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MODELING ENVIRONMENTAL SUSCEPTIBILITY OF MUNICIPAL SOLID WASTE DISPOSAL SITES IN REGIONAL SCALE

Victor Fernandez Nascimento

Doctorate Thesis of the Graduate Course in Earth System Science, guided by Drs. Jean Pierre Henry Balbaud Ometto, and Pedro Ribeiro de Andrade Neto, approved in May 08, 2017.

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Tel.:(012) 3208-6923/6921
E-mail: pubtc@inpe.br

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Aprovado (a) pela Banca Examinadora em cumprimento ao requisito exigido para obtenção do Título de ***Doutor(a)*** em

Ciência do Sistema Terrestre

Dra. Regina Célia dos Santos Alvalá

Presidente / CEMADEN / São José dos Campos - SP

Dr. Jean Pierre Henry Balbaud Ometto

Orientador(a) / INPE / São José dos Campos - SP

Dr. Pedro Ribeiro de Andrade Neto

Orientador(a) / INPE / São José dos Campos - SP

Dr. Felipe Siqueira Pacheco

Membro da Banca / INPE / São José dos Campos - SP

Dr. Pedro Ivo Mioni Camarinha

Convidado(a) / CEMADEN / São José dos Campos - SP

Dr. Edson Luís Piroli

Convidado(a) / UNESP / Ourinhos - SP

Este trabalho foi aprovado por:

( ) maioria simples

(X) unanimidade

São José dos Campos, 08 de maio de 2017

“Never discourage anyone…who continually makes progress, no matter how slow”

—**Plato**

“He who knows all the answers has not
been asked all the questions.

–**Confucius**

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I am very thankful to have with me during these years my life partner, Anahi, without her the way would be much more difficult and without flowers.

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ABSTRACT

The world population is increasing and since the last decade is considered predominantly urban. The enormous population growth is causing changes in the Earth System that can have serious and lasting consequences. Anthropogenic activities in urban areas are always associated with municipal solid waste (MSW) production. Currently, the MSW generation in the world does not favor an appropriate use of natural resources and the large amount of MSW generated exceeds the capacity of the environment to decompose and recycle these wastes through natural processes. Properly managing this MSW is a global environmental challenge. The improper Municipal solid waste disposal (MSWD) locally cause environmental impacts, such as contamination of soil and water sources, and also globally cause environmental impacts, such as increase of Greenhouse gases (GHG) due to methane emissions. The main objective of this thesis is to contribute to Municipal solid waste management (MSWM) through the environmental susceptibility analysis of Municipal solid waste disposal sites (MSWDS) in regional scale from an interdisciplinary overview. This thesis explored an innovative modeling approach using Multi-criteria decision analysis (MCDA) and Analytic hierarchy processes (AHP) coupled with Geographic information system (GIS) to develop an environmental impact susceptibility model (EISM) for MSWDS. The model was applied for the two most populous states and largest MSW generators in South and North America, São Paulo state and California state, respectively. The EISM considers factors such as geology, pedology, geomorphology, water resources, and climate represented by several sub-factors that vary according to the geographical characteristics of the area and data availability. The results of this thesis demonstrate that approximately half of MSW generated in California and São Paulo state is disposed in environmentally susceptible areas and can cause several impacts on the lithosphere, atmosphere, hydrosphere and biosphere. In summary, the EISM findings can help decision makers, landfill managers, and local governments develop control and mitigation measures against the occurrence of negative environmental impacts caused by MSWDS.

MODELAGEM ESPACIAL DA SUSCEPTIBILIDADE AMBIENTAL EM LOCAIS DE DISPOSIÇÃO FINAL DE RESÍDUOS SÓLIDOS URBANOS EM ESCALA REGIONAL

RESUMO

O aumento da população, que desde a última década é considerada predominantemente urbana, vem causando diversas mudanças no sistema terrestre. Atividades antropogênicas em áreas urbanas estão sempre associadas com a geração de resíduos sólidos urbanos (RSU). Atualmente, a taxa de geração dos RSU vem crescendo e gerenciar adequadamente estes resíduos é um desafio ambiental global. A disposição inadequada dos RSU causa diversos impactos ambientais locais como a contaminação dos solos e recursos hídricos, e globais como a geração do gás metano, que contribui para o efeito estufa. Este trabalho objetivou contribuir no gerenciamento dos resíduos sólidos urbanos através da análise de suscetibilidade de impacto ambiental em locais de disposição final de RSU em escala regional, a partir de uma abordagem interdisciplinar. Esta tese tratou de forma inovadora a elaboração de um modelo espacial, que utiliza análise multi critério de decisão e análise hierárquica de processos, acoplado a um sistema de informação geográfica para desenvolver uma ferramenta de avaliação da suscetibilidade a impactos ambientais em locais de disposição final de RSU. Este modelo foi aplicado para os dois estados mais populosos e maiores geradores de RSU da América do Sul e do Norte, respectivamente o estado de São Paulo, no Brasil, e o estado da Califórnia, nos EUA. O modelo leva em consideração fatores como geologia, pedologia, geomorfologia, recursos hídricos e clima e é representado por diversos subfatores que variam de acordo com as características geográficas da área e da disponibilidade de dados espaciais. Os resultados desta tese demonstram que aproximadamente metade dos RSU em São Paulo e na Califórnia é disposto em áreas suscetíveis a sofrer impactos ambientais, podendo causar diversos impactos ao sistema terrestre. Em conclusão, os resultados do modelo permitem que tomadores de decisão, gestores municipais e órgãos fiscalizadores, desenvolvam medidas de controle e mitigação contra a ocorrência de impactos ambientais causados pelos locais de disposição de RSU.

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LIST OF ABREVIATIONS

ABRELPE - Brazilian Association of Public Cleaning and Special Waste

AHP - Analytic Hierarchy Process

BOD - Biochemical Oxygen Demand

BSWP - Brazilian Solid Waste Policy

Cal Poly - California Polytechnic State University

CETESB - Environmental Company of São Paulo State in Brazil

CNM - Confederation of Municipalities in Brazil

COD - Chemical Oxygen Demand

CR - Consistency Ratio

DEM - Digital Elevation Model

EISM - Environmental Impact Susceptibility Model

EU - European Union

GHG - Greenhouse Gases

GIS - Geographic Information System

IBGE - Brazilian Geography and Statistics Institute

INPE – Brazilian Institute for Space Research

IPEA – Brazilian Applied Economic Research Institute

MCDA - Multi-Criteria Decision Analysis

MMA - Ministry of Environment in Brazil

MSW - Municipal Solid Waste

MSWD - Municipal Solid Waste Disposal

MSWDS - Municipal Solid Waste Disposal Sites

MSWM - Municipal Solid Waste Management

NAD83 - North American Datum of 1983

PET - Polyethylene Terephthalate

SIRGAS - Geocentric Reference System for the Americas

USA - United States of America

UTM - Universal Transverse Mercator

WLC - Weight Linear Combination

CONTENT

1 INTRODUCTION

The world population is increasing (UNITED NATIONS, 2014) and since 2008 it is considered predominantly urban (SETO; SÁNCHEZ-RODRÍGUEZ; FRAGKIAS, 2010). The rapid world population growth and economic development are causing changes in terrestrial systems that can have serious and lasting consequences. Anthropogenic activities in urban areas are always associated with Municipal solid waste (MSW) production (ADAMOVIĆ et al., 2016). Concerns related to Municipal solid waste disposal (MSWD) started when cities were created and strengthened after industrialization (GOMES; STEINBRUCK, 2012), when large parts of the population migrated from rural to urban areas (AHMAD et al., 2016).

The MSW generation, in the world, is increasing and reflects consumer habits and lifestyles (GALLARDO et al., 2014; SANTIBAÑEZ-AGUILAR et al., 2015) and does not favor an appropriate use of natural resources (HOORNWEG; BHADA-TATA, 2012). The large amount of MSW generated exceeds the capacity of the environment to decompose and recycle these wastes through natural processes (JOVANOVIC et al., 2015).

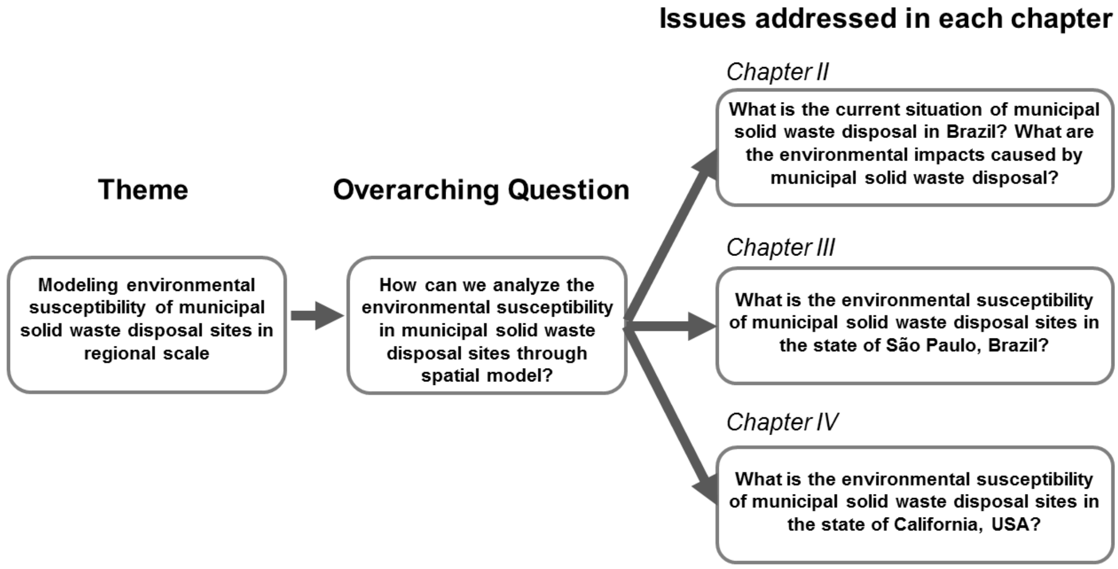
The lack of proper Municipal solid waste management (MSWM) is a major environmental problem (NASCIMENTO et al., 2015). Sustainable MSWM is required to achieve low environmental impact and the old low-cost practices are no longer economically, environmentally and socially acceptable (RADA; RAGAZZI; FEDRIZZI, 2013). One essential part in this process is to properly dispose waste, since disposal sites are permanent facilities that pose risks to the environment and population as they need to be monitored for extended periods of time (LEÃO; BISHOP; EVANS, 2004).

The improper MSWD locally cause environmental impacts, such as contamination of soil (ANILKUMAR; SUKUMARAN; VINCENT, 2015; GAŁKO, 2015; OGUNMODEDE; ADEWOLE; OJO, 2015; YAZDANI et al., 2015), water sources (ANILKUMAR; SUKUMARAN; VINCENT, 2015; DE ANDRADE PEREIRA; DE LIMA, 2016; HAN et al., 2016; X et al., 2016) and health public impacts (MAVROPOULOS; NEWMAN, 2015; ALIMBA et al., 2016) and also globally cause environmental impacts, such as increase of Greenhouse gases

(GHG) due to methane emissions (HOORNWEG; BHADA-TATA, 2012; CHOI et al., 2016). Consequently, these impacts has a potential to directly and indirectly affect atmosphere, hydrosphere, lithosphere and biosphere (BUTT et al., 2016).

The main objective of this thesis was to assess the environmental susceptibility of Municipal solid waste disposal sites (MSWDS) in regional scale through spatial analysis using an interdisciplinary approach. The hypothesis was that populous states in both, developed and developing countries, disposed the majority of MSW in environmental susceptible areas. To assess that an Environmental impact susceptibility model (EISM) was developed and applied to the state of São Paulo, Brazil and California, USA, the two most populous states in the South America and North America, respectively. The main research questions of this thesis are illustrated in (**Figure 1-1**).

Figure 1-1 - The main research question of the thesis



Source: Elaborated by the author

This thesis is based and elaborated as a collection of four papers related to the theme of environmental impacts caused by MSWDS developed during my years as a PhD student in the Earth System Science Center at the National Institute for Space Research - INPE (Brazil) with part-time in the Global Waste

Research Institute at the California Polytechnic State University – Cal Poly (USA). A brief description of the structure of each chapter is presented forward:

Chapter 2: This chapter reviews the development and challenges in MSWM in Brazil and explores the recent improvements and remaining challenges in the MSWD, as well as identifies the main environmental impacts caused by MSWDS.

Chapter 3: In this chapter, the EISM for MSWDS was developed and applied to the state of São Paulo, Brazil. To elaborate this model we considered local factors such as geology, pedology, geomorphology, water resources, and climate, represented by fifteen associated sub-factors. We used a Multi-criteria decision analysis (MCDA) approach via an Analytic hierarchy process (AHP) coupled with Geographic information system (GIS) to develop the spatial model. The results discussed and point out the environmental susceptibility classification for São Paulo state focusing in the MSWDS located in the highest categories.

Chapter 4: In this chapter, the EISM for MSWDS was developed and applied to the state of California, USA. To elaborate this model we considered local factors such as geology, pedology, geomorphology, water resources, and climate, represented by thirteen associated sub-factor. We used MCDA approach via an AHP coupled with GIS to develop the spatial model. The results discussed and point out the environmental susceptibility classification for California state, focusing in the MSWDS located in the highest categories.

Chapter 5: This chapter points out the final remarks, including the major finds of this studies under the light of the thesis hypothesis. In this chapter are also included the modeling approach and limitations found during this investigation, the future research needs and some policy recommendations.

2 RECENT IMPROVEMENTS AND REMAINING CHALLENGES IN THE MUNICIPAL SOLID WASTE DISPOSAL IN BRAZIL[1]

2.1 Introduction

The world population continues to increase (UNITED NATIONS, 2014) and since 2008 it is considered predominantly urban (SETO; SÁNCHEZ-RODRÍGUEZ; FRAGKIAS, 2010). The large population growth in South American nations causes a large number of new environmental problems (MÜNNICH; MAHLER; FRICKE, 2006). Concerns related to MSWD started with the onset of city dwelling and strengthened after industrialization (GOMES; STEINBRUCK, 2012), when large parts of the population migrated from rural to urban areas (AHMAD et al., 2016). Latin America is considered the most urbanized region in the world, with over 80% of its population living in cities (UN-HABITAT, 2012). According to the 2010 census carried out by the Brazilian Geography and Statistics Institute (IBGE), approximately 84% of Brazil's population lives in urban areas.

According to the law No. 12.305/2010, which implements the Brazilian Solid Waste Policy (BSWP), MSW is defined as a solid waste generated by municipalities or other local authorities, and includes household, commercial, institutional and public and private parks' waste (BRASIL, 2010). However, the definition of MSW in the world can vary according to the country and the diversity of MSWM practices (IPCC, 2006; LETCHER; VALLERO, 2011).

MSWM is one of the major environmental challenges for all societies (GALLARDO et al., 2014) and consists of a multidisciplinary activity, which includes generation, separation, storage, collection, transfer, transport, processing, recovery and MSWD (ZELENOVIĆ VASILJEVIĆ et al., 2012). Proper MSWM is a major challenge for developing countries (HENRY; YONGSHENG; JUN, 2006; SAIKIA; NATH, 2015) where urban agglomerations presents

[1] This chapter is based on the paper: NASCIMENTO, V.F.; SOBRAL, A.C.; FEHR, M.; YESILLER, N.; ANDRADE, P.R.; OMETTO, J.P.B.; Recent improvements and remaining challenges in the municipal solid waste disposal in Brazil. Submitted to the **International Journal of Environment and Waste Management.**

challenges for governance, but also opens opportunities for sustainable solutions (SETO; SÁNCHEZ-RODRÍGUEZ; FRAGKIAS, 2010). The old low-cost practices of MSWM are no longer economically, environmentally and socially acceptable (RADA; RAGAZZI; FEDRIZZI, 2013).

Among diverse kinds of environmental degradation caused by humans, MSWD is one of the most impactful, because MSW is retained in the same place where it is deposited, even though the waste undergo chemical and physical transformations over the years (NASCIMENTO; SILVA; SOBRAL, 2015; CHONATTU; PRABHAKAR; PILLAI, 2016). MSWD has a potential to directly and indirectly affect the four main spheres of the environment, which are atmosphere, hydrosphere, lithosphere and ultimately biosphere (BUTT et al., 2016).

The increasing generation and improper MSWD cause local environmental impacts, such as contamination of soil and water sources, as well as cause public health impacts (MA; HIPEL, 2016), such as the increase in dengue virus (BHADA-TATA; HOORNWEG, 2016) and zika virus incidence (DIENG et al., 2017). Improper MSWD can also cause global environmental impacts from emissions of carbon dioxide and methane and numerous trace organic compounds during anaerobic decomposition of the wastes (HOORNWEG; BHADA-TATA, 2012; ONYANTA, 2016; ZHOU; JIANG; ZHAO, 2016).

In most developing countries inefficiency in collection, disposal, and inappropriate treatment processes compromises the potential benefits of proper MSWD (CHERIAN; JACOB, 2012; JOEL; MARK; J, 2012; ONYANTA, 2016). In addition, MSWD is crucial for urban planning and must consider not only the economic efficiency of the processes, but also the viability of these processes from an environmental and social point of view (CHANG; LIN, 2013).

This study considers the environmental impacts caused by MSWD in Brazil due to various factors. First, the volume of MSW generated in the country is growing as well as the per capita generation (JACOBI; BESEN, 2011; ABRAMOVAY; SPERANZA; PETITGAND, 2013; CEMPRE, 2013; ABRELPE, 2016). Second, the complexity of MSWM in Brazil (WALDMAN, 2012a, 2012b; MA; HIPEL, 2016) affects implementation of regulatory policies. Finally, the BSWP dictated that all open dumps and uncontrolled landfills must have been closed by the year 2014, which has not yet occurred.

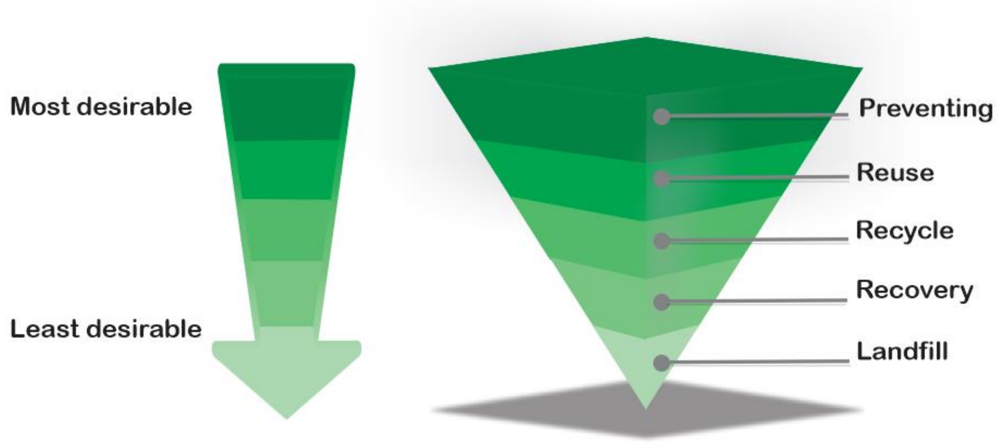
Therefore, the objective of this chapter is to assess the recent improvements and remaining challenges of MSWD in Brazil focusing on the environmental impacts caused by the inappropriated MSWD. In Section 2.2, a review of MSWM including data about generation, collection, treatment and MSWD in Brazil is presented. In Section 2.3, a discussion about the environmental impacts caused by MSWDS is provided. To conclude, in Section 2.4 final considerations about the challenges to improve MSWM and consequently MSWD in Brazil are presented.

2.2 Municipal solid waste management in Brazil[2]

Brazil is following a MSWM hierarchy very similar to that of developed countries, such as the European Union (EU, 2008) and the USA (US-EPA, 2009). The BSWP's priority order is no generation, reduction, reuse, recycling, treatment and finally disposal (**Figure 2-1**). Another important point of the BSWP is that MSW should be recycled and composted and only the remains from these treatments steps must be disposed in sanitary landfills (BRASIL, 2010). The following sections provided an overview of generation, collection, treatment and disposal of MSW in Brazil.

[2] This sub-chapter is based in an updated and brief version of the paper: NASCIMENTO, V.F.; SOBRAL, A.C.; ANDRADE, P.R.; OMETTO, J.P.H.B.; Development and challenges in Brazilian municipal solid waste management. Published at: **Revista Ambiente & Agua-An Interdisciplinary Journal of Applied Science**, v. 10, n. 4, p. 889–901, 2015. DOI:10.4136/1980-993X.

Figure 2-1 - Hierarchy of municipal solid waste management in Brazil



Source: Adapted from Nascimento et al. (2015).

2.2.1 Generation

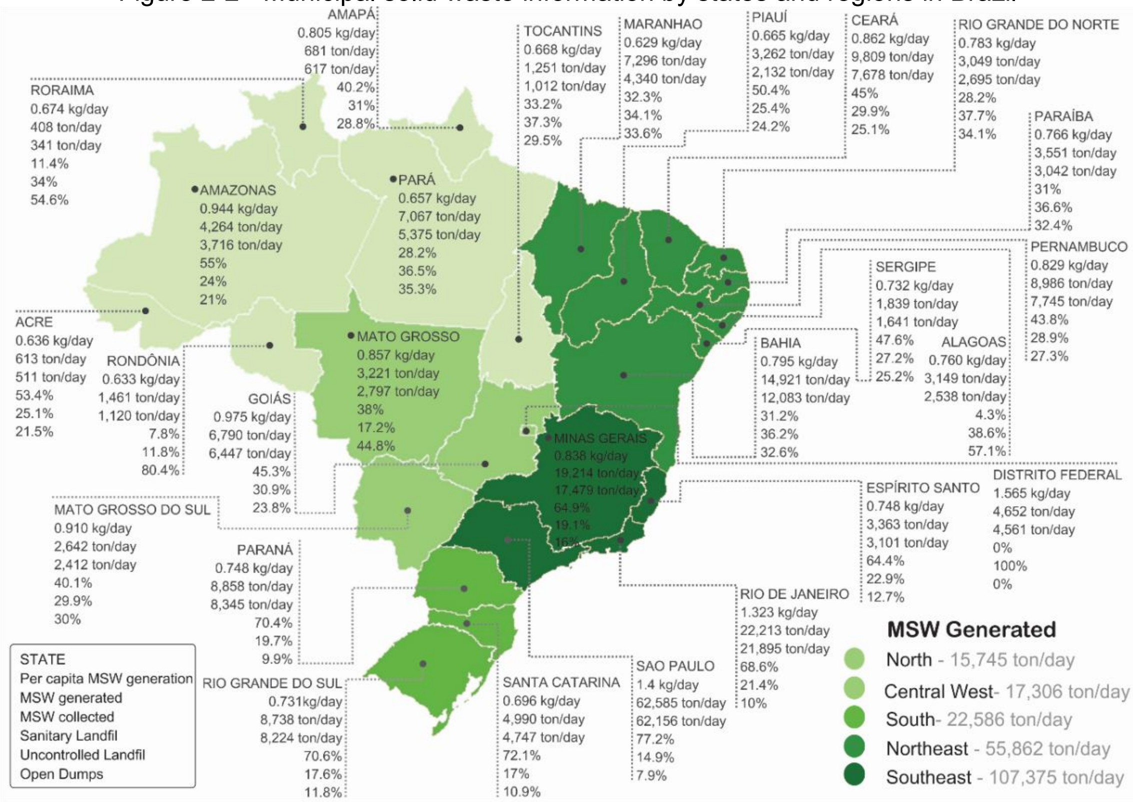
In Brazil, it is difficult to quantify the total MSW generation because of three main issues: MSW is informally collected, waste is irregularly disposed of, and public collection system is insufficient, which collectively result in a divergence of data (IPEA, 2012). In 2015, the Brazilian population with more than 204 million people (IBGE, 2015) generated approximately 80 million tons of MSW according to the Brazilian association of public cleaning and special waste (ABRELPE, 2016).

The quantity of MSW produced by a given population is considered as a marker of consumption habits, living standards, cultural factors, and family income (OJEDA-BENÍTEZ; VEGA; MARQUEZ-MONTENEGRO, 2008; CAMPOS, 2012; SUTHAR; SINGH, 2015; ADAMOVIĆ et al., 2016). Brazil is the 5th biggest country in the world by area and also has the 5th largest population. The amount of waste generated in Brazil is not uniform throughout the country. Generation depends on the economic structure (agricultural, industrial, service), settlement structure (rural, urban), standard of education and climate (MÜNNICH; MAHLER; FRICKE, 2006).

Brazil's regions have a socio-economic and cultural heterogeneity that influences the MSW generation (SNIS, 2016). For example, the ascending order of MSW generation per capita in the Brazilian regions are: south - 0.77, north - 0.90, northeast - 0.98, midwest - 1.12, and southeast - 1.25 kg/habitant/day

(ABRELPE, 2016). As the southeast and northeast are the most populous regions in Brazil (IBGE, 2015), these two regions are the largest overall generators of MSW, together producing more than 74% of all MSW generated in Brazil (ABRELPE, 2016). More information about the per capita generation, the total MSW generated and collected, and the percentages of this MSW that goes to sanitary landfills, uncontrolled landfills, and open dumps are presented in (**Figure 2-2**).

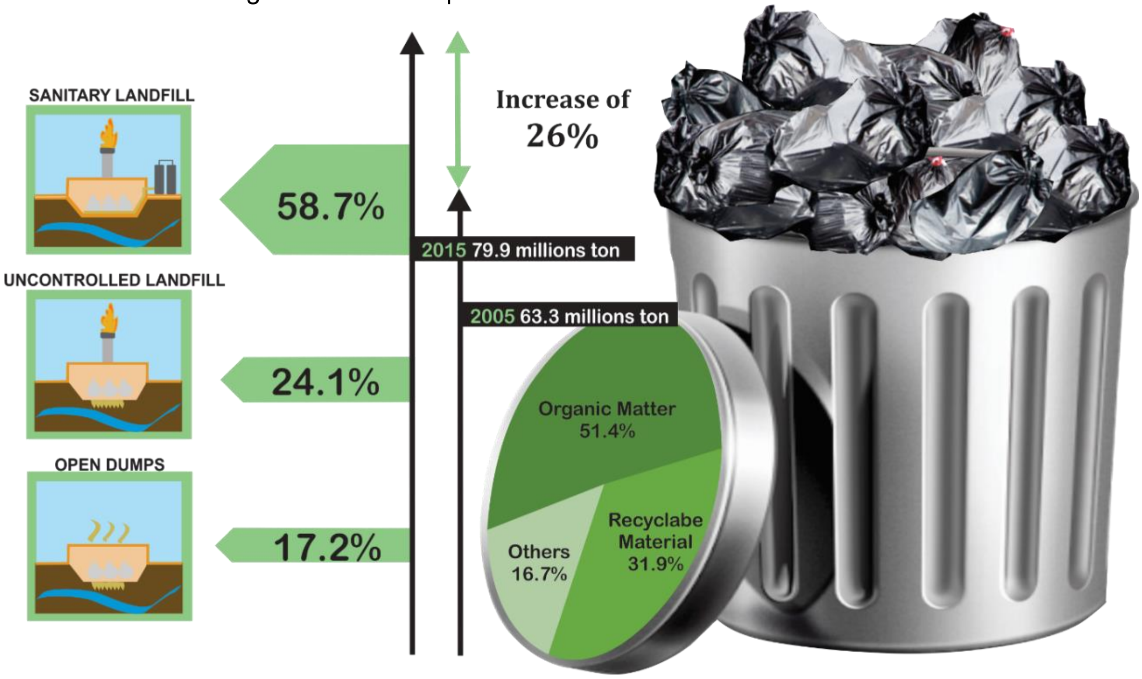
Figure 2-2 - Municipal solid waste information by states and regions in Brazil



Source: Elaborated by the author. The data was obtained in ABRELPE (2016).

Another factor related to socio-economical characteristics of the population is the MSW composition (OJEDA-BENÍTEZ; VEGA; MARQUEZ-MONTENEGRO, 2008; SUTHAR; SINGH, 2015; ADAMOVIĆ et al., 2016; KHAN; KUMAR; SAMADDER, 2016; MIGUEL et al., 2016). In Brazil, there is a predominance of organic matter in the MSW (BRASIL, 2012). However, the composition has been changing and the percentage of recyclables has increased significantly in the recent years (MMA, 2012). In 2008, the MSW composition in Brazil was 31.9% recyclable material, 51.4% organic matter and 16.7% other, which is the waste that cannot be recycled and materials that are technically or economically not viable for recycling (**Figure 2-3**) (BRASIL, 2012).

Figure 2-3 - Municipal solid waste characterization in Brazil



Source: Elaborated by the author. The data was obtained in IBGE (2008); ABRELPE (2016).

Demographic projections in Brazil for the period 2000-2060 indicate that the population will peak in the year 2042, with approximately 228.4 million inhabitants (IBGE, 2013). If the per capita MSW generation is maintained at its current level, approximately 1.07 kg/person/day (ABRELPE, 2016), 89.2 million tons of MSW will be generated in 2042. Moreover, MSW generation rate per capita in the country was observed to have grown in greater proportions than the population growth rate (ABRELPE, 2014).

Several studies have used mathematical models to estimate the generation of MSW (KESER; DUZGUN; AKSOY, 2012; YOUNES et al., 2015b; ABBASI; HANANDEH, 2016; GHINEA et al., 2016) and composition of MSW (SAHIMAA et al., 2015; LIIKANEN et al., 2016) in the world. There are also several studies that analyzed the generation (SIMONETTO, 2014; URBAN, 2016) and composition of MSW in Brazil (AGUIAR; SILVEIRA, 2015; MIGUEL et al., 2016).

Having an estimate of MSW generation is essential for MSWM as well as simulating various environmental impact scenarios (ADAMOVIĆ et al., 2016). Furthermore, knowledge of the evolution of MSW generation is needed to follow the BSWP and planning the MSWM activities of collection, treatment, and disposal (CAMPOS, 2012).

2.2.2 Collection

The collection of MSW in Brazil's urban areas is well developed and cover almost all the households, with approximately 98.4% of coverage (IBGE, 2008; IPEA, 2012). However, if the rural areas are also considered, the extent of MSW collection decreases considerably. For example, considering urban and rural MSW collection, the northeast and north regions have the lowest collection rates of 78.5% and 80.6% among Brazil's five regions (ABRELPE, 2016).

As mentioned before, 80 million tons of MSW were generated in Brazil in 2015. Approximately, 9.2% of this amount was not collected (ABRELPE, 2016). The comparison between generation and collection indicate that 7.3 million tons of MSW was not collected in 2015.

2.2.3 Treatment - Recycling and Composting

Various MSW treatment techniques are available including: gasification (ZHU et al., 2016), pyrolysis (LIU et al., 2016), incineration (HAVUKAINEN et al., 2016), composting (SHARIFI; HOSSAINI; RENELLA, 2016), recycling (CHALLCHAROENWATTANA; PHARINO, 2016), and anaerobic digestion (EDWARDS; OTHMAN; BURN, 2015). Individually and combined these treatments have advantages and disadvantages (IPCC, 2006). This highlights the importance of selecting appropriate technology for a sustainable MSWM program in a given city or region (MARCHEZETTI; KAVISKI; BRAGA, 2011; AICH; GHOSH, 2016).

The treatment of MSW should be considered with caution and include advanced planning, mainly due to the impact on the environment and society (SANTIBAÑEZ-AGUILAR et al., 2015). Recycling and composting are important processes for treatment of MSW, which are highlighted in the technical and scientific literature and emphasized in the BSWP. Both processes involve changing physical, chemical or biological characteristics of MSW, in order to converter the waste into raw materials or new products (ABRELPE, 2016).

In 2014, only 5.2% of wastes collected in Brazil was recycled (SNIS, 2016). Although there is a goal to increase recycling (CEMPRE, 2013), according to (WALDMAN, 2012a, 2012b) the percentage of recycled waste in Brazil is negligible. One of the few studies of the financial aspects of recycling in Brazil was carried out by the Brazilian applied economic research institute (IPEA) in 2010, and concluded that the country lost 8 billion reals annually, which was approximately 4.5 billion dollars, by burying instead of recycling the appropriate constituents in the MSW.

Overall, recycling rates for PET (polyethylene terephthalate) bottles and aluminum cans are the highest among all recyclable materials in the Brazilian recycling market (CEMPRE, 2015). In 2007, 51.3% of PET bottles were recycled, which ranked the country as the second largest recycler of this material in the world (ABIPED, 2010; RODRIGUEZ et al., 2012). In addition, since 2002, Brazil is also the aluminum-recycling leader in the world (FIGUEIREDO, 2012), recycling 98.4% of this material in 2011 (ABRELPE, 2013; CEMPRE, 2013). The progress of recycling, specifically for these two types of materials, is mainly based in the informal waste sector and the waste pickers[3] workforce (CAMPOS, 2014; ASSAD, 2016; FRACALANZA; BESEN, 2016) and is a result of the need to earn income through trading these materials and not as expected due to environmental awareness (POLZER; PERSSON, 2016).

Regarding organic matter treatment, in 2015, only 72 composting units were present in Brazil (SNIS, 2016). In 2008, the percentage of all MSW collected and treated by composting was only 1.6% (IPEA, 2012). This clearly demonstrates the country's deficiency to treat organic matter. One of the main difficulties with composting in Brazil is the absence of organic waste separation in households, which contaminates the organic matter with other types of waste (IBGE, 2011).

The goal of the Brazilian Solid Waste Plan is to increase the recycling and composting rates. This may happen with the development of selective collection

[3] Since 2002, waste pickers is legally recognized as a profession in Brazil. A waste picker is defined as someone who collects, sorts and sells recyclable material. Usually in Brazil, these professionals are self-employed or members of cooperatives or associations (FRACALANZA; BESEN, 2016).

and training cooperatives of recyclers with public and corporate investment (BRASIL, 2012). There are several important reasons to increase recycling and composting rates in Brazil, but one of the most relevant is reducing the amount of MSW that is landfilled, which would reduce the area required for MSWDS and also decrease the environmental impacts caused by improper MSWD.

2.2.4 Disposal

Mainly three methods of MSWD are used in Brazil including open dumps, uncontrolled landfills, and sanitary landfills. The oldest and most broadly used is open dumps in which MSW is placed directly on the ground without any engineered controls. In addition, no provisions exist for collection or treatment of the contaminated liquids (i.e., leachate) generated in the waste mass, which percolates into the subsurface contaminating surrounding soils and water sources (IBGE, 2011). Furthermore, no means exist for collection and removal of the various high global warming gases generated and emitted by the disposed wastes. This method is considered the most harmful to the environment and society (IBGE, 2011). Uncontrolled landfills are considered an intermediate option between the open dumps and sanitary landfills. The main advantage of uncontrolled landfills is the use of daily soil covers over disposed wastes, which reduces odors and disease vectors. The main disadvantage of these facilities compared to sanitary landfills is the lack of bottom and permanent cover liner systems and leachate and gas collection systems. MSWD in uncontrolled landfills has increased in Brazil, particularly in small and medium size cities (IBGE, 2011), even though these facilities are considered to be inadequate for proper MSWD (ABRELPE, 2011). Sanitary landfills, considered the best method for proper MSWD, represent the engineered facilities with bottom and cover liner systems as well as with provisions for collection and removal of leachate and gas.

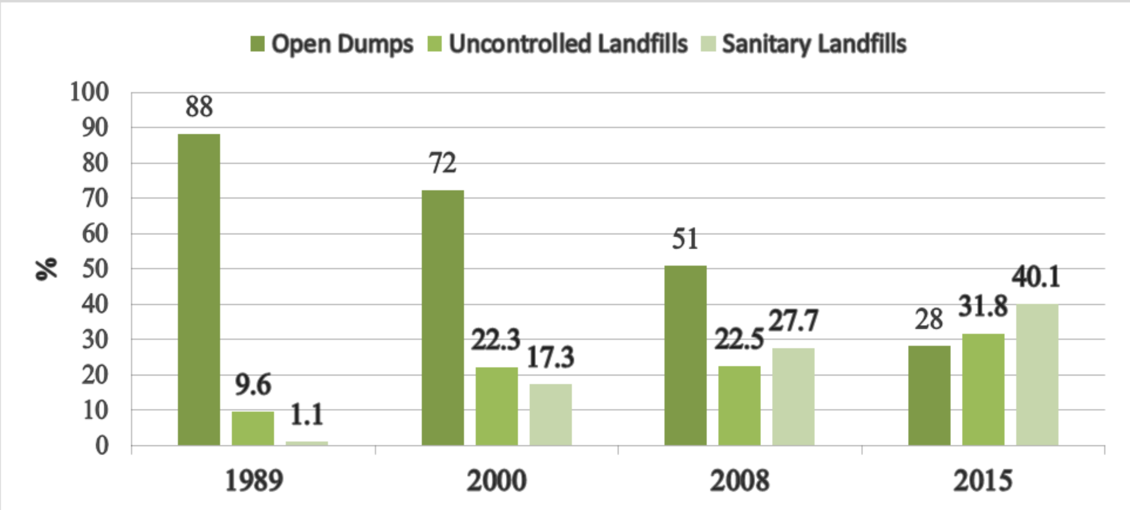
In Brazil, approximately 80.3% of all MSW collected is disposed of in open dumps or uncontrolled and sanitary landfills, 9.6% is burned[4], 7.2% is displaced

[4] In Brazil the MSW is mainly disposed of in landfills, there are only few available incineration plants that are used mainly for medical waste and waste from individual business (MÜNNICH; MAHLER; FRICKE, 2006).

in dumpsters, 2% is disposed of in vacant lots or public sites, 0.6% is buried in the homeowners' property, 0.2% is transferred to another type of destination, and 0.1% is thrown in rivers, lakes or the sea (CEMPRE, 2013).

In 2008, 50.8% of Brazilian cities disposed of MSW in open dumps and 22.5% in uncontrolled landfills (**Figure 2-4**). By adding these two inadequate MSWD methods, approximately 73.3% of all municipalities in Brazil improperly disposed of MSW (IBGE, 2008).

Figure 2-4 - MSW final destination by municipalities in Brazil - 1989/2015



Source: Elaborated by the author. The information for the years 1989, 2000 and 2008 was obtained in IBGE (2008), while the information for 2015 was obtained in ABRELPE (2016).

The south and southeast regions had the fewest cities using open dumps as a method of MSWD, 15.8% and 18.7% respectively. Meanwhile, in the north and northeast regions there is a predominance of cities disposing MSW inappropriately, 85.5% and 89.3%, respectively (IBGE, 2008). This contrast is probably caused by the differences in socio-economic-technological development between Brazil's regions.

Although in 2008 only 27.7% of Brazilian cities disposed of MSW in sanitary landfills, there was an increase in the number of municipalities using this method of MSWD (JACOBI; BESEN, 2011). For example, the 13 most populous cities in Brazil, each with over one million inhabitants, are also the biggest solid waste producers and dispose MSW in sanitary landfills. Therefore, approximately 60% of all MSW collected was disposed of in sanitary landfills in 2015, even though only 40% of Brazil's cities have used sanitary landfills as a MSWD method (ABRELPE, 2016).

Though there was an increase in the number of Brazilian cities using sanitary landfills, the increasing generation of MSW caused the rise in the amount of MSW disposed improperly, reaching 30 million tons in 2015 (ABRELPE, 2016). Overall, the appropriate MSWD becomes one of the most critical problems faced by municipalities (SIMONETTO, 2014), which can causes serious negative environmental impacts. Therefore, while MSWD in sanitary landfills does not eliminate all possible environmental impacts, it reduces the probability of negative impacts.

2.3 Environmental impacts caused by MSWD in Brazil

Climate change, increasing urbanization, and population growth are the most significant aspects that can make considerable impacts on the environment, particularly related to waste management (HETTIARACHCHI; ARDAKANIAN, 2016). The environmental impacts caused by MSW in Brazil is a complicated issue resulting from a combination of increase in MSW generation, insufficient selective collection, low rates of recycling and composting, and finally improper MSWD methods, all contributing to the lack of BSWP fulfillment.

As mentioned before, the MSW generation is increasing in Brazil and will probably reach per capita generation levels similar to developed countries soon (CAMPOS, 2012). Besides, the MSWD method used are not entirely exempt from environmental impacts (ABRAMOVAY; SPERANZA; PETITGAND, 2013). Disposing MSW in nature without any treatment causes an unhealthy relationship between society and nature, because even if the best method of MSWD were chosen, there would still be negative factors such as the cost of construction, operation, and closure of these facilities (ABRAMOVAY; SPERANZA; PETITGAND, 2013).

In Brazil, the environmental costs of inadequate methods of MSWD result in contamination of lithosphere, hydrosphere and atmosphere. The environmental risks caused by MSW is highlighted due to the dominance of organic matter in the overall waste composition. Additionally, the lack of national legislation related to MSW until 2010, allowed the proliferation of open dumps and uncontrolled landfills, creating numerous environmental problems (GOMES; STEINBRUCK, 2012).

The pollution of soil and groundwater is caused by leakage of leachate (CUCCHIELLA; D'ADAMO; GASTALDI, 2014), which is a liquid produced by decomposition of organic matter (BELLEZONI et al., 2013; MOODY; TOWNSEND, 2016). Leachate is harmful to the environment, because is highly concentrated in dissolved organic matter, inorganic chemicals, and heavy metals (LOTHE; SINHA, 2016; MISHRA et al., 2016). Consequently, one of the main environmental concerns related to the operation of the MSWDS is the leakage of leachate and spreading of contaminants (ANILKUMAR; SUKUMARAN; VINCENT, 2015; GRUGNALETTI et al., 2016).

Once the soil and groundwater near the MSWDS are contaminated, it is very difficult to remediate these areas (KIM; OWENS, 2011). In order to identify the environmental contamination associated with MSWDS, groundwater analysis is necessary in the surrounding area. Parameters that need to be analyzed include Chemical oxygen demand (COD), Biochemical oxygen demand (BOD), pH, alkalinity, chloride and heavy metals such as (Pb, Cd, Cu, Ni and Zn) (CASTAÑEDA et al., 2012; LOPES et al., 2012; NAVEEN et al., 2016).

Burying waste in MSWDS does not allow aeration of the organic matter, leading to anaerobic decomposition (without presence of oxygen) and thus generating toxic gases. The main landfill gases, carbon dioxide and methane, are also GHG. In addition, more than 200 traces organic compounds have been detected in landfill gas with varying degrees of global warming potential and other harmful environmental and human health effects.

In the waste sector, usually waste collection and transport contribute less than 5% of GHG emissions. The main driver of GHG emission in MSWM is the MSWD, which globally account for 11% of methane emission (BHADA-TATA; HOORNWEG, 2016). In Brazil, according to GHG Annual Emission Estimate (BRASIL, 2016), the MSW treatment generated, 17.332 Gg CO_2 eq. in 1990 and 32.449 Gg CO_2 eq. in 2014, which indicates an increase of 87.2% in 24 years. In addition, a growing emissions trend of these gases is projected for the future.

Another environmental impact that can be caused by improper, ineffective, or nonexistent MSWD is associated with flood events. According to the National research on basic sanitation, between 2004 and 2008, 2,274 Brazilian municipalities have declared flooding in their urban area and 30.7% of these municipalities considered that improper MSWD in streets, avenues and water bodies were the main cause of this problem IBGE (2008). Human health is also threatened when flooding events are associated with improper MSWD and diseases such as leptospirosis, viral hepatitis and diarrhea can be proliferated (IBGE 2011).

People who work directly in MSWDS can become prone to health problems, such as chronic bronchitis, worms, intestinal infection, leptospirosis, dengue, meningitis, allergies, nausea and flu, transmitted by urine, feces, contact with saliva, paws, and by animal bites (CARDOSO; CARDOSO, 2016). Moreover, the foul odor arising from MSWDS can cause loss of appetite, headache, nausea, and vomiting (MAVROPOULOS; NEWMAN, 2015; BUTT et al., 2016). The control of these diseases is dependent on environmental hygiene and appropriate MSWD methods (TAUIL, 2006; GUARNIERI, 2015; VUČIJAK; KURTAGIĆ; SILAJDŽIĆ, 2016).

MSWD in densely urbanized areas poses additional environmental threats (CHANG; PARVATHINATHAN; BREEDEN, 2008; JACOBI; BESEN, 2011; WANDERLEY et al., 2017). In Brazil, landfills in almost all metropolitan areas are completely full or almost full, and the new landfills need to be located farther from the cities. This results in an increase in the MSW transportation requirements and consequently more gas emissions to the atmosphere coming from the collection vehicles. On the other hand, in small towns the lack of infrastructure, qualified staff, and financial resources also negatively interfere in the properly MSWD, causing more environmental impacts.

MSWM is an important challenge that both developed and developing countries face (WANG et al., 2011). Problems with MSW generation and MSWD options are indicated to be the biggest, most difficult and most complex challenge for government authorities (ZAMAN, 2014). The growth and increase in the standard of living of the population, the process of urbanization, deficiencies in environmental education, and social formation are the main challenges related to MSWM around the world (HOORNWEG; BHADA-TATA; KENNEDY, 2013). To find solutions to these issues, strategies that integrate different sectors of society are needed (LAURENT et al., 2014).

Brazilian solution to become an environmentally healthier society through reduction of MSW generation and enforcement of the BSWP with the implementation of the “polluter pays principle” is suggested by (SILVA FILHO; SOLER, 2013). There are several examples of "pay as you throw" applications (pay according to what you throw away), in the USA and in the European Union (ELIA; GNONI; TORNESE, 2015). This practice promotes the best possible use of materials, consequently lowering environmental pollution (ABRAMOVAY; SPERANZA; PETITGAND, 2013), and moving towards a more sustainable economy (ZORPAS; LASARIDI, 2013).

Another alternative global trend to reduce the amount of MSWD in landfills is to encourage heat treatment using MSW as an energy source (MAYA et al., 2016). Incineration that is the most common heat treatment has been used in many developed countries (HORTTANAINEN et al., 2013; SANTIBAÑEZ-AGUILAR et al., 2013). However, heat treatment of MSW is not happen in Brazil not because of the environmental concerns but mainly due to high cost (MAYA et al., 2016). To reduce the amount of MSW disposed in landfills in Brazil, the BSWP gives priorities to recycling and composting instead of incineration, which is good for the environment particularly as reductions in carbon emissions, minimizing the impact on climate change through reuse and recycling (ZELENOVIĆ VASILJEVIĆ et al., 2012).

As mentioned in section 2.2.3, even though there is a tendency in Brazil to increase recycling and composting, these rates are still very low and the majority of MSW continues to be buried. Besides, the initiative of selective collection for recycling, occurs only in 62% of the Brazilian municipalities and does not reach the entire territory or all the municipal population (ABRELPE, 2014). To make organic matter composting and recycling efficient in Brazil, it is first necessary to educate the public, industry, and public agencies to separate MSW at source before collection, which can be enforced by incentives in environmental education projects, or even by restricting the current legislation (CARDOSO; CARDOSO, 2016).

One of the alternatives to reduce the impact caused by MSWD in landfills is to generate energy through the collection and burning of gases from the decomposition of organic matter, mainly methane, which is one of the largest contributors to GHG (LU et al., 2009; IPCC, 2013; BHADA-TATA; HOORNWEG, 2016).

Most well managed landfills in the world use methane as a fuel source or at least, flare the gas, converting methane into carbon dioxide, to avoid worst environmental impacts (BHADA-TATA; HOORNWEG, 2016). In Brazil, there are only few landfills, such as *Bandeirantes* and *São João João* landfills in the city of São Paulo that use methane to produce electricity. This is mainly because energy production from methane is not a national priority in the BSWP, which emphasizes treatment of organic matter before MSWD. An alternative solution is using these gases to generate electricity through bio-digesters (IRVINE; LAMONT; ANTIZAR-LADISLAO, 2010; ASSAMOI; LAWRYSHYN, 2012; BHADA-TATA; HOORNWEG, 2016). In these applications, there is an opportunity to control gases emission, generating an important reduction mechanism for GHG emissions in Brazil.

It is important to point out that since the introduction of the 1988 Brazilian Federal Constitution, municipalities are responsible for ensuring MSWM, which include collection, treatment and final disposal of MSW (TENÓRIO et al., 2012; FRACALANZA; BESEN, 2016). In addition, the BSWP aimed to close all the inadequate forms of MSWD by the year 2014, however these goals were not reached. The legislation was altered by the Provisional Measure No. 651/14, which proposes staggered targets for the municipalities between the years of 2018 and 2021, according to city population number[5].

With the implementation of the BSWP (2010), in order to obtain federal resources to manage solid waste, municipalities are also required to develop Municipal Solid Waste Management Plan. These Plans must contain the goals of reduction, reuse, recycling, and composting with the objective of only forwarding the rejects to landfills. However, according to the National Confederation of Municipalities (CNM, 2013), only 10% of Brazilian municipalities have made such plans. Consequently, 90% of the Brazilian municipalities will not receive

[5] The Bill 2289/2015, approved by the Senate and under process in the Chamber of Deputies, sets the deadline until July 31, 2018, for capitals and metropolitan regions; Until July 31, 2019, for municipalities with a population greater than 100 thousand inhabitants; Until July 31, 2020, for municipalities with a population between 50 thousand and 100 thousand inhabitants and until July 31, 2021, for those with a population of less than 50 thousand inhabitants to close all improperly MSWDS.

resources from the federal government to manage their MSW until they follow the legislation, which results in one more difficulty to control the adequate MSWD. Furthermore, in 2015, 3,326 cities, approximately 60% of all Brazilian municipalities, disposed of MSW in inappropriate places (ABRELPE, 2016).

The lack of a national MSWM strategy combined with the absence of participation of the general public and industry contributes to an improper MSWD in Brazil (GONÇALVES; VALE; GONÇALVES, 2016). Overall, in the last 20 years, there have been federal and state government efforts in MSWM that culminated in improvements mainly in southeast and south regions in Brazil.

The main objective of MSWM is to protect the population's health, promote environmental quality, promote sustainability and provide support for economic productivity (KARAK; BHAGAT; BHATTACHARYYA, 2012). To meet these objectives every city need to develop an efficient MSWM plan to assure a healthy living standard and protection of the environment (GALLARDO et al., 2014). In addition, local governments must integrate a sustainable approach to develop the MSWM plan, considering environmental, social and economic aspects (CUCCHIELLA; D'ADAMO; GASTALDI, 2014).

MSWM is an environmental problem of high relevance for all societies (GALLARDO et al., 2014). The environmentally responsible MSWM must go further than an appropriated MSWD; it must have a sustainable point of view, changing the patterns of production and consumption.

2.4 Conclusions

This chapter assessed the recent improvements and remaining challenges of MSWM in Brazil focusing on the environmental impacts caused by the inappropriate MSWD. The review about MSWM in Brazil, demonstrated that the actual trends of population growth and increase of MSW generation, the insufficient selective collection system, the low rates of recycling and composting, and finally the improper MSWD is causing several negative environmental impacts.

The results also indicated that although there was an increase in the number of cities disposing MSW in sanitary landfills, more than half of the cities still dispose their MSW improperly, which makes this issue one of the most critical problems faced in the nation. Furthermore, the non-fulfillment of the BSWP with the postponement of the deadlines for closure the open dumps and uncontrolled landfills heightens these environmental impacts. Even though MSWD in sanitary landfills does not eliminate all possible environmental impacts, it reduces the negative impacts and needs to be encouraged.

Brazil still faces challenges in order to achieve a desirable MSWM scenario, especially with regard to the MSWD. It is therefore up to the Brazilian citizens' pressure for the BSWP fulfillment and support the shared MSWM responsibility. Active participation of the population is required to reduce consumption and generation of MSW, to separate organic and recyclable materials at source, to increase the pressure for MSW treatment and finally properly disposal of the rejects in sanitary landfills. Meanwhile the negative impacts to the atmosphere, hydrosphere, lithosphere, and ultimately biosphere will continue until the MSWD issues are resolved.

3 MODELING ENVIRONMENTAL SUSCEPTIBILITY OF MUNICIPAL SOLID WASTE DISPOSAL SITES IN SÃO PAULO STATE, BRAZIL[6]

3.1 Introduction

The rapid world population growth and economic development are causing changes in terrestrial systems that can have serious and lasting consequences. The large amount of MSW generated exceeds the capacity of the environment to decompose and recycle these wastes through natural processes (JOVANOVIC et al., 2015). The lack of proper MSWM is a major environmental problem (NASCIMENTO et al., 2015). Sustainable MSWM is required to achieve low environmental impact. One essential part in this process is to properly dispose waste, since MSWDS are permanent facilities that pose risks to the environment and population as they need to be monitored for extended periods of time (LEÃO; BISHOP; EVANS, 2004).

Among many methods to dispose MSW in underdeveloped countries, the most common are open dumps and landfills. Open dumps are uncontrolled facilities where waste is directly disposed in the ground without any control causing several impacts. In contrast, sanitary landfills use techniques and methods to better control environmental impacts and are commonly used around the world, particularly in developed countries (WENG et al., 2015). Although the number of sanitary landfills is increasing in the last decades in Brazil (MIGUEL et al., 2016), the nation is through an inadequate MSWD scenario, with more than 60% of its cities still disposing MSW in open dumps as demonstrated in **Chapter 2**.

It is important take into consideration the environmental impact caused by MSWD in São Paulo, Brazil due to several factors. First, São Paulo is the most populous state in America and Western Hemisphere. Second, São Paulo is the

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[6] This Chapter is based on the paper: NASCIMENTO, V.F.; SOBRAL, A.C.; ANDRADE, P.R.; OMETTO, J.P.H.B.; YESILLER, N.; Modeling Environmental Susceptibility of Municipal Solid Waste Disposal Sites: A Case Study in São Paulo State, Brazil. Published at: **Journal of Geographic Information System**, v. 9, n. 1, p. 8–33, 2017. DOI: 10.4236/jgis.2017.91002

biggest producer of MSW among all Brazilian states. Third, the per capita waste generation rate in São Paulo state is the biggest rate in Brazil with 1.4kg/habitant/day with a growing trend over the years (ABRELPE, 2016). Finally, various São Paulo cities still dispose MSW improperly (CETESB, 2015a). Therefore, all these factors together lead to the occurrence of negative environmental impacts.

For this reason, assessing the environmental impact caused by MSWDS must consider different parameters, to avoid potential negative effects. Developing a model for assessing environmental impact susceptibility must take into consideration multiple issues, values, scales and degrees of uncertainty, as well as assist stakeholder engagement. In this process, the models are usually built to satisfy one or more of five main purposes: (i) prediction, (ii) forecasting, (iii) management and decision-making under uncertainty, (iv) social learning, and (v) developing system understanding and experimentation (LETCHER et al., 2013).

In this study to develop the EISM for MSWDS, we used a MCDA approach via an AHP coupled with GIS. This chapter is organized as follows: Section 3.2 discusses the literature review of GIS, MCDA and AHP applied to environmental studies. Section 3.3 describes the methods used to develop the EISM and describes the study area. Section 3.4 presents the model results for the state of São Paulo and the MSWDS assessment. Finally, the conclusions are presented in Section 3.5.

3.2 Background Literature Review

In this section, the literature review is divided into three parts: Section 3.2.1 includes the advantages of GIS in environmental studies, Section 3.2.2 demonstrates the importance of MCDA applied to MSW issues, and Section 3.2.3 explains the use of AHP.

3.2.1 Geographic Information System

The use of GIS is one of the most promising approaches to investigate complex spatial phenomena, because GIS has the advantage of storing, retrieving and analyzing a considerable amount of disaggregated data from various sources and displaying the results spatially, which helps decision makers solve several problems (GBANIE et al., 2013; KALLEL; SERBAJI; ZAIRI, 2016).

GIS has been used for several purposes (MALCZEWSKI, 2004), including environmental applications. Examples include estimating groundwater recharge (HORNERO et al., 2016), assessing water pollution (EL-ZEINY; EL-KAFRAWY, 2016), identifying forest fire susceptibility (TIEN BUI et al., 2017), mapping landslide susceptibility (FEIZIZADEH et al., 2014) and flood susceptibility (TEHRANY; PRADHAN; JEBUR, 2014), modeling erosion (GANASRI; RAMESH, 2015), and evaluating ecological vulnerability of sites (CANIANI et al., 2016).

GIS has also been used in numerous studies to improve MSWM. Examples include predicting generation and composition patterns of MSW (KESER; DUZGUN; AKSOY, 2012; GALLARDO et al., 2014), improving MSW collection and transport (ABDULAI et al., 2015; SANJEEVI; SHAHABUDEEN, 2015; XUE; CAO, 2015; KALLEL; SERBAJI; ZAIRI, 2016; SON; LOUATI, 2016), selecting locations for MSW transfer stations (BOSOMPEM; STEMN; FEI-BAFFOE, 2016; YADAV et al., 2016), assessing groundwater vulnerability (CHONATTU; PRABHAKAR; HARIKUMAR, 2016; CHONATTU; PRABHAKAR; PILLAI, 2016) and impact (DESHMUKH; AHER, 2016) near a MSWDS, and identifying areas for siting landfills (AL-HANBALI; ALSAAIDEH; KONDOH, 2011; DEMESOUKA; VAVATSIKOS; ANAGNOSTOPOULOS, 2013, 2014, 2016; SHAHABI et al., 2014; MOTLAGH; SAYADI, 2015; KHAN; SAMADDER, 2015; AHMAD et al., 2016; RAHMAT et al., 2016; TORABI-KAVEH et al., 2016; YILDIRIM; GÜLER, 2016; BAHRANI et al., 2016; CHABUK et al., 2016; ESKANDARI; HOMAEE; FALAMAKI, 2016; KHARAT et al., 2016).

3.2.2 Multi-criteria decision analysis

MCDA is a method to structure a problem through the action concepts and intelligible criterion group to facilitate the communication in decision process, forming a conviction rather than determining an optimum (ROY, 1997). Combining MCDA with spatial decision problems usually contains a large set of feasible alternatives and conflicts with an incommensurate evaluation criteria (MALCZEWSKI, 2006).

The MCDA applied to environmental studies had a significant growth over the last decade (HUANG; KEISLER; LINKOV, 2011; GUARNIERI, 2015). The integration of spatial analysis using GIS with MCDA has been used in different environmental studies. Examples include, analyzing the possibility to convert pastures to croplands in Brazil (ALKIMIM; SPAROVEK; CLARKE, 2015), mapping the landslide susceptibility (FEIZIZADEH et al., 2014), and identifying geotechnical land suitability (AKYOL; KAYA; ALKAN, 2016).

Spatial analyses associated with MCDA is considered one of the main application for GIS (CARVER, 1991), and have also been used in several studies related to MSW issues (SUMATHI; NATESAN; SARKAR, 2008; ESKANDARI; HOMAEE; MAHMODI, 2012; ALEXAKIS; SARRIS, 2013; GBANIE et al., 2013; DEMESOUKA; VAVATSIKOS; ANAGNOSTOPOULOS, 2013, 2014, 2016; HAMZEH; ALI ABBASPOUR; DAVALOU, 2015; KHAN; SAMADDER, 2015; KHORRAM et al., 2015; MOTLAGH; SAYADI, 2015; YOUNES et al., 2015a; ESKANDARI et al., 2015; FIDELIS; FERREIRA; COLMENERO, 2015; BAHRANI et al., 2016; TORABI-KAVEH et al., 2016; YILDIRIM; GÜLER, 2016; BOSOMPEM; STEMN; FEI-BAFFOE, 2016; ESKANDARI; HOMAEE; FALAMAKI, 2016). Predominantly, because MSWM involves multiple factors such as environmental, economic, political and social (SON; LOUATI, 2016), and combining MCDA with GIS increases the analysis effectiveness and accuracy (DEMESOUKA; VAVATSIKOS; ANAGNOSTOPOULOS, 2016) helping to understand the complexity of the problem, ensuring the robustness and reliability of the final decision.

3.2.3 Analytic Hierarchy Process

The AHP was developed by Saaty in the 1970s (SAATY, 1977) and consists of an assessment theory through pairwise comparison to help decision makers set priorities and choose the best decision (KHARAT et al., 2016; SON; LOUATI, 2016). The AHP in combination with GIS has been widely used in the field of natural resources and environmental management (JOTHIBASU; ANBAZHAGAN, 2016), first because the combined approaches are easy to implement using map algebra operations and cartographic models, and second because the approaches are intuitively appealing to decision makers (MALCZEWSKI, 2006). The comparisons are made using a scale of absolute judgments ranging from one to nine, where one represents equal importance and nine represents the highest importance from one element to another (**Table 3-1**). In addition, a reciprocal value is used to express the inverse comparison (SAATY, 2008).

Table 3-1 - The comparison scale in AHP

Definition	Intensity of Importance
1	Equal importance
3	Weak importance
5	Essential or strong importance
7	Demonstrated importance
9	Absolute importance
2,4,6,8	Intermediate values between adjacent judgments

Source: Saaty (1977).

The process of AHP determination involves these subsequent steps: (i) compute sum of values in each column of pairwise matrix, (ii) normalize the matrix by dividing each element by its column total, and (iii) compute the mean of the elements in each row of the normalized matrix (KHAN; SAMADDER, 2015).

Afterwards to determinate the consistency of the AHP judgment, a consistency index (CI) (**Equation 3.1)** is determined (SAATY, 1977).

$$CI = \frac{(\lambda_{\max} - n)}{(n-1)} \tag{3.1}$$

In this equation, λ_{max} is the principal judgement matrix value (SAATY, 1977, 2008). Subsequent the determination of CI, a consistency ratio (CR) needs to be calculated (**Equation 3.2**) (SAATY, 1977).

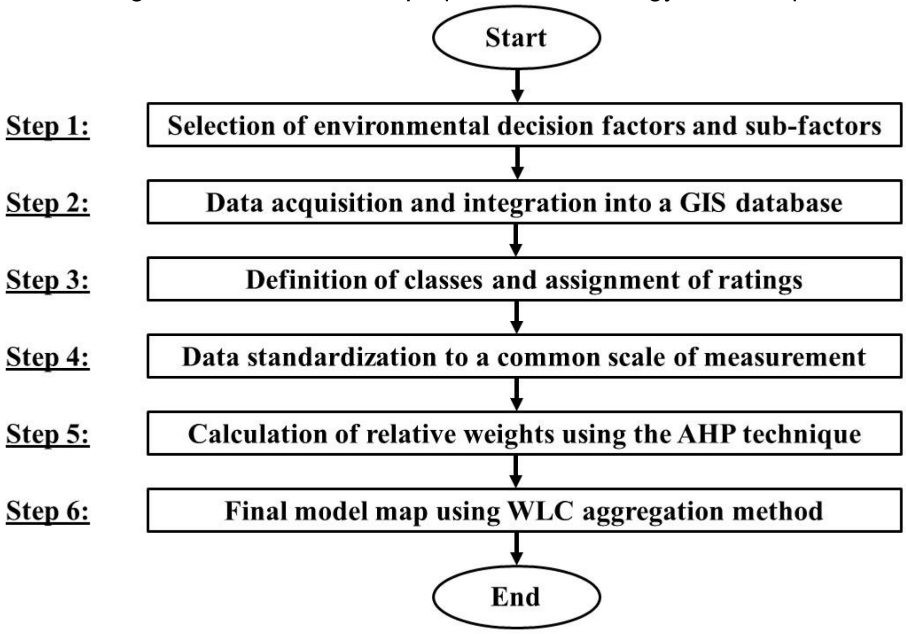
$$CR = \frac{CI}{RI} \tag{3.2}$$

In this equation, random index (RI) depends on the number of elements being compared (SAATY, 1977, 2008). The CR is acceptable if its value is less than 10%. However, if this number is higher than 10%, the judgments may be inconsistent and should be re-evaluated (YILDIRIM; GÜLER, 2016).

3.3 Methods

To develop the EISM for MSWDS, we considered six major steps: (1) selection of environmental decision factors and sub-factors; (2) data acquisition and integration into a GIS database; (3) definition of classes and assignment of ratings; (4) data standardization to a common scale of measurement; (5) calculation of relative weights using the AHP technique; and (6) derivation of the final model map using Weight linear combination (WLC) aggregation method (**Figure 3-1**). Each step is described as follows.

Figure 3-1 - Flowchart of proposed methodology to develop the EISM

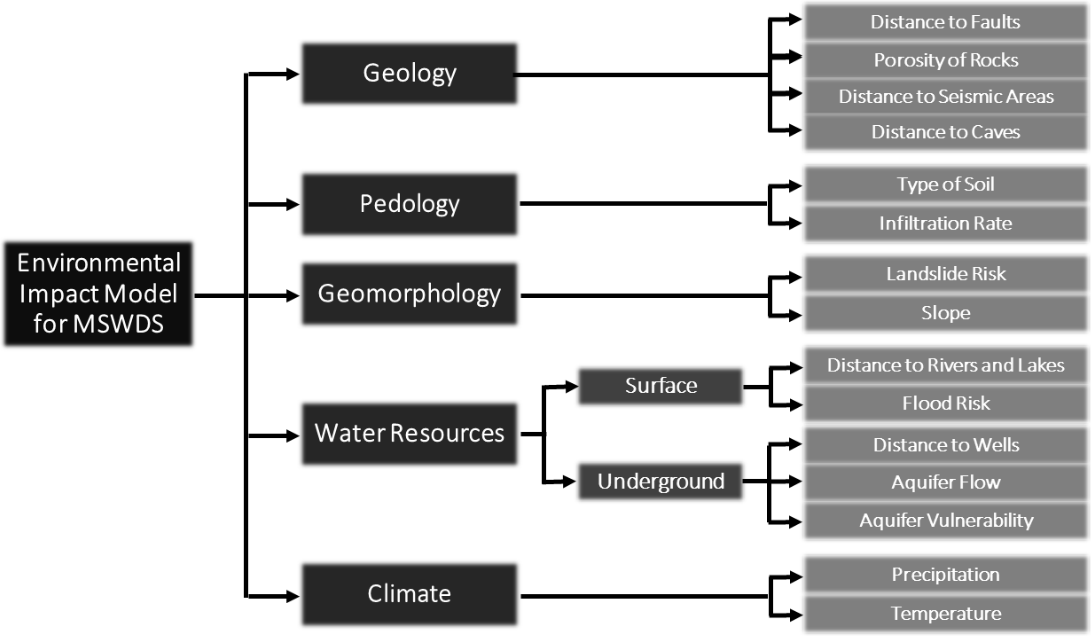


Source: Nascimento et al. (2017a).

3.3.1 Selection of environmental decision factors and sub-factors

In this study, the selection of environmental factors and sub-factors was based on the literature that takes into account the environmental impact susceptibility associated with MSWD e.g. (LEÃO; BISHOP; EVANS, 2004; BUTT; LOCKLEY; ODUYEMI, 2008; ESKANDARI; HOMAEE; MAHMODI, 2012; GBANIE et al., 2013; BUTT et al., 2014; KHAN; SAMADDER, 2015; MAANIFAR; FATAEI, 2015; MOTLAGH; SAYADI, 2015; ESKANDARI et al., 2015; BAHRANI et al., 2016; KHARAT et al., 2016; YILDIRIM; GÜLER, 2016; ZHANG et al., 2016; CHABUK et al., 2016; CHONATTU; PRABHAKAR; HARIKUMAR, 2016; CHONATTU; PRABHAKAR; PILLAI, 2016; DEMESOUKA; VAVATSIKOS; ANAGNOSTOPOULOS, 2016; ESKANDARI; HOMAEE; FALAMAKI, 2016). We also took into consideration guidelines, relevant legislation and regulations, experts' opinions, and available data. Overall, a total of five factors including geology, pedology, geomorphology, water resources, and climate, with fifteen associated sub-factors were used in the model (**Figure 3-2**). This list is not exhaustive; we only considered what the literature included as the most important criteria to develop the EISM for MSWDS in the state of São Paulo.

Figure 3-2 - Factors and sub-factors used to develop the EISM for MSWDS in São Paulo.



Source: Nascimento et al. (2017a).

3.3.1.1 Geology

Geological features influence the environmental susceptibility of MSWDS because they can cause land instability in an earthquake region (AKYOL; KAYA; ALKAN, 2016). They can also, influence water infiltration if the rock formations are porous or have faults (DEEPA et al., 2016). For this reason, when MSW is disposed above susceptible rocks, the process of waste landslide and water contamination may occur. Some geological aspects are considered in previous studies, including (AYDI et al., 2016; BAHRANI et al., 2016; CHONATTU; PRABHAKAR; HARIKUMAR, 2016; YILDIRIM; GÜLER, 2016; ZHANG et al., 2016). However, these studies did not consider simultaneously the four geological sub-factors used in this model, which are (i) distance to faults, (ii) porosity of rocks, (iii) distance to seismic areas, and (iv) distance to caves.

3.3.1.2 Pedology

Soil parameters, such as depth and physical characteristics, could interfere in environmental susceptibility related to siting MSW facilities, mainly for two reasons. First, strength characteristics of the soil are important to support the overlying load from the waste mass. Second, the soil permeability can interfere in infiltration process, which in turn can cause contamination of water bodies. Multiple studies in MSWDS issues included pedologic aspects in their assessments, e.g., (LEÃO; BISHOP; EVANS, 2004; MAANIFAR; FATAEI, 2015; MOTLAGH; SAYADI, 2015; ZHANG et al., 2016). In particular, we used the pedology sub-factors of (i) type of soil and (ii) infiltration rate.

3.3.1.3 Geomorphology

Geomorphology is mainly related to terrain features and the influence of these characteristics on the topography and runoff process. For example, flat areas influence leachate infiltration, while steep areas influence terrain instability. Therefore, both can cause environmental impacts. Many studies took into consideration topographical aspects, e.g., (GBANIE et al., 2013; KHAN; SAMADDER, 2015; KHARAT et al., 2016; ZHANG et al., 2016). In particular, we used the geomorphological sub-factors of (i) landslide risk and (ii) slope.

3.3.1.4 Water Resources

Another aspect that affects environmental susceptibility is associated with surface and underground water resources. It is not appropriate to have MSWDS close to surface water sources or in areas where the water table level is shallow due to the higher contamination risk. Several studies took into consideration these aspects, e.g., (GBANIE et al., 2013; ESKANDARI et al., 2015; KHAN; SAMADDER, 2015; MAANIFAR; FATAEI, 2015; MOTLAGH; SAYADI, 2015; BAHRANI et al., 2016; CHABUK et al., 2016; CHONATTU; PRABHAKAR; HARIKUMAR, 2016; YILDIRIM; GÜLER, 2016). In this study, we used surface water resources sub-factors of (i) distance to rivers and lakes and (ii) flood risk, while, for underground water resources, we used the sub-factors of (i) distance to wells, (ii) aquifer flow, and (iii) aquifer vulnerability to pollution.

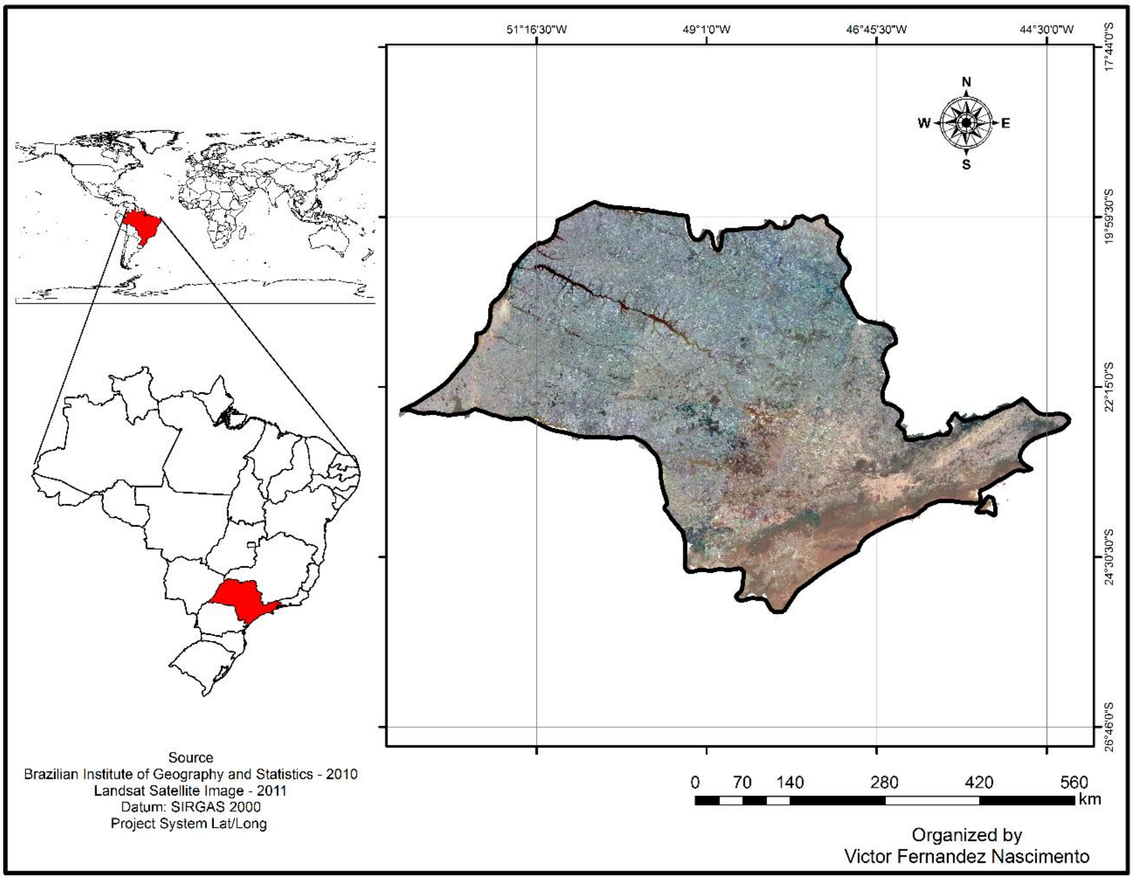
3.3.1.5 Climate

Climate factors need to be used in modeling the environmental impact susceptibility for MSWD, mainly because they can interfere in the decomposition process of solid waste and in the volume of leachate generated, due to the water balance as well as the amount of landfill gas generated. Climate aspects also were considered in previous investigations, e.g., (MAANIFAR; FATAEI, 2015; CHONATTU; PRABHAKAR; PILLAI, 2016; ESKANDARI; HOMAEE; FALAMAKI, 2016; KHARAT et al., 2016). In this study, we used the climatic sub-factors of (i) precipitation and (ii) temperature.

3.3.2 Study area

São Paulo state, in Southeastern Brazil, is located between 19º and 25º South latitude and 44º and 53º West longitude. It borders the Minas Gerais state to the north, Rio de Janeiro state to the northeast, the Atlantic Ocean to the east, Paraná state to the south, and Mato Grosso do Sul state to the west (**Figure 3-3**). São Paulo is the most populous Brazilian state, with approximately 44.4 million inhabitants in 2015 living in 645 municipalities with a total area around of 248,2 thousand km^2 (IBGE, 2016). São Paulo is also the biggest producer of MSW in Brazil, generating approximately 39 thousand tons per day, which are disposed in 420 official MSWDS (CETESB, 2015a).

Figure 3-3 - Map of the state of São Paulo, Brazil



Source: Nascimento et al. (2017a).

3.3.3 Data acquisition and integration into a GIS database

The spatial database used in the EISM for MSWDS applied to the São Paulo state was created using a variety of sources including geologic, pedologic, geomorphologic, hydrologic and, climatologic data of different scales (**Table 3-2**). The successful use of GIS depends on the accessibility of data, as well as its quality, representing the real world conditions through diverse layers (AL-HANBALI; ALSAAIDEH; KONDOH, 2011).

In this study, all data layers were stored, manipulated, analyzed, and visualized using ArcGIS version 10.2 ModelBuilder as a starting point for a MCDA. ModelBuilder is a GIS extension that encodes complex sequences of GIS operations into a simple graphic model from which the steps can be executed (ALLEN, 2011). The data layers were georeferenced using the UTM System Datum SIRGAS 2000 (Zone 22 and 23 South).

Table 3-2 - Spatial data used in the EISM for MSWDS in the state of São Paulo

Factors	Sub-factors	Sources	Information used to create layers	Format	Scale or Resolution	Date
Geology	Distance to Faults	Geology Report: (PEIXOTO; THEODOROVICZ, 2009)	Structures	Digital	1:700,000	2009
	Porosity of Rocks	Geology Report: (PEIXOTO; THEODOROVICZ, 2009)	Primary porosity	Digital	1:700,000	2009
	Distance to Seismic Areas	Geology Report: (PEIXOTO; THEODOROVICZ, 2009)	Geological/ Geotechnical Risks and Earthquakes	Digital	1:700,000	2009
	Distance to Caves	Permanent Cave Protection Areas in the São Paulo state: (CECAV, 2015)	Caves	Digital	1:50,000	2015
Pedology	Type of Soil	Pedology Report: (OLIVEIRA, 1999)	Type of Soil	Digital	1:500,000	1999
	Infiltration Rate	Pedology Report: (OLIVEIRA, 1999)	Factor K	Digital	1:500,000	1999
Geomorphology	Landslide Risk	Landslide Hazard Index (SÃO PAULO, 2014)	Landslide Hazard Classes	Digital	1:75,000	2014
	Slope	Digital Elevation Model - DEM (SÃO PAULO, 2013a)	Calculated using DEM	Digital	1:50,000	2013
Water Resources - Surface	Distance to Rivers and Lakes	Hydrology Report: (PEIXOTO; THEODOROVICZ, 2009)	Hydrography Unifilar and Bifilar	Digital	1:700,000	2009
	Flood Risk	Flood Hazard Index (SÃO PAULO, 2014)	Flood Hazard Classes	Digital	1:75,000	2014
Water Resources - Underground	Distance to Wells	Hydrology Report: (PEIXOTO; THEODOROVICZ, 2009)	Representative Wells	Digital	1:700,000	2009
	Aquifer Flow	Hydrology Report: (PEIXOTO; THEODOROVICZ, 2009)	Aquifer Flow Classes	Digital	1:700,000	2009
	Aquifer Vulnerability	Natural vulnerability of aquifer to pollution (SÃO PAULO, 2013b)	Aquifer Vulnerability Classes	Digital	1:1,000,000	2013
Climate	Precipitation	Zoning bioenergy crops in São Paulo state report: (SÃO PAULO, 2008)	Isohyet Lines	Digital	1:500,000	2008
	Temperature	Zoning bioenergy crops in São Paulo state report: (SÃO PAULO, 2008)	Isotherm	Digital	1:500,000	2008

Source: Nascimento et al. (2017a).

3.3.4 Definition of classes and rating

Each of the fifteen sub-factors used in the EISM for MSWDS applied to the state of São Paulo was divided into classes. Each class was rated on a scale from one to ten, where one represents the lowest level of susceptibility and ten represents the highest level of susceptibility for environmental impact.

The rating intervals from one to ten was selected based on similar scales used by (ALAVI et al., 2013; ZAKERIAN; MOKHTARI; ALHOSSEINI ALMODARESI, 2015; CHONATTU; PRABHAKAR; HARIKUMAR, 2016; RAHMAT et al., 2016), as well as based on the experience and judgment of the authors. Furthermore, the importance for each class could vary based on the region of interest and characteristics of the specific area (AL-HANBALI; ALSAAIDEH; KONDOH, 2011). In this study the classes were assigned considering the relevant conditions in the state of São Paulo (**Table 3-3**).

Table 3-3 - Rating classes for sub-factors in the state of São Paulo

Factors	Sub-factors	Class	Rating
Geology	Distance to Faults	<500 m	10
		500 – 1000 m	9
		1000 – 1500 m	8
		1500 – 2000 m	7
		2000- 2500 m	6
		2500– 3000 m	5
		3000– 3500 m	4
		3500– 4000 m	3
		4000– 4500 m	2
		>4500 m	1
	Porosity of Rocks	High (>30%)	10
		Uncertain (0>30%)	9
		Moderate (15 – 30%)	8
		Low (0 – 15%)	3
	Distance to Seismic Areas	<10,000 m	10
		10,000 – 20,000 m	9
		20,000 – 30,000 m	8
		30,000 – 40,000 m	7
		40,000 – 50,000 m	6
		50,000 – 60,000 m	5
		60,000 – 70,000 m	4
		70,000 – 80,000 m	3
		80,000 – 90,000 m	2
		>90,000 m	1
	Distance to Caves	<500 m	10
		500 – 1000 m	9
		1000 – 1500 m	8
		1500 – 2000 m	7
		2000- 2500 m	6
		2500– 3000 m	5
		3000– 3500 m	4
		3500– 4000 m	3
		4000– 4500 m	2
		>4500 m	1
Pedology	Type of Soil	Histosols	10
		Gleysols	9
		Spodosols	8
		Chernosols	7
		Neosols	6
		Nitosols	5
		Cambisols	4
		Planosols	3
		Latosols	2
		Argisols	1
	Infiltration Rate (Factor K)	0,0549 – 0,0610	10
		0,0488 – 0,0549	9
		0,0427 – 0,0488	8
		0,0366 – 0,0427	7

Continues

Table 3-3 - Continuation

Factors	Sub-factors	Class	Rating
		0,0305 – 0,0366	6
		0,0244 – 0,0305	5
		0,0183 – 0,0244	4
		0,0122 – 0,0183	3
		0,0061 – 0,0122	2
		<0,0061	1
Geomorphology	Landslide Risk	P5	10
		P4	8
		P3	6
		P2	4
		P1	2
		P0	1
	Slope	>45 %	10
		45 – 30 %	9
		30 – 25 %	8
		25 – 20 %	7
		20 – 15 %	6
		15 – 10 %	5
		10 – 8 %	4
		8 – 6 %	3
		6 – 4 %	2
		4 – 2 %	1
		<2 %	10
Water Resources - Surface	Distance to Rivers and Lakes	<500 m	10
		500 – 1000 m	9
		1000 – 1500 m	8
		1500 – 2000 m	7
		2000- 2500 m	6
		2500– 3000 m	5
		3000– 3500 m	4
		3500– 4000 m	3
		4000– 4500 m	2
		>4500 m	1
	Flood Risk	P5	10
		P4	8
		P3	6
		P2	4
		P1	2
		P0	1
Water Resources - Underground	Distance to Wells	<500 m	10
		500 – 1000 m	9
		1000 – 1500 m	8
		1500 – 2000 m	7
		2000- 2500 m	6
		2500– 3000 m	5
		3000– 3500 m	4
		3500– 4000 m	3
		4000– 4500 m	2
		>4500 m	1

Continues

Table 3-3 - Conclusion

Factors	Sub-factors	Class	Rating
	Aquifer Flow	120 – 80 m^3	10
		100 – 7 m^3	9
		80 – 40 m^3	8
		40 – 20 m^3	6
		23 – 3 m^3	5
		20 – 10 m^3	4
		12 – 1 m^3	3
		10 – 0 m^3	2
		6 – 1 m^3	1
	Aquifer Vulnerability	High	10
		Medium	6
		Low	2
Climate	Precipitation	>2000 mm	10
		2000 – 1600 mm	9
		1600 – 1500 mm	8
		1500 – 1400 mm	7
		1400 – 1300 mm	6
		1300 – 1200 mm	5
		<1200 mm	4
	Temperature	>24 ºC	10
		24 – 23 ºC	9
		23 – 22 ºC	8
		22 – 21 ºC	7
		21 – 20ºC	6
		20 – 19 ºC	5
		19 – 18 ºC	4
		18 – 16 ºC	3
		<16 ºC	2

Source: Nascimento et al. (2017a).

3.3.5 Data standardization to a common scale of measurement

In order to overlay the spatial information to calculate the environmental impact susceptibility, it is necessary to standardize the data into a common measurement scale. Therefore, the fifteen sub-factors were converted into raster grid format consisting of 50m x 50m cells resulting in an image of 18790 columns and 12744 rows.

3.3.6 Criteria weight assignment using AHP

The construction of a comparison matrix and the derivation of weights in our study uses the AHP web-based tool developed by (GOEPEL, 2013). First, the AHP methodology was applied to the factors (**Table 3-4**) and sub-factors (**Table 3-5**). Then, by multiplying these two results, the global weighting for each sub-factors was obtained (**Table 3-6**).

Table 3-4 - Pairwise comparison matrix, ranking, and weights for factors in the EISM for MSWDS applied to the state of São Paulo

Factors (CR 2.1%)	**[1]**	**[2]**	**[3]**	**[4]**	**[5]**	**[6]**	**Rank**	**Weight (%)**
Geology	1						5	5.6
Pedology	3	1					2	17.9
Geomorphology	2	1/2	1				4	10.4
Surface Water Resources	4	2	2	1			1	26.0
Underground Water Resources	4	2	2	1	1		1	26.0
Climate	3	1/2	2	1/2	1/2	1	3	14.1

Source: Nascimento et al. (2017a).

Table 3-5 - Pairwise comparison matrix, ranking, and weights for sub-factors in the EISM for MSWDS applied to the state of São Paulo

Factors (CR %)		Sub-factors	[1]	[2]	[3]	[4]	Rank	Weight (%)
Geology CR (5.6%)		Distance to Faults	1				2	20.6
		Porosity of Rocks	5	1			1	64.0
		Distance to Seismic Areas	1/4	1/7	1		4	6.0
		Distance to Caves	1/3	1/6	2	1	3	9.4
Pedology CR (0.0%)		Type of Soil	1				2	33.3
		Infiltration Rate	2	1			1	66.7
Geomorphology CR (0.0%)		Landslide Risk	1				2	20.0
		Slope	4	1			1	80.0
Water Resources	Surface CR (0.0%)	Distance to Rivers /Lakes	1				1	85.7
		Flood Risk	1/6	1			2	14.3
	Underground CR (1.0%)	Distance to Wells	1				3	16.3
		Aquifer Flow	2	1			2	29.7
		Aquifer Vulnerability	3	2	1		1	54.0
Climate CR (0.0%)		Precipitation	1				1	66.7
		Temperature	1/2	1			2	33.3

Source: Nascimento et al. (2017a).

Table 3-6 - Global weighting for each criteria in the EISM for MSWDS applied to the state of São Paulo

Factors		Sub-factors	Global Rank	Global Weight (%)
Geology		Distance to Faults	13	1.2
		Porosity of Rocks	11	3.6
		Distance to Seismic Areas	15	0.3
		Distance to Caves	14	0.5
Pedology		Type of Soil	7	6.0
		Infiltration Rate	3	11.9
Geomorphology		Landslide Risk	12	2.1
		Slope	5	8.3
Water Resources	Surface	Distance to Rivers/Lakes	1	22.3
		Flood Risk	10	3.7
	Underground	Distance to Wells	9	4.2
		Aquifer Flow	6	7.7
		Aquifer Vulnerability	2	14.0
Climate		Precipitation	4	9.4
		Temperature	8	4.7

Source: Nascimento et al. (2017a).

3.3.7 Weight linear combination method

After checking the reliability of the pairwise comparisons for factors and sub-factors, the EISM for MSWDS in the state of São Paulo was built using a WLC method, following (**Equation 3.3**).

$$S = \sum_{i=1}^{n} w_i \, x_i \tag{3.3}$$

In this equation, S is the EISM final score, W_i is the sub-factor weight, and X_i is the standardized class rating of factor i. As the sum of weight for factor i is a multiplication of W_i and X_i for each sub-factor, the W_i is constrained to one, while X_i varies from zero to ten, and the final combined estimate is presented on this scale.

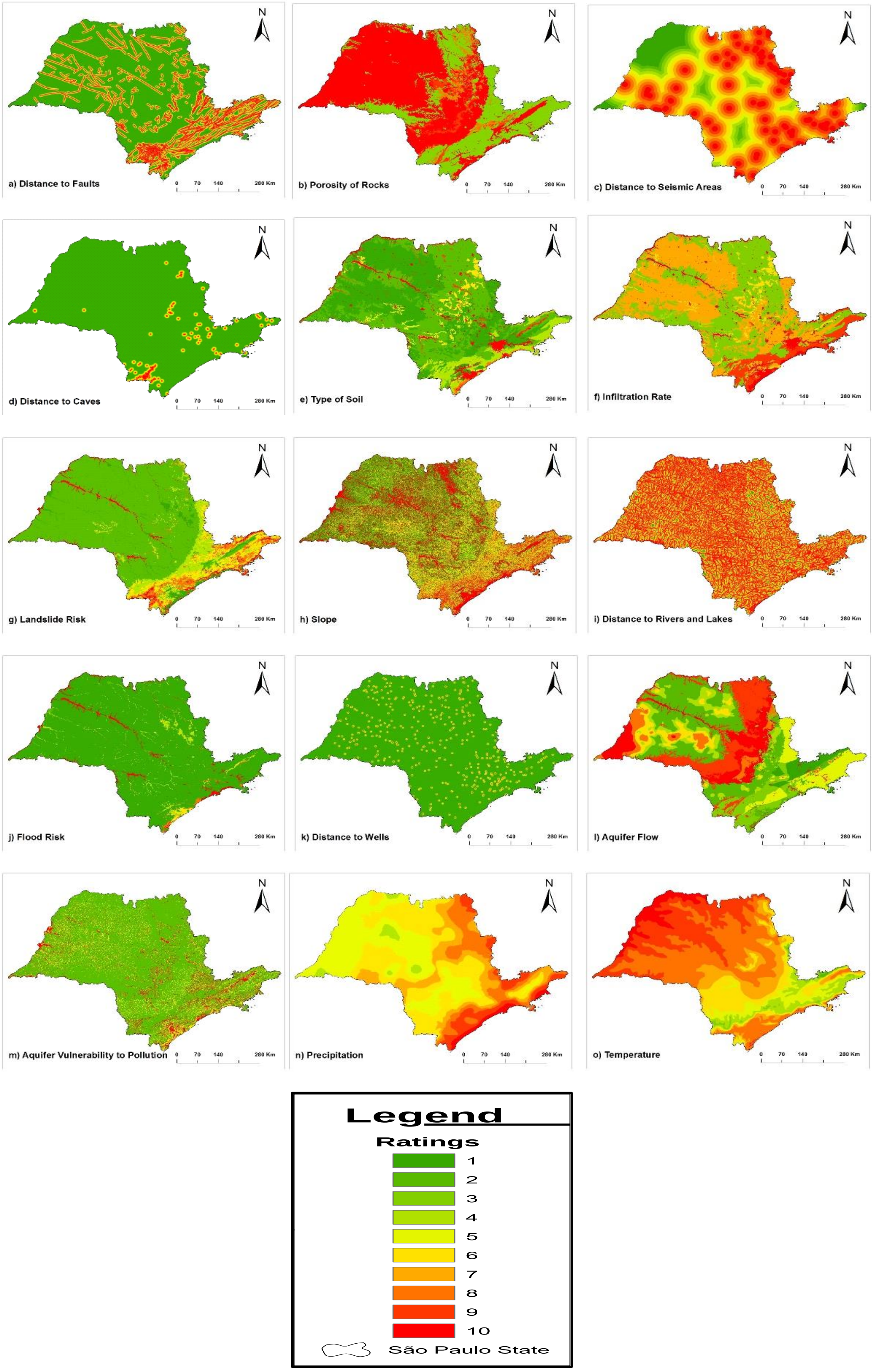
Therefore, the EISM final score was obtained for each raster cell as a sum of the products of ratings assigned for each class (**Table 3-3**) and global weights obtained by AHP (**Table 3-6**) (**Figure 3-4**). The results were grouped into five categories of environmental impact susceptibility for MSWDS: Very Low (S1), Low (S2), Medium (S3), High (S4) and Very High (S5) (**Table 3-7**).

Table 3-7 - EISM categories for MSWDS in the state of São Paulo

Categories	Values
Very Low (S1)	0-2
Low (S2)	2-4
Medium (S3)	4-6
High (S4)	6-8
Very High (S5)	8-10

Source: Nascimento et al. (2017a).

Figure 3-4 - Maps with all selected sub-factors in the state of São Paulo



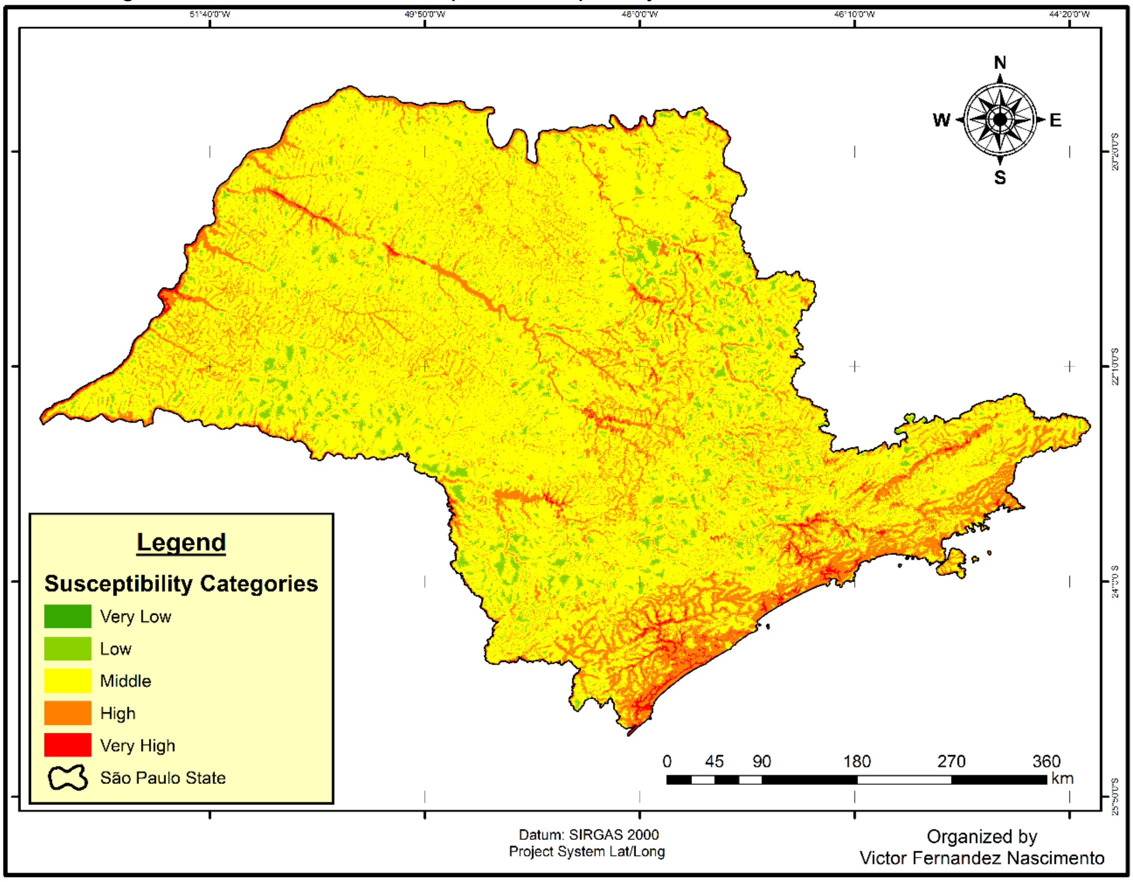
Source: Nascimento et al. (2017a).

3.4 Results and Discussion

3.4.1 Environmental impact susceptibility model for MSWDS

The results of the EISM for MSWDS in the state of São Paulo are presented in (**Figure 3-5**). The area for each susceptibility category indicate that most part of São Paulo state, 77.3% have medium environmental impact susceptibility category (S3), 16.8% has high category (S4), 4.8% has low category (S2), 1.1% has very high category (S5) and there is no representative areas for the very low category (S1) (**Table 3-8**).

Figure 3-5 - Environmental impact susceptibility for MSWDS in São Paulo state



Source: Nascimento et al. (2017a).

Table 3-8 - Environmental susceptibility categorization for MSWDS in São Paulo state

Environmental impact susceptibility categories	**Area (km^2)**	**Area Percentage**
Very Low (S1)	0	0 %
Low (S2)	12,054	4.8 %
Medium (S3)	192,631	77.3 %
High (S4)	41,764	16.8 %
Very High (S5)	2,677	1.1 %
Total	249,126	100%

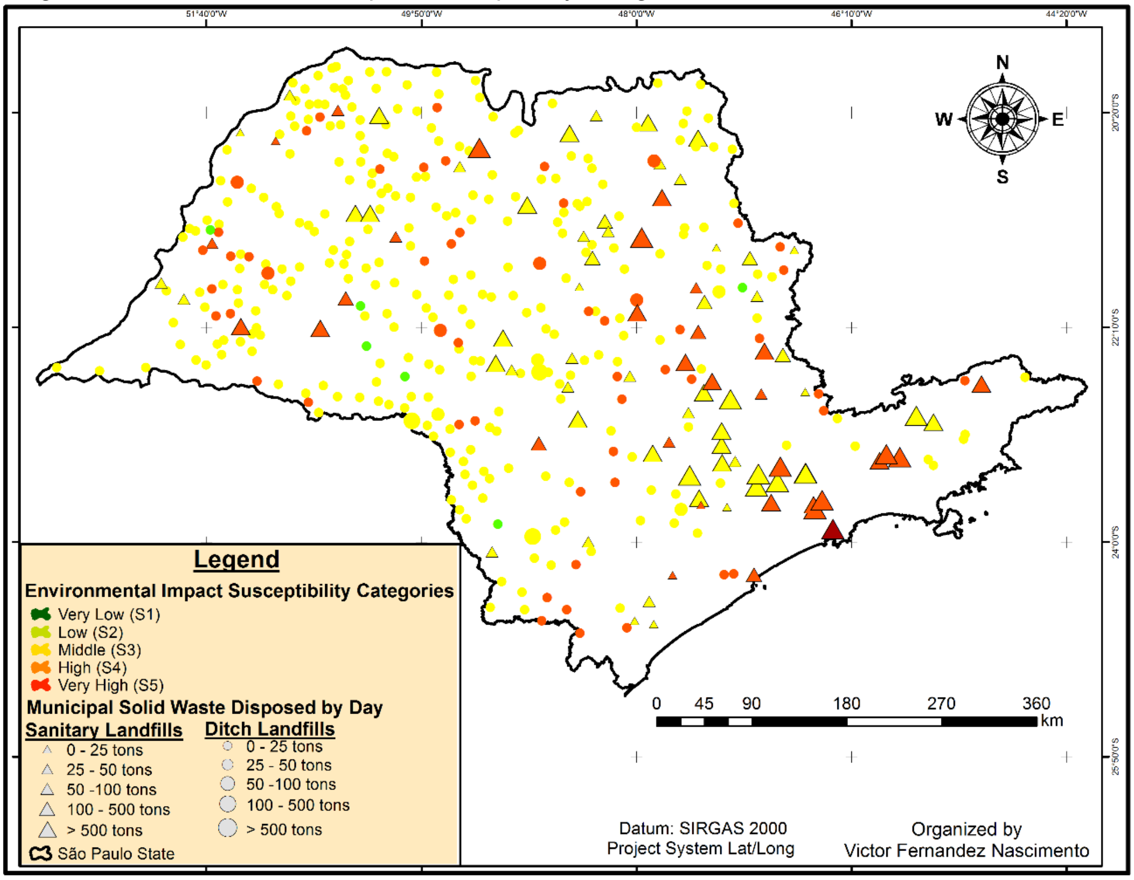
Source: Nascimento et al. (2017a).

The high and very high categories (S4 and S5, respectively) in the state of São Paulo extend are located near the surface water resources, which is correlated to the EISM global weights that has the sub-factor distance to rivers and lakes as the most important contributor. There is also a concentration of the higher categories near the Atlantic Ocean mainly in the southeast of the state of São Paulo, which can be explained by a combination of geographical variables. For example, there is a mountain range in this area formed by the *Serra do Mar* and *Serra da Mantiqueira*, which has a concentration of steep areas. In addition, these mountain range stop the humidity that comes from the ocean to the continent, which makes the precipitation near the coast very high in comparison to the rest of the state of São Paulo.

3.4.2 Analysis of susceptibility for MSWDS in São Paulo

In order to evaluate the environmental impact susceptibility for each MSWDS in São Paulo state we developed a spatial analysis (**Figure 3-6**) and statistical study (**Table 3-9**).

Figure 3-6 - Environmental impact susceptibility categorization of MSWDS in São Paulo state



Source: Nascimento et al. (2017a).

Table 3-9 - MSWDS in the state of São Paulo according to environmental susceptibility category

Environmental impact susceptibility category	**Number of Ditch Landfills**	**Number of Sanitary Landfills**	**MSW/Day (tons)**
S1+S2	6	0	38.57
S3	271	57	20,957.56
S4	54	31	16,430.81
S5	0	1	1,454.82
Total	331	89	38,880.76

Source: Nascimento et al. (2017a).

The geographical coordinates of MSWDS for the 645 municipalities in São Paulo state were obtained from spreadsheets used to assess the waste quality index developed by the Environmental Company of São Paulo State (CETESB, 2015b). Because some of São Paulo's cities use consortia to dispose solid waste, there are currently 420 MSWDS cataloged and evaluated in the annual Inventory of Solid Waste (CETESB, 2015a). Furthermore, after visual assessment through RapidEye satellite images for the years of 2013 and 2014, provided by the Ministry of Environment (MMA), it was determined that some of the MSWDS were mislocated in the spreadsheets, for that reason, the locations were corrected and additionally the MSWDS areas were defined.

Afterwards, a spatial analysis was performed by overlaying the results of the EISM and the locations of MSWDS in the state of São Paulo. Thus, it was possible to identify the specific MSWDS and the amount of MSW disposed of in each environmental impact susceptibility categories. For cases where the MSWDS had more than one susceptibility category, the highest category was assigned.

In São Paulo state, two different kinds of MSWD approach are used: ditch landfills (331 units) and sanitary landfills (89 units). Ditch landfills are a disposal technique for MSW on the ground without compaction and consequently with fewer requirements for implementation than a sanitary landfill. This procedure allows small towns, with population under to 25,000 inhabitants and daily generation of MSW less than ten tons to have their waste disposed without the necessity to construct a sanitary landfill (SÃO PAULO, 2010). Even though the quantity of MSW disposed in ditch landfills are smaller than the quantity disposed in sanitary landfills, usually ditch landfills pose more environmental risks and cause environmental impacts

São Paulo is one of the states in Brazil where almost all cities use landfill instead of open dumps, which represent an improvement to avoid negative environmental impacts caused by MSWDS. Nevertheless, MSWD in sanitary landfills instead of ditch landfills does not eliminate all possible environmental impacts but reduces the probability of their occurrence.

In addition, the increasing population and MSW generation in the São Paulo state has caused pressure in the old MSWDS that are almost filled. This problem added to the lack of suitable areas for new sanitary landfills are some of the most critical problems faced by municipalities, especially near the metropolitan areas of *São Paulo, Campinas, Baixada Santista* and *Vale do Paraíba*, where there is a high concentration of population and consequently production of MSW.

The assessment for MSWDS in the state of São Paulo, indicates that the number of landfills located in each environmental impact susceptibility category has a positive correlation with the extent of each category in the state area. If sanitary and ditch landfills are added in the assessment, approximately, 1.6% of them are placed in very low, low and very high environmental impact susceptibility categories (S1, S2 and S5 respectively). Approximately 20.4% of the landfill sites are located in high category (S4) and, the great majority, approximately 78% are situated in medium susceptibility category (S3).

When a separate analysis was performed for sanitary and ditch landfills, a total of six ditch landfills were in the lower susceptibility categories (S1 and S2) and just one sanitary landfill was in the very high susceptibility category (S5) (**Table 3-9**). Even though only 54 ditch landfills and 32 sanitary landfills are in the (S4 and S5) categories, a large amount of MSW (17,886 tons) is disposed of at these MSWDS daily, which corresponds to approximately 46% of the total MSW disposed in the state of São Paulo.

Based on the total amount of MSW classified under the highest susceptibility categories (S4 and S5), 97.5% is disposed in sanitary landfills, and only 2.5% is disposed in ditch landfills. This is a positive finding, since if properly operated and monitored, sanitary landfills provide better environmental protection than ditch landfills. The list of municipalities and the quantity of MSW disposed in sanitary and ditch landfills located in the high susceptibility categories are provided in (**Table 3-10)**.

Table 3-10 - MSWDS located at high and very high categories in the state of São Paulo

Categories	Sanitary Landfills	MSW/Day (tons)	Ditch Landfills	MSW/Day (tons)
S5	Santos	1,454.82	0	0
S4	Avaré	70.6	Adamantina	26.47
	Cachoeira Paulista	327.37	Alvarez Machado	15.49
	Caieiras	1,629.74	Americo de Campos	3.48
	Cerquilho	33.62	Andradina	42.71
	Dracena	33.69	Anhembi	3.29
	Embu	233.15	Apiaí	12.82
	Guatapará	1,301.61	Bálsamo	5.58
	Jacareí	199.55	Barra do Turvo	2.26
	Jales	36.76	Bernardino de Campos	6.99
	Jambeiro	507.92	Bõa Esperança do Sul	9.03
	Jardinópolis	150.79	Cajati	14.83
	Juquia	8.59	Campina do Monte Alegre	3.48
	Leme	79.17	Cassia dos Coqueiros	1.26
	Limeira	256.82	Charqueada	10.33
	Mauá	2,585.55	Corumbataí	1.52
	Mogi-Guaçu	124.84	Divinolândia	5.41
	Onda Verde	539.96	Dourado	5.69
	Pedreira	35.74	Estiva Gerbi	6.01
	Penópolis	6.90	Gália	3.63
	Pereira Barreto	8.80	Garça	32.36
	Peruíbe	7.90	Gastão Vidigal	2.84
	Piedade	7.60	Guiaçara	7.32
	Porto Ferreira	42.75	Guapiara	5.06
	Presidente Prudente	194.49	Guareí	6.68
	Quatá	293.96	Ibaté	25.48
	Rio Claro	174.23	Iporanga	1.70
	Santo André	205.70	Iracemopolis	15.21
	São Carlos	317.80	Itaoca	1.27
	São José dos Campos	733.90	Itápolis	30.57
	São Paulo*	5,676.56	Itariri	7.42
	Tupã	50.37	Junqueirópolis	11.47
			Marinópolis	1.19
			Nantes	1.85
			Óleo	1.22
			Ouro Verde	5.33
			Pacaembú	7.17
			Pedra Bela	1.05
			Pedrinhas Paulista	1.81
			Pedro de Toledo	5.25
			Piquete	9.31
			Pirangi	7.01
			Poloni	3.60
			Presidente Bernardes	7.39
			Ribeirão dos Indios	1.33
			Sabino	8.10
			Sales	8.60
			Sales de Oliveira	8.20
			Santa Maria da Serra	7.70
			São Francisco	1.55
			Severinia	11.11
			Tapiratiba	7.55
			Torre de Pedra	1.08
			Tupi Paulista	8.28
			Vargem	3.41

Source: CETESB (2015a); *Landfill located at Av. Sapopemba, nº 22254 - CTL.

3.5 Conclusions

The development of EISM for MSWDS applied to the state of São Paulo proceeded well due to the availability and reliability of spatial data for this area. Overall, the five factors - geology, pedology, geomorphology, water resources, and climate, represented by fifteen corresponding sub-factors selected, indicated a decent environmental impact susceptibility representation of the state in a regional scale.

The results of the EISM indicated that even though more than 82% of the land area in São Paulo state is situated in very low, low, and medium susceptibility categories, 85 of 420 landfills, were located in the high and very high susceptibility categories. In these landfills, approximately 17,886 tons of MSW are disposed on a daily basis, which indicated that 46% of all MSW of the state of São Paulo is disposed in environmentally susceptible areas. For that reason, MSWDS in São Paulo state require more attention and control to prevent the occurrence of negative environmental impacts and reduce the economic as well as social consequences.

4 MODELING THE ENVIRONMENTAL SUSCEPTIBILITY OF MUNICIPAL SOLID WASTE DISPOSAL SITES IN CALIFORNIA STATE, USA[7]

4.1 Introduction

Anthropogenic activities are usually associated with the generation of MSW (ADAMOVIĆ et al., 2016). Even if the capacity of different means of MSWM approaches and facilities such as recycling, composting, and incineration are increased, landfills are still necessary and remain a common method for MSWD in many regions of the world, including the USA (OECD, 2015; TOWNSEND et al., 2015; USEPA, 2015). Data from 2013 indicate that 64.7 million tons of MSW were recovered through recycling and 22 million tons were recovered through composting in the USA. Subtracting out what was recycled and composted, the remaining 167 million tons of waste were placed in sanitary landfills (USEPA, 2015). For the near future, landfilling is expected to be the dominant method to MSWD in the USA (QIAN; KOERNER; GRAY, 2002; POWELL; TOWNSEND; ZIMMERMAN, 2015; USEPA, 2015).

The most significant potential environmental threats associated with landfill disposal are release of gases and leachate (TCHOBANOGLOUS; THEISEN; VIGIL, 1993). The main landfill gases are methane and carbon dioxide, which are GHG. In addition, many trace gas components in the landfill gas are also ozone-depleting substances (USEPA, 2017). Furthermore, migration of leachate to surface or underground water has potential for contamination of these water resources. Geotechnical instability and failure of the waste mass or containment system components also can pose significant environmental risks due to the uncontrolled release of landfilling by-products of

[7] This Chapter is based on the paper: NASCIMENTO, V.F.; YESILLER, N.; CLARKE, K.; OMETTO, J.P.H.B.; ANDRADE, P.R.; SOBRAL, A.C.; Modeling the environmental susceptibility of landfill sites in California. Published at: **GIScience & Remote Sensing Journal**, 1-21, 2017. DOI: 10.1080/15481603.2017.1309126

gas and leachate as well as the waste materials (KOERNER; SOONG, 2000; QIAN; KOERNER; GRAY, 2002).

The lack of more sustainable MSWM is a major environmental problem (MISHRA et al., 2016). Sustainable MSWM is required to achieve low environmental impact (ADAMOVIĆ et al., 2016), and an essential part in this process is the proper MSWD. MSWDS are usually permanent facilities that pose risks to the environment and population, and need to be monitored for extended periods of time (LEÃO; BISHOP; EVANS, 2004).

The overall objective of this study is to spatially assess the environmental susceptibility of MSWDS. An improvement in understanding how physical factors such as geology, pedology, geomorphology, climate, and surface and underground water resources are connect and influence the environmental susceptibility is essential to avoid any negative impacts of MSWDS. In this study, we developed an EISM for MSWDS considering at least three of the five main modeling purposes of prediction, management decision-making under uncertainty, and developing system understanding and enabling experimentation. To accomplish this task, we used MCDA with AHP method coupled with GIS to apply the EISM for MSWDS to the state of California, USA.

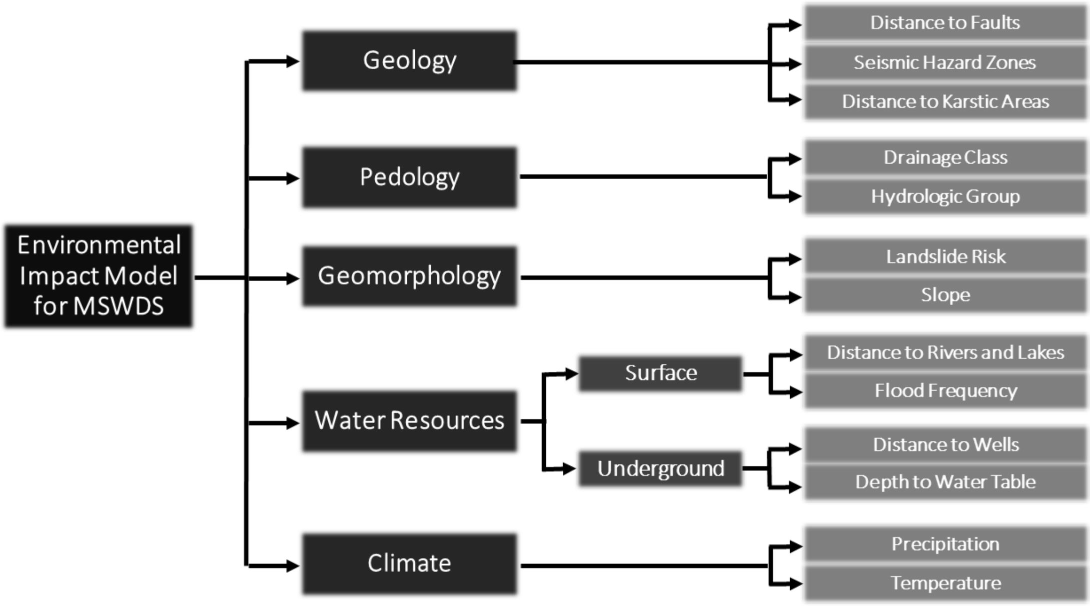
4.2 Methods

To build the EISM for MSWDS, six major steps were considered: (1) selection of environmental decision criteria; (2) data acquisition and integration into a GIS database; (3) definition of classes and assignment of ratings; (4) data standardization to a common scale of measurement; (5) calculation of relative criteria weights using the AHP technique; and (6) derivation of the final model map using the WLC aggregation method. Each step is described as follows.

4.2.1 Selection of environmental decision factors and sub-factors

In this study, the environmental factors and sub-factors selected were based on literature that took into account environmental impact susceptibility associated with MSWD (LEÃO; BISHOP; EVANS, 2004; BUTT; LOCKLEY; ODUYEMI, 2008; ESKANDARI; HOMAEE; MAHMODI, 2012; GBANIE et al., 2013; BUTT et al., 2014; KHAN; SAMADDER, 2015; MAANIFAR; FATAEI, 2015; MOTLAGH; SAYADI, 2015; ESKANDARI et al., 2015; BAHRANI et al., 2016; KHARAT et al., 2016; YILDIRIM; GÜLER, 2016; ZHANG et al., 2016; CHABUK et al., 2016; CHONATTU; PRABHAKAR; HARIKUMAR, 2016; CHONATTU; PRABHAKAR; PILLAI, 2016; DEMESOUKA; VAVATSIKOS; ANAGNOSTOPOULOS, 2016; ESKANDARI; HOMAEE; FALAMAKI, 2016). In addition, existing guidelines, relevant legislation and regulations, experts' opinions obtained in informal meetings, and available relevant data were considered in the development of the EISM for MSWDS. Overall, a total of five environmental factors - geology, pedology, geomorphology, water resources, and climate - as thirteen associated sub-factors were transformed into layers and used in the model (**Figure 4-1**). This list is not exhaustive; the most important criteria as indicated in previous studies and deemed significant by the authors were used to develop the EISM for landfill sites in the state of California.

Figure 4-1 - Factors and sub-factors used to develop the EISM for MSWDS in California.



Source: Nascimento et al. (2017b).

4.2.1.1 Geology

Geological features influence the environmental susceptibility of MSWDS because they can cause land instability in an earthquake region (QIAN; KOERNER; GRAY, 2002; AKYOL; KAYA; ALKAN, 2016). The geological features can also influence water infiltration if the rock formations are porous or include faults (DEEPA et al., 2016). For this reason, when MSW is disposed of above susceptible geological formations, instability of the containment systems and the waste mass may occur resulting in potential contamination of the surrounding surface and subsurface soils and water. Geological criteria were considered in previous studies that investigated environmental impacts caused by MSWD in landfills (AYDI et al., 2016; BAHRANI et al., 2016; CHONATTU; PRABHAKAR; PILLAI, 2016; YILDIRIM; GÜLER, 2016; ZHANG et al., 2016). However, these studies did not consider simultaneously the three geological sub-factors used in the current study, which were (i) distance to faults; (ii) seismic hazard zones; and (iii) distance to karstic areas. Karst areas are limestone landforms subject to rapid ground erosion by dissolution, with potential release of wastes and leachates into the subsurface water bodies.

4.2.1.2 Pedology

Soil parameters, such as depth and physical characteristics, also affect the environmental susceptibility related to siting of landfills, because permeability of the soil underlying and overall surrounding a landfill facility can influence the infiltration process, which in turn can cause contamination of groundwater (SHARMA; REDDY, 2004). Multiple studies on landfilling issues have included pedologic aspects in their assessments (LEÃO; BISHOP; EVANS, 2004; MAANIFAR; FATAEI, 2015; MOTLAGH; SAYADI, 2015; ZHANG et al., 2016). Of great importance is the rate of soil water infiltration, indeed often landfills are lined with clays that saturate quickly and prevent water percolation (TALALAJ; BIEDKA, 2016). In particular, we used (i) drainage class and (ii) hydrologic soil group as pedologic sub-factors in this study.

4.2.1.3 Geomorphology

Geomorphology is related to terrain features and the influence of these characteristics on the topography. For example, the increase of slope steepness also increases the terrain instability (QIAN; KOERNER; GRAY, 2002; SHARMA; REDDY, 2004). In addition, landfills should not be located in areas susceptible to stream erosion or landslides. Many previous studies have taken topographical aspects into consideration (GBANIE et al., 2013; KHAN; SAMADDER, 2015; KHARAT et al., 2016; ZHANG et al., 2016). In particular, we used the geomorphological sub-factors of (i) landslide risk and (ii) slope.

4.2.1.4 Water Resources

Another significant aspect that affects environmental susceptibility is associated with surface and underground water resources. It is not appropriate to have MSWDS close to surface water sources or in areas where the water table level is shallow due to the higher contamination risk (QIAN; KOERNER; GRAY, 2002; SHARMA; REDDY, 2004). Several studies have taken into consideration these aspects (GBANIE et al., 2013; ESKANDARI et al., 2015; KHAN; SAMADDER, 2015; MAANIFAR; FATAEI, 2015; MOTLAGH; SAYADI, 2015; BAHRANI et al., 2016; CHABUK et al., 2016; CHONATTU; PRABHAKAR; PILLAI, 2016; YILDIRIM; GÜLER, 2016). In this study, we used the surface water resource sub-factors of (i) distance to rivers and lakes and (ii) flood frequency, while, for underground water resources we used the sub-factors of (i) distance to wells, and (ii) depth to water table.

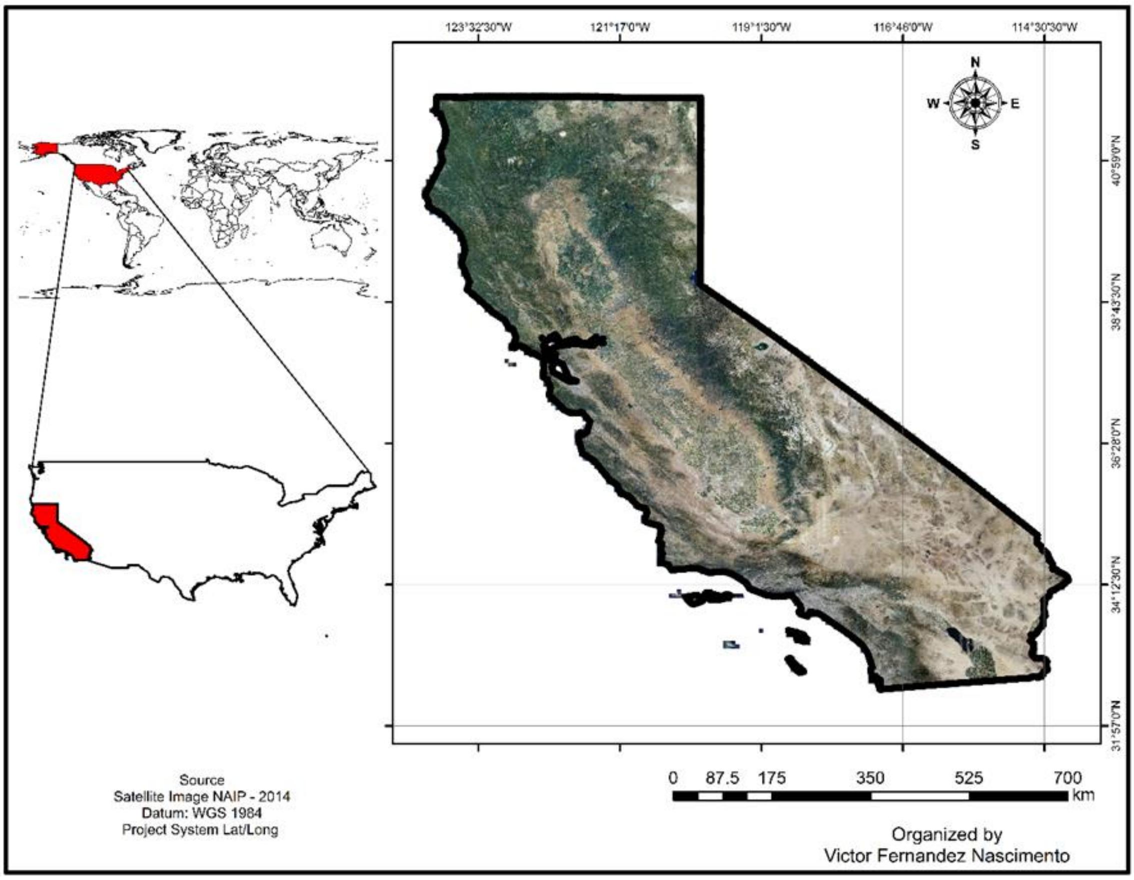
4.2.1.5 Climate

Climate factors, which are the average and succession of meteorological conditions, also need to be considered in modeling the environmental impact susceptibility for MSWDS. Climatic conditions significantly influence MSW decomposition and degradation process, which control the generation of three main by-products of MSW landfilling which are leachate, gas, and heat (TCHOBANOGLOUS; THEISEN; VIGIL, 1993; YESILLER; HANSON; LIU, 2005). Climatic aspects were also considered in previous investigations (MAANIFAR; FATAEI, 2015; CHONATTU; PRABHAKAR; HARIKUMAR, 2016; ESKANDARI; HOMAEE; FALAMAKI, 2016; KHARAT et al., 2016). In this study, we used the most significant climatic sub-factors of (i) precipitation and (ii) temperature. Data for the 30-year period from 1981 to 2010 were used in the analysis.

4.2.2 Study area

The state of California, on the West Coast of the USA, is located between 32º and 42º north latitude and 114º and 124º west longitude. It borders the states of Oregon to the north, Nevada to the northeast, Arizona to the southeast, Baja California, Mexico to the south, and the Pacific Ocean to the west (**Figure 4-2**). California is the most populous state in the USA with a population of approximately 39.2 million in July 2016 (CALIFORNIA, 2016). Moreover, the state is also one of the biggest producers of solid waste in the USA, generating approximately 31.3 million tons of solid waste in 2014 (CALRECYCLE, 2015).

Figure 4-2 - Map of the state of California, USA.



Source: Nascimento et al. (2017b).

California is also the third largest state by land area in the USA, with an area approximately of 408,000 km^2, and a diverse geography from forests to deserts and several large cities, including the nation's second largest, Los Angeles. Furthermore, the state is considered to be the most crowded subnational entity in the Western Hemisphere and the Americas, with a population second only to that of São Paulo state in Brazil.

Generally, densely populated areas are subject to more concerns associated with MSWD that is widely practiced through the landfill method in both developed and developing countries (AHMAD et al., 2016). In California, the mainly method of MSWD is sanitary landfill. For these reasons, we chose the state of California to assess the environmental impact susceptibility and to analyze the susceptibility of the existing MSWDS, which is mainly carried out through sanitary landfills sites in its territory.

4.2.3 Data acquisition and integration into a GIS database

The spatial database used in the EISM for MSWDS applied to the state of California was created using a variety of sources including geologic, pedologic, geomorphologic, hydrologic, and climate data at different scales (**Table 4-1**). The table provides the data used to create the layers. All data used were available in digital format and dated between the years 2001 and 2016. Furthermore, all data used to develop the EISM are available for downloading online with specific references to the relevant websites provided under the references.

The spatial data used to develop the EISM were the most recent and highest resolution data available for the study area. In some cases, better resolution or more recent data were identified for a specific municipality or county, but not for the entire state of California. In such cases, the data available for the entire state were used to prevent bias that may have resulted from using different resolutions in the analysis.

All the data layers were collected, stored, projected, manipulated, analyzed, and visualized using ArcGIS version 10.2 ModelBuilder as a starting point for the MCDA. ModelBuilder is a GIS extension that encodes complex sequences of GIS operations into a simple graphic model from which the steps can be executed (ALLEN, 2011). The data were georeferenced using the Universal Transverse Mercator (UTM) system and the North American Datum of 1983 (NAD83) (Zones 10 and 11 North).

Table 4-1 - Spatial data used in the EISM for MSWDS in the state of California

Factors	Sub-factors	Sources	Information used to create layers	Format	Scale or Resolution	Date
Geology	Distance to Faults	State Geologic Maps (USGS, 2005)	Structures	Digital	1:750,000	2005
	Seismic Areas	Rukstales (2012)	Seismic Areas	Digital	1:2,000,000	2012
	Distance to Karstic Areas	Tobin and Weary (2005)	Location of Karstic Areas	Digital	1:7,500,000	2005
Pedology	Drainage Class	Digital General Soil Map of USA (USDA/NRCS, 2006)	Drainage Class	Digital	1:250,000	2006
	Infiltration Rate	Digital General Soil Map of USA (USDA/NRCS, 2006)	Hydrologic Soil Group Class	Digital	1:250,000	2006
Geomorphology	Landslide Risk	Godt (2001)	Incidence and Susceptibility for Landslides	Digital	1:4,000,000	2001
	Slope	Digital Elevation Model – DEM (USDA/NRCS, 2015)	Calculated using DEM	Digital	30 meters	2015
Water Resources - Surface	Distance to Rivers and Lakes	(USDA/NRCS, 2016)	Rivers, Streams and Lakes	Digital	1:24,000	2016
	Flood Frequency Class	Digital General Soil Map of USA (USDA/NRCS, 2006)	Flood Frequency Class	Digital	1:250,000	2006
Water Resources - Underground	Distance to Wells	California Department of Conservation Division of Oil , Gas and Geothermal Sources (2016)	Representative Wells	Digital	1:100,000	2016
	Depth of Water Table	Digital General Soil Map of USA (USDA/NRCS, 2006)	Depth of Water Table	Digital	1:250,000	2006
Climate	Precipitation	Climate Data (USDA/NRCS, 2012)	Isohyetal Lines (1981-2010)	Digital	30 meters	2012
	Temperature	Climate Data (USDA/NRCS, 2012)	Isotherm Lines (1981-2010)	Digital	30 meters	2012

Source: Nascimento et al. (2017b).

4.2.4 Definition of classes and rating

Each of the thirteen sub-factors used in the EISM for MSWDS applied to the state of California was divided into classes. Each class was rated on a scale from one to ten, where one represents the lowest level of susceptibility and ten represents the highest level of susceptibility for environmental impact (**Table 4-2**). The rating interval from one to ten was selected based on similar scales used by comparable studies (ALAVI et al., 2013; ZAKERIAN; MOKHTARI; ALHOSSEINI ALMODARESI, 2015; CHONATTU; PRABHAKAR; HARIKUMAR, 2016; RAHMAT et al., 2016) and based on the experience and judgment of the authors. The specific classes were assigned considering the relevant conditions in California.

Table 4-2 - Rating classes for sub-factors in the state of California

Factors	**Sub-factors**	**Class**	**Rating**
Geology	Distance to Faults	<500 m	10
		500 – 1000 m	9
		1000 – 1500 m	8
		1500 – 2000 m	7
		2000- 2500 m	6
		2500– 3000 m	5
		3000– 3500 m	4
		3500– 4000 m	3
		4000– 4500 m	2
		>4500 m	1
	Seismic Hazard Zones	>100 pG	10
		100 – 80 pG	9
		80 – 60 pG	8
		60 – 40 pG	7
		40 – 30 pG	6
		30 – 25 pG	5
		25 – 20 pG	4
		20 – 15 pG	3
		15 – 10 pG	2
		<10 pG	1
	Distance to Karstic Areas	<1000 m	10
		1000 – 2000 m	9
		2000 – 3000 m	8
		3000 – 4000 m	7
		4000- 5000 m	6
		5000– 6000 m	5
		6000– 7000 m	4
		7000– 8000 m	3
		8000– 9000 m	2
		>9000 m	1
Pedology	Drainage Class	Excessively Drained	10
		Somewhat Excess. Drained	9
		Well Drained	7
		Moderately Well Drained	6
		Poorly Drained	5
		Somewhat Poorly Drained	4
		Very Poorly Drained	3
	Hydrologic Group	Group A	10
		Group B	8
		Group C	6
		Group D	4
Geomorphology	Landslide Risk	High	10
		Combo-High	8
		Susceptibility-High	6
		Moderate	4
		Susc. Moderate	2
		Low	1

Continues

Table 4-2 - Continuation

Factors	Sub-factors	Class	Rating
	Slope	>40 %	10
		40 – 35 %	9
		35 – 30 %	8
		30 – 25 %	7
		25 – 20 %	6
		20 – 15 %	5
		15 – 10 %	4
		10 – 5 %	3
		<5%	2
Water Resources - Surface	Distance to Rivers and Lakes	<500 m	10
		500 – 1000 m	9
		1000 – 1500 m	8
		1500 – 2000 m	7
		2000- 2500 m	6
		2500– 3000 m	5
		3000– 3500 m	4
		3500– 4000 m	3
		4000– 4500 m	2
		>4500 m	1
	Flood Frequency	Frequent	10
		Occasional	8
		Rare	6
		None	5
Water Resources - Underground	Distance to Wells	<500 m	10
		500 – 1000 m	9
		1000 – 1500 m	8
		1500 – 2000 m	7
		2000- 2500 m	6
		2500– 3000 m	5
		3000– 3500 m	4
		3500– 4000 m	3
		4000– 4500 m	2
		>4500 m	1
	Depth to Water Table	< 20 m	10
		20 – 40 m	9
		40 – 60 m	8
		60 – 80 m	7
		80 – 100 m	6
		100 – 120 m	5
		120 – 140 m	4
		140 – 160 m	3
		160 – 180 m	2
		>180 m	1
Climate	Precipitation	>100 inch	10
		100 – 90 inch	9
		90 – 80 inch	8
		80 – 70 inch	7
		70 – 60 inch	6
		60 – 50 inch	5

Continues

Table 4-2 - Conclusion

Factors	Sub-factors	Class	Rating
		50 – 40 inch	4
		40 – 30 inch	3
		30 – 20 inch	2
		<20 inch	1
	Temperature	>90 F	10
		90 – 85 F	9
		85 – 80 F	8
		80 – 75 F	7
		75 – 70 F	6
		70 – 65 F	5
		65 – 60 F	4
		60 – 55 F	3
		55 – 50 F	2
		<50 F	1

Source: Nascimento et al. (2017b).

4.2.5 Data standardization to a common scale of measurement

In order to overlay the spatial information to calculate the environmental impact susceptibility, it was necessary to standardize the data to a common measurement scale. Therefore, the thirteen sub-factors data were converted into raster grid format consisting of 50 m x 50 m cells resulting in an image of 19311 columns and 21769 rows.

4.2.6 Criteria weight assignment using AHP

In this study, we used AHP, the construction of a comparison matrix and the derivation of weights were conducted using the web-based tool developed by Goepel (2013). First, the AHP methodology was applied to the factors (**Table 4-3**) and sub-factors (**Table 4-4**). Then, by multiplying the factors weights by the sub-factors weights, the global weighting for each criterion was obtained (**Table 4-5**).

Table 4-3 - Pairwise comparison matrix, ranking, and weights for factors in the EISM for MSWDS applied to the state of California

Factors (CR 2.8%)	**[1]**	**[2]**	**[3]**	**[4]**	**[5]**	**[6]**	**Rank**	**Weight (%)**
Geology	1						1	24.8
Pedology	1/3	1					6	5.8
Geomorphology	1/3	2	1				4	14.5
Surface Water Resources	1/2	3	1	1			5	12.7
Underground Water Resources	1	4	1	2	1		2	21.1
Climate	1	4	1	2	1	1	2	21.1

Source: Nascimento et al. (2017b).

Table 4-4 - Pairwise comparison matrix, ranking, and weights for sub-factors in the EISM for MSWDS applied to the state of California

<table>
<tr><th colspan="2">Factors
(CR %)</th><th>Sub-factors</th><th>[1]</th><th>[2]</th><th>[3]</th><th>Rank</th><th>Weight
(%)</th></tr>
<tr><td colspan="2" rowspan="3">Geology
CR (0.0%)</td><td>Distance to Faults</td><td>1</td><td></td><td></td><td>1</td><td>45.5</td></tr>
<tr><td>Seismic Hazard Zones</td><td>1</td><td>1</td><td></td><td>1</td><td>45.5</td></tr>
<tr><td>Distance to Karstic Areas</td><td>1/5</td><td>1/5</td><td>1</td><td>3</td><td>9.0</td></tr>
<tr><td colspan="2" rowspan="2">Pedology
CR (0.0%)</td><td>Drainage Class</td><td>1</td><td></td><td></td><td>1</td><td>50.0</td></tr>
<tr><td>Hydrologic Group</td><td>1</td><td>1</td><td></td><td>1</td><td>50.0</td></tr>
<tr><td colspan="2" rowspan="2">Geomorphology
CR (0.0%)</td><td>Landslide Risk</td><td>1</td><td></td><td></td><td>1</td><td>66.7</td></tr>
<tr><td>Slope</td><td>1/2</td><td>1</td><td></td><td>2</td><td>33.3</td></tr>
<tr><td rowspan="4">Water Resources</td><td rowspan="2">Surface
CR (0.0%)</td><td>Distance to Rivers/Lakes</td><td>1</td><td></td><td></td><td>2</td><td>33.3</td></tr>
<tr><td>Flood Frequency</td><td>2</td><td>1</td><td></td><td>1</td><td>66.7</td></tr>
<tr><td rowspan="2">Underground
CR (0.0%)</td><td>Distance to Wells</td><td>1</td><td></td><td></td><td>2</td><td>25.0</td></tr>
<tr><td>Depth to Water Table</td><td>3</td><td>1</td><td></td><td>1</td><td>75.0</td></tr>
<tr><td colspan="2" rowspan="2">Climate
CR (0.0%)</td><td>Precipitation</td><td>1</td><td></td><td></td><td>1</td><td>80.0</td></tr>
<tr><td>Temperature</td><td>1/4</td><td>1</td><td></td><td>2</td><td>20.0</td></tr>
</table>

Source: Nascimento et al. (2017b).

Table 4-5 - Global weighting for each criteria in the EISM for MSWDS applied to the state of California

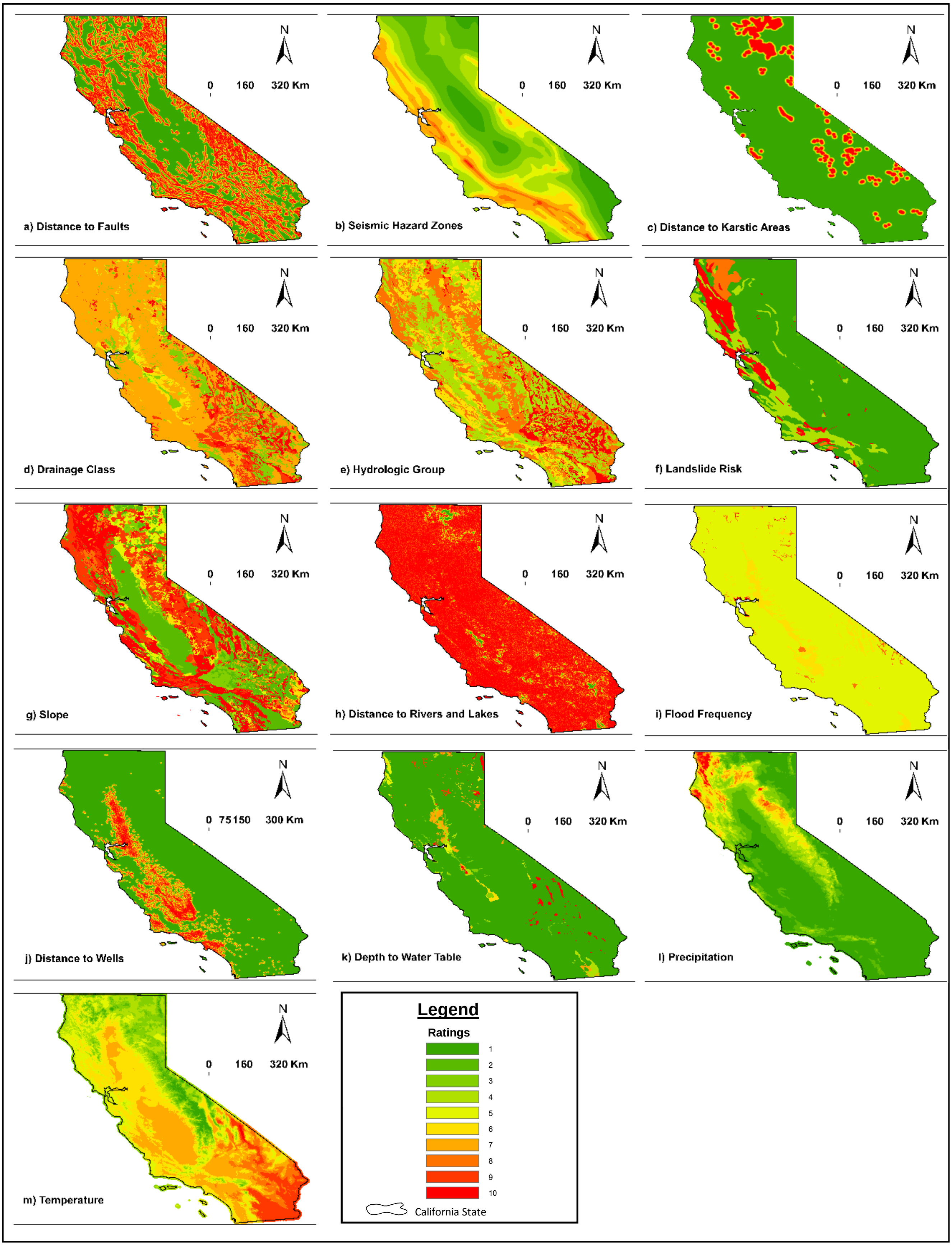
Factors		Sub-factors	Global Rank	Global Weight (%)
Geology		Distance to Faults	3	11.3
		Seismic Hazard Zone	3	11.3
		Distance to Karstic Areas	10	2.4
Pedology		Drainage Class	9	2.9
		Hydrologic Group	9	2.9
Geomorphology		Landslide Risk	4	9.6
		Slope	7	4.8
Water Resources	Surface	Distance to Rivers/Lakes	8	4.2
		Flood Frequency	5	8.4
	Underground	Distance to Wells	6	5.3
		Depth to Water Table	2	15.8
Climate		Precipitation	1	16.9
		Temperature	8	4.2

Source: Nascimento et al. (2017b).

4.2.7 Weight linear combination method

After checking the reliability of the pairwise comparisons for factors and sub-factors, the EISM for MSWDS in California was built using a WLC method. The final score was obtained for each raster cell as a sum of the products of ratings assigned to each of the classes (**Table 4-2**) and the global weights obtained by AHP (**Table 4-5**) (**Figure 4-3**). The results varied from 1.93 to 8.01, the minimum and maximum values, respectively. This interval was classified by the natural breaks method (JENKS; CASPALL, 1971) and then classified into five categories of environmental impact susceptibility for MSWDS: Very Low (S1), Low (S2), Medium (S3), High (S4), and Very High (S5).

Figure 4-3 - Maps with all selected sub-factors in the state of California



Source: Nascimento et al. (2017b).

4.3 Results and Discussion

Through the development of the EISM for MSWDS using MCDA and the AHP coupled with GIS, it was possible to identify the most and least environmentally susceptible areas. With the application of the model, it was also possible to assess the current susceptibility of landfill sites in the state of California, USA.

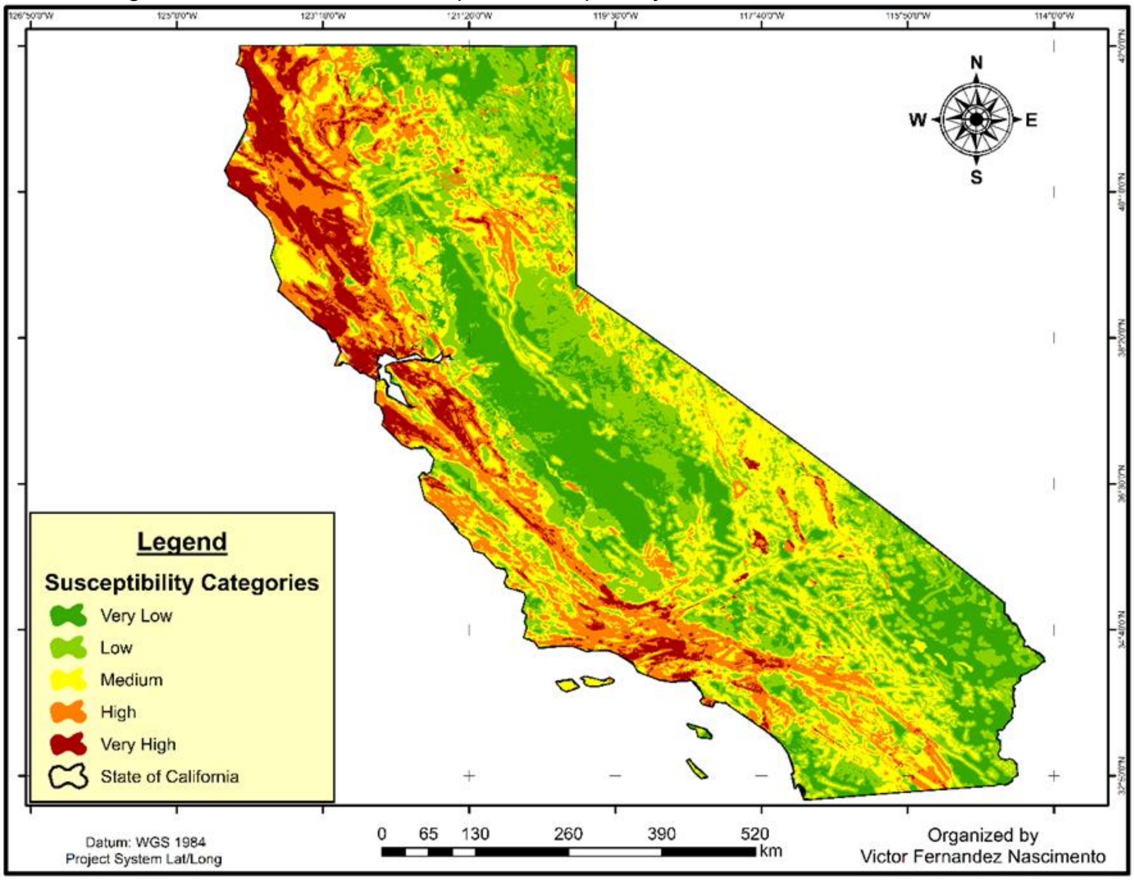
The geographical coordinates of 207 landfill sites in the state of California were obtained from spreadsheets used for the landfill tonnage reports between the years of 2000 and 2015. Of these 207 sanitary landfills, 133 were classified as active, 10 as inactive, 8 as closing, 1 as planned, and 55 as closed (CALRECYCLE, 2016a).

A spatial analysis was performed by overlaying the results of the EISM and the locations of MSW landfill sites in the state of California. This analysis allowed identification of the specific landfills included in each of the environmental impact susceptibility categories and the amount of solid waste disposed of during the period of 2000 to 2015 in each class of susceptibility.

4.3.1 Environmental impact susceptibility model for MSWDS

The results of applying the EISM for MSWDS in California are presented in (**Figure 4-4**). The area for each susceptibility category indicated that almost half of California's land, 47.4%, is classified under very low (S1) and low (S2) environmental impact susceptibility categories, 28.3% is under medium (S3) category, and 24.3% is under the high (S4) and very high (S5) categories (**Table 4-6**).

Figure 4-4 - Environmental impact susceptibility for MSWDS in California state



Source: Nascimento et al. (2017b).

Table 4-6 - Environmental susceptibility categorization for MSWDS in California state

Environmental impact susceptibility categories	Area (km^2)	Area Percentage
Very Low (S1)	78,233	19.2 %
Low (S2)	115,184	28.2 %
Medium (S3)	115,787	28.3 %
High (S4)	68,793	16.8 %
Very High (S5)	30,492	7.5 %
Total	408,489	100%

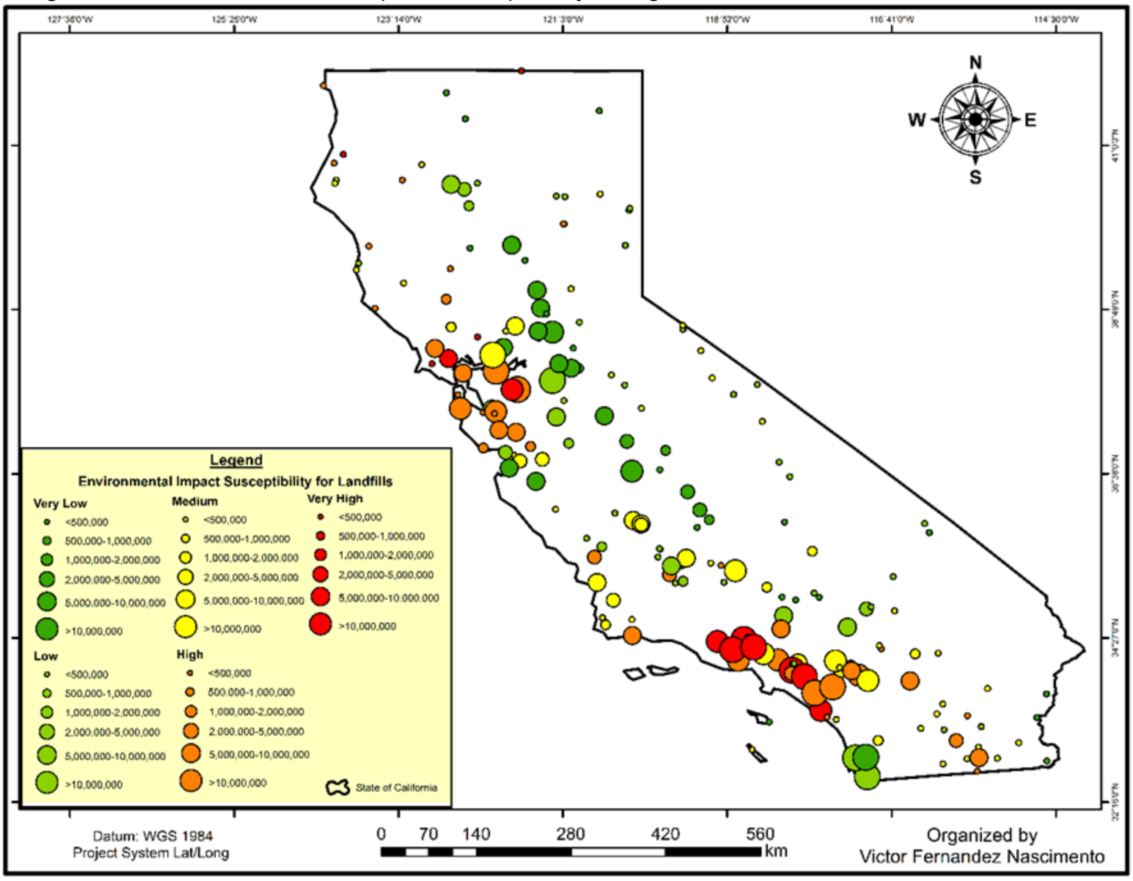
Source: Nascimento et al. (2017b).

The very high class alone has an area of 30,492 km^2, which represents 7.5% of the land area of California. This area is located mainly less than 100 km from the ocean, on the North Coast, in the San Francisco Bay Area and near the city of Los Angeles. This can be explained by a combination of geographical variables. On the North Coast, the highest rate of precipitation was observed, which is the sub-factor with the highest level of importance in the EISM. The very high environmental impact susceptibility observed near the San Francisco Bay Area and near the city of Los Angeles, resulted mainly from the geologic sub-factors of seismic hazard zones and distance to faults, the third and fourth most important sub-factors in this study.

4.3.2 Analysis of susceptibility for MSWDS in California

In order to evaluate the environmental impact susceptibility for each MSWDS in California, a spatial analysis (**Figure 4-5**) and a statistical summary (**Table 4-7**) were developed.

Figure 4-5 – Environmental impact susceptibility categorization of MSWDS in California sate



Source: Nascimento et al. (2017b).

Table 4-7 – MSWDS in the state of California according to environmental susceptibility category

Environmental impact susceptibility category	Number of Landfills	Tons of solid waste disposed during the period from 2000 to 2015
S1	39	70,915,928
S2	49	84,296,137
S3	58	74,782,438
S4	48	165,868,838
S5	13	142,122,911
Total	207	537,986,252

Source: Nascimento et al. (2017b).

The number of landfills included in each environmental impact susceptibility category has a positive correlation with the extent of each category in the state of California. Approximately 70% of the landfills are located in very low, low, and medium environmental impact susceptibility categories (S1, S2, and S3, respectively). Even though only 30% of the landfills are located in the high and very high categories (S4 and S5, respectively), a large amount of MSW (307,991,749 tons) was disposed of in these facilities over the last fifteen years (**Table 4-7**). The list with the information about the landfills and the quantity of MSW disposed in the two highest susceptibility categories is provided in (**Table 4-8**).

From the 13 landfills located in the very high category, three did not receive MSW during the period 2000 to 2015. Among the remaining ten landfills, eight are active, one is closing, and one is closed. These landfills received in total 142,122,911 tons, which represents more than 26% of the total MSW disposed of in the state of California.

From 48 landfills located in the high environmental impact susceptibility category, six did not receive solid waste during the period of 2000 to 2015. Among the remaining 42 landfills, 29 are active, one is inactive, one is closing, and 11 are closed. These landfills received in total 165,868,838 tons of MSW, which represented more than 30% of the total MSW disposed of in the state of California.

When the amount of MSW in the 12 largest landfills located in the high and very high environmental impact susceptibility categories are added, the total MSW disposed is more than 238 million tons, which represents more than 77% of the total MSW disposed in landfills located in these higher categories.

Table 4-8 - MSWDS located at high and very high categories in the state of California

Category	Landfill Codes	Location (County/City)	Classification	Tons of solid waste disposed over the period 2000-2015
S5	01-AA-0010	Alameda/Livermore	Active	5,803,172
	12-AA-0029	Humboldt/Arcata	Inactive	0
	19-AA-0052	Los Angeles/Castaic	Active	20,482,418
	19-AA-0053	Los Angeles/Whittier	Closing	43,253,356
	21-AA-0001	Marin/Novato	Active	4,836,102
	21-AA-0002	Marin/Point Reyes Statio	Closed	0
	28-AA-0003	Napa/Napa	Closed	0
	30-AB-0019	Orange/Santa Ana	Active	9,071,686
	30-AB-0035	Orange/Santa Ana	Active	29,373,407
	47-AA-0027	Siskiyou/Yreka	Closed	633
	56-AA-0005	Ventura/Ventura	Active	5,668,447
	56-AA-0007	Ventura/Simi Valley	Active	11,457,885
	19-AA-2000	Los Angeles/Sylmar	Active	12,175,805
S4	01-AA-0009	Alameda/Oakland	Active	19,677,794
	06-AA-0002	Colusa/Colusa	Active	433
	07-AA-0001	Contra Costa/Richmond	Closed	2,231,245
	07-AA-0002	Contra Costa/Martinez	Active	270,085
	07-AA-0032	Contra Costa/Pittsburg	Active	11,965,716
	08-AA-0006	Del Norte/Crescent City	Closed	103,552
	12-AA-0005	Humboldt/Eureka	Closing	11,747
	13-AA-0004	Imperial/El Centro	Active	28,196
	13-AA-0010	Imperial/El Centro	Active	2,511
	13-AA-0019	Imperial/Imperial	Active	2,185,886
	13-AA-0022	Imperial/Calipatria	Active	1,086,760
	15-AA-0044	Kem/Bakersfield	Closing	0
	15-AA-0105	Kem/McKittrick	Active	1,275,857
	17-AA-0001	Lake/Lakeport	Active	787,086
	19-AA-0012	Los Angeles/Whittier	Active	5,260,922
	19-AA-0015	Los Angeles/Whittier	Closed	127,089
	19-AA-0056	Los Angeles/Whittier	Active	5,539,475
	19-AA-0057	Los Angeles/Saugus	Inactive	0
	19-AA-5624	Los Angeles/Palmdale	Active	2,600,059
	19-AF-0001	LA/West Covina	Closed	0
	19-AH-0001	Los Angeles/Whittier	Active	1,321,848
	23-AA-0007	Mendocino/Branscomb	Closed	34,586
	23-AA-0018	Mendocino/Ukiah	Inactive	2,456
	30-AB-0018	Orange/Santa Ana	Closed	0
	30-AB-0360	Orange/Santa Ana	Active	30,092,453
	32-AA-0007	Plumas/Portola	Closed	2,349
	32-AA-0008	Plumas/Quincy	Closed	200

Continues

Table 4-8 - Continuation

Category	Landfill Codes	Location (County/City)	Classification	Tons of solid waste disposed over the period 2000-2015
	33-AA-0006	Riverside/Moreno Valley	Active	9,222,599
	33-AA-0011	Riverside/Moreno Valley	Closed	2,256,622
	33-AA-0217	Riverside/Corona	Active	31,011,179
	36-AA-0056	San Ber/San Bernardino	Closed	69,425
	36-AA-0087	San Ber/San Bernardino	Active	2,639,749
	37-AA-0902	SD/Camp Pendleton	Active	13,670
	39-AA-0010	San Joaquin/Costa Mesa	Closed	0
	40-AA-0008	SLO/Templeton	Active	1,116,915
	41-AA-0002	San Mat/Half Moon Bay	Active	9,971,118
	41-AA-0008	San Mateo/Colma	Closed	341,014
	42-AA-0015	Santa Bar/Santa Barbara	Active	3,097,695
	43-AA-0004	Santa Clara/Gilroy	Closed	513,949
	43-AM-0001	Santa Clara/Palo Alto	Closed	246,007
	43-AN-0001	Santa Clara/San Jose	Active	298,833
	43-AN-0003	Santa Clara/Milpitas	Active	9,316,879
	43-AN-0007	Santa Clara/San Jose	Active	128,764
	43-AN-0008	Santa Clara/Morgan Hill	Active	3,709,806
	43-AN-0015	Santa Clara/San Jose	Active	3,083,076
	44-AA-0001	Santa Clara/Santa Cruz	Active	827,500
	49-AA-0001	Sonoma/Petaluma	Active	3,395,733
	53-AA-0035	Trinity/Hayfork	Closed	0

Source:CALRECYCLE (2016a, 2016b).

4.4 Conclusions

The development of EISM for MSWDS applied to the state of California proceeded well due to the availability and reliability of spatial data for this area. Overall, the five factors - geology, pedology, geomorphology, water resources, and climate, represented by thirteen corresponding sub-factors selected, indicated a decent environmental impact susceptibility representation of the state in a regional scale.

The results obtained using the EISM indicated that even though more than 75% of California’s land is situated in very low, low, and medium susceptibility categories, 29% (61 of 207) of the landfills in the state are located in the high and very high susceptibility categories. In these 61 landfills, approximately 308 million tons of MSW was disposed of during 2000 to 2015, which indicates that more than 57% of solid waste disposed of in California was placed in environmentally susceptible areas. The results of this study can help decision makers, landfill managers, and local governments develop control and mitigation measures against the occurrence of negative environmental impacts from these landfills.

5 FINAL REMARKS

This thesis explored an innovative modeling approach using MCDA and AHP coupled with GIS to analyze the environmental impact susceptibility of MSWDS. To understand how this topic contributes to advance Earth System Science, we first review the MSWM in Brazil focusing on the environmental impacts caused by inappropriate MSWD. We highlighted in this review that even though the improper MSWDS cause local environmental impacts, such as contaminations of soil and water, they can also cause global environmental impacts through the emission of methane and other GHG that contributes to climate change. Based on this environmental impact review, a set of environmental indicators were classified in factors and sub-factors and used to develop the EISM in regional scale for MSWDS, which was applied to the state of São Paulo, Brazil and the state of California, USA. This two study areas were selected because they are the most populous states in their countries and, consequently, the largest MSW generators in South and North America, respectively.

This final chapter synthetizes the major findings of the whole thesis and discusses how these findings confirm the hypothesis of this research, which assert that populous states in both, developed and developing countries, tends to dispose MSW in environmental susceptible areas. This last chapter is divided in three sections, section 5.1 presents the major finds for each chapter, section 5.2 discuss about the modeling approach and future research needs, and in section 5.3 some policy recommendations were pointed out to avoid and to help mitigate the environmental impacts caused by inappropriate MSWD.

5.1 Major finds

Chapter 2 assessed the recent improvements and remaining challenges of MSWD in Brazil and the state of the art of environmental impacts caused by inappropriate MSWD. This chapter addressed MSWM in Brazil and demonstrated that (i) the actual trends of population growth and increase of MSW generation, (ii) the insufficient selective collection system, (iii) the low rates of recycling and composting, and finally (iv) the improper MSWD is causing several negative environmental impacts in the lithosphere, atmosphere, hydrosphere, and can cause changes in the Earth System that can have serious and long lasting consequences.

The results showed that although there was an increase in the number of cities disposing MSW in sanitary landfills in Brazil, more than half of them dispose their MSW improperly, which makes this issue one of the most current critical environmental problem faced by the nation. Furthermore, the non-fulfillment of the BSWP with the postponement of the deadlines for closure open dumps and uncontrolled landfills reinforces these impacts. Although the hierarchy of MSWM in Brazil enforces preventing, reusing, recycling and recovering before MSWD in sanitary landfills, the country remains in the failed attempt to accomplish the goal of properly dispose of MSW.

Chapter 3 assessed the most and the least environmentally susceptible areas in the state of São Paulo, Brazil for MSWDS through the EISM. This model considers MCDA and AHP coupled with GIS. The EISM took into consideration five environmental factors – geology, pedology, geomorphology, water resources and climate - associated with fifteen sub-factors (i) distance to faults, (ii) porosity of rocks, (iii) distance to seismic areas, (iv) distance to caves, (v) type of soil, (vi) soil infiltration rate, (vii) landslide risk, (viii) slope, (ix) distance to rivers and lakes, (x) flood risk, (xi) distance to wells, (xii) aquifer flow, (xiii) aquifer vulnerability to pollution, (xiv) precipitation, and (xv) temperature.

With the application of the EISM we were able to assess the current susceptibility of MSWDS in São Paulo state, Brazil. The findings of this chapter demonstrate that even though more than 82% of the land area in São Paulo state is situated in very low, low, and medium susceptibility categories, 85 of 420 landfills, are located in the high and very high susceptibility categories. In these landfills, approximately 17,886 tons of MSW are disposed on a daily basis, which indicates that 46% of all MSW of the state of São Paulo is being disposed in environmentally susceptible areas.

Chapter 4 assessed the most and the least environmentally susceptible areas in the state of California, USA for MSWDS through the EISM. This model considers MCDA and AHP coupled with GIS. The EISM took into consideration six environmental factors - geology, pedology, geomorphology, climate, surface and underground water resources - associated with thirteen associated sub-factors (i) distance to faults, (ii) seismic hazard zones, (iii) distance to karstic areas, (iv) drainage soil class, (v) hydrologic soil group, (vi) landslide risk, (vii) slope, (viii) distance to rivers and lakes, (ix) flood frequency, (x) distance to wells, (xi) depth to water table, (xii) precipitation, and (xiii) temperature.

The finds obtained by the EISM indicated that even though more than 75% of California's land is situated in very low, low, and medium susceptibility categories, 29% (61 of 207) of the landfills in the state are located in the high and very high susceptibility categories. In these 61 landfills, approximately 308 million tons of MSW was disposed of during 2000 to 2015, which indicates that more than 57% of solid waste disposed of in California was placed in environmentally susceptible areas.

In summary, this thesis provides a groundbreaking approach of environmental impact susceptibility analysis of MSWDS in regional scale. In addition, this thesis applied the EISM for the two most populous states and largest MSW generators in South and North America, São Paulo and California state, respectively.

Nevertheless, the EISM for these two states have some similarities, they differ in the number of sub-factors and in the weigh relevance of factors and sub-factors. For example, while for the São Paulo state the most relevant factor is related to water resources, for the California state the most relevant factor is geology. That succeed because California is an area of constant earthquakes and with several geological faults, which influence the environmental susceptibility of the area.

Another interesting finding is that, despite each EISM developed in this thesis have more than 10 sub-factors, the four most relevant sub-factors for both São Paulo and California states comprises more than half importance in the EISM (**Table 5-1**).

Table 5-1 - Comparison between São Paulo and California global weights in the EISM

	São Paulo		California	
Ranking	**Sub-factors**	**Global Weight (%)**	**Sub-factors**	**Global Weight (%)**
1º	Distance to rivers and lakes	22.3	Precipitation	16.9
2º	Aquifer vulnerability	14.0	Depth to Water Table	15.8
3º	Soil infiltration Rate	11.9	Distance to Faults	11.3
4º	Precipitation	9.4	Seismic Hazard Zone	11.3
Total		**57.6**		**55.3**

Source: Elaborated by the author.

This information shows that a simple model using just the four most significant sub-factors should have similar results than the more complex EISM. This is of great important because a study area, mainly in underdeveloped and developing country, cannot have all necessary data available to accomplish the EISM, and if the most relevant sub-factors are used the results will still be accurate and reliable. In conclusion, the EISM for MSWDS developed in this thesis, with some adaptations, can be applied in other areas of interest changing accordingly to the local physical characteristics and data availability.

5.2 Modeling approach and future research needs

The EISM for MSWDS applied to the state of São Paulo and California explored an innovative modeling approach and are a pioneering study for these areas. The EISM provided an improvement over previous models for three main reasons: (i) a higher number of factors used, (ii) a higher number of sub-factors used, and (iii) a more extensive set of combined factors and sub-factors used.

The EISM can be applied to different areas, especially in developing countries, where most of the MSW is disposed directly in the ground, without control, resulting in adverse environmental impacts. Although the EISM was developed focusing in MSWDS, the model can also be used with some adaptations for other point source of environmental impact, such as, fuel stations, mines, and any type of solid waste disposal facilities such as industrial or hazardous wastes.

The main limitation in the development of the EISM is the accessibility of spatial data, as well as its quality. In addition, there is the subjectivity of class and rating definition of the sub-factors and the weight assignment using AHP, where variation in these values can cause a different result in the analysis. Furthermore, the importance for each class could vary based on the region of interest and local physical characteristics of the specific area.

Another limitation to assess the environmental impact susceptibility for MSWDS is that the analysis rely on the physical characteristics of the area in the EISM, but also depends on the composition and quantity of MSW involved and the quality of the landfill's operation and management. In this thesis, we consider the quantity of MSW involved and the physical characteristics of the area to develop our assessment, for futures studies we recommend to take into consideration the composition of MSW as well as the quality of MSWDS operation and management.

Considering the model approach, the development of the EISM took three main modeling purposes into consideration, including prediction, management decision-making under uncertainty, and developing system understanding and experimentation. For future studies, to improve the environmental impact susceptibility assessment for MSWDS we suggest adding (i) forecasting, using different climate scenarios that influence leachate generation and emission of GHG, which can improve the assessment of the environmental impact susceptibility, and (ii) social learning, coupling a social model with the EISM, which could result in a greater understanding of global susceptibility for the siting and management of landfills.

5.3 Policy recommendations

The results of the EISM for MSWDS developed in this thesis demonstrate that approximately half of MSW disposed in California and São Paulo state is disposed in environmentally susceptible areas. In summary, this information can help decision makers, landfill managers, and local governments develop control and mitigation measures against the occurrence of negative environmental impacts caused by MSWDS. In addition, this type of spatial analysis can also assist stakeholders in the process of identifying areas for new landfills in zones with less environmental impact susceptibility.

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