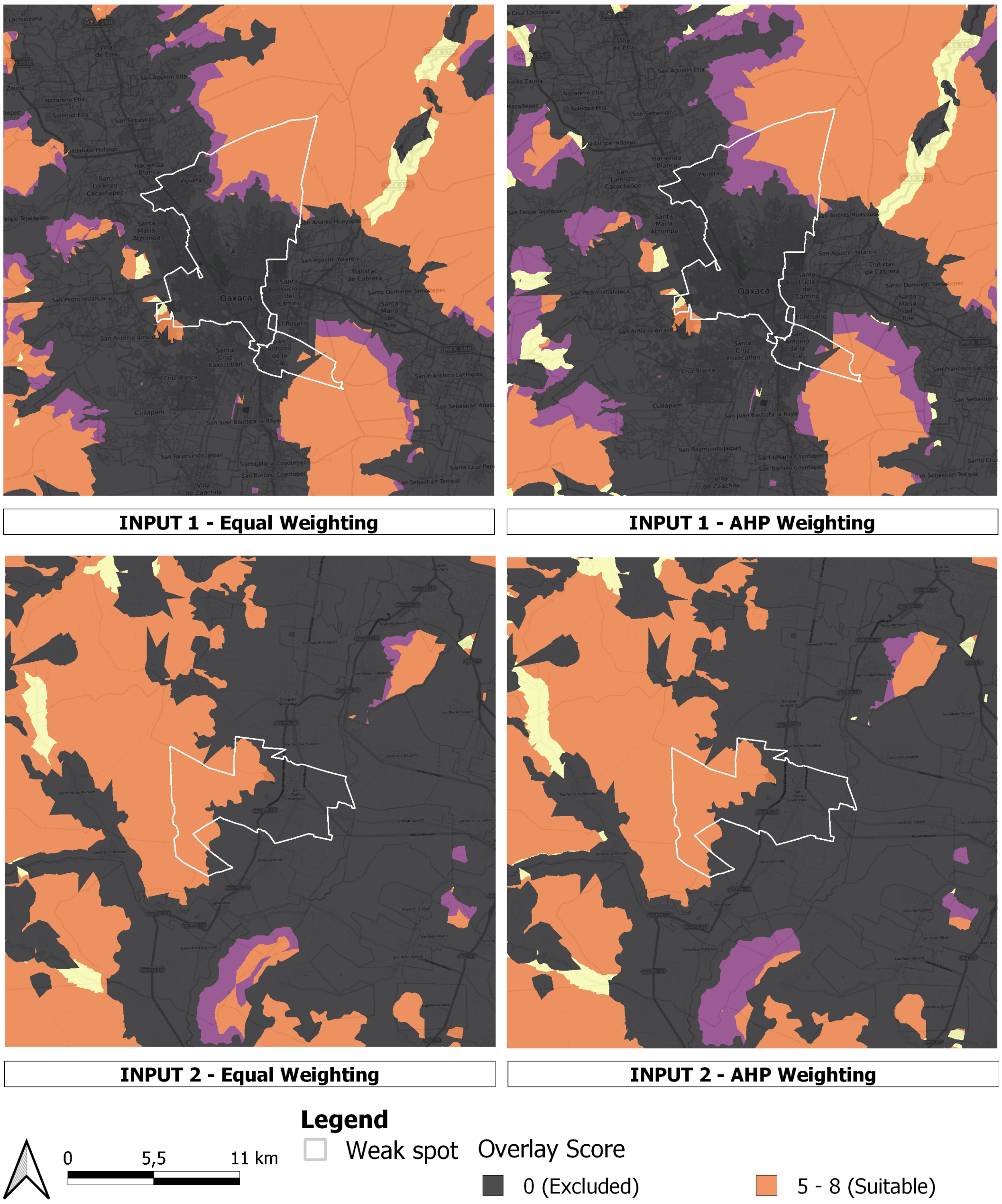


Figure 4.10. Potential location for new waste facilities for Input 1 and Input 2

Figure 4.10 and Figure 4.11 show the result from the SDSS plugin. Overall, these results are based on overlay the selected input layer together with 7 criteria layers: 1) settlement footprint, 2) airports, 3) road network, 4) industrial, agriculture, livestock farming, 5) natural area, 6) rivers, 7) flood zone area. In conclusion, the plugin is able to determine potential areas for investment into new waste facilities and also areas that should be excluded because of the constraints. From both weighting scenarios, most "best suitable" areas are located dispersed outside of the weak spot area. This shows that the plugin suggests potential areas which are not located on the constraints but still accessible based on travel distance. Most results show as a line structure since we use road network as one of the criteria layer, so the closest area from the road will get the highest score.

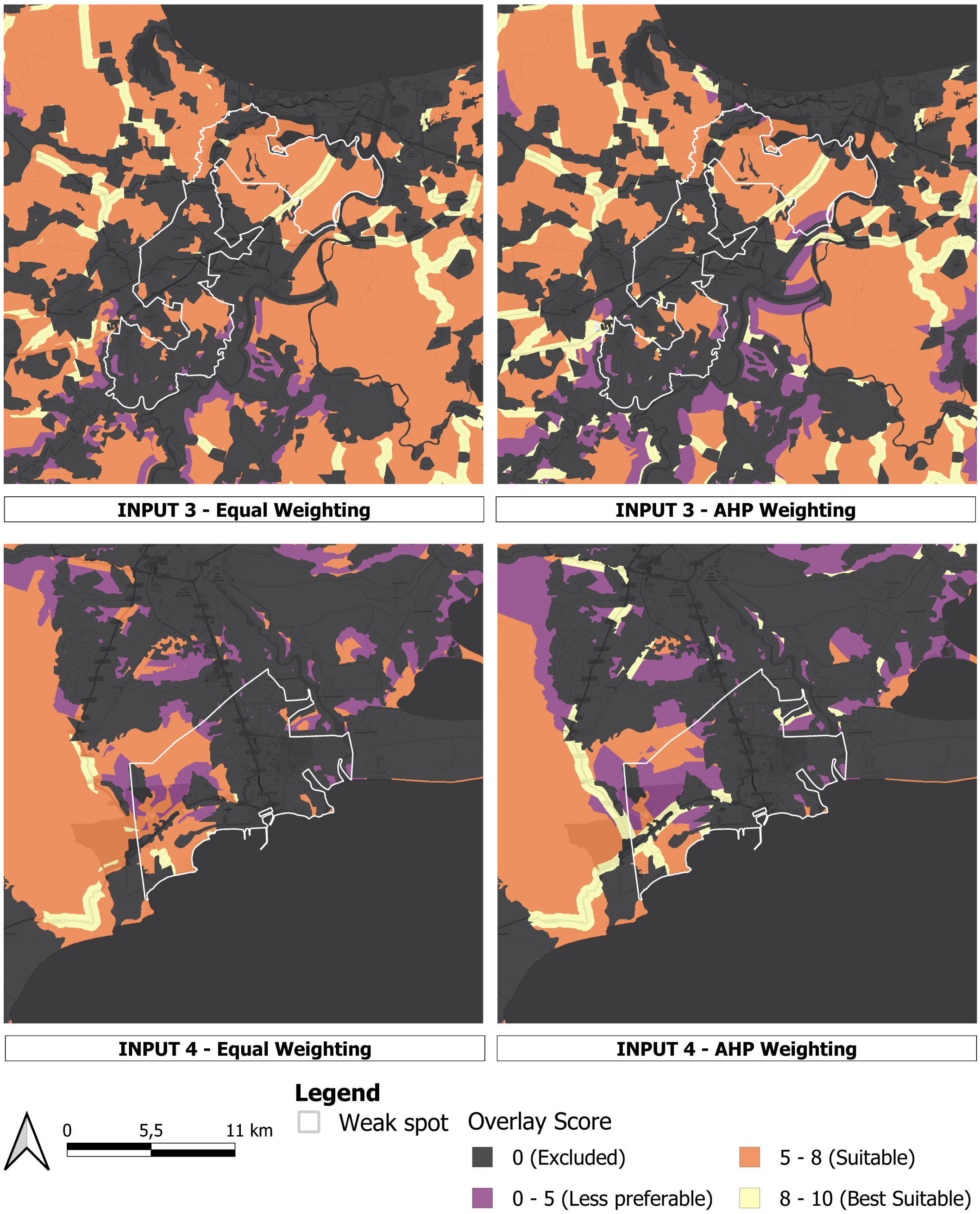


Figure 4.11. Potential location for new waste facilities for Input 3 and Input 4

If we compare on both weighting scenarios results, the result with equal weighting has smaller area than the result with AHP weighting. This happens because we set hierarchy of criteria on AHP weighting so the criteria that has highest weight will be prioritised. For instance, the "travel distance" has the highest score than other criteria. Therefore, for AHP weighting, most of the potential location are located near highway road. Based on this, we can conclude that the weighting of the criteria affects the size of the potential location.

Chapter 5

Discussion

5.1 Data collection

Although classifying the INEGI dataset on the final disposal of waste was not difficult, it was however time consuming. It would have been better if data with regards to the type of waste facility or open dump was collected and presented in a manner to make it able for the users to quickly process it. There could be, for instance, six categories of waste facilities or dumps: sanitary landfills, controlled open dumps, uncontrolled open dumps, transfer stations, recycling centres, and composting centres. Each of these six categories would be given a number from one to six. If users would then process the data, they would only have to apply some queries to classify the types of waste facilities and dumps based on this number. This would certainly be less time consuming than visual inspection. Another method which could also be less time consuming, is the use of machine-learning to identify the structures and to classify them.

5.2 Weak spot detection

5.2.1 Significance and implications of results

Firstly, the maps of weak spots might give an impression that the situation of the waste infrastructure is not that bad in Mexico, but this is not true. Since the range of the overlay score varies from 0 to 1, areas with score close to 0 do indicate poor waste infrastructure, but areas with score close to 1 do not necessarily indicate good waste infrastructure. They are only comparatively better than other regions in the country, hence, they are not strategically prioritised regarding the investment in waste infrastructure.

Secondly, we chose the third scenario to be our final weak spots map because we want to further look into the locations to develop sanitary landfills. In case the investor has other preferences, for example remote solutions for rural area, it is more appropriate to choose scenario 1, or to combine a different set of factors that prioritise the factors related to rural areas.

Thirdly, the set of indirect factors that shows a high correlation with the waste factors might only true for countries that have a similar development background as Mexico. To confirm that, a comparative study among different countries should be carried out.

Finally, our approach in detecting weak spots could also be used for other strategic investment program in infrastructure, both nationwide and state-wide, with different inputs for the direct and indirect factors. It is also noted that such approach might not be appropriate at the region or city scale, where spatial elements and spatial data are more complex, as well as the relationship between them.

5.2.2 Limitations of results

Due to the limited time scope of the project, as well as the working context, our products have some limitations as follows:

- The set of direct and indirect factors can still be expanded through a more extensive literature study, or through consultations from experts in the field.
- The data generated for the factors is not always in the same scale, most of it is at the municipality scale, but some of it is in the state scale. If more time was given, we might had found or generated all the datasets at the municipality level, which might had affected the final results of the weak spots.
- There are also better approaches to generate the datasets for the factors if more information is collected. For example, we do not have data on the time the waste facilities will reach its maximum lifespan. Thus, we dropped the option of forecasting waste disposal demand (using population growth rate) and the supply of the waste facilities in the upcoming year. However, it is more accurate to calculate the gap capacity in such manner.
- For the sake of simplicity, we apply the same weight for the factors, and only try to increase the weight for the gap capacity in landfill. In reality, a weighting system could be developed from a group of related experts, that might give a better result for the weak spots.

5.3 Selecting potential locations for new landfills

5.3.1 Significance and implications of results

The most useful aspect of our results is to show which areas are suitable and unsuitable for sanitary landfill siting based on legislation (the amendment of Mexican standard NOM-083-SEMARNAT-2003). Our research uses the criteria from both the social, economic aspects and Mexican regulations. This can serve as a reference for government departments and enterprises that want to select sites for new landfills.
In addition to this, our research leads to an interesting application of the plugin: it could be used to determine which landfills do not comply with legislation. We noticed that the attribute table of the existing waste facilities includes information about their compliance with government regulations (based on a census performed by INEGI). However, we found that many landfills marked as "conforming" in the attributes table do not actually meet the criteria mentioned in the amendment. Here in figure 5.1, the rasterised mask in 0 (black) is the excluded area which is not suitable for siting landfills and the white triangles are the “conforming” landfills. We can see that some triangles fall in the mask so they are landfills that not follow the regulations.

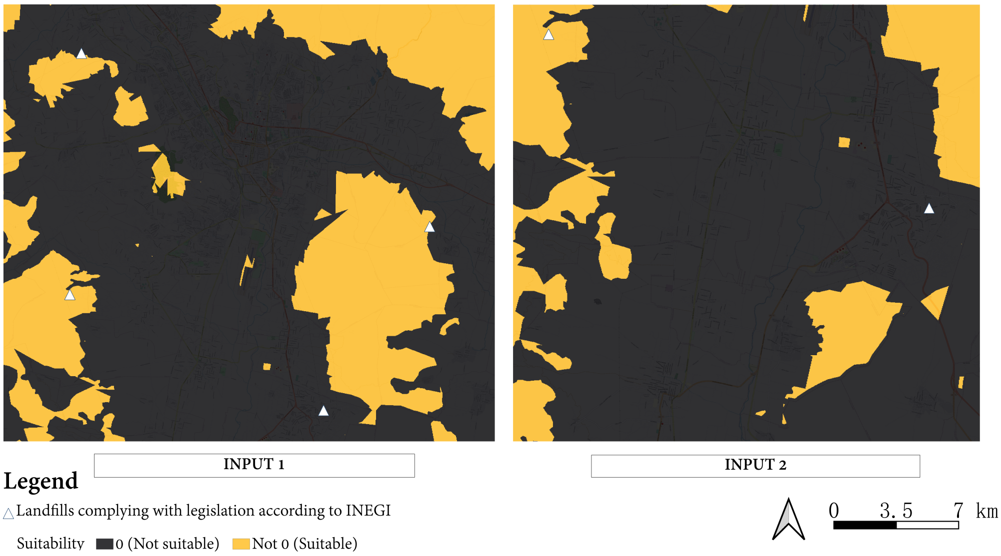


Figure 5.1. SDSS results compare with current landfills

5.3.2 Limitations of results

Our research approach for selecting suitable locations for new waste facilities has a number of limitations. Firstly, we only considered 7 criteria in our model due to the limits of time and the computational complexity. Most of our standards are based on Mexican regulations, but their limitations are that many of criteria only take into account environmental factors without the participation of economic, social and cultural criteria. Therefore, we believe that expanding the criteria lists through more literature study can narrow down the potential site selection suitability and obtain more comprehensive results. Second, we did not determine the robustness of our results with AHP weighting. In order to obtain more reliable results, the pairwise comparison of criteria should have been based on multiple expert opinions and take average of their results. In addition, we could have considered the current locations of landfills that truly meet the regulations as a reference and used this to check the validity of our results. Thirdly, our plugin is only suitable for in-land areas, not coastal areas since we have not performed a buffer analysis on how far the landfills should be located from the sea. The final major limitation of our plugin is that it only focuses on solutions for urban areas, whereas many of the weak spots in Mexico's waste disposal infrastructure are located in rural areas. For these areas, potential solutions could be based on literature study provided in section 2.3.

In addition to the general limitations of our research approach, there are also a number of limitations of the plugin we developed for QGIS. Firstly, our plug-in does not implement the function for users to customize different weights for each criteria. To implement this, we need to add the advanced parameter button and the button shows the weights for each criteria. In our script, we also need to call the raster calculator function to get the final result depending on the condition of weighting. However, due to the limited time and the difficulty of the code, we did not complete this function. Secondly, the locations of existing sanitary landfills are not taken into account, so the user does not know which of the selected suitable locations may already be covered by waste disposal facilities. These two aspects could have been implemented as advanced optional parameters, as shown in the conceptual GUI in figure 3.7. In addition to these two limitations, our consideration of accessibility was limited to only the Euclidean distance from the main road network. The implementation of a road-based travel distance algorithm within the plugin would have provided a more realistic view on accessibility and led to better results.

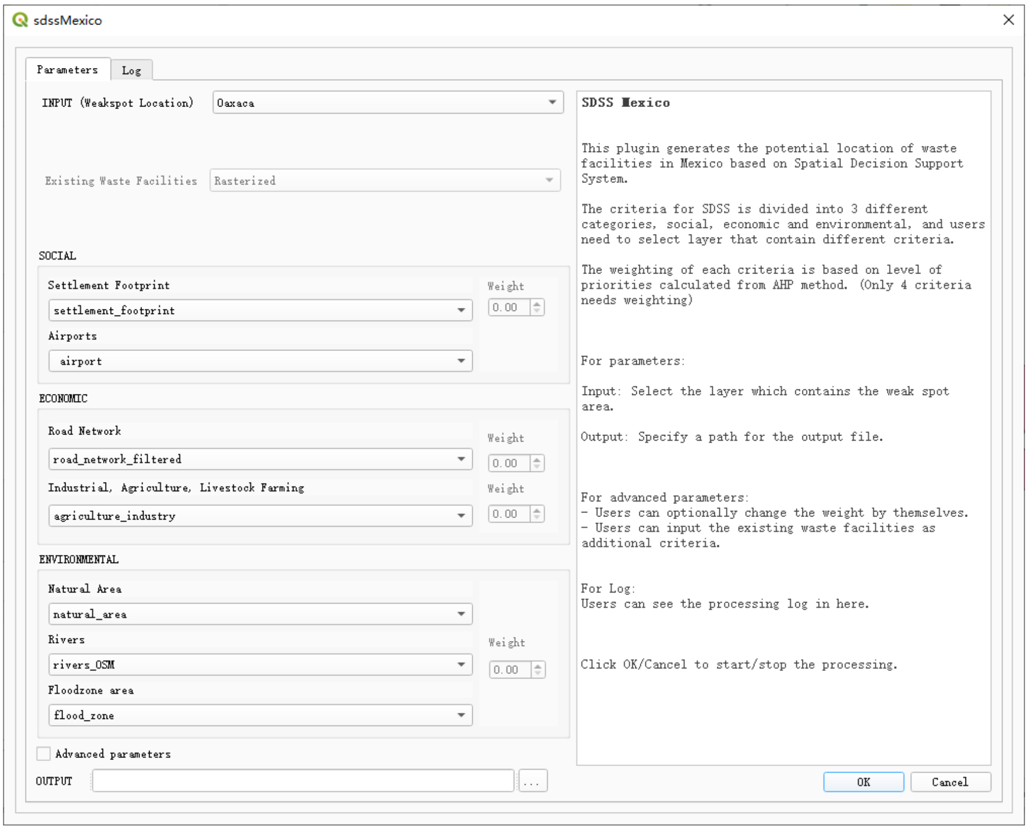


Figure 5.2. Conceptual UI of the plugin

Chapter 6

Conclusions and future work

6.1 Conclusions

Our Geomatics Synthesis project aims to provide an overview on waste management in general and in Mexico, and to strategically tackle the waste problem in the country. Our approach is to first detect the weak spots in the waste infrastructure within the country, and then filter out the weakest areas to find the new locations for sanitary landfills to be invested.

It was found that the waste infrastructure is not equally administered and organised throughout the country and that some areas still depend on open dumps or have little access to proper waste collection and treatment. Therefore, the waste infrastructure in some parts of the country are comparatively weaker, which need attention first in investment. To detect those weak spots, we incorporated different factors that are directly or indirectly related to the waste problems, generated the data-sets and the score for the factors, and then overlay them to find the areas with lowest scores as the weak spots. We developed three scenarios for the weak spots, with three different sets of factors. The first scenario is to detect weak spots based on direct factors, with no priority, the second scenario used indirect factors as an alternative, and the third scenario is to detect weak spots for investment in landfills.

We chose the third scenario to be the input for the next step in finding the new locations for sanitary landfills to be invested, as it should be the priority to tackle the waste problem of urban areas in Mexico in the near future. Then, we develop a spatial decision support system (SDSS) to find the suitable location for landfill siting, and embed the framework into a QGIS plugin. On the other hand, we also provide some suggestions for the waste problem in rural areas by means of literature reviews.

It can be noted that our approach in weak spot detection can also be used in defining weak spots for other infrastructure at the country scale or at the state scale. Moreover, since the criteria used for the SDSS are mostly taken from the Mexican legislation, the plugin can also be used to detect landfills that violate the regulation.

This research project has produced a strategic approach for solving the issue of selecting potential locations for the construction of new sanitary landfills in Mexico. However, other issues with waste management concerning the legal framework, informal sector, and current open dumps are also present and need to be resolved. In order to do so, the Mexican government has to improve and enforce current laws, standards and regulations. They should improve the data collection methods and develop and implement strategies to formalise the informal sector. The current open dumps must also be closed or upgraded to sanitary landfills if this is possible. The implementation of these solutions will contribute to a more comprehensive approach of tackling the problems in waste management in Mexico.

6.2 Future work

Due to the scope of the project, we encountered some limitations that can be improved in future works:

- The data-sets on the waste facilities by INEGI are not up to date, so it is practical to develop an algorithm to automatically detect the waste facilities, especially open dumps from satellite or aerial images.
- In reality, it would better to have group of experts in the field to give opinion on the selection of factors for the weak spot detection and the selection of criteria for the SDSS. With their participation, a more practical weighting system could have also been employed.
- For the SDSS framework, more criteria can be included as presented in the Appendix C. Moreover, it is more practical to take into account the size of the landfills by estimating the demand from waste disposal sources in the next years.

Project review

The past ten weeks we have been working on the Geomatics Synthesis project as a group of six TU Delft students. Of course we had our ups and downs.
One of our first limitations was the outbreak of Covid-19 which left us housebound and unable to come together for meetings. This took some time figuring out what methods of communication work best and how to participate without actually seeing each other.
Enthusiastically we started writing our PID, divided tasks, created our initial methodology, implemented the MoSCoW rules and made a planning. Where we were perhaps a bit too optimistic about what we could get done in only 10 short weeks.
The following weeks were a bit of a struggle to get the methodology in such a way that we felt was interesting, satisfied the wish of the client and was "Geomatics-related-enough". The creation of the methodology took longer than we had expected, and it took some extra meetings with our supervisors to get it the way we wanted.

After these initial difficulties we were excited to get going with the project. We did lots of background reading and collecting of data. Quickly we decided to work in smaller groups of two and three instead of working all together. This improved the speed of the process a lot, we were able to work on multiple part of the project at the same time and allowed for easier communication.
The analysis of the weak spots started of fairly smoothly but was limited by our knowledge on statistics and correlations. With the advice of our supervisors we got there in the end and improved our knowledge about statistics.
When we started on the search for potential locations the idea of automating the process by creating QGIS plugin was quickly suggested. The creation of the plugin turned out to be quite challenging in itself and was finished only just in time.
The last challenge of this project was the writing of the actual report. Especially in a way that people who haven't been looking at the same data-sets for 10 weeks also understand what you're doing. We all worked extremely hard the last few days (perhaps a little too) to be able to finish it satisfactorily.

All this being said, with the deadline now very much in sight, we finish the project feeling satisfied with our results. We learned a lot of new information about waste management, spatial decision support systems, statistics, spatial analysis, cartography, Spanish and general project management. Of course there are some things we would do differently if we were to do it again, such as the exploration of more recent data-sets for the selection of weak-spots and expand the amount of SDSS criteria. Given our knowledge and time however we feel like we did the best we can.

Glossary

analytic hierarchy process multi-criteria analysis approach used to assess the relative weight of multiple criteria based on pairwise comparison (Saaty, 1987).. 26

average nearest neighbour this tool measures the distance between each feature centroid and its nearest neighbour's centroid location. It then averages all these nearest neighbour distances. If the average distance is less than the average for a hypothetical random distribution, the distribution of the features being analysed is considered clustered. If the average distance is greater than a hypothetical random distribution, the features are considered dispersed. The average nearest neighbour ratio is calculated as the observed average distance divided by the expected average distance (with expected average distance being based on a hypothetical random distribution with the same number of features covering the same total area) (ArcGIS, n.d.-b).. 18, 19

benefit factor the higher the value of the factor, the stronger the place regarding the provision of waste infrastructure.. 16, 23

completeness to check if the set of factors already covers all important aspects of the assessed problem.. 16

cost factor the higher the value of the factor, the weaker the place regarding the provision of waste infrastructure.. 16, 23

generate near table an ArcGIS tool to calculate distances and other proximity information between features in one or more feature class or layer. Unlike the Near tool, which modifies the input, Generate Near Table writes results to a new stand-alone table and supports finding more than one near feature.(ArcGIS, n.d.-a).. 19, 21

human settlements places where people live. It refers to the totality of human community with all the social, material, organisational, spiritual, and cultural elements that sustain it. Any form of human dwelling, from the smallest house to the largest city, where groups of people reside and pursue their life goals, can be understood as settlement. Human settlements come in many forms and can be permanent and temporary, rural and urban, mobile and sedentary, disseminated and agglomerated (Živković, 2019).. 12, 15

municipal solid waste defined as waste generated by households, offices, markets, other institutions and public roads and places in a municipality.. 1, 4, 5, 11

mutual dependence of references to check if the factors are independent from each other. If mutual dependence exists, the weighting system could be biased, in other words, does not reflect the real level of importance of the factor.. 16

normalisation is a transformation process to obtain numerical and comparable input data by using a common scale to ensure comparability of criteria. Normalisation techniques usually map attributes (criteria) with different measurement units to a common scale in the interval [0-1] (Vafaei et al., 2016).. 16, 23

pearson's correlation coefficient (pcc) or r measures the linear correlation between a two variables. r ranges from -1 (strong negative correlation) to +1 (strong positive correlation).. 22

redundancy unimportant or duplicated factors that do not add up much for the overall score of weak spots, or add more weight for a same field of factors.. 16

sanitary landfill a waste facility where it is possible to manage the leachate and isolate waste from the environment until it is safe for public health and environment. In other words, until waste is completely degraded biologically, physically and chemically. This solution is often chosen over incineration for its price, which is two to ten times cheaper(Cointreau, n.d.).. 1

spatial analysis 'a set of techniques designed to find patterns, detect anomalies, or test hypotheses and theories, based on spatial data' (Goodchild, 2008).. 18

spatial decision support system 'computer-based system combining spatial data and decision logic to aid the decision making process' (Crossland, 2008).. 24

total gap capacity The difference between the Daily waste collection amount by waste facilities (capacity/supply) and the Daily waste disposal (demand) per municipality, the greater the gap, the more severe the problem.. 21, 22

variance inflation factor the quotient of the variance in a model with multiple terms by the variance of a model with one term alone. It quantifies the severity of multicollinearity in an ordinary least squares regression analysis. It provides an index that measures how much the variance (the square of the estimate's standard deviation) of an estimated regression coefficient is increased because of collinearity.. 16, 23, 35

weighted linear combination method for combining criteria in multi-criteria decision analysis, implemented in practice by overlaying weighted standardised criteria maps in GIS software (Demesouka et al., 2014).. 28

weighted overlay method to solve multi-criteria problems. Where all criteria are firstly normalised and then given a certain weight based on importance. The average of these weights multiplied by the normalised value gives the overlay score for a certain location (between 0 and 1).. 16

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Appendices

A Raw data

Table 1. Raw data sources for weak spot analysis

DATA SET	SCALE	YEAR	NAME	SOURCE
Territorial entities				
State boundaries	-	2018	mex_admbnda_adm1_govmex	INEGI
Municipal boundaries	-	2018	mex_admbnda_adm2_govmex	INEGI
Settlement footprints (rural/urban)	-	2015	murinegi15gw	INEGI
Waste facilities and services				
Waste disposal sites	-	2017	Disp_final_RSU_cngmd2017_dbf	INEGI
Urban solid waste services:	Municipality	2016	CNGMD2017_M6	INEGI
- Waste collection services				
- Number of vehicles				
- Daily average waste collected				
Waste disposal methods	State	2010	mamb284	INEGI
Waste expenses	State	2018	-	INEGI
Pop. with access to waste facilities	Municipality	2015		
Socio-economic data				
Population 2010 (% rural/%urban)	Municipality	2010	dem10gw	CONABIO
Population 2020	Municipality	2020	?	?
Human Development Index (HDI)	Municipality	2010	idhmun10gw	CONABIO
Degree of marginalisation	Locality	2010	marloc10gw	CONABIO
Poverty rate	Municipality	2018	?	STATISTICA
Literacy rate	Municipality	2010	marmun10gw	CONABIO
Average education years	Municipality	2010	idhmun10gw	CONABIO
GDP	State	2018	PIBE_2	INEGI
Employment per sector	State	2010	emegt10cw	CONABIO
Income	Municipality	2010	ingmun10gw	CONABIO

Table 2. Raw data sources for landfill site selection

DATA SET	YEAR	NAME	SOURCE
Settlement footprints	2015	murinegi15gw	INEGI
Airports	2017	sitio_de_interes	INEGI
Industrial & agricultural areas	2017	usv250s6cw	INEGI
Natural areas	2017	usv250s6cw	INEGI
Rivers & streams	2020	waterway	OpenStreetMap
Road network	2020	highway	OpenStreetMap
Flood zones	2007	grinundmgw	CENAPRED via CONABIO Geo-portal

B Classification of waste facilities

B.1 INEGI Dataset of final disposal of waste

The dataset used for the locations of the sanitary landfills and the open dumps consists of data from 2016 and was collected by INEGI as part of the National Census of Municipal and Delegational Governments 2017 (INEGI, 2018). The dataset was classified by the client into sanitary landfills and open dumps with the use of keywords. 353 values from the dataset were not classified. These values could either be a sanitary landfill, open dump or maybe another type of waste facility. In order to achieve the most accurate result, we decided to also classify the 353 unclassified values.

B.2 Unclassified data

The unclassified data was further classified, mainly by visual inspection, as part of this Synthesis project. Each data value has a latitude and longitude coordinate. These coordinates were inserted into Google Maps. Assessing each structure on characteristics more common to sanitary landfills or open dumps, made it possible to classify them as such. In general, sanitary landfills are organised and well-constructed, with a number of waste facility structures on the terrain (see Figure 1, left), while open dumps are less organised and usually do not have any structures on the terrain (see Figure 1, middle). Open dumps are also located next to roads and rivers (see figure 1, right). In some cases, Google Maps provided more information on the structure which helped in classifying them.

After visual inspection most values were classified. If visual inspection was not sufficient, then with the use of data from the dataset that corresponded to the specific value and by searching in Google more information was retrieved in order to classify the structure. Of the 353 values, 33 were classified as sanitary landfills and 303 as open dumps. Two new categories were created to classify structures different from sanitary landfills and open dumps: recycling centres and unknown structures. From the unclassified data 5 structures were classified as recycling centres and 12 as unknown structures. These 12 values, were not well visible in Google Maps and most of them pointed to a location in a forest. Although other locations in forests were open dumps it could not be confirmed that this was also the case for these locations because of the lack of visibility and information.

Figure 1. Examples of visual inspection: 1. Sanitary landfill 2. Controlled open dump 3. Uncontrolled open dump

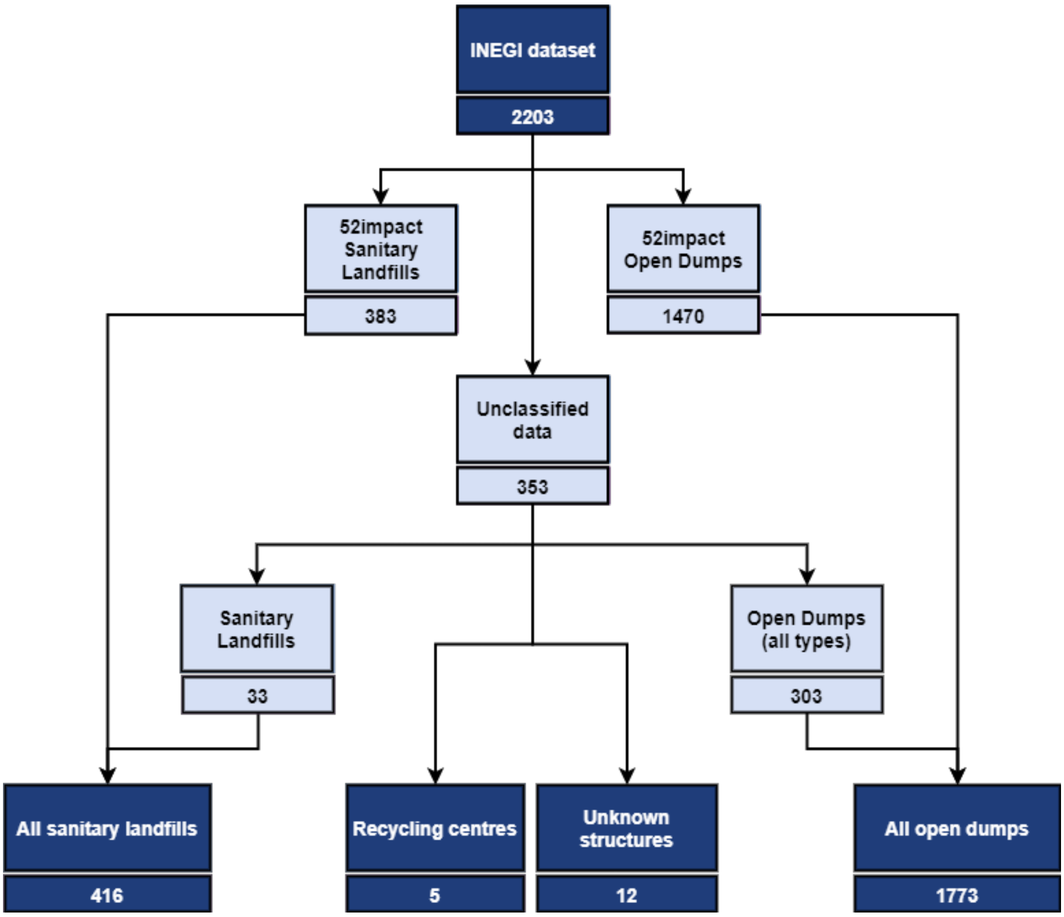


Figure 2. Flowchart of classification of the INEGI dataset with unique number of data values

After the classification (figure 2), the values from the sanitary landfills and open dumps were added to those of the datasets of the clients. This resulted in four datasets with 416 sanitary landfills, 1773 open dumps, 5 recycling centres and 12 unknown structures (see figure 3 for a map with the locations of the waste facilities and structures)

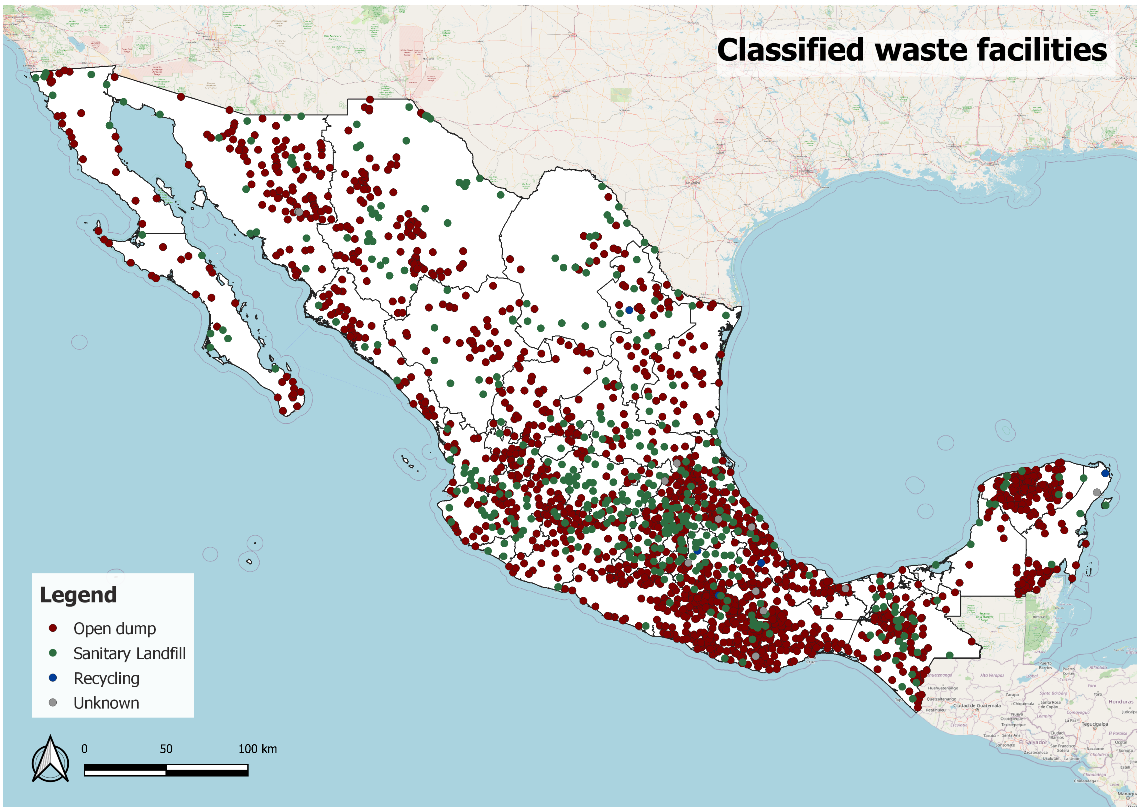


Figure 3. Classified waste facilities

B.3 Controlled and uncontrolled / illegal dumps

After the classification of the unclassified data, we decided to classify the open dumps into controlled and uncontrolled open dumps. Even though controlled dumps are not sanitary landfills, they are still adequate as a waste facility, while uncontrolled open dumps are not. With regards to the spatial analysis it would therefore be more appropriate to separate them.

The classification of controlled dumps was not done with the 'All open dumps' dataset, but with the separate open dump datasets (see figure 4 for the flowchart of the classification). The open dumps that were classified from the unclassified data, were further classified into controlled and uncontrolled dumps with the use of keywords. The following keywords were used to select the controlled dumps on name: 'sitio controlado' (controlled site), 'relleno' (landfill), 'sitio de disposicion final' (final disposal site), 'deposito disposicion final' (final disposal deposit), 'sistema integral para el manejo ecologico y prociesamento de desechos' (integral system for the ecological management of waste), 'centro de acopio' (collection centre), 'citirs' (abbreviation for integral waste treatment centre), 'tratamiento integral de residuos solidos' (integral treatment of waste), 'centro municipal' (municipal centre), 'confinamiento municipal' (municipal confinement), 'centro intermunicipal' (intermunicipal centre), 'predio' (farm) and 's.a. de c.v.' (abbreviation that of a stock company). The selected values were then visually inspected by inserting the latitude and longitude coordinates into Google Maps. Some of them were reclassified as uncontrolled / illegal open dumps.

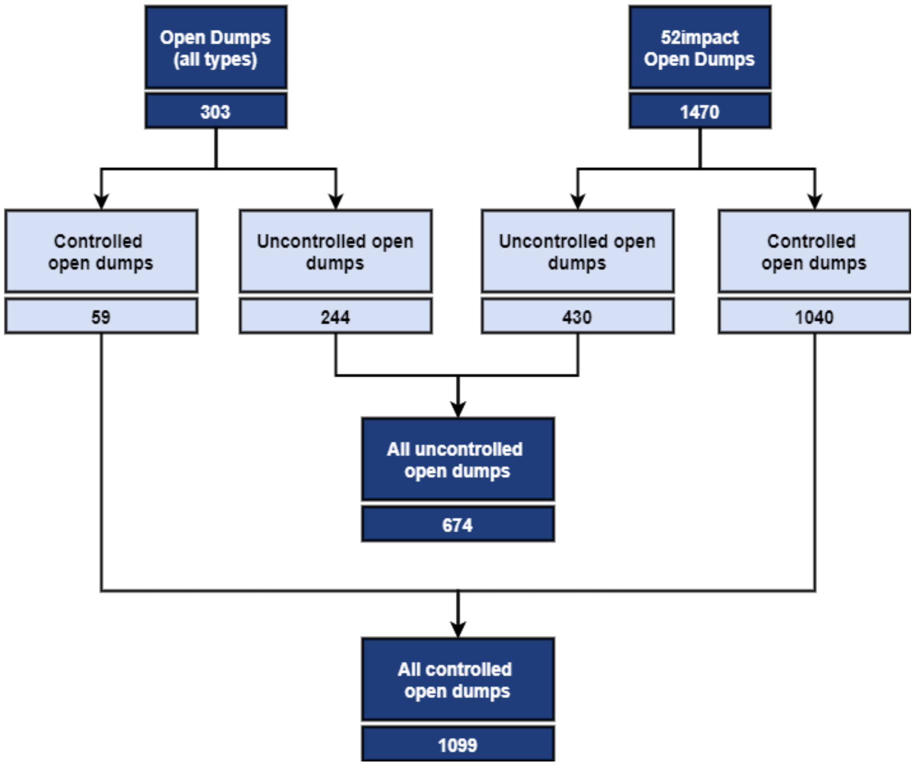


Figure 4. Flowchart of the classification of controlled and uncontrolled open dumps

The classification process for the open dumps file of the client was the same, with one difference. In this process all the values that corresponded to 'tiradero a cielo abierto' (open dump) were selected and classified as uncontrolled open dumps. Hereafter, the following keywords were used to select the controlled dumps on: 'basurero municipal' (municipal dump), 'basurero municipio' (municipal dump), 'basurero publico' (public dump), 'tiradero municipal' (municipal dump), 'vertedero municipal' (municipal dump), 'sitio controlado' (controlled site), 'sitio de disposicion' final (final disposal site) and 'centro de acopio' (collection centre). Other names that resembled the keywords were also selected.

After the classification of controlled and uncontrolled open dumps, two datasets were produced: one containing 1099 controlled open dumps and one with 674 uncontrolled open dumps. It was however decided that these datasets were not to be used for analysis since classification with keywords was deemed not to be reliable. This was concluded from visually inspecting a selection of the values and determining that the classification of these structures was incorrect. Therefore, for further analysis the 'All open dumps' dataset was used.

B.4 Other classification methods

Another method for classifying the waste facilities is with the use of machine learning. With this method sanitary landfills, open dumps and maybe other types of waste facilities with specific characteristics that define them would be used for a training dataset. By developing an algorithm based on the training dataset, the different types of waste facilities could be automatically recognised and classified.

C Overview of landfill siting criteria

Table 3. Overview of landfill site selection criteria

CRITERIA	DESCRIPTION	TYPE	SOURCE(S)
Social			
Distance to cultural site	Must not be located on archaeological zones or sites of cultural/historical value. Buffer zones of up to 3km.	DCC	SEMARNAT, 2004; Eskandari et al., 2012
Distance to settlement	More than 1km and less than 10 km (bird fly distance)	DCC	Ersoy and Bulut, 2009; Nas et al., 2010
Distance to railways	More than 500 meters	DCC	Nas et al., 2010; G. Wang et al., 2009
Distance to national borders and coastlines	0.3 to 0.5 km buffer zones respectively	DCC	Sadek et al., 2006; Yildirim, 2012
Visibility	Exclude zone with direct optical intrusion from settlements and road network	C	Chang et al., 2008; Kontos et al., 2005; Moeinaddini et al., 2010
Landfill capacity	Site should be at least 1km2	DCC	Leao et al., 2004; Sharifi and Retsios, 2003
Economic			
Travel distance from waste production area	less than 30 km (road network based distance)	DC	Josimovi and Mari, 2012; G. Wang et al., 2009; Ersoy and Bulut, 2009
Distance from main roads	200 - 500 meters	DC	G. Wang et al., 2009; Nas et al., 2010
Cover material availability	5 km from areas that provide cover material	DC	Gorsevski et al., 2012
Land use	Exclusion of high-productivity cultivated sites, economically valuable areas, mountainous areas, wetland and forests. Most suitable are uncultivated / low productivity agricultural sites	DCC	Nas et al., 2010; Demesouka et al., 2013 Kontos et al., 2005
Mineral resource exploitation	Areas near mineral explotation industries or water reserve facilities are inappropriate and excluded with buffer zones	DCC	Moeinaddini et al., 2010; Demesouka et al., 2013
Cost of land acquisition	Land with low economic value	DC	G. Wang et al., 2009; Chang et al., 2008; Demesouka et al., 2013
Environmental			
Groundwater depth	1 km from significant aquifers	DCC	Yildirim, 2012
Soil Thickness	High soil thickness preferred, less than 50% fines then minimum thickness of 30 cm	DC	SEMARNAT, 2004; Sharifi and Retsios, 2003
Soil Type	Best type: loamy or silty soils that are free of large stones and excess gravel, low permeability	DC	Chang et al., 2008; Sharifi and Retsios, 2003
Seismic hazard assessment	Areas where geological fractures and faults exist are excluded with buffer zones 0.1 km to 0.5 km	DCC	Sadek et al., 2006

Table 3 continued from previous page

CRITERIA	DESCRIPTION	TYPE	SOURCE(S)
Saline water intrusion area	Excluded with buffer zones	DCC	Demesouka et al., 2013, Gemitzi et al., 2007; Kontos et al., 2003
Land elevation	Areas with a high sea level are considered most suitable	DC	Demesouka et al., 2013
Land slope	Flat ground or small land slope (less than 15%)	DC	Nas et al., 2010
Wind speed	Exclusion of areas with strong wind / 5km from major cities	C	Demesouka et al., 2013; Salmon Mahini and Gholamalifard, 2006
Wind direction	Exclusion of locations with slopes in the prevailing wind direction	C	Demesouka et al., 2013
Precipitation	Areas with high precipitation index are excluded	C	Sadek et al., 2006; Zamorano et al., 2008
Temperature	Areas with extremely low temperature are unsuitable (can affect the biological activity)	C	Moeinaddini et al., 2010
Air pollution	Areas with low level of air pollution are more suitable	DC	Sumathi et al., 2008
Institutional			
Proximity to settlements	Minimum distance of 500 m from the outer limit of the existing urban trace or the planned urban limit described in the Urban Development Plan (for towns greater than 2500).	DCC	SEMARNAT, 2004
Proximity to water extraction wells	Must be at least an additional 100 m from the maximum horizontal projection of the cone of depression from extraction wells	DCC	SEMARNAT, 2004
Proximity to natural area	Must not located on: marshes, mangroves, swamps, wetlands, estuaries, floodplains, rivers, aquifer recharge areas, archaeological sites, or on caves, fractures or geological faults.	C	SEMARNAT, 2004
Proximity to natural protected land	Must not located on Natural Protected Land of Mexico (Areas Naturales Protegidas)	C	SEMARNAT, 2004
Proximity to public facilities	Must not lie within 15 km of an international airport	C	SEMARNAT, 2004
Proximity to surface water bodies	Must be at least 500 m	DCC	SEMARNAT, 2004
Distance to Floodzone	Located outside of flood zones with return periods of 100 years	C	SEMARNAT, 2004

Note: C = constraint; DC = decision criteria; DCC = decision criteria and constraint

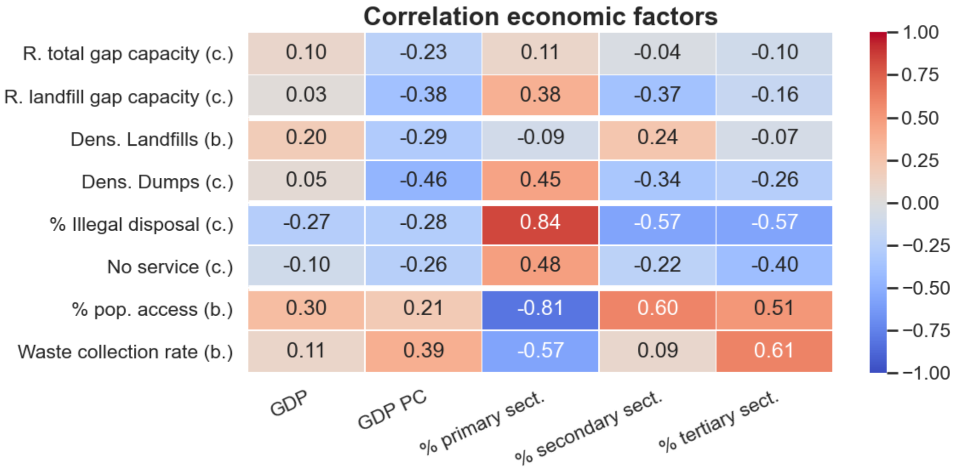
D Overview data-sets used for statistical analysis

Table 4. Overview datasets used for statistical analysis

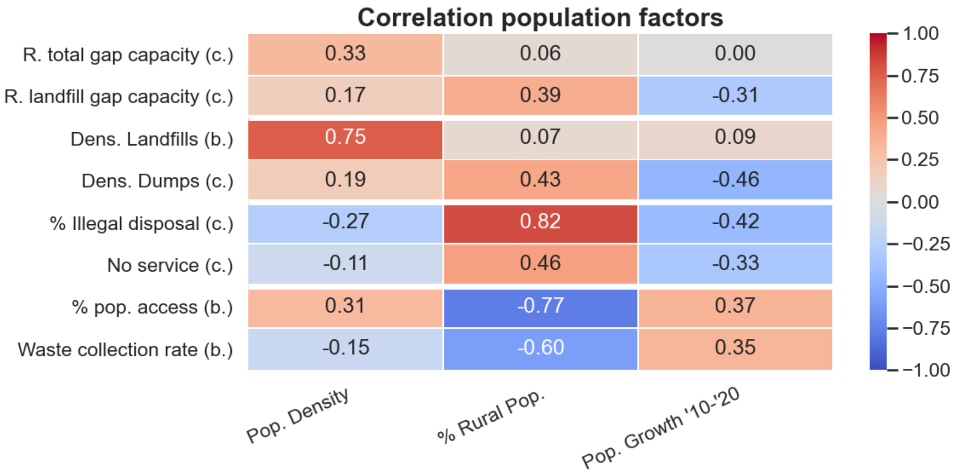
ABV. NAME	DESCRIPTION	SCALE	YEAR
Direct factors			
R. total gap capacity (c.)	Gap in total gapacity (ratio disposal/capacity)	State/Mun	2017
R. landfill gap capacity (c.)	Gap in landfill gapacity (ratio disposal/capacity)	State/Mun	2017
Dens. Landfills (b.)	Density landfills	State/Mun	2017
Dens. Dumps (c.)	Density dumps	State/Mun	2017
% Illegal disposal (c.)	% of illegal waste disposal	State	2010
No service (c.)	No. of municipalities without waste services	State/Mun	2016
% pop. access (b.)	% of pop with access to waste collection service	State	2015
Waste collection rate (b.)	% of total MSW that is collected	State/Mun	2010
Indirect factors			
Population factors			
Pop. Density	Population density /km2	State/Mun	2018
Pop. Growth ’10-’20	Population growth	State	
% Rural Pop.	% of rural population	State/Mun	2010
Economic factors			
GDP’18	GDP in millions of mex$	State	2018
GDP’18 PC	GDP in mex$ per capita	State	2018
% primary sect.	% of working pop in primary economical sector	State/Mun	2010
% secondary sect.	% of working pop in secondary economical sector	State/Mun	2010
% tertiary sect.	%of working pop in tertiary economical sector	State/Mun	2010
Social factors			
% poverty	% of pop living in moderate to severe poverty	State/Mun	2018
% illiterate	% of pop above 15 that is illiterate	State/Mun	2010
Avg. years edu.	Average years of education	State	2010
HDI	Humand development index	State/Mun	2010
% pop. <min. wage	% of working pop that earns less than min wage	State/Mun	2010
Settlement distribution			
% rural ftpt area	% of rural footprint area out of total ftpt area	State/Mun	2015
% large sett.	% of large settlements	State/Mun	2015
% medium sett.	% of medium sized settlements	State/Mun	2015
% small sett.	% of small settlements	State/Mun	2015
NNR settlements	Avg distance betw. a landfill and nearest landfill	State/Mun	2015
Waste management			
No. of vehicles	Number of waste vehicles	State/Mun	2016
Waste expenses ’18	Mex$ per year spent on waste management	State	2018
% uncontr. Dumps	% of uncontrolled dumps out of total dumps	State/Mun	2017
NNR opendumps	Avg distance betw. a dump and its nearest dump	State/Mun	2017
NNR landfills	Avg distance betw. a landfill and its nearest landfill	State/Mun	2017

E Correlation Matrices

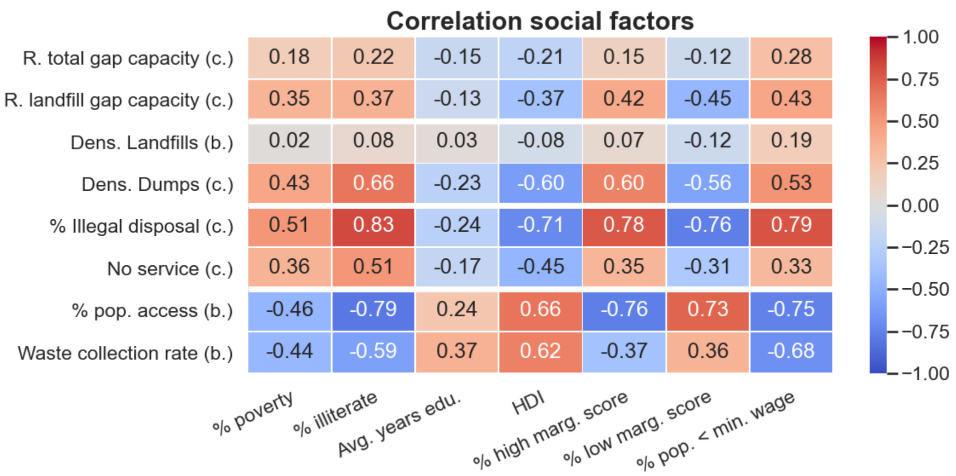
The full description and explanation of the data-sets used is visible in appendix D



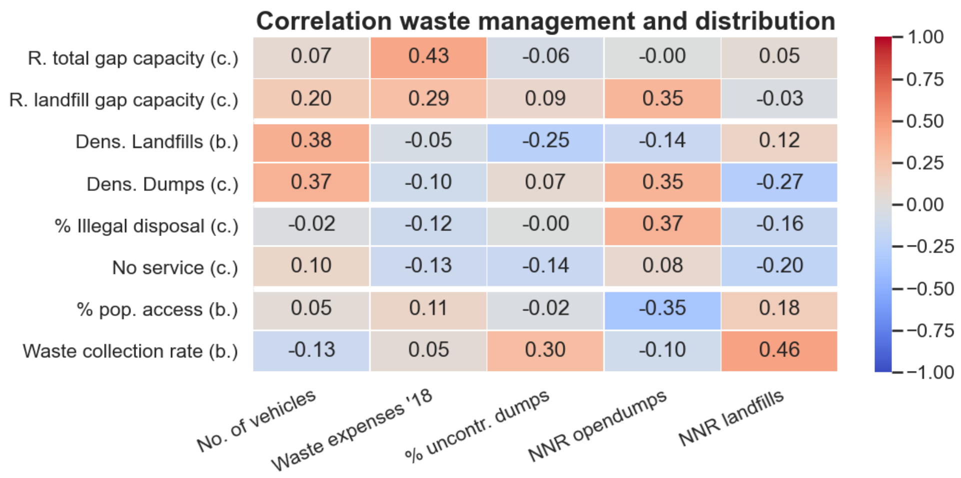
(a)



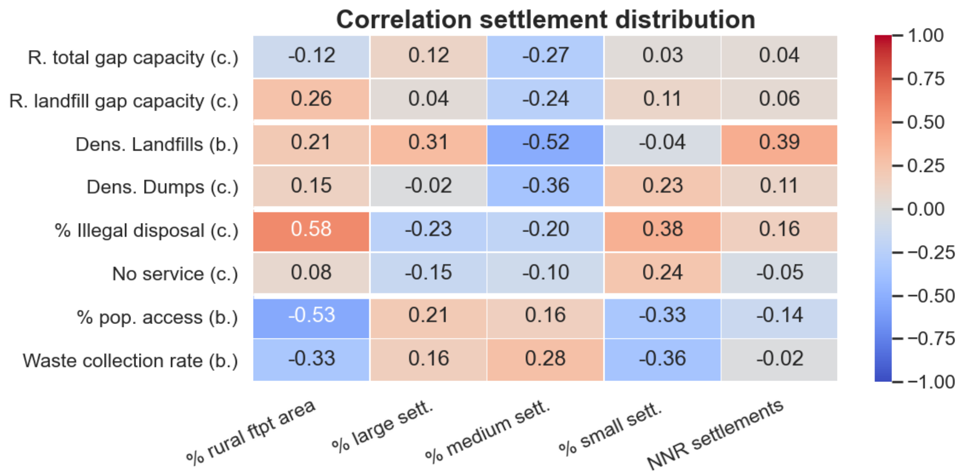
(b)



(c)



(d)

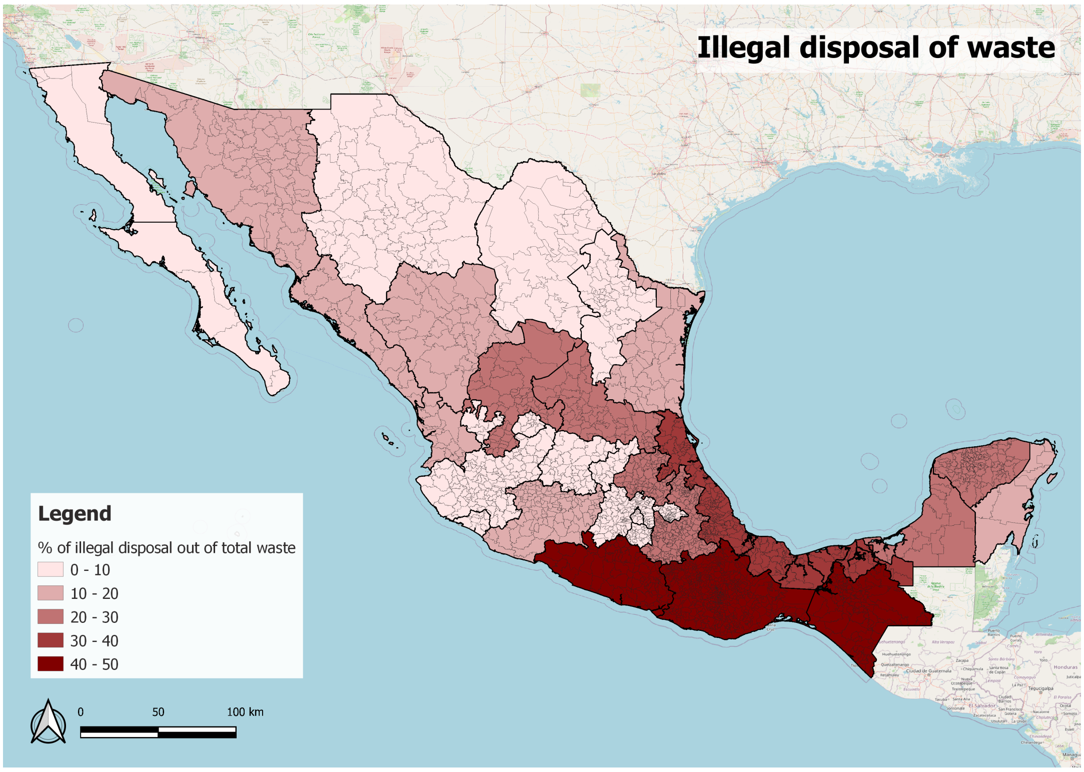


(e)

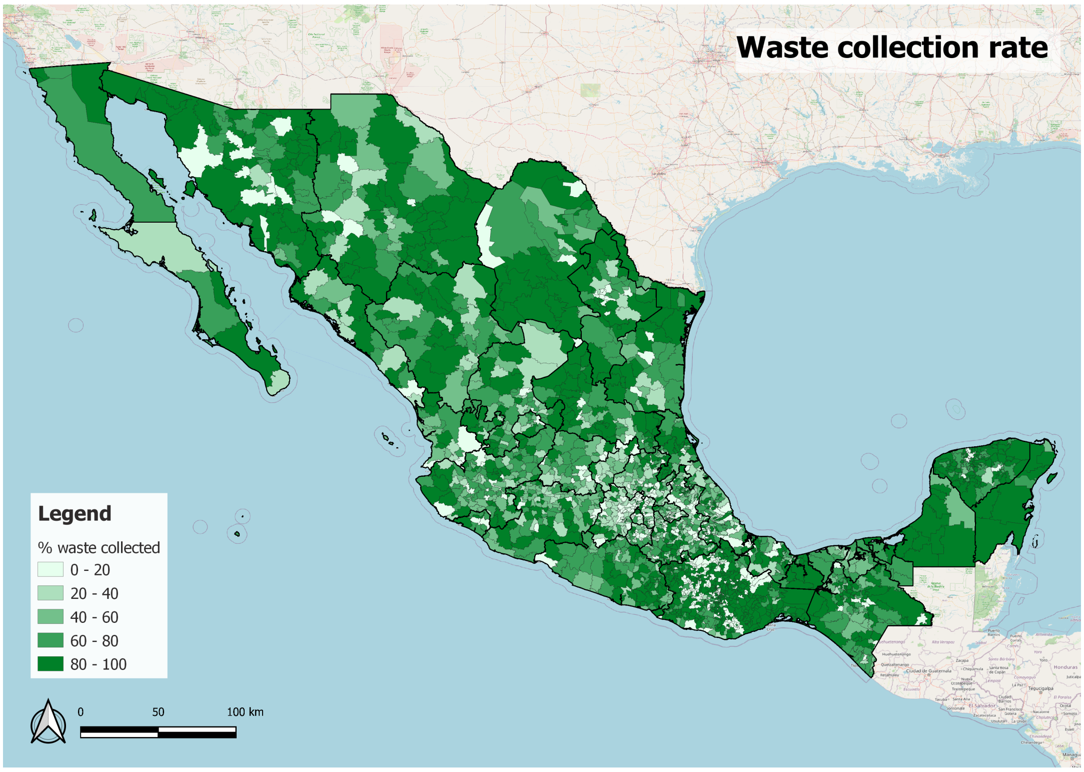
Figure 5. Correlation matrices divided by topic

F Maps on separate factors

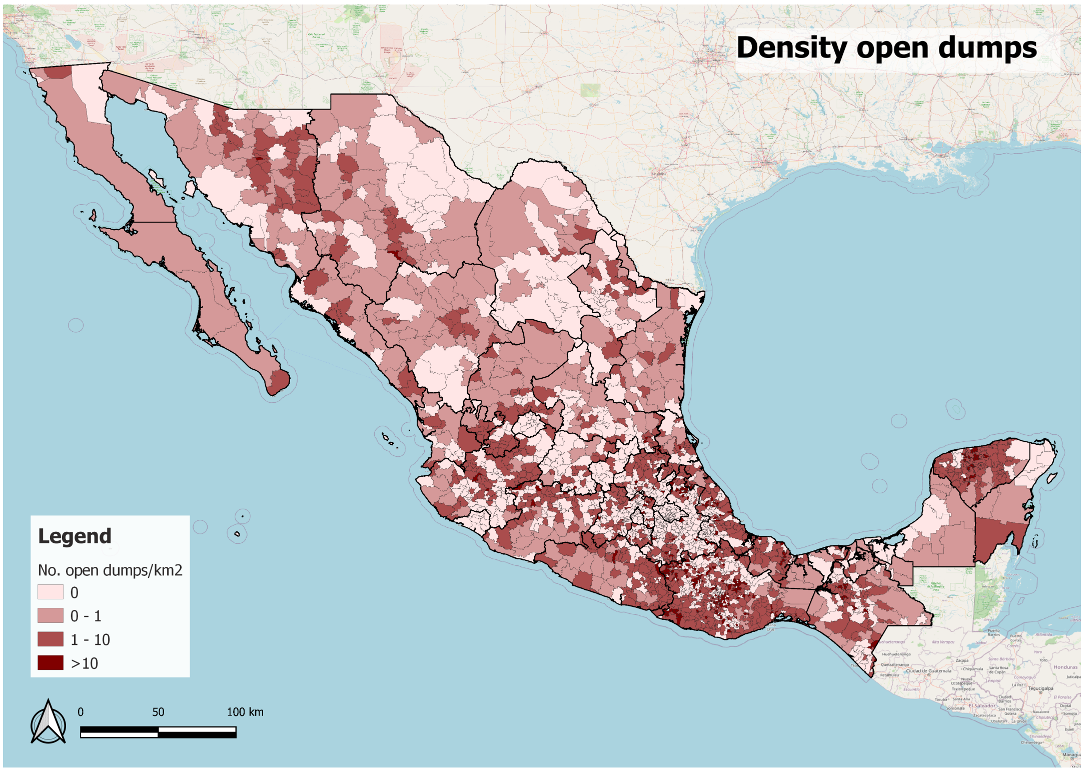
F.1 Maps on direct factors



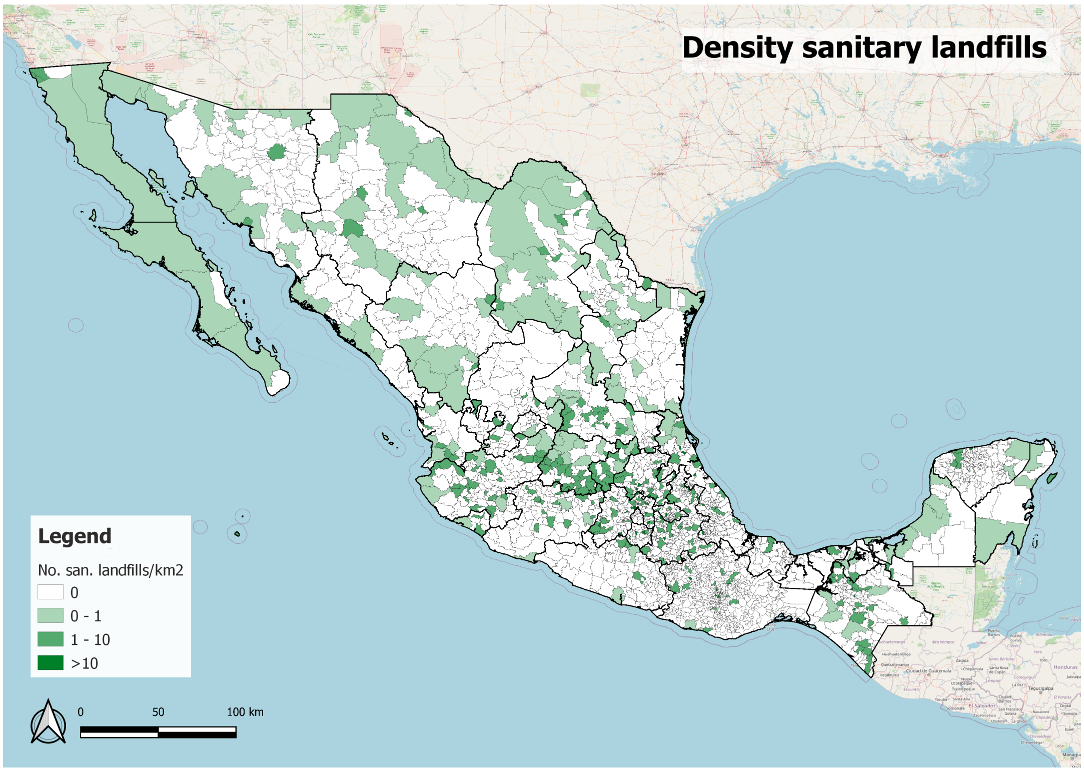
(a) Percentage of illegal disposal



(b) Waste collection rate



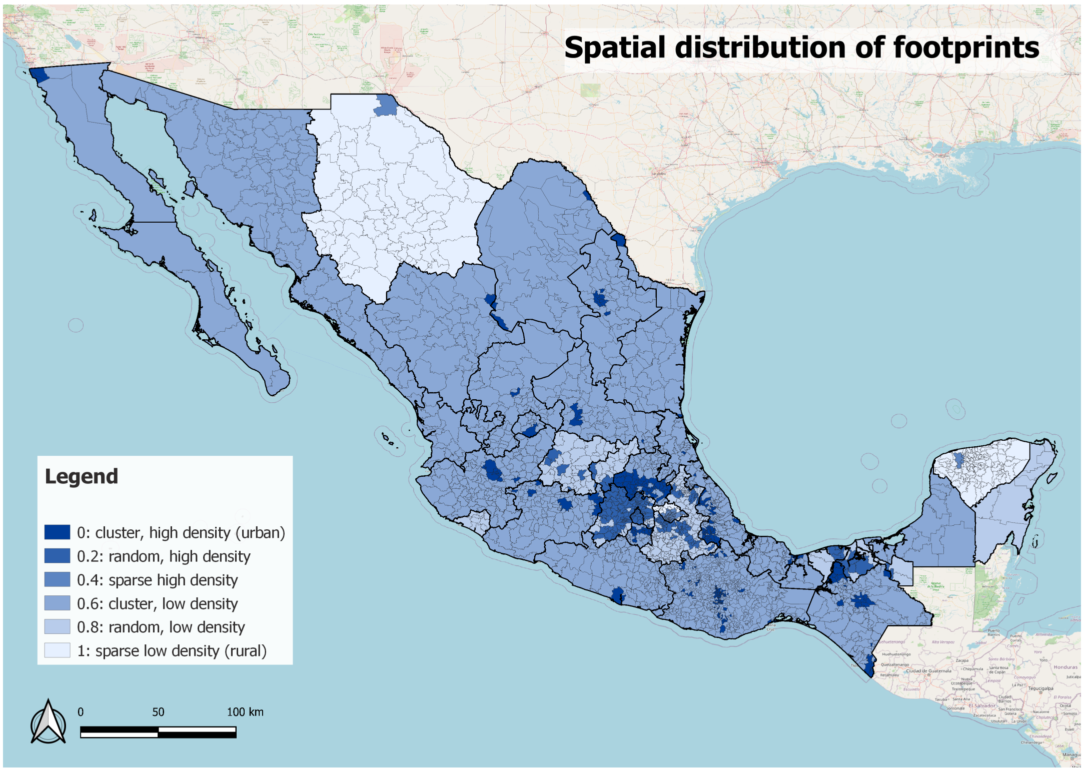
(c) Density of open dumps



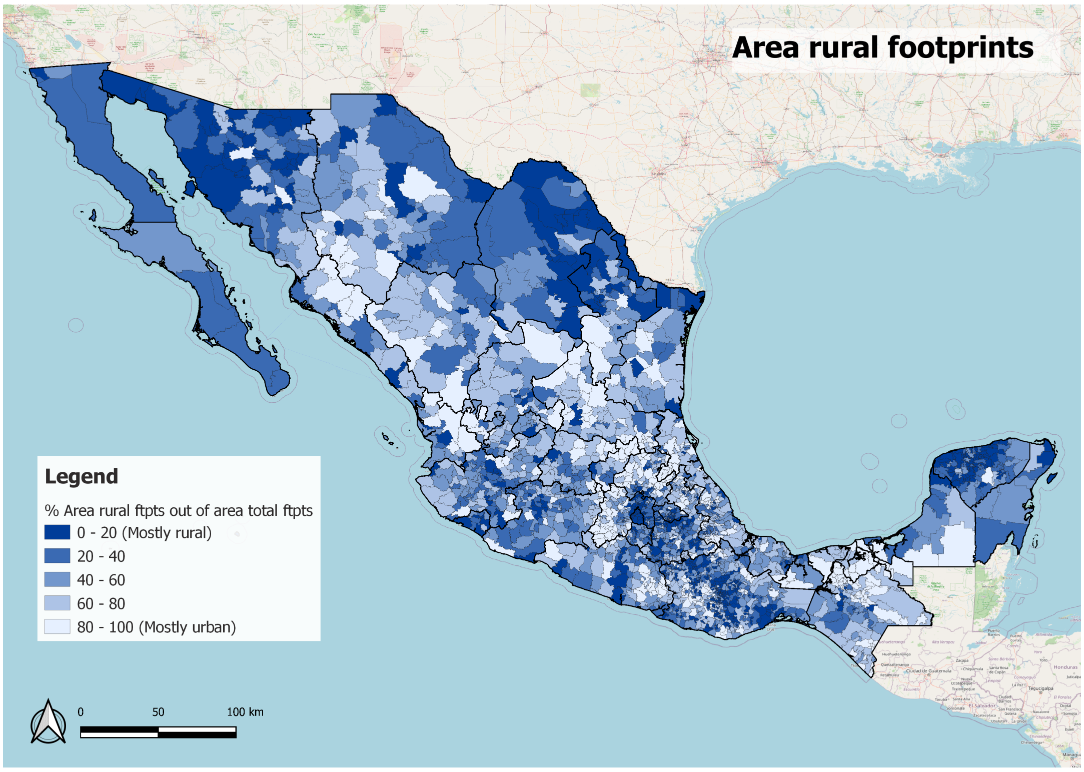
(d) Density of sanitary landfills

(e) Waste services municipalities

Figure 6. Maps on directly related factors



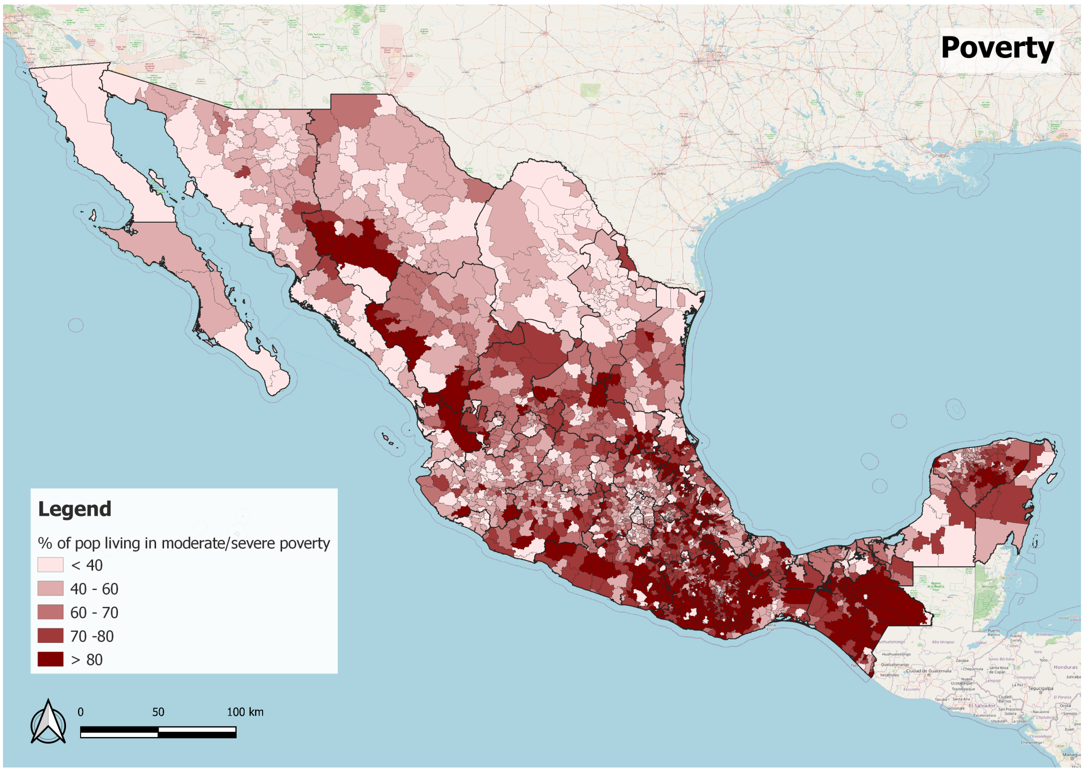
(a) Spatial distribution of footprints



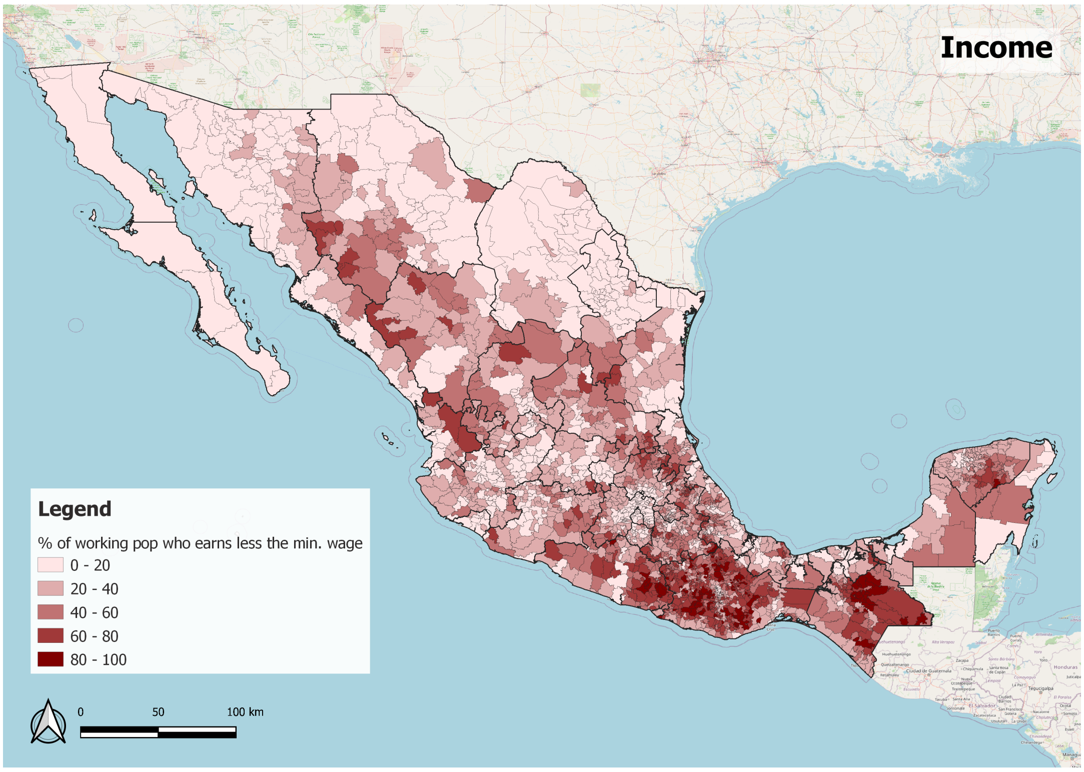
(b) Ratio of rural footprints

Figure 7. Factors favouring landfills

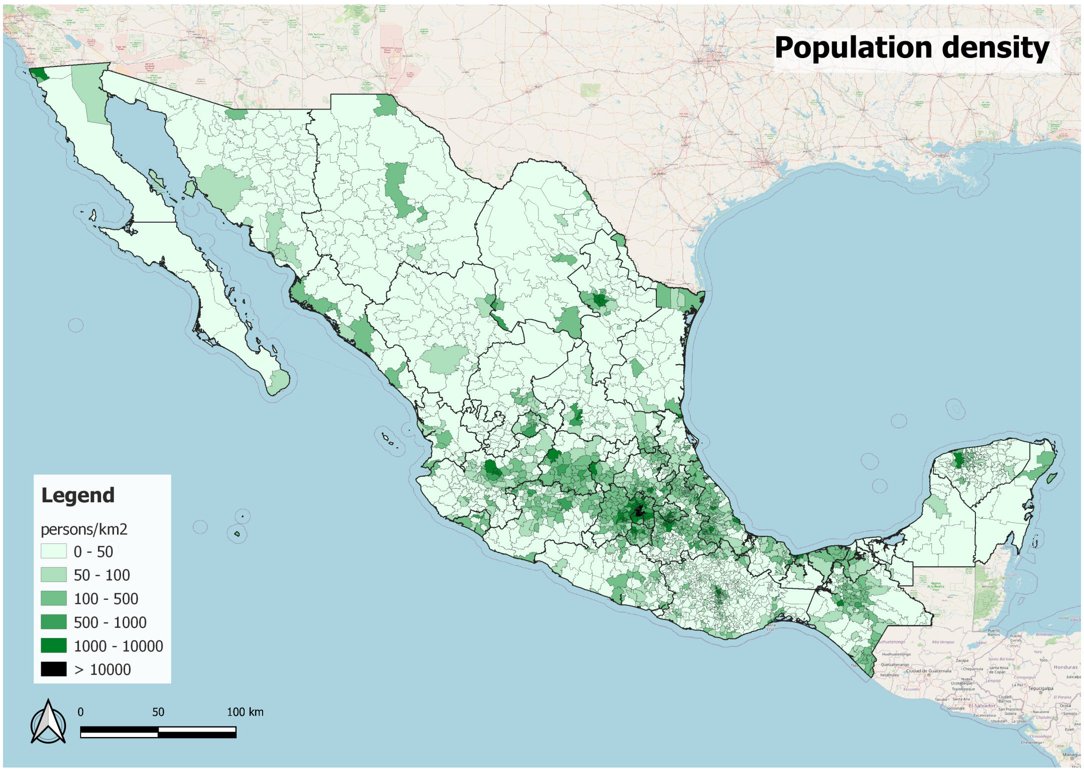
F.2 Maps on indirect factors



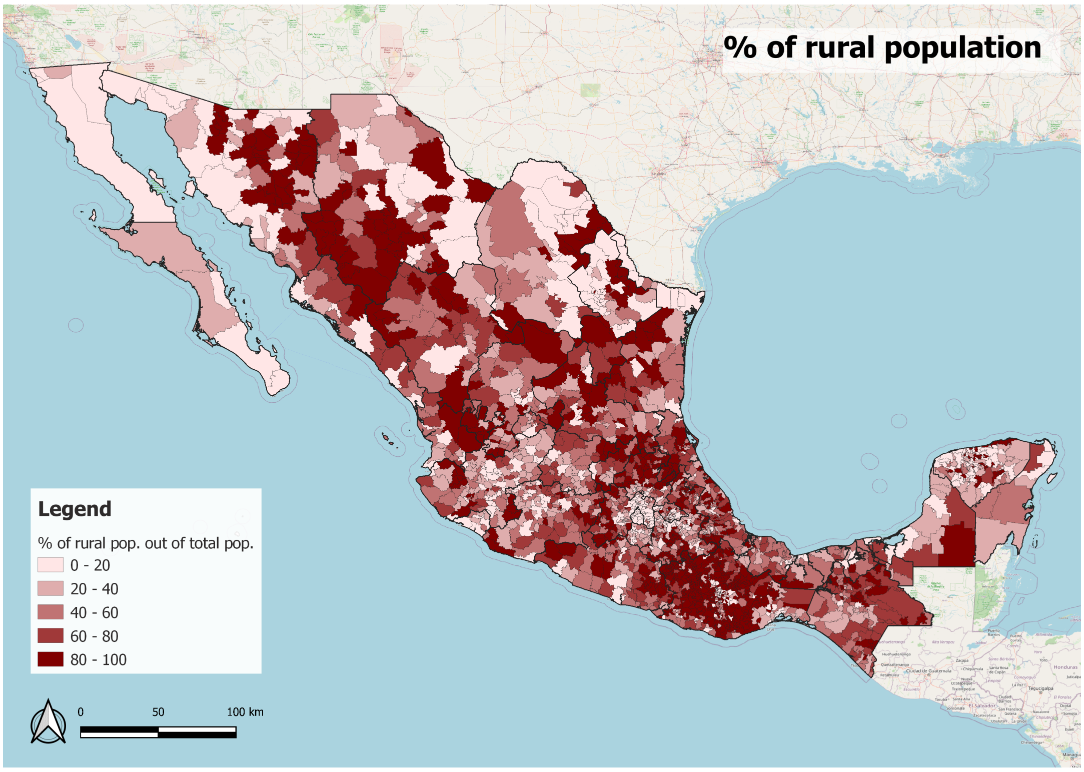
(a) Poverty rate



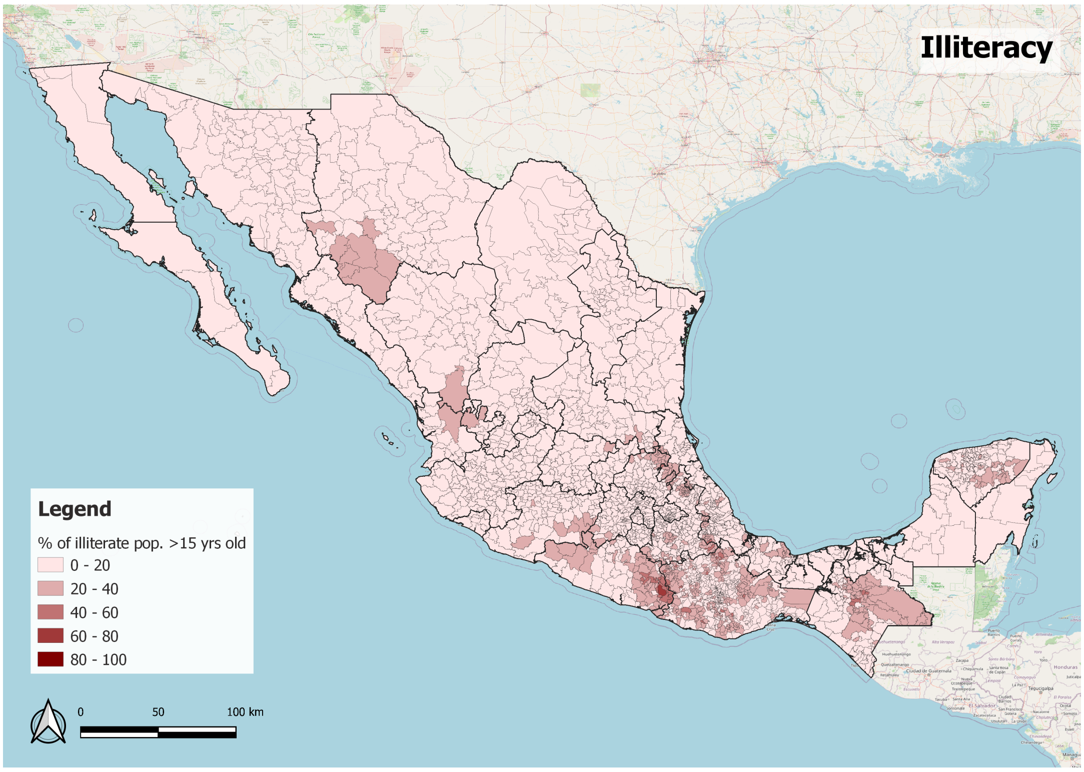
(b) Population earning less then minimum wage



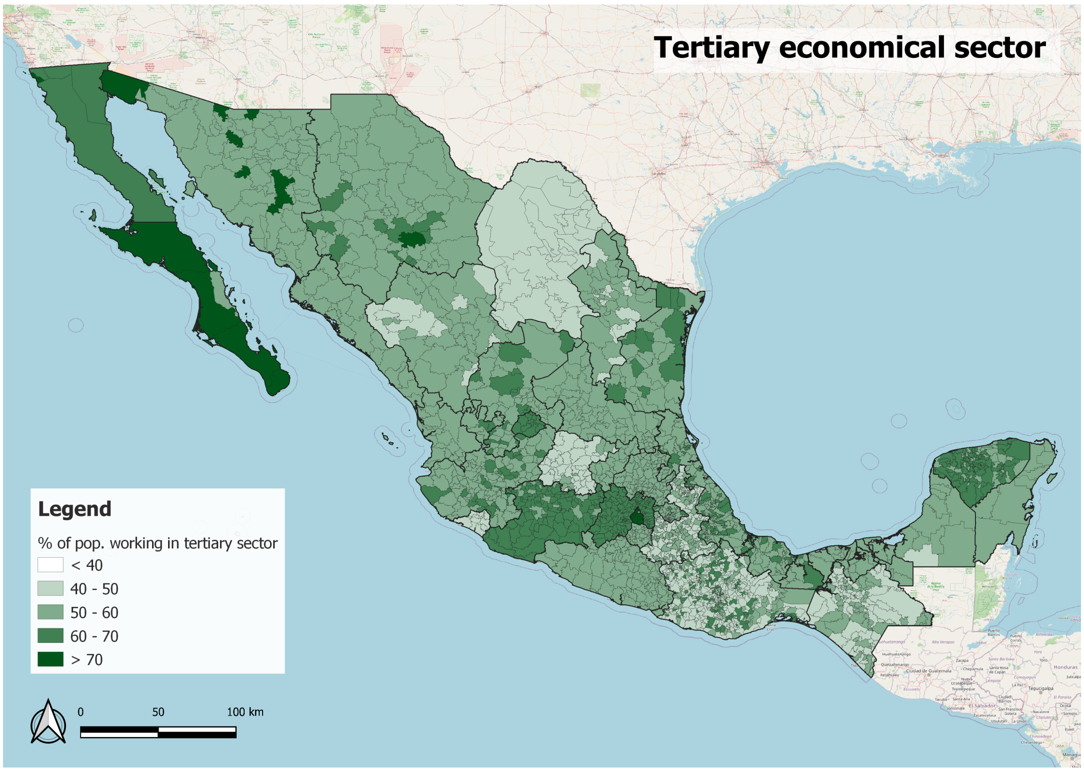
(c) Population density



(d) Percentage of rural population



(e) Illiteracy among population above 15 years old



(f) Population working in tertiary economical sector

Figure 8. Maps on indirectly related factors