A GIS-AHP Combination for Assessment of Municipal Solid Waste Landfill Sites in Songkhla, Thailand

Ismail Kamdar

A Thesis Submitted in Fulfillment of the Requirements for the Degree of
Master of Science in Sustainable Energy Management
Prince of Songkla University
2019

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Thesis Title A GIS-AHP Combination for Assessment of Municipal Solid Waste Landfill Sites in Songkhla, Thailand

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ABSTRACT

Finding an appropriate landfill site has become necessary in current global scenario because of increasing waste generation and the use of improper disposal of waste that can adversely affect ecosystem. In this research a scientific technique is used to identify suitable landfill sites. The objective of the study consists of morphological, environmental and socio-economic factors. Integrating Geographic Information System (GIS) and Analytic Hierarchy Process (AHP) in order to evaluate data obtained from government organizations and online portals, including a recent data of waste production centres from Regional Environmental Office. To demonstrate the methodology, a case study from Southern Thailand was employed. Thirteen landfill site selection criteria were finalized based on expert opinion. The results showed an area of 560.59 ha (very highly suitable), 993.19 ha (highly suitable) and 180.72 ha (moderately suitable) for landfill sites whereas the remaining portion of the study area being unsuitable for landfill sites. This work has high potential to contribute in future waste management policies by assisting stakeholders in landfill site selection that may reduce harmful effects on the ecosystem.

Keywords: Landfill siting, municipal solid waste, Geographic Information System, multi-criteria decision making, Thailand.

DEDICATION

This thesis is dedicated to my beloved mother.

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Ismail Kamdar

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

LIST OF ABBREVIATIONS

MSW	Municipal Solid Waste
MSWM	Municipal Solid Waste Management
GIS	Geographic Information System
MCDM	Multi-Criteria Decision Making
AHP	Analytical Hierarchy Process
CI	Consistency Index
CR	Consistency Ratio
RI	Random Index
PCD	Pollution Control Department
NIMBY	Not In My Backyard
WLC	Weighted Linear Combination
IDW	Inverse Distance Weighting
LSI	Landfill Suitability Index

LIST OF PUBLICATIONS

1. Ismail Kamdar, Shahid Ali, Adul Bennui, Kuaanan Techato & Warangkana Jutidamrongphan* (2019). Municipal solid waste landfill siting using an integrated GIS-AHP approach: A case study from Songkhla, Thailand. Resources, Conservation & Recycling. (Impact Factor 7.044; ISI Science Citation Index Expanded) https://doi.org/10.1016/j.resconrec.2019.05.027

2. Ismail Kamdar, Dilawer Ali, Juntakan Taweekun*, Warangkana Jutidamrongphan & Kuaanan Techato (2019). A review study on municipal solid waste management and waste to energy technologies. International Journal of Integrated Engineering (IJIE). (SCOPUS) (Accepted)

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CHAPTER 1

INTRODUCTION

1.1. Background

Municipal solid waste (MSW) depicts daily use items that people utilize and discard in the form of papers, food scraps, bottles, glasses, grass clippings, clothing, furniture, paint, appliances, batteries etc. (Makarichi et al., 2018). It may comprise waste generated from residential, commercial, institutional and public parks. It may contain the waste produced from household, commercial and recreational centres (Ng et al., 2014). The management of MSW has become a great challenge for metropolitan areas and decision makers due to growing population, urbanization and limited land area (Kamdar et al., 2019). MSW is also one of the serious threat to our environment (Javaheri et al., 2006) as treatment and dumping of solid wastes environmentally challenging approaches (Ojha et al., 2007). These environmental challenges along with social, economic, political and land space issues have created an alarming situation for land management and evaluation techniques (Khan et al., 2018).

Delineation of the disposal site is one of the significant steps in the disposal of MSW. Reduction, reuse, recycling and energy recovery are the main approaches of the modern waste management. In spite of the methods, it seems impossible to eradicate all forms of waste; a better way to deal waste is to follow techniques that make sure less impacts on environment (Gbanie et al., 2013).

Landfilling is an integral part of the waste management chain and is considered at the bottom of waste management hierarchy (see Fig. 1.1) which needs a proper inspection to minimize its detrimental impacts on environment (Mahini and Gholamalifard, 2006; Rahman et al., 2008). It is one of the economical ways of waste treatment but has, however, caused environmental issues. Landfill is a waste disposal approach in which basic principles of engineering are used (Sumathi et al., 2008). This can be accomplished by spreading waste into thin cells, squeezing it into slight volumes and, finally, covering it with a soil layer.

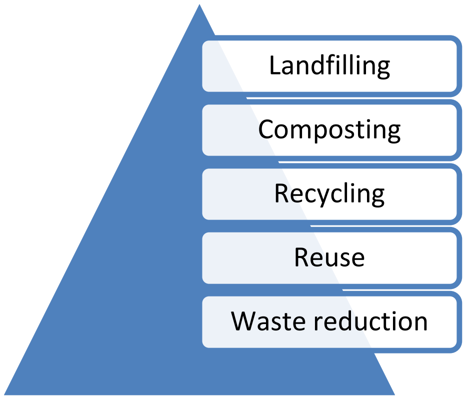

Fig. 1.1 Waste management hierarchy (Gbanie et al., 2013)

Establishing waste treatment facilities or landfills nearby public areas is a critical problem for decision makers that comes under public opposition, a phenomenon known as Not In My Backyard (NIMBY) syndrome (Demesouka et al., 2019). In spite of that, a careful assessment of economic and morphological factors is essential before opening of a new landfill facility to minimize their cost and maximize their productivity. Hence, a comprehensive inspection of landfill site is important in a developing country like Thailand.

Geographic Information System (GIS) has been appeared a useful tool in landfill site evaluation process. GIS is a computer-based decision support system with the capacity to manage, analyze and display geospatial reference data (Khan et al., 2018). Moreover, multi-criteria decision making (MCDM) is a popular technique that is used to solve complex issues in waste management such as landfill site assessment (Demesouka et al., 2018). Saaty presented analytic hierarchy process (AHP) approach as a type of MCDM that decomposes the problem into hierarchical form, where the goal is the top priority (Saaty, 1990). In our study, the goal was to identify appropriate locations for landfill.

1.2. Statement of problem

Municipal solid waste is a critical problem in developing countries like Thailand that have severe negative effects on human health and surrounding environment. Thailand has generated around 27 million tonnes of solid waste in 2016 as reported by Pollution Control Department (PCD), Thailand. Most of the MSW has been dumped in open dumpsites which is an alarming situation for the country in the form of air pollution, soil and water contamination and climate change.

Coming towards south of the Thailand, Songkhla province, that also borders Malaysia to the south and hence hosts many tourists each year. As a result hundreds of tonnes of waste is generated each day, including increasing waste from the southernmost districts of Songkhla, Na Thawi, Chana, Thepa and Sabayoi, that are densely populated and large land areas which produces around 228 tonnes of waste per day (Buranasing, 2015). It was noticed in 2015 survey that the wastes composition is made 60% of food, 25% of plastic, 5% of glass, 5% of gardening waste, 2% of paper, 2% of polystyrene and 1% of metal. Waste disposal sites that exists in those places were selected manually, hence, bringing serious health issues to residents nearby. Due to this, public have become susceptible to the NIMBY syndrome, a recent example of which was in Chana, where the public opposed the establishment of a waste transfer station. A comprehensive scientific study following local administration can only regain the public confidence.

To the best of our knowledge, no recent study was found on suitable locations for landfill sites applying GIS-AHP approach. The only similar study in which geological barriers were considered for landfill site selection by (Charusiri and Ladachart, 2008) in Songkhla province, however, AHP approach and an important factor like socio-economic has not been considered in their research.

1.3. Research objectives

The objective of our study has been described below;

1) To apply an integrated GIS-AHP approach for landfill siting.
2) To find the suitable locations for landfill sites in Songkhla province, Thailand.

1.4. Research questions

This study seeks an answer to the following questions.

1) Which are the most appropriate locations in the southernmost four districts: Chana, Thepa, Na Thawi and Sabayoi (Songkhla province) for landfill siting?
2) Is the location physically able to accommodate a prospective waste to energy facility?

3) Are the locations selected for landfill sites are suitable for MSW in order to provide a reliable source of clean energy for the local community in future?

1.5. Research significance

The aim of our study is to find the ideal siting locations for MSW landfill in the southernmost disctricts of Songkhla Province, using GIS and AHP. To the best of the authors' knowledge, no previous study has been conducted in the study area to determine potential locations for landfill sites using the AHP approach with GIS.

The only previous study carried out by (Charusiri and Ladachart, 2008) for landfill sites selection used GIS tool by determining geological barriers in Songkhla province, but fails to consider AHP approach and socio-economic parameters in their research.

Therefore, in this present inspection, we are overcoming the shortcomings of Charusiri and Ladachart's study (Charusiri and Ladachart, 2008), using local experts and stakeholders to provide some basis for our AHP calculations, as well as choosing significant factors like morphological, environmental and socio-economic. Therefore, our study will greatly contribute to clean energy from MSW waste to energy facility in future.

1.6. Research scopes

The present study is focused on its aim of identifying the suitable locations for MSW landfill in the southernmost districts: Chana, Thepa, Na Thawi and Sabayoi (Songkhla province). The study hugely relied on the reputation of the online portals and government organizations for the information for most of the secondary data which has been used in this research.

CHAPTER 2

LITERATURE REVIEWS

2.1. Municipal solid waste management

Due to fast growing human population and rapid urbanization, the current level of global population from 7.6 billion is expected to reach a level between 9.5 and 10 billion in 2050 (Singh, 2019). During the recent past, the production of municipal solid waste (MSW) has been substantially increased due to rapid urbanization (Cheng and Hu, 2010; Harris-Lovett et al., 2018; Zhang and Huang, 2014). The present human standard of living has direct connection with this huge amount of municipal waste. Municipal waste disposal is considerably increased from 0.5 kg/person-day to 1.7 kg during the last few decades (Ramayah et al., 2012). Several environmental problems have been noticed in areas where MSW organization failed due to inefficient successful plans (Guerrero et al., 2013). MSW management is a decisive approach in current scenario that has to deal with community needs and poor management of this can create several issues that might have detrimental impacts on human heath due to bugs that cause pathogens, water contamination etc. (Singh, 2019). Along with, increasing soil and air pollution can affect environmental conditions and hinders sustainability (Alavi Moghadam et al., 2009; Kurian Joseph et al., 2012).

Municipal solid waste management (MSWM) services are considered as vital being provided in cities. MSWM services efficiency and quality show the sustainability of communities and cities. According to goal#11 (making cities sustainable, safe, inclusive and resilient) of the 2030 Agenda for Sustainable Development, is among the big challenges faced by the 17 Sustainable Development Goals (SDGs). Hence, defining proper direction for development of sustainable communities and cities is significant. To achieve the goal of reducing the adverse per capita environmental impact of cities relevant targets have been set up as a mechanism that comprise of particular attention to municipal waste management by 2030 (Phonphoton and Pharino, 2019). Solid waste is a crucial environmental problem in urban areas of developing countries. The increasing amount of MSW in urban areas is due to urbanization, growing population, higher income and use of packaging intensively. It has been estimated that worldwide two billion tons per annum urban waste is produced which is expected to increase by nearly 20 % at the end of 21^{st} century as reported by the United Nations Environment Programme Global Waste Management Outlook (Wilson et al., 2015).

MSW has been noticed a critical environmental issues in Thailand as like other developing nations. A total of 27 million tonnes of MSW has produced across the country in 2016, as reported by Pollution Control Department (PCD, 2017a). Thai people generates around 1.14 kg/person/day waste that is higher by comparing to the average figure of middle income countries i.e. 0.79 kg according to World Bank (Hoornweg and Bhada-Tata, 2012). Environmental impacts in the form of water, soil contamination, air pollution that occur mainly due to landfilling and open dumping and are the most the common ways of disposing solid waste in Thailand. (Vassanadumrongdee and Kittipongvises, 2018). The selection procedure of landfill site in Thailand is costly, time consuming and manual that can cause detrimental impacts on environment.

MSW segregation before landfilling has been suggested under the concept of 3Rs (Reduce, Re-use and Recycle) to broaden the landfills operating life span and lessen the environmental effects on stakeholders. Although, local municipal authorities struggle to integrated recycling system within MSWM systems due to limited investment, inadequate technical support and lack of participation as their main reason (Ezebilo, 2013). On the other hand, introducing "Pay as You Throw" (PAYT) scheme as pricing the disposal of MSW has been employed for incentivizing to reduce MSW disposal and for promotion of recyclable materials in various cities having good track records (Challcharoenwattana and Pharino, 2016).

2.2. Challenges in municipal solid waste management

MSWM is among big challenges for municipal authorities which is a significant service provided by a city. Serious issues related to public health, ecosystem, biodiversity, soil, water and air pollution, along with undesirable socio-economic outcomes occur due to uncontrolled and inappropriate management of MSW (Ejaz et al., 2010; Sisto et al., 2017).

To handle the physical waste various options are included in waste management hierarchy. It leads from the most preferred towards least i.e. waste reduction, re-using, recycling, energy recovery and waste disposal. Waste treatment has become the great concern globally among all MSWM strategies due to its impacts on economic development, protection to environment and public health (Mohammadi et al., 2019; Soltani et al., 2015).

Landfilling is the most common waste disposal route adopted globally because of its convenience of execution. A simple definition for landfill site is to dispose waste materials through various practices. Landfill sites are of significant importance for disposal of those waste items that has no useful use or impossible to recycle. Establishing new technologies in order to minimize the amount of waste items governments invest and consume time, but still a big amount of waste items comes from both commercial and residential sector. Hence, it is a big problem in urban development and planning to determine the suitable location for landfill facility, since it comprises of significant effect on environment, economy and ecology of an area. Landfill site selection primary purpose is to identify suitable location that should have minimum effects on the surrounding environment and human health (Kahraman et al., 2018; Uyan, 2014).

2.3. Role of GIS in land suitability analysis process

Geographic Information System (GIS) has been proven a powerful tool for landfill site selection. GIS is a computer-based system that manage, store, analyze and display spatial or geospatial data (Khan et al., 2018). GIS is an important tool in investigating optimal land, keep and control spatial data by integrating numerical and descriptive data with spatial data. In addition, multi-criteria decision making (MCDM) is a well-establish technique that is used to resolve complex decision-making issues in landfill site selection process (Demesouka et al., 2019). Saaty presented a method known as analytic hierarchy process (AHP), a type of MCDM technique, which is used to break down a problem into simple form in the form of a hierarchy, where the goal is a top priority (Saaty, 1990).

GIS combined with AHP method has been preferred by many researchers for landfill site procedure. It has been used widely to investigate hazardous waste landfill siting considering land scarcity for waste disposal (Feo and De Gisi, 2014; Sharifi et al., 2009). It can be utilized for designing an optimal system for storage, collection and transfer of household waste (Dehghani et al., 2018b, 2018a). Many studies have applied GIS-AHP successfully in an optimal siting of solid waste conversion facilities (Babalola, 2018; Hariz et al., 2017; Khan et al., 2018). It can also be employed for land use suitability analysis such as livestock development planning, urban services planning, agricultural purposes, etc. (Akinci et al., 2013; Parry et al., 2018; Qiu et al., 2017). It has been proven to be a powerful tool in evaluation of the aforementioned applications.

2.4. GIS based studies on landfill site selection

O.B Delgado (Delgado et al., 2008) used three spatial decision models for sanitary waste disposal site on regional level in Mexico. GIS was applied for socio-economic and bio-physical analysis. The Boolean logic model showed greater limitations due to evaluation of single attributes but easier to perform. On the contrary, binary evidence and overlapping index models needed attribute weightings but comparatively much complex. In this study only one region which was categorized highly suitable while 1.5 to 5% area was found most suitable. Mexican regulations lack socio-economic standard which is necessary for economic feasibility of landfill siting. Thus, this methodology proposed an economical option for decision makers in developing countries.

Sehnaz Sener (Şener et al., 2011) executed GIS and AHP technique for feasibility study of landfill siting in Senirkent-Uluborlu Basin, Turkey. In this research ten distinct parameters namely water bodies, lithology, water aquifer, land area, lineaments, feature, terrain elevation, land scope and road network were investigated for waste disposal site selection. For weighting individual criteria, AHP methodology was analyzed. Using GIS, suitability map produced through overlay analysis. According to resulting maps, unsuitable, moderately suitable and most suitable areas were found to be 96.3%, 1.6% and 2.1% respectively. Finally, feasible areas were identified for solid waste disposal sites.

Ahmad Al-Hanbali (Al-Hanbali et al., 2011) implemented GIS based weighted linear combination (WLC) analysis and remote sensing techniques for waste disposal sites in Mafraq city, Jordan. Vector and raster formats were used for collection of data. Landsat satellite was used for obtaining data during selection of landfill siting. Approximately 84% land area was found “most suitable” to “moderately suitable” for waste disposal sites whereas 16% area was included in “poorly suitable” and “unsuitable” category. The outcomes of their study showed three optimum locations which provided useful information for planner and decision makers for selection of waste disposal sites.

Demesouka (Demesouka et al., 2013) has used combined GIS-AHP and compromise-programming methods to evaluate the suitability of potential MSW landfill sites in Greece considering hydrogeology, geology, morphology, environmental, socio-economic, technical and economic factors.

Ali Jalil Chabuk (Chabuk et al., 2017) has employed a scientific selection criteria using GIS in Iraq to solve the problem of the selection landfill sites. To find optimal solution for disposal of solid waste, two methods of MCDM i.e. analytic hierarchy process (AHP) and simple additive weighting (SAW) were applied to obtain the weights for the criterion’s maps using GIS to get potential landfill sites. Comparing the results of both methods determined two suitable candidate landfill sites.

T. Kontos (Kontos et al., 2005) used GIS to execute spatial statistics and spatial clustering process to find out the most feasible locations for waste disposal site. To mitigate siting problem into a decision making form, multi-criteria analysis (MCA) was applied. In this study landfill siting issues were analyzed by using Analytic Hierarchy Process (AHP) and Simple Additive Weighting (SAW) approaches in order to find the relative importance weights and compute the suitability indexes respectively.

Mevlut Uyan (Uyan, 2014) studied combined GIS-AHP for MSW landfill site selection for Konya, Turkey. Multi-criteria evaluation method to find suitable landfill site that should have minimum detrimental impacts on environment and human health. The author inspected that 50.72 % of the area is highly suitable for landfill site construction whereas rest of the area is moderately, low and unsuitable.

W. Guiqin (Guiqin et al., 2009) manipulated spatial information technologies and analytical hierarchy process (AHP) during a case study in Beijing, China for selection of landfill site. In this study, a hierarchy model was presented on the basis of environmental and economic factors for selection of optimal site for solid waste landfill. Grading system was applied from 1 (less suitable) to 5 (more suitable) by considering 9 parameters and a buffer zone was set for each parameter such as for residential areas and water bodies, buffer zones more than 2000 m were graded as 5. Similarly, for protected lands (airport), buffer zones more than 12000 m were ranked as 5 while in case of land cover, agricultural and free land was graded as 5. Slope of the land was computed through digital elevation model (DEM) whereas areas with range of 0 to 10% slope were given highest score. For highways and railways, a buffer zone of 500 m was applied while nearness to waste centers within 500m radium was graded as 5. Landfill site selection was divided as ‘best’, ‘good’ and ‘unsuitable’ whereas best areas for landfill showed optimal locations while good areas for waste disposal represented as back-up candidate locations. This study proposed a methodology for site selection and presented important support for investors and decision-makers in the evaluation of issues coming is waste management in Beijing and for fast growing cities in developing regions.

M. Eskandari (Eskandari et al., 2012) applied an integrating multi-criteria approach in Marvdasht, Iran, for waste disposal siting in a contradictory position among environmental, economical and socio-cultural classification. This study was done on the basis of sampling and questionnaire opinion from experts well known from regional conditions, the local environmental and worldwide laws. GIS-database was established on the basis of selected criteria i.e. 13 constraints and 15 factors by considering environmental, economical and socio-cultural categories. In this study standardization and weighting criteria were performed while AHP and rank order methodology on the basis of expert’s views were analyzed for the relative importance weights of criteria and sub-criteria estimation respectively. For getting suitability results for wastes disposal siting, simple additive weighting technique was implemented and thus final suitability result was achieved by crossing the resulting maps in a contradictory situation among environmental, economical and socio-cultural classification for landfill structure.

Mahdi Khodaparast (Khodaparast et al., 2018) find out MSW landfill site locations considering a case study in Qom city, Iran, by applying integrated GIS-

AHP tool. The authors selected several main factors including: geomorphology-hydrography, environmental-social factors and design criteria which were further divided into sub-categories. These criteria were selected according to regional condition after taking opinion of experts. The outcomes of the study after applying AHP and WLC indicated that only 7 % of the area was found with appropriate condition for landfill siting and later the field inspection confirmed this.

CHAPTER 3

STUDY AREA

3.1. Study area description

Songkhla is one of the provinces of southern Thailand that is situated near the Malaysian border, covering an area of 7,394.9 km^2 and more than 1.5 million populations according to National Statistical Office of Thailand. It lies at distance of 968.3 km from Bangkok towards the south and is ranked 26th among other provinces of Thailand. Geographically, it is located at 7.1988^0 North (latitude) and 100.5951^0 East (longitude).

In this study, four major districts of Songkhla province has been inspected namely: Na Thawi, Sabayoi, Chana and Thepha (see Fig. 3.1). Na Thawi has covered an area of 619.8 km^2 which is divided into 10 sub-districts and is further sub-divided into 92 villages. Similarly, the total area of Sabayoi is covering 852.81 km^2 and comprises of 10 sub-districts and 92 villages. Along with this, Chana has covered 502.98 km^2, having 14 sub-districts and 139 administrative villages. Finally, Thepha has covered an area of 978.0 km^2 and has 7 sub-districts and 65 villages.

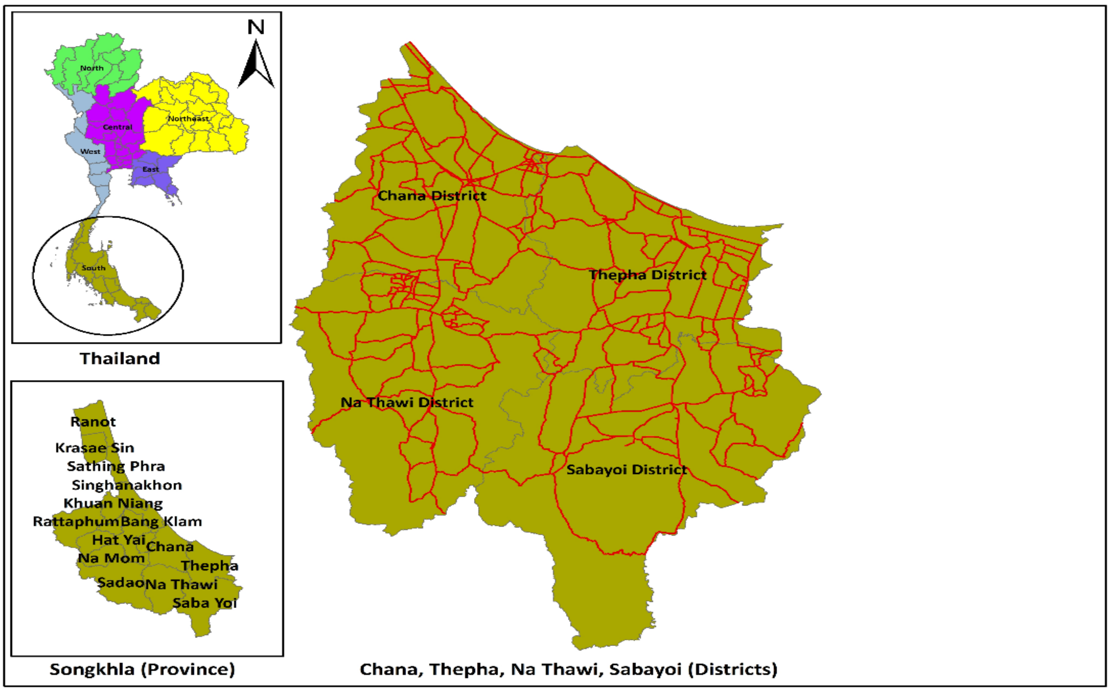

Fig. 3.1 The inspected area: southernmost districts of Songkhla (Southern Thailand)

3.2. Waste management issues in Thailand

It has been estimated that each person in Thailand generates 1.14 kg of solid waste per day, out of which 50 % is biodegradable (Post, 2016). As stated by Pollution Control Department (PCD), around 27 million tonnes of solid waste has been generated in Thailand in 2016 (PCD, 2017b). Due to growing population and tourism, Thailand is facing severe solid waste management issues. As reported by PCD, the volume of solid waste could be expected to increase up to 0.6 million tonnes a year (Mala, 2016). Thailand waste management plan has announced that 75 % of the total solid waste generates in the country has to be recycle or properly disposed by 2021. For this purpose, Thai government and private sector has planned to spend a budget of total of 177 billion Baht on public awareness campaigns and waste-to-value technologies (Charoenrut, 2018).

3.3. Waste composition of the study area

Songkhla province hosts a lot of tourists each year due to its borders with Malaysia. Therefore, hundreds of tonnes of waste per day is generated in Songkhla province, comprise of waste from four major districts which are Sabayoi, Na Thawi, Chana and Thepha. All of these districts are covering large land areas and populations which generates around 228 tonnes of MSW/day (Buranasing, 2015). As reported in 2015, various MSW types are comprise of food (60 %), plastic (25 %), glass (5 %), gardening waste (5 %), paper (2 %), polystyrene (2 %) and metal (1 %) (REO, 2016). The selection of some existing waste disposal sites in the aforementioned districts of Songkhla were on manual basis, hence, created severe health issues to the nearby local people. Due to this reason, the local people have become susceptible to the NIMBY (*Not-in-My-Backyard*) syndrome. A recent example was found in Chana, where the local residents strongly opposed the construction of a waste transfer station. Therefore, a comprehensive scientific based study can only be helpful in regaining the public confidence.

CHAPTER 4

RESEARCH METHODOLOGY

4.1. Methodology overview

Fig. 4.1. is showing the workflow of the methodology for landfill site selection. In this study, the first step was to inspect study area which include four southernmost districts (Chana, Thepha, Na Thawi and Sabayoi) of Songkhla province. In the next step, a comprehensive literature review related to municipal solid waste, municipal solid waste management, landfill sites, GIS and AHP was carried out. In the third step, data from various online portals and government organizations was collected which was converted into shapefile. In the fourth step, selection of criteria that involved the main criteria, sub criteria and sub-sub criteria was carried out on the basis of reading international literature, national and international guidelines and experts' opinion. In the fifth step, regional experts' interviews paper-based questionnaires were conducted to confirm the criteria selected according to the study area and to achieve scoring for the AHP approach. In the sixth step, weights for criteria, sub-criteria and sub-sub criteria was measured using AHP approach. In the seventh step, multi-criteria decision making (MCDM) was applied under integrated GIS-AHP approach. In final stage, suitable locations were identified for landfill siting after applying the aforementioned steps.

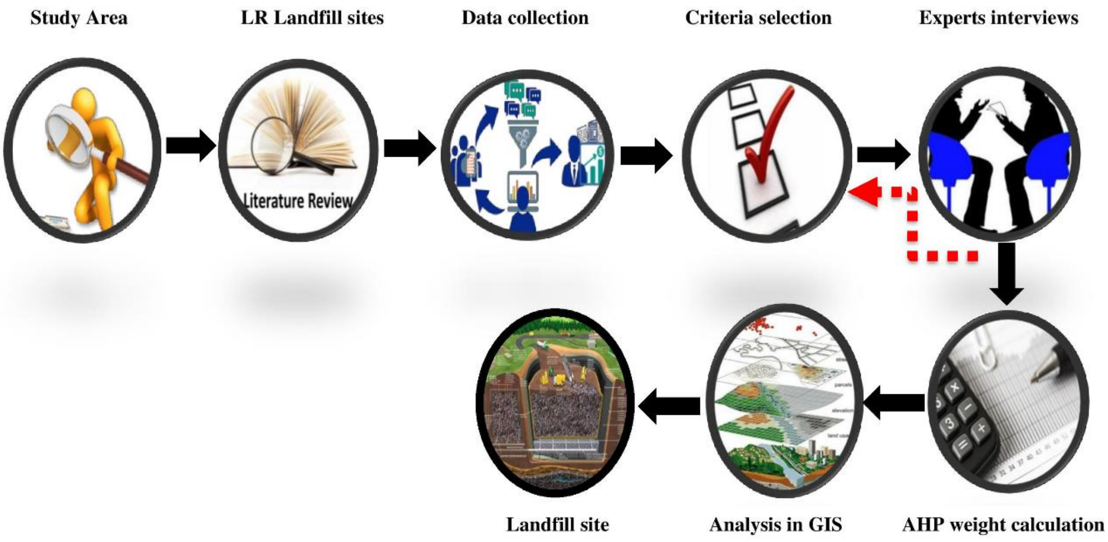

Fig. 4.1 Methodology overview of this study

4.2. Data sources

The main aim of this research was to assess ideal locations for MSW landfill siting. This study was conducted by considering previous literatures, existing legislations and questionnaire results of local experts' judgement.

Criteria selection was carried out on the basis of these factors which included three main criteria (morphological, environmental and socio-economic) and various sub-criteria and their attributes. After criteria selection, data sets related to slope, elevation and surface water were obtained from Royal Thai Survey Department of Thailand (RTSD, 2018) and converted into digital format. The available information on groundwater table were collected in descriptive format from Department of Groundwater Resource Songkhla, Thailand (DGR, 2018) and were mapped in GIS environment. Data related to road network, residential areas, surface water, land use and soil texture were obtained from the Land Development Department, Thailand (LDD, 2014). Slope and elevation contour lines data was got from Royal Thai Survey Department (RTSD, 2018). Thailand Flood Monitoring System online portal was accessed for floodplain data (GISTDA, 2018). In last, the geological fault areas and historical places data was attained from Department of Mineral Resources and Southern Regional Center of Geo-Informatics and Space Technology Development Agency (GISTDA), Thailand, respectively. Various criterion data sets, their formats and sources of data are demonstrated in Table 4.1.

Table 4.1 List of data sets, their formats and sources of data.

Dataset	Format	Spatial resolution	Source of data	Edited source
Slope	Raster to Vector conversion	30 m	Royal Thai Survey Department, 1999 (RTSD, 2018).	Southern Regional Centre of Geo-Informatics and Space Technology Development Agency, Prince of Songkla University (PSU) (2017) (FEM, 2017).
Elevation	Raster to Vector conversion	30 m		
Surface water	Vector	500 m		
Road network	Vector	500 m		
Soil texture	Vector	500 m	Land Development Department, 2002 (LDD, 2014).	
Residential areas	Vector	500 m		
Land use	Vector	500 m		
Aquifer	Vector	250 m	Bureau of Groundwater Resources Region 12 (Songkhla), 2018 (DGR, 2018).	
Groundwater table	Excel, X, Y Coordinates	GIS Spatial Interpolation		
Geological fault areas	Vector	250 m	Department of Mineral Resources, 1985 (DMR, 2016).	
Floodplain	Vector	100 m	Geo-Informatics and Space Technology Development Agency (GISTDA, 2018).	
Waste production centres	Excel, X, Y Coordinates	Imported to GIS	Office of Environment Region 16 (Songkhla), 2016.	

Dataset	Format	Spatial resolution	Source of data	Edited source
Historical places	Vector	500 m	Southern Regional Centre of Geo-Informatics and Space Technology Development Agency, PSU 2017 (FEM, 2017).	

4.3. Site selection criteria for landfill

In this study, thirteen input map layers such as slope, elevation, soil texture, aquifer, groundwater table, surface water, geological fault areas, flood plain, road network, waste production centers, residential areas, historical places and land use were selected for assessment of landfill suitability map. Criteria selection in any site selection project is significant part of the assessment because sites' reliability primarily depends on these factors. Therefore, consultation with local experts and reading relevant international literature were reviewed for selecting various criteria (Bosompem et al., 2016; Chabuk et al., 2017; Feo and De Gisi, 2014; Motlagh and Sayadi, 2015; Spigolon et al., 2018).

The selected criteria were classified into three main groups: morphological, environmental and socio-economic which had been selected as the main criteria in this research, with sub and sub-sub criteria in a hierarchical structure.

The first group comprised of morphological criteria which are associated with morphological characteristics and soil texture of the study area. This criterion has been selected as to make sure low groundwater pollution threat against leachate contaminations and reduction of landfill construction and operation costs (Demesouka et al., 2013).

The second group included environmental criteria that should be the foremost concern in landfill siting because various contaminants are released from MSW landfills to the surroundings via landfill gas or landfill leachate, which present a major threat to the environment, causing permanent deterioration of environmental quality (Krčmar et al., 2018).

The third group encompassed socio-economic criteria of the study area's ecology which aim is to protect aesthetic and economic deterioration of the candidate sites on account of the execution of MSW landfills (Demesouka et al., 2018).

4.3.1 Selection of Experts panel

In this research, regional experts (south of the Thailand) who were familiar with local conditions, were selected. The experts were researchers, engineers, university professors, stakeholders and government officers with a strong background knowledge of municipal solid waste management. The aim of including experts' opinion was to validate the literature studied for the proposed work, as well as to lessen the conflicts of interest and personal bias in assigning values to parameters and site selection. The final list of experts and their affiliated organization, country, educational background and discipline are listed in Table 4.2.

Table 4.2 The background of experts' panel.

Group	Organization	Country	Discipline
Academia	Prince of Songkla University	Thailand	Energy conservation and renewable energy
	Prince of Songkla University	Zimbabwe	Environment
	Prince of Songkla University	Pakistan	Renewable energy
	Thammasat University	Thailand	Economics
Government	Regional Environmental Office	Thailand	Environment and climate change
	Regional Environmental Office	Thailand	Environment
Private	Development of Environment and Energy Foundation	Thailand	Waste management
Industry	Zero Waste Company Limited	Thailand	Renewable resources and environment
	Municipality Solid Waste-to-Energy Power Plant	Thailand	Engineering
	Municipality Solid Waste-to-Energy Power Plant	Thailand	Construction

4.3.2. Morphological features

4.3.2.1. Slope and elevation

Slope and elevation are the two important parameters in the establishment of a landfill site (Kontos et al., 2005). Steep slopes and high elevation surfaces are considered unsuitable for siting a landfill and, also, very steep slope will require higher excavation costs (Guiqin et al., 2009; Kahraman et al., 2018; Şener et al., 2010). Excessive steep slope would cause complications in constructing a landfill site while too flat surface areas would influence on runoff drainage (Nas et al., 2010). Hence, various researchers have been suggested that land slopes between 0^0 to 10^0 would be appropriate for establishing a landfill sites (Chabuk et al., 2017; Effat and Hegazy, 2012; Şener et al., 2011, 2010).

The term ‘elevation’ means the height above the sea level which may vary from area to area. Landfill site far above the sea level are inappropriate due to high transportation costs whereas location of landfill sites near to sea level can cause high risk of flood and water bodies infection (Demesouka et al., 2013). More details are included in Table 4.3.

4.3.2.2. Soil texture

Soil is very important and it has greater influence on the amount of groundwater recharge that can go through ground, and can cause groundwater pollution. Silt and clay soil has the ability to decrease the relative soil permeability because it contains fine particles and can also restrict the pollutants movement (Lee, 2003). Sand and sandy loam are highly permeable soil (unsuitable), whereas, clay and clay loam are low permeable soil (suitable), and sandy clay are relatively low to medium permeable soil (fairly suitable) (Aydi et al., 2013; Bahrani et al., 2016). Clay-rich soil containing greater than 50 % clay, very low soil permeability i.e. 0.05 meters/day or less than this and high soil thickness should be considered for constructing landfill site. Sandy soil should not be used for landfill sites due to high porosity and high permeability rate of water, and it can also affect water quality in area nearby landfill (Motlagh and Sayadi, 2015), hence, silty clay has been suggested as the best soil texture which is followed by silty sand (see Table 4.3).

4.3.3. Environmental Features

4.3.3.1. Hydrogeology

Aquifers

It is significant to place a landfill site in areas having shallow groundwater contamination risk. Several factors such as the permeability of aquifers units and the aquifer properties are used to determine groundwater contamination from landfills. In this study, data related to aquifers were obtained from the Department of Groundwater Resources, Songkhla. Based on the assessment of local geologists, seven aquifers units were formed which are namely; colluvial deposits, granitic, carboniferous metasedimentary, old terrace deposits, lampang, floodplain deposits and triassic carbonate. Lampang has preponderance of sand which makes it highly potential for water absorption and was categorized as permeable. Colluvial deposits and old terrace deposits have limited potential of water absorption and were categorized as semi-permeable due to presence of sand, gravel and clay from old river deposits. Granitic, carboniferous metasedimentary, floodplain deposits and Triassic carbonate consist of clay, rock and shale content which make them impermeable and were evaluated as highly suitable for landfill sites construction (see Table 4.3).

Groundwater table

Groundwater table has significant importance in landfill site selection process. Construction of landfill site nearby area where the groundwater level is sufficiently low, while site nearby area where the groundwater level is high, require a special design. To determine the depth of the groundwater table, an inverse distance weighting (IDW) method in GIS environment was applied to the water level data. In this study, 671 existing wells data was obtained from Department of Groundwater Resources to establish groundwater table and groundwater depth readings were applied to inspect the potential landfill sites. Further details are included in Table 4.3.

Surface water

Landfill sites should not be placed nearby surface water i.e. rivers, ponds, streams and lakes as it produces leachate and poisonous gases (N. Alavi et al., 2013; Colvero et al., 2018; Demesouka et al., 2018; Gbanie et al., 2013; Kahraman et al., 2018; Motlagh and Sayadi, 2015; Nas et al., 2010; Simsek et al., 2014). According to Pollution Control Department (PCD, 1998), at least a minimum of 300 m buffer zone should be kept for man-made water body or any kind of natural and, increasing the distance from water sources can make landfill sites more suitable (Motlagh and Sayadi, 2015). Further details are included in Table 4.3.

4.3.3.2. Geology

Geological fault areas

As reported by the Pollution Control Department (PCD, 1998), active geological formations or other subsurface topographies are unsuitable for landfill sites construction. Hence, landfill construction is not recommended in areas with dormant or active faults (Eskandari et al., 2012). Fault areas should be avoided as it plays an important role to prevent pollution which might be occurred due to seismic activity (Gorsevski et al., 2012). Fault areas increases the permeability of rocks and hence can cause groundwater pollution due to leachate (Moeinaddini et al., 2010). Unstable land area and seismic risk are important factors for decision makers while determining landfill sites (Demesouka et al., 2013). Moreover, landfill sites are not feasible in areas which have active or potentially active landslides (Motlagh and Sayadi, 2015). To reduce the possibility of natural disasters, it is essential to place landfill sites at a location distant from fault lines (Kahraman et al., 2018). Hence, a 300 m buffer zone was created around geological fault areas, as shown in Table 4.3.

Floodplain

Construction of landfill site is not recommended in areas where frequent or periodic flooding happens as reported by the Pollution Control Department (PCD, 1998). A landfill should not be placed nearby floodplain as it could cause overland drainage pollution (Lin and Kao, 2005). Floodplains of major rivers cause severe damage and effect the stability of the waste disposed in the landfill, hence, areas falling under 100-years floodplain are unsuitable for landfills. Therefore, landfill should not located within 300 m range where major rive exist (Bagchi, 2004; Şener et al., 2010; Simsek et al., 2014). Although, the secondary streams floodplains can be applied for landfills by establishing an embankment (Bagchi, 1994). Further details related to floodplain are included in Table 4.3.

4.3.4. Socio-economic features

4.3.4.1. Accessibility

Road network

A buffer zone of 1000 m from road network has been recommended for siting a landfill site by various researchers (Al-Hanbali et al., 2011; Baban and Flannagan, 1998; Chang et al., 2008; Delgado et al., 2008b). Considering transportation costs, the landfill sites should not be located far away from the road network. Moreover, the suitability ranking declines by moving away from road network (Kahraman et al., 2018; Uyan, 2014b; Yal and Akgün, 2014). For small operations, there should be 5 m wide road while for larger landfills, it should be 6 to 8 m wide (Ersoy et al., 2013). Moreover, traffic streams should not be obstructed by garbage trucks (Guiqin et al., 2009). A buffer zone of 250 m was considered for road networks in this study. Further details are included in Table 4.3.

Waste production centres

Proximity of a landfill site near to waste production centre will reduce transportation costs because economic feasibility of a candidate landfill site is an important factor (Guiqin et al., 2009; Kahraman et al., 2018). In addition, constructing landfill site far away from the waste production centre is not acceptable as it would require long distance for garbage trucks (Demesouka et al., 2013). In this research, the distance between all the existing landfills, waste production centres and candidate landfill sites was inspected. The data regarding waste production centres and existing landfills were acquired from the Regional Environmental Office (Songkhla), and it was analyzed that candidate landfill sites nearby waste production centres and existing landfills would be highly feasible (see Table 4.3).

4.3.4.2. Public places

Residential areas

This is an important criterion due to public opposition which is known as NIMBY syndrome and is mainly responsible to restrict the number of feasible locations for landfill siting. Constructing of landfill site nearby public areas can cause various environmental problems concerning health issues, land prices and prospective urban planning development (Kahraman et al., 2018; Nas et al., 2010; Şener et al., 2010). Siting a landfill site within 500 m distance from residential area is unacceptable according to European regulations (Demesouka et al., 2018, 2013; Gorsevski et al., 2012). Moreover, international literature (Chabuk et al., 2016; Ersoy and Bulut, 2009; Nas et al., 2010; Şener et al., 2010; Uyan, 2014b) and experts judgement recommended that landfill site should not be placed within 1000 m distance nearby residential areas. Therefore, to avoid public opposition, a 1000 m buffer zone was considered for residential areas in this study (see Table 4.3).

Historical places

The study area has included some important historical places such as temples, mountain tunnels, waterfalls and national park. Any ancient monument as defined under the Ancient Monuments, Antiques and National Museum Act of 1961 is inappropriate for landfill sites, as reported by the Pollution Control Department (PCD, 1998). According to PCD and international literature, construction of landfill sites at a distance of less than 1000 m from historical places is prohibited (Chabuk et al., 2016; Kahraman et al., 2018; Uyan, 2014b; Yildirim, 2012). Therefore, 1000 m buffer zone was created around all historical place using GIS software (see Table 4.3).

4.3.4.3. Land type

Land use

Land use portrays human's use of landscape and natural environs. Land use classes has been categorized into agricultural, forests, industrial, residential, archaeological and military (Simsek et al., 2014). (Gorsevski et al., 2012) divided land use into forest, water, agricultural and barren land while (Nadali Alavi et al., 2013) categorized it into agricultural, industrial, residential and unused land. Although, (Kontos et al., 2005) separated pasture and agricultural lands whereas (Chabuk et al., 2016) determined unused lands and orchards as the most feasible areas for landfill siting. The purpose of this criterion is to keep safe underdeveloped and highly productive lands to make sure low capital costs. Hence, mixed forests and residential areas were evaluated as unsuitable for landfill siting, including tourist areas as inappropriate. Industrial areas were considered very important due to its role in development of a region and were categorized as moderately suitable whereas orchards and agricultural lands were classified as highly suitable for siting landfills. In this study, pasture and grasslands were considered as the most highly suitable areas for siting landfills (see Table 4.3).

Table 4.3 MSW landfill site location selection criteria.

Factors	**Ranges**	**Suitability ranking**
Slope (degree)	0-5	3
	5-10	2
	10-15	1
	>15	0
Elevation (m)	0-40	3
	40-80	2
	80-120	1
	>120	0
Soil texture	Silty clay	3
	Clay	2
	Mixed soil	1
	Sandy / Gravelly	0

Factors	Ranges	Suitability ranking
Aquifer	Carboniferous metasedimentary	Impermeable
	Granitic	
	Triassic carbonate	
	Floodplain deposits	
	Colluvial deposits	Semi-permeable
	Old terrace deposits	
	Lampang	Permeable
Groundwater table (m)	>4.5	3
	4.5-3	2
	3-1.5	1
	1.5-0	0
Surface water (m)	>900	3
	900-600	2
	600-300	1
	<300	0
Geological fault areas (m)	>500	3
	500-400	2

Factors	Ranges	Suitability ranking
	400-300	1
	<300	0
Floodplain	Non-floodplain	3
	Floodplain	0
Road network (m)	>1000	3
	1000-750	2
	750-250	1
	<250	0
Waste production centres (m)	<2000	3
	2000-4000	2
	4000-6000	1
	>6000	0
Residential areas (m)	>2000	3
	2000-1500	2
	1500-1000	1
	<1000	0

Factors	Ranges	Suitability ranking
Historical places (m)	>2000	3
	2000-1500	2
	1500-1000	1
	<1000	0
Land use	Grassland / Pastureland	3
	Agricultural land / Orchard land	2
	Industrial area	1
	Mixed forests / Tourist areas / Residential areas	0

4.4. Integrated GIS-AHP applications

Since the morphological, environmental and socio-economic criteria are partially or totally contradictory, diverse in nature and represented in different units. Hence, the integration of MCDM method and GIS tool was applied by various researchers for landfill site selection (Demesouka et al., 2018, 2013; Feo and De Gisi, 2014; Gbanie et al., 2013; Motlagh and Sayadi, 2015). Integrated MCDM with GIS is an intelligent method to get valuable information through exploitation and conversion of spatial and non-spatial data which can be used to deal with critical decision after the judgement of the decision maker (Chen et al., 2010; Gbanie et al., 2013; Sumathi et al., 2008).

In this research, the main purpose of using MCDM in a GIS environment is to assess the most feasible locations for landfills siting. Various criteria weights were assigned using MCDM. Each criterion was assigned a weight after conducting meeting with experts and stakeholder's familiar with local scenario. Taking into consideration the local situation of the MSWM sector and lack of organized scientific approaches and technical skills accessible in the four districts (Na Thawi, Saba Yoi, Chana, Thepha) of Songkhla province. Hence, (Chang et al., 2008; Demesouka et al., 2013; Gbanie et al., 2013; Kahraman et al., 2018) used 2,3 and 5 experts judgement in their previous studies. In this study, a total of 10 experts from various fields such as provincial environmental agency, local administration office, soil science, mining and materials engineering, civil engineering, sociology, operators of the waste-to-energy power plant (Hat Yai) and stakeholders were considered. Experts and stakeholders ranking exhibited the importance of criteria for them. For example, environmental issues should assign first priority because they are more significant for environmental scientists. On contrary, stakeholders and sociologists insisted on important issues such as waste disposal expenses and aesthetic places in the study area. Whereas, civil engineers and soil science experts emphasized on the topographic condition of the area that neglecting morphological criteria would ultimately lead to failure any landfill site project. To avoid conflicting problems political groups were not included.

In this study, AHP approach has been used to calculate the weights for the main criteria, sub-criteria and sub-sub criteria (attributes). AHP combined with GIS is a widely applicable decision making method for inspection of feasible landfill sites. Three basic steps are essential for execution of AHP method (Saaty and Vargas, 2001). In first step, the decision making problem is break down into a hierarchical structure. The hierarchical structure steps for this study can be seen in Figure in Fig. 4.2.

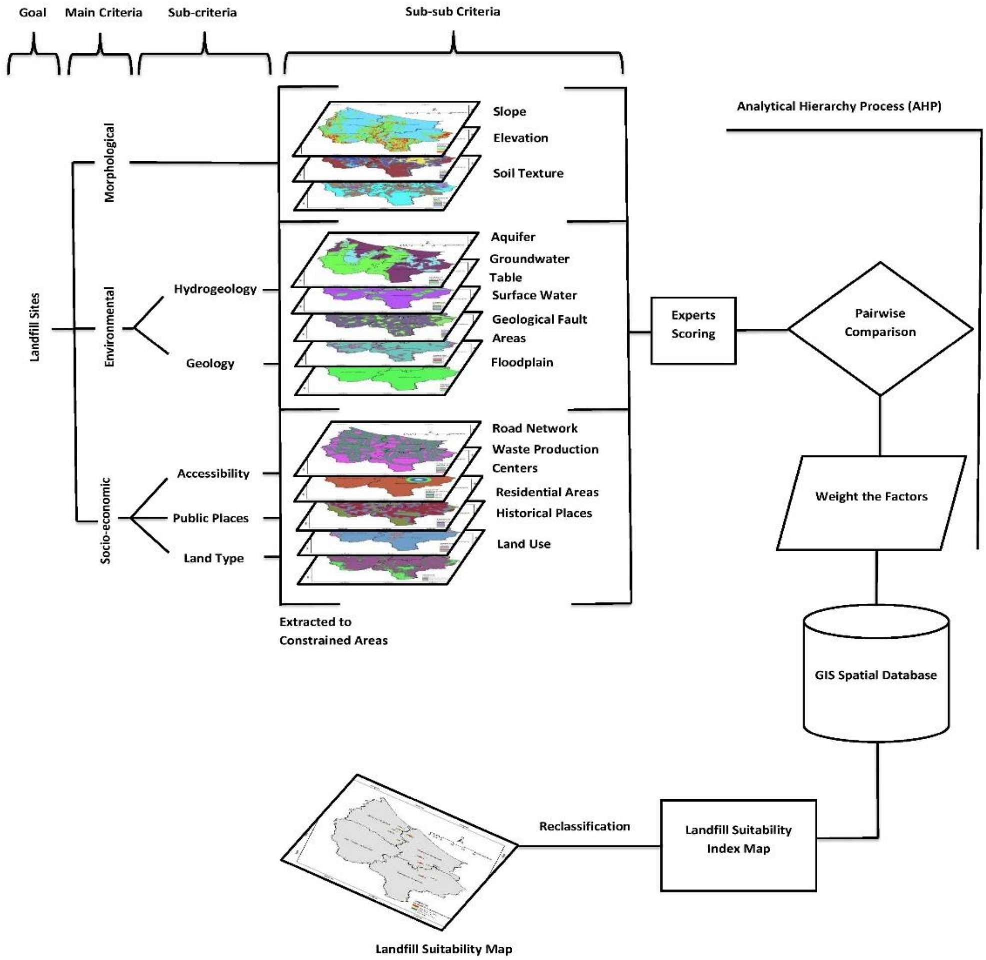

Fig. 4.2 Flowchart of the methodology (adapted source (Şener et al., 2011))

To determine the weights for various criteria, the next step in AHP is to apply pairwise comparison. The weight of a particular criterion is determined by ranking their importance and suitability. Experts judgement completes the evaluation process of the pairwise comparison. (Saaty, 1990) has described a 9-point scale for comparison of various criteria which can be seen in Table 4.4.

Table 4.4 The pairwise comparison scale in AHP (Saaty, 1990).

Intensity of Importance	**Definition**	**Explanation**
1	Equal importance	Two criteria contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favour one activity over another
5	Strong importance	Experience and judgment strongly favour one activity over another
7	Very strong importance	An activity is favoured very strongly, and its dominance is demonstrated in practice
9	Extreme importance	The evidence favouring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values	When compromise is needed
Reciprocals	If one activity, *i* has one of the above activities assigned to it when compared with activity *j*, then *j* has the reciprocal value when compared with *i*	

The pairwise comparison 9-point scale introduced by Saaty was employed in this study (see Table 4.4). To derive a square matrix ($\boldsymbol{Mx}$) for pairwise comparison of various criteria that are applicable in siting a landfill was used as expressed in equation (1). Ten experts who were familiar with local situation, judged the criteria for further evaluation.

$$Mx = \begin{bmatrix} C_{11} & C_{12} & C_{13} & \dots & C_{1n} \\ C_{21} & C_{22} & C_{23} & \dots & C_{2n} \\ C_{31} & C_{32} & C_{33} & \dots & C_{3n} \\ \dots & \dots & \dots & \dots & \dots \\ C_{n1} & C_{n2} & C_{n3} & \dots & C_{nn} \end{bmatrix} \tag{1}$$

$\boldsymbol{Mx = [Cij]}\ \forall\ \boldsymbol{i, j = 1, 2, 3, \dots, n}$ for $\boldsymbol{n}$ criteria that impact the final goal of this study. $\boldsymbol{Cij}$ validates the relative importance of the criteria such as $\boldsymbol{Ci}$ over $\boldsymbol{Cj}$ and the reciprocal will be $\boldsymbol{Cji}$ or $\boldsymbol{1/Cij}\ \forall\ \boldsymbol{i \neq j}$ and $\boldsymbol{Cii = 1}$ (Saaty, 1990). Applying the matrix as in equation (1), the main criteria, sub-criteria and their attributes were calculated. Similarly, the individual eigenvector linked with the principle eigenvector of the reciprocal ratio matrix was normalized to measure the weights. Lastly, all criteria weights and their ranking values were normalized to '1'. In this study, AHP method was applied and experts' judgments inspected the final weights for landfill site selection (see Table 4.5). Also, see Appendix A for pairwise comparison.

Table 4.5 Significance weights of main criteria, sub-criteria and sub-sub criteria.

Main criteria	**W1**	**Sub-criteria**	**W2**	**Sub-sub criteria**	**W3**	**Final weight**
Morphological	0.2231	Slope	0.3515	Slope	1	0.0784
		Elevation	0.3222	Elevation	1	0.0719
		Soil texture	0.3261	Soil texture	1	0.0727
Environmental	0.4958	Hydrogeology	0.6666	Aquifer	0.1527	0.0504
				Groundwater table	0.4318	0.1427
				Surface water	0.4154	0.1373
		Geology	0.3333	Geological fault areas	0.625	0.1033
				Floodplain	0.375	0.0619
Socio-economic	0.2809	Accessibility	0.3005	Road network	0.5	0.0422
				Waste production centers	0.5	0.0422
		Public places	0.4757	Residential areas	0.75	0.1002
				Historical places	0.25	0.0334
		Land type	0.2237	Land use	1	0.0628

Key: W1: weight of layer 1, W2: weight of layer 2, W3: weight of layer 3, Final weight= W1*W2*W3, CR: consistency ratio ≤ 0.1.

The consistency ratio was checked in the final step because involvement of experts' judgements may cause inconsistencies. For this purpose, Saaty introduced a measure that is known as consistency ratio (CR), to evaluate the level of inconsistencies (Saaty, 1990). Previous researchers who deal with MSWM applications used this widely (Chabuk et al., 2016, 2017; Eskandari et al., 2015; Gorsevski et al., 2012; Khan et al., 2018; Moeinaddini et al., 2010). To calculate CR, the mathematical expression is given by equation (2):

$$\mathbf{CR} = \frac{\mathbf{CI}}{\mathbf{RI}} \tag{2}$$

CI represents consistency index where ***RI*** is the mean consistency index or random index. *CI* can be calculated by using equation (3):

$$\mathbf{CI} = \frac{\boldsymbol{\lambda}\mathbf{max} - \mathbf{n}}{\mathbf{n} - \mathbf{1}} \tag{3}$$

$\boldsymbol{\lambda max}$ indicates the principle eigenvalue and $\boldsymbol{n}$ is representing the matrix size in a pairwise comparison. *RI* values depend on the matrix size (Şener et al., 2011; Ying et al., 2007) while the values used for various matrix sizes are shown in Table 4.6.

Table 4.6 ***RI*** values for dssifferent matrix sizes (Donegan and Dodd, 1991).

n	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
RI	0.00	**0.00**	**0.58**	0.90	1.12	1.24	1.32	1.41	1.45	1.49

In order to keep the consistency of the matrix, *CR* values should be retained at less than 10 % (Şener et al., 2010). Although, consistency greater than 10 % shows inconsistency in experts' decision which needs re-evaluation. In this study, the *CR* values calculated was 5 % for morphological, 3 % for environmental and 2 % for socio-economic criteria. All the *CR* values measure were less than 10 % that shows that the weights given based on experts' judgement were appropriate. As stated by Saaty, keeping the number of factors into small group, maintaining the homogeneity of factors within individual group and analyzing the problem bitterly, can improve the *CI* (Saaty, 1993).

Weighted linear combination (WLC) technique is based on MCDM which is applied in GIS environment to aggregate the calculated weights of various criteria. In this study, multiple map layers and their various weights were combined in ArcGIS 10.3.0 tool using the WLC technique. Previous studies applied this technique widely for landfill site selection (Gbanie et al., 2013; Gorsevski et al., 2012; Motlagh and Sayadi, 2015; Shahabi et al., 2014). To bring the distinct data layers together into a common scale spatial resolution, a base map of 500 m was used for the entire data set of the study area. In this study, a 4-point scale was used for suitability analysis to rank the various criteria selected such as 3 showed 'very highly suitable', 2 showed 'highly suitable', 1 showed 'moderately suitable' and 0 showed 'unsuitable' as given in Table 4.1. Subsequently, the GIS overlay tool was used to overlay the multiple map layers having different weights. Finally, the total suitability was measured by summing the weight of various criteria as expressed in the mathematical equation (4):

$$\mathbf{SI} = \sum \mathbf{w_i s_i} \qquad (\mathbf{4})$$

$\mathbf{SI}$ = suitability index for area, $\mathbf{w_i}$ = weight of criterion $\mathbf{i}$, $\mathbf{s_i}$ = standardized suitability score of criterion $\mathbf{i}$. This permitted to merge the distinct data layers to achieve the stated objective.

CHAPTER 5

RESULTS AND DISCUSSION

5.1. Overview and AHP calculation results

This is the first-ever study carried out in the study area to identify potential locations for landfill sites using an integrated GIS-AHP approach in the four southernmost districts of Songkhla province, Thepa, Na Thawi, Sabayoi and Chana. In total, thirteen parameters were selected under morphological, environmental and socio-economic perspective on the basis of local experts' judgement and international literature. ArcGIS 10.3.0 tool was used for preparing the map for each criterion, applying the weights measured from AHP calculation, which highly relied on the experts' judgement. In this study, the weight calculated are given in Table 5.1.

Table 5.1 Final weights for landfill sites.

Main criteria	Sub-criteria	Sub-sub criteria	Final weight
Morphological	Slope	Slope	0.0784*
	Elevation	Elevation	0.0719
	Soil texture	Soil texture	0.0727
Environmental	Hydrogeology	Aquifer	0.0504
		Groundwater table	0.1427*
		Surface water	0.1373
	Geology	Geological fault areas	0.1033*
		Floodplain	0.0619
Socio-economic	Accessibility	Road network	0.0422*
		Waste production centers	0.0422*
	Public places	Residential areas	0.1002*
		Historical places	0.0334
	Land type	Land use	0.0628
*indicates the highest weighting factors		Sum	=**1.000**

5.2. Highest weighting factors in this study

In this study, groundwater table has been found as the most significant factor in landfill site selection process after experts' scoring. In terms of environmental perspective, groundwater table obtained a weight of 0.1427 (14.27 %). Previous studies have been considered this factor as a severe threat to the environmental health (Wang et al., 2018). The next most significant criterion within the environmental perspective is surface water that were assigned a weights of 0.1373 (13.73 %) by the experts whereas the third most significant criterion with a weight of 0.1033 (10.33 %) was considered as geological fault areas. Similarly, public places were evaluated as the most crucial criterion under economic perspective due to the NIMBY syndrome (Demesouka et al., 2018) and was assigned a weight of 0.1002 (10.02 %). Slope, soil texture and elevation obtained weight of 0.0784 (7.84 %), 0.0727 (7.27 %) and 0.0719 (7.19 %) as the three most important factors under the morphological perspective, respectively.

In this study, environmental factor was found to be the dominant criterion after experts' judgement familiar with the local conditions that obtained a total weight of 0.4958 (49.58 %). The next factor judged after experts' judgement was socio-economic perspective with a total weight of 0.2809 (28.09 %). Finally, the least important factor assessed in this study was morphological perspective that attained a total weight of 0.2231 (22.31 %).

5.3. Criterion thematic map layers

Thematic map layers of various criterion after reading previous literature, guidelines and regional experts' judgement are presented in figure (s) (5.1 to 5.13) below;

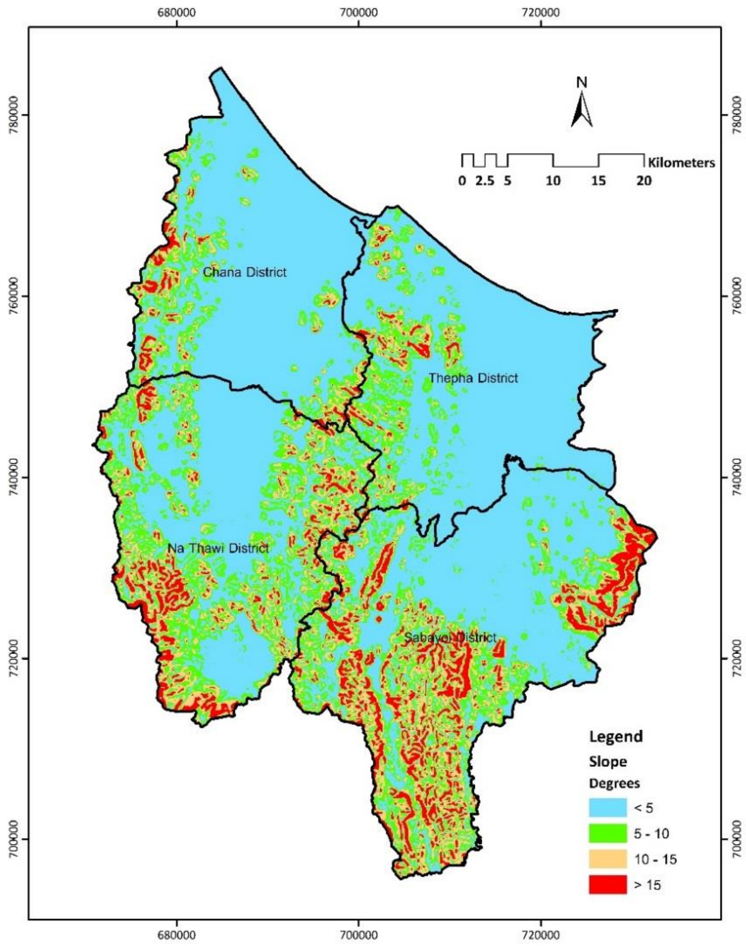

Fig. 5.1 Slope map of the study area

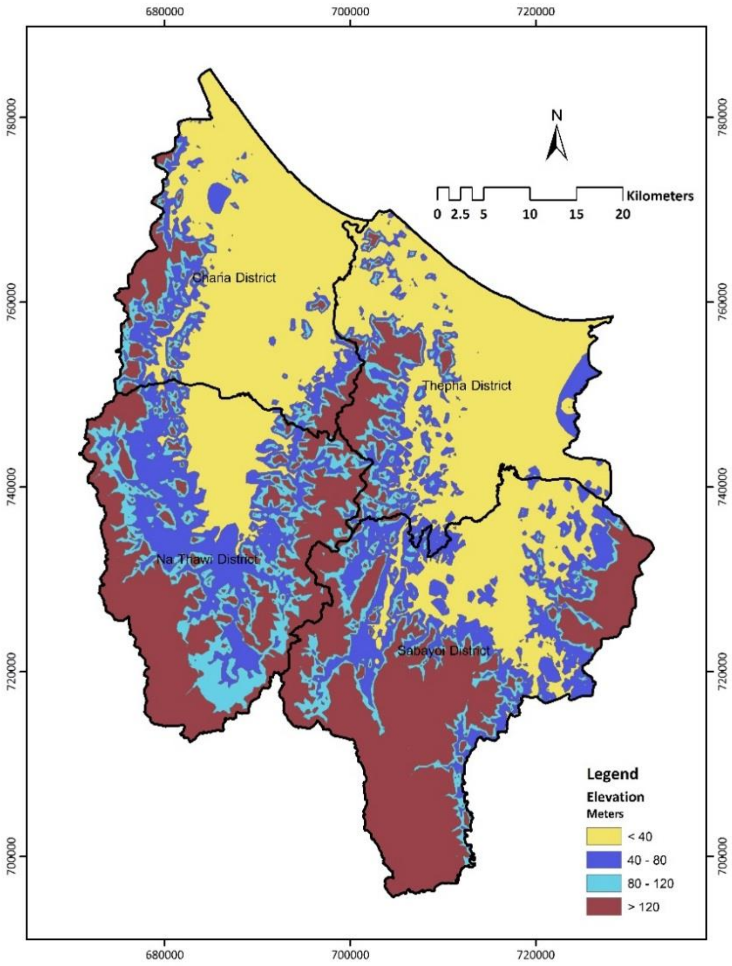

Fig. 5.2 Elevation map of the study area

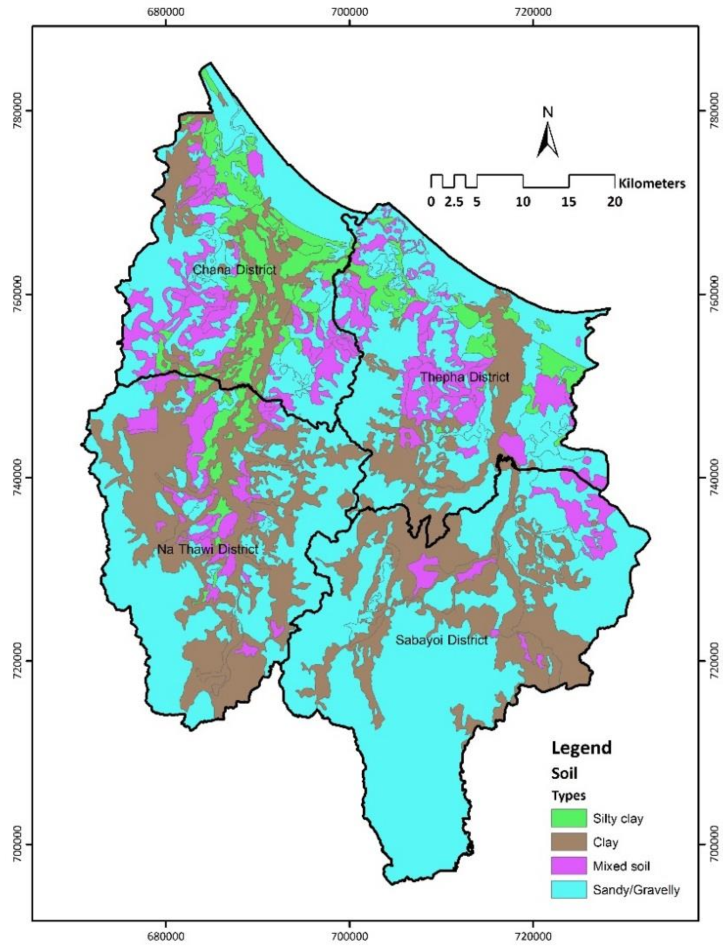

Fig. 5.3 Soil texture map of the study area

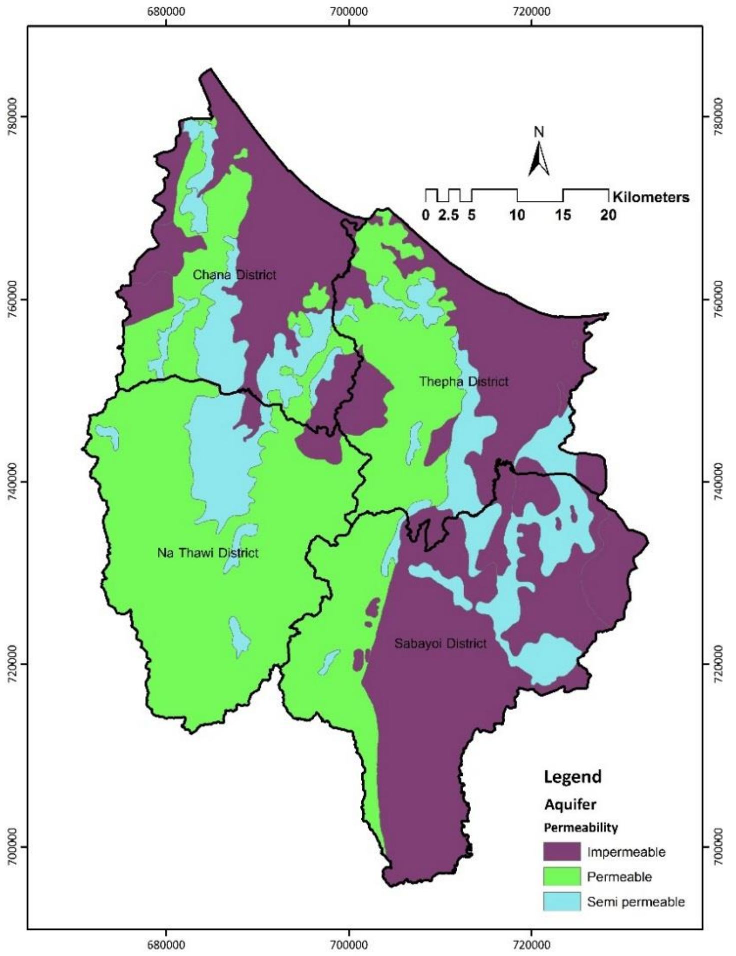

Fig. 5.4 Aquifer map of the study area

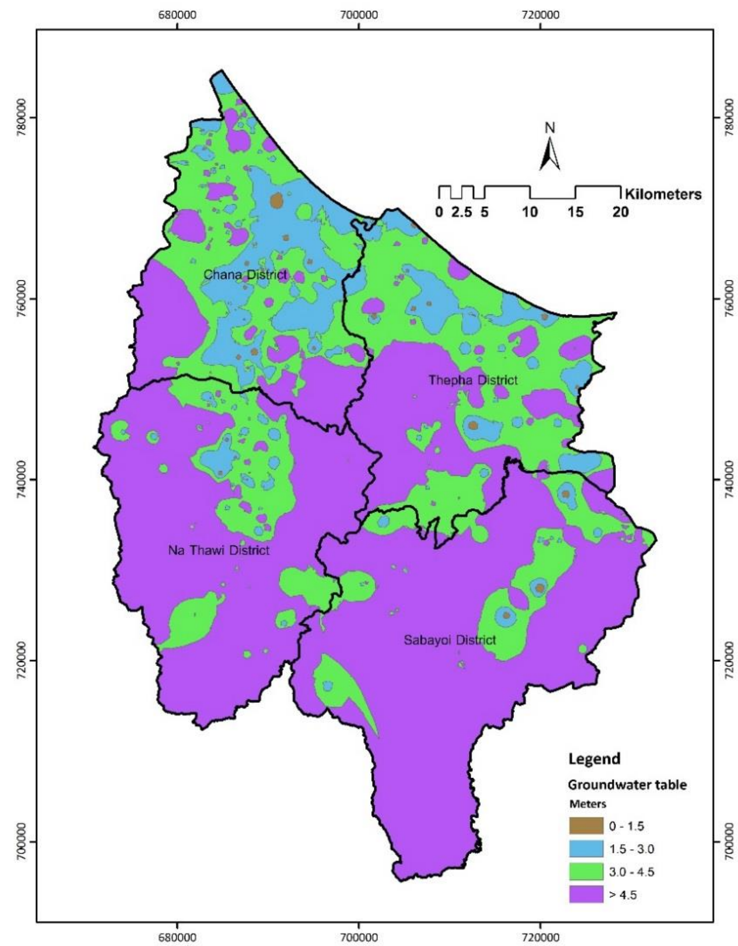

Fig. 5.5 Groundwater table map of the study area

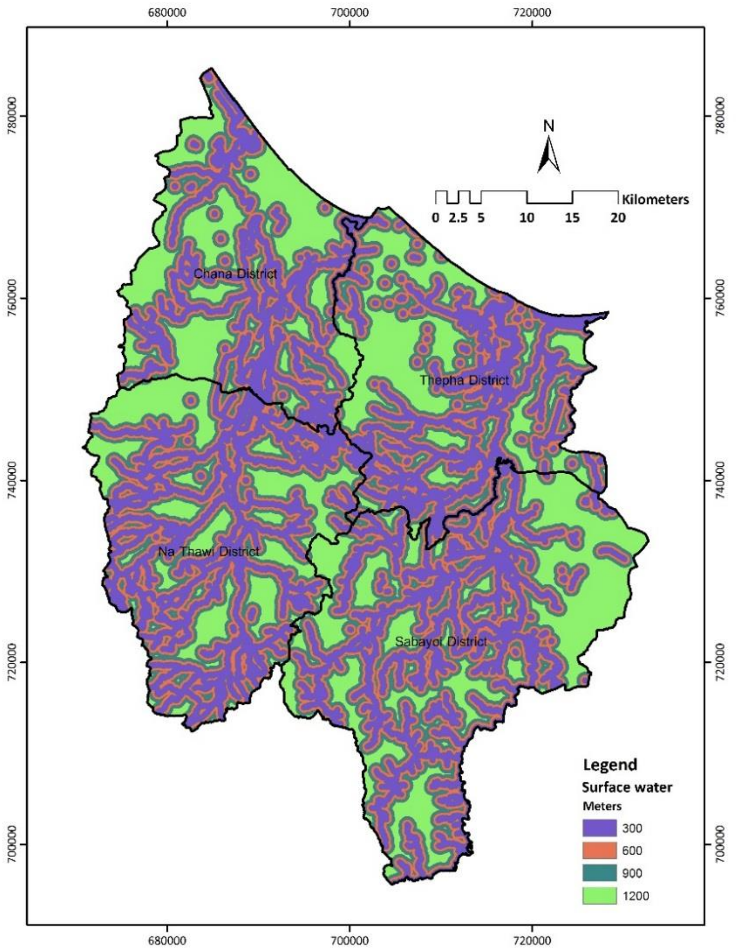

Fig. 5.6 Surface water map of the study area

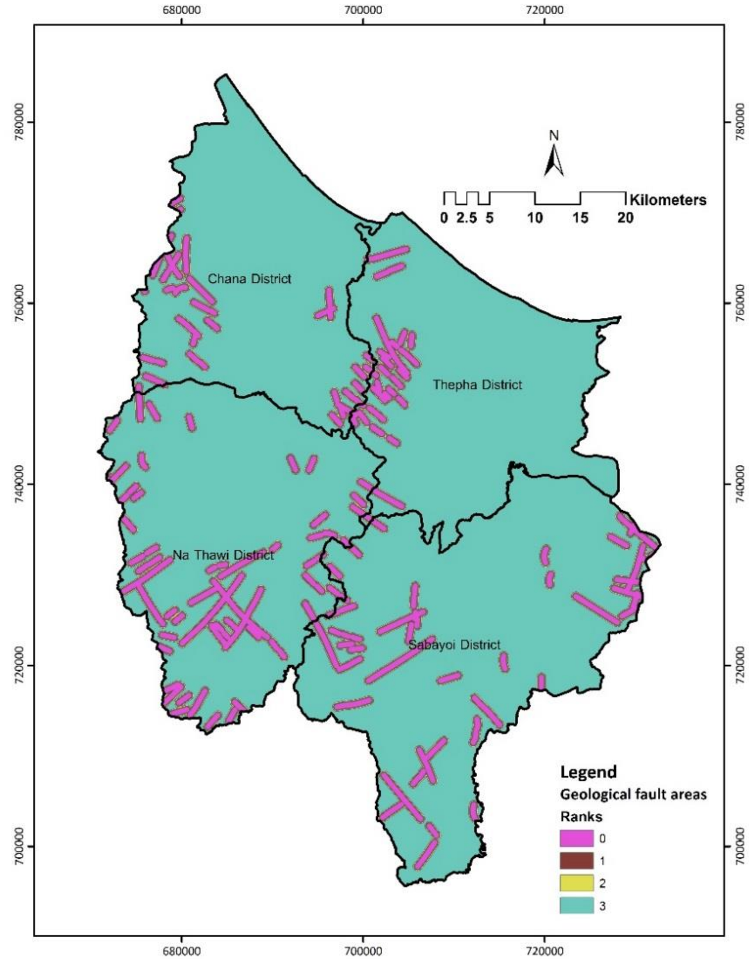

Fig. 5.7 Geological fault areas map of the study area

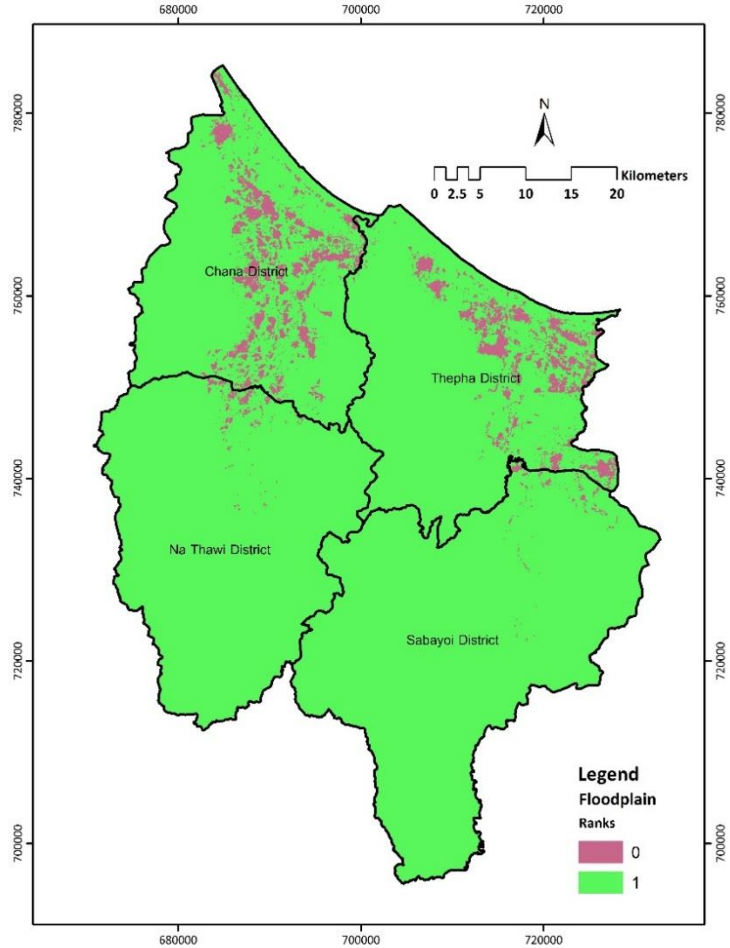

Fig. 5.8 Floodplain map of the study area

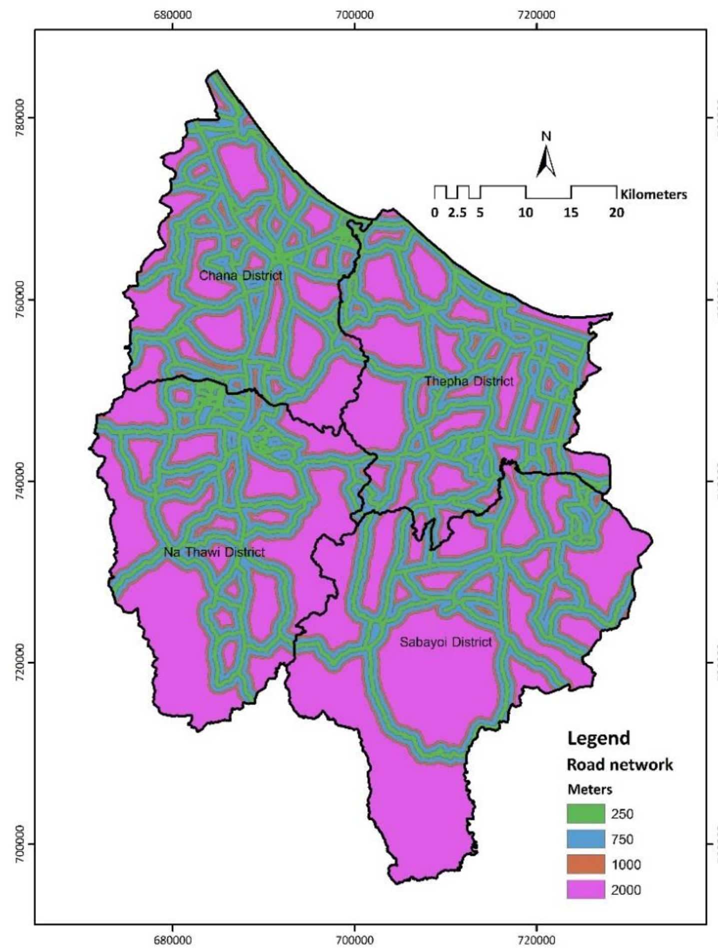

Fig. 5.9 Road network map of the study area

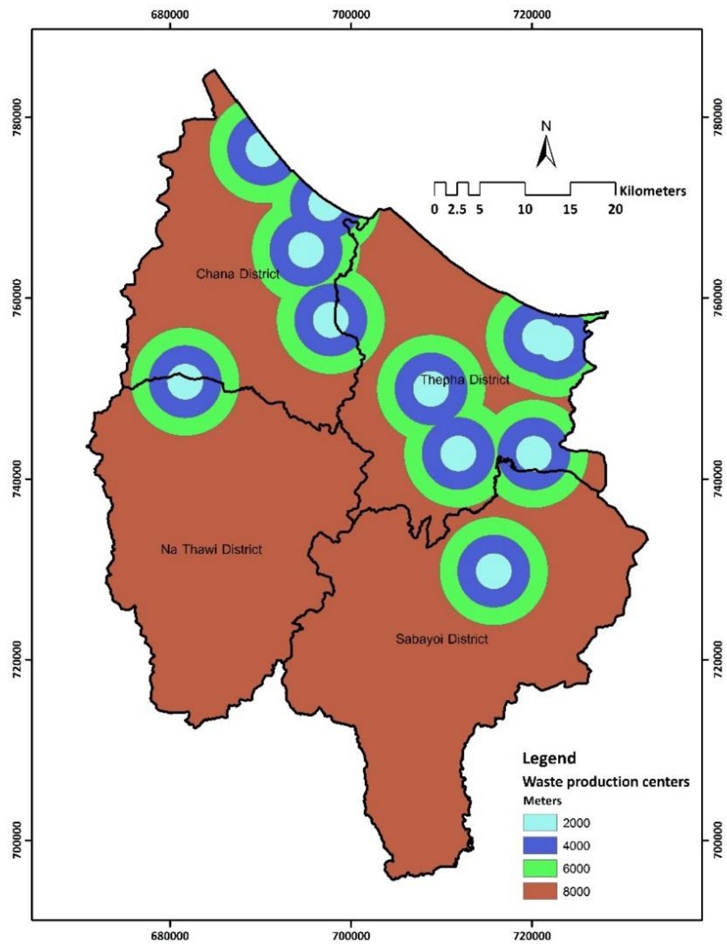

Fig. 5.10 Waste production centres map of the study area

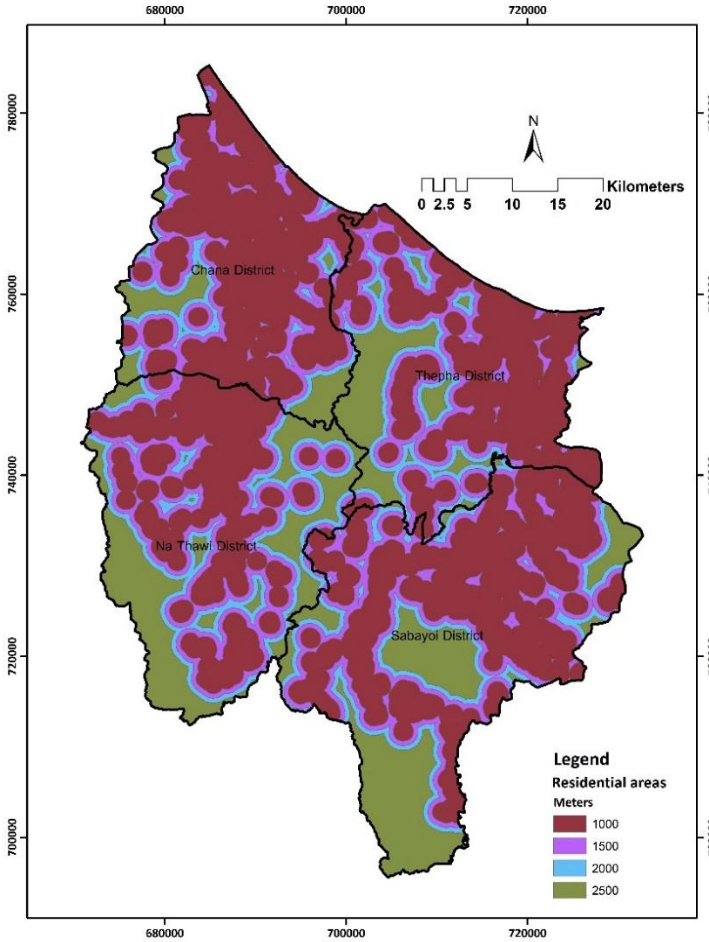

Fig. 5.11 Residential areas map of the study area

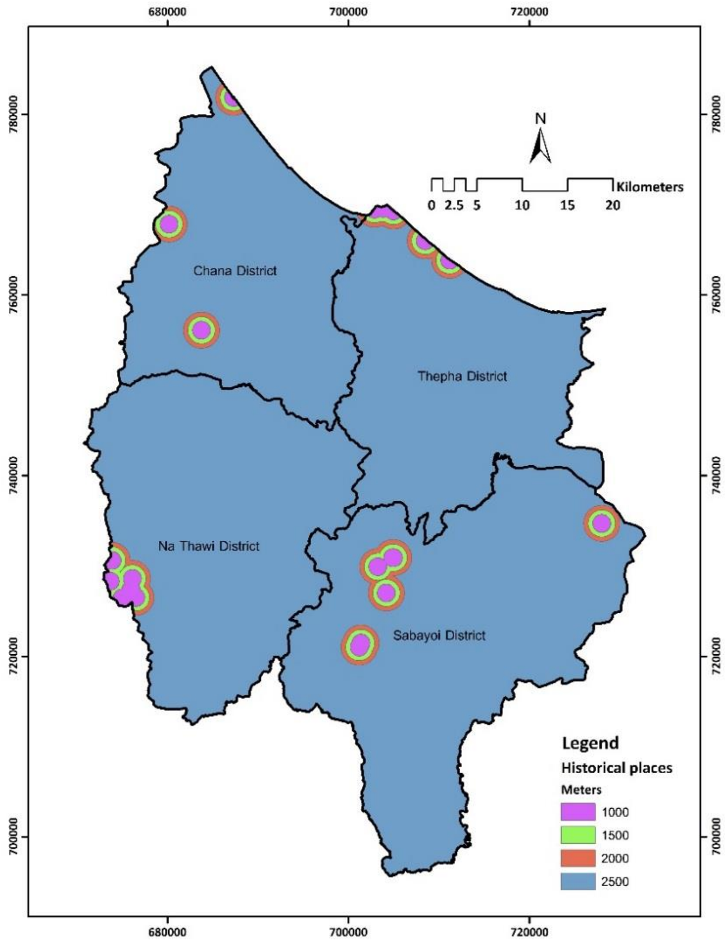

Fig. 5.12 Historical places map of the study area

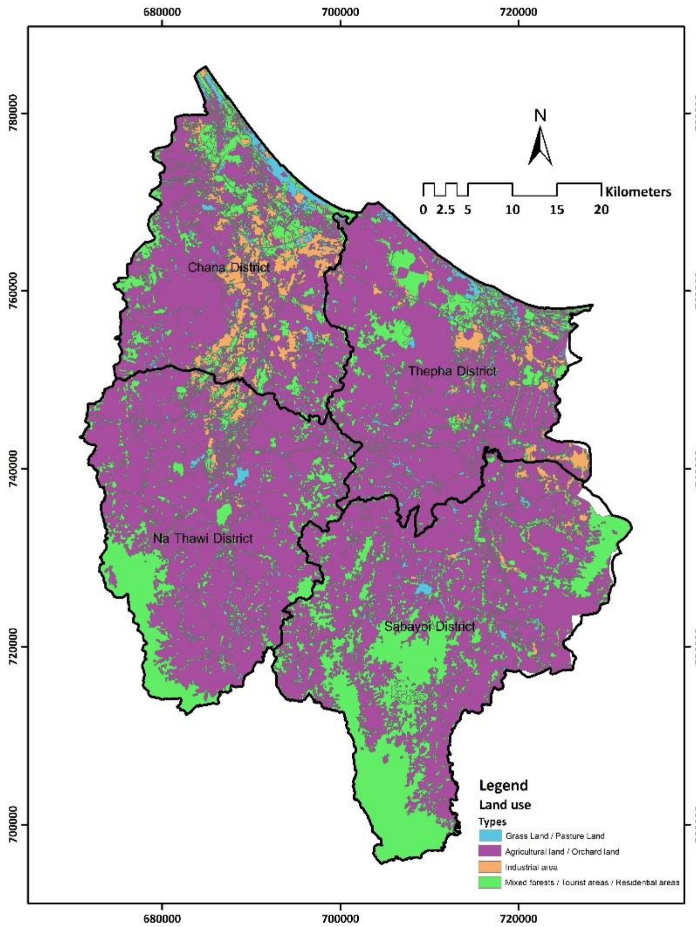

Fig. 5.13 Land use map of the study area

5.4. Final suitability map for landfill sites selection

Applying ArcGIS analysis tool, map layers for each criterion was created by using weight values whereas to produce final suitability the authors used field calculator and overlay union of the ArcGIS analysis tool (see Fig. 5.14). In this study, restricted areas were screened out while suitability for landfill siting was measured through landfill suitability index (LSI). The measuring range of the LSI was set in between 2.00184 and 3.05589. An equal interval classification method was applied to divide the range of attribute values into sub-ranges of equal proportion to understand the scale easily. The landfill suitability values of the study area were classified into three classes: moderately suitable (2.00184 – 2.35319), highly suitable (2.35319 – 2.70454) and very highly suitable (2.70454 – 3.05589).

In this study, a total of 302944.51 hectare (ha) area was scrutinized, out of which, 560.59 ha (0.19 %) is very highly suitable, 993.19 (0.33 %) is highly suitable and 180.72 ha (0.06 %) is moderately suitable for landfill siting. The remaining 301,210.01 ha (99.43 %) is unsuitable for landfill siting as shown in Table 5.2. The results of this study found that 560.59 ha of the study area can be measured as very highly suitable for landfill siting considering the morphological, environmental and socio-economic factors. In this study, Sabayoi had 121.80 ha very highly suitable, Thepha had 385.31 ha, whereas Chana has 53.47 ha very highly suitable for landfill siting according to Table 5.2. On the one hand, Na Thawi was found unsuitable for establishment of landfill sites.

Table 5.2 Area-based suitability classes of the total study area.

District	Very highly Suitable (ha)	Highly suitable (ha)	Moderately suitable (ha)	Unsuitable (ha)	Total area (ha)
Chana	53.47	394.66	47.58	62,265.88	62,761.60
Na Thawi	-	-	-	78,389.58	78,389.58
Sabayoi	121.80	191.41	28.60	95,470.99	95,812.81
Thepha	385.31	407.11	104.54	65,083.55	65,980.52
Total	560.59	993.19	180.72	301,210.01	302,944.51

Pollution Control Department (PCD, 1998) has recommended land requirement guidelines for landfill capacities, as shown in Appendix B. In this study, eighteen candidate sites from CS1 to CS18 were selected for landfill siting following the recommended guidelines by Pollution Control Department. According to the outcomes of this study, Thepha has been found very highly suitable for landfill siting having total eight candidate sites. Thepha is meeting all the requirements of guidelines on the basis of amount of MSW (tons/day) and land requirement (hectares). In Thepha, the candidate sites CS6 - CS8 could accommodate 10 to 50 tons/day MSW, CS11 for 50 to 100 tons/day MSW, CS14 for 100 to 300 tons/day MSW and CS15, CS17, CS18 for 300 to 500 tons/day MSW were selected for landfill siting. Whereas, Sabayoi has total four candidate sites including CS1 and CS4 for 10 to 50 tons/day MSW, CS13 for 50 to 100 tons/day MSW and CS16 for 300 to 500 tons/day of MSW for placing landfill site. Similarly, Chana has six candidate site such as CS2, CS3, CS5 and CS9, CS10, CS12 which can be utilized for 10 to 50 tons/day and 50 to 100 tons/day of MSW, respectively, for landfill site. Whereas, Na Thawi is not falling under the aforementioned guideline. Further details are included in Appendix B and Appendix C, and the final suitability map can be seen in Fig. 5.14.

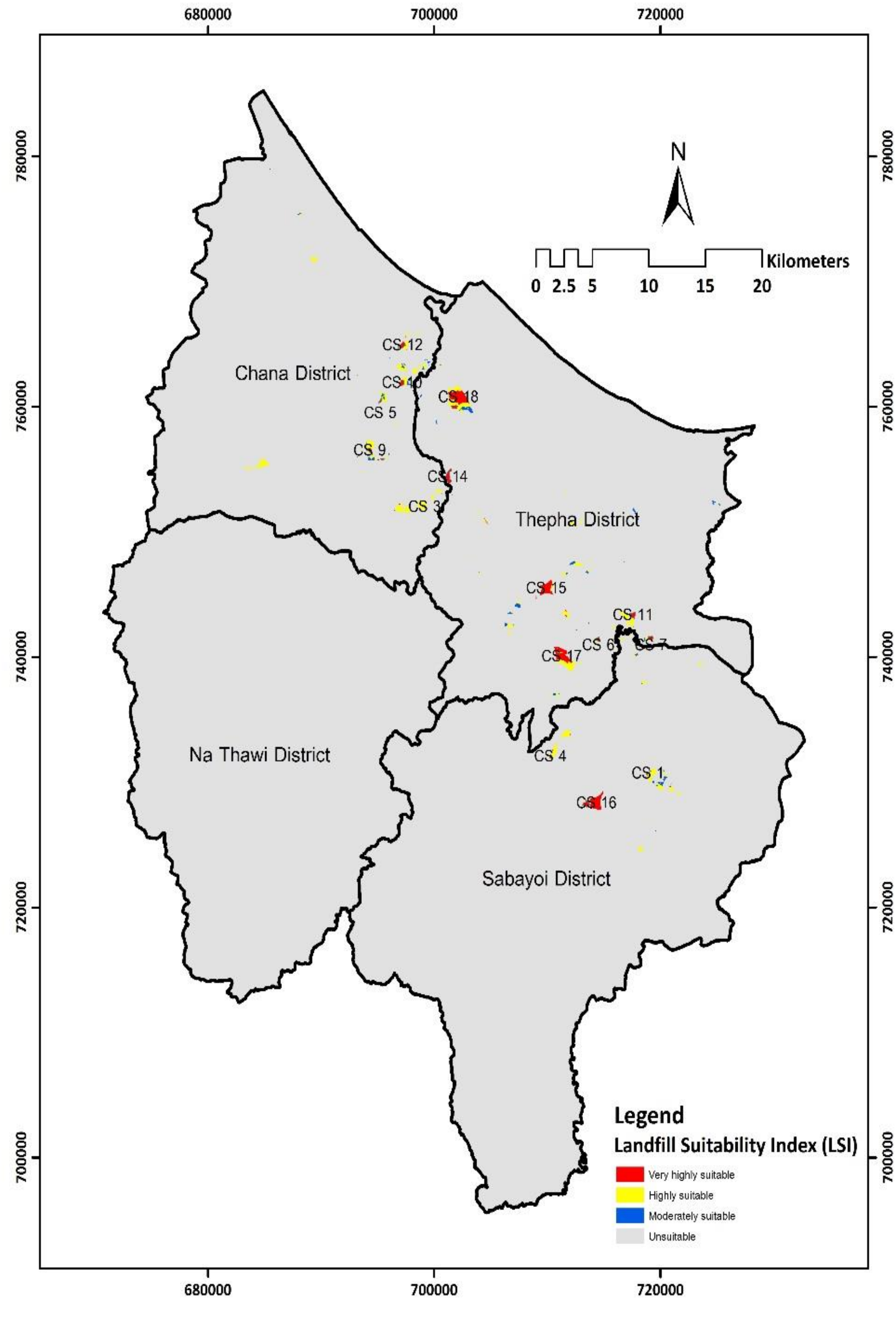

Fig. 5.14 Final landfill suitability map

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

Landfill site selection is a tremendous task which involves certain complexities in the terms of morphological, environmental and socio-economic domains. In this study, multi-criteria decision making technique was used under GIS environment to inspect the ideal locations for landfill sites in the four southernmost districts of Songkhla province namely: Thepha, Na Thawi, Chana and Sabayoi. Considering previous literature, experts’ judgment and national guidelines, most significant factors such as morphological, environmental and socio-economic were analyzed. The weights of various criteria were measured using AHP approach to create thirteen input map layers which supported GIS tool to generate a final suitability map using overlay analysis tool.

The authors also analyzed that in developing countries landfilling is the most common approach used for solid waste disposal, but, these countries are lacking the concept of landfill tax. Landfill tax can be effective in terms of reducing the amount of waste going to landfills. The tax rate for landfills should be put at a fairly high level. Introducing unit-based pricing to waste disposal services can play a vital role in this regard. The effectiveness of the landfill tax can be enhanced by applying unit-based pricing system to household waste collection. To promote prevention and recycling, embedding landfill tax into waste management policy is necessary. Furthermore, the financial attractiveness of waste to value to landfilling can be enhanced by introducing high landfill tax. Landfilling can be more expensive waste treatment facility through higher landfill tax. To achieve this, municipal authorities would require to pass on higher costs of landfilling to households by bringing unit-based system to household waste. Hence, keeping higher the landfill tax would increase the recycling rate and energy recovery process.

In this study, eighteen candidate sites were found very highly suitable for landfill siting. Thepha has eight candidate sites, six candidate sites for Chana, and four candidate sites in Sabayoi that all are very highly suitable based on morphological, environmental and socio-economic factors. Although, based on the suitability criteria employed, Na Thawi district has been analyzed unsuitable for landfill siting. This study also examined that some of the previous existing sites in the study area were selected on manual basis which posed detrimental health issues on the surrounding community. This methodology can be further expanded by considering more criteria for landfill sites such as environmental health risk assessment, contaminants in soil and water by introducing spatial interpolation tools from GIS and in this way the uncertainty factor can be reduced. Furthermore, landfill siting process can be solve using participatory GIS (PGIS) analysis in future. This will provide support for public opinion in decision making process.

Therefore, the outcomes of this research has the capability to solve the problems related to potential landfill sites in future because the methodology used in this study is scientific in its approach and can be effective tool for planners, stakeholders and decision makers during deciding site for landfills. The method adopted for this study area can be applied for potential landfill siting in other parts of the world such tropical regions like Thailand.

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APPENDICES

APPENDIX A

AHP weight calculation for landfill sites.

				Sum of rows	Final weight	CR
	Morphological	**Environmental**	**Socio-economic**			
Morphological	1	0.5	0.75	2.25	0.2231	0.0086
Environmental	2	1	2	5	0.4958	
Socio-economic	1.33	0.5	1	2.83	0.2809	
	Slope	**Elevation**	**Soil Texture**			
Slope	1	1.4	0.83	3.23	0.3515	0.0530
Elevation	0.71	1	1.25	2.96	0.3222	
Soil Texture	1.2	0.8	1	3	0.3261	
	Aquifer	**Groundwater table**	**Surface water**			
Aquifer	1	0.4	0.33	1.73	0.1527	0.0327
Groundwater table	2.5	1	1.4	4.9	0.4318	
Surface water	3	0.71	1	4.71	0.4154	

				Sum of rows	Final weight	CR
	Accessibility	**Public Places**	**Land use**			
Accessibility	1	0.8	1.2	3	0.3005	0.0273
Public Places	1.25	1	2.5	4.75	0.4757	
Land use	0.83	0.4	1	2.23	0.2237	
	Hydrogeology	**Geology**				
Hydrogeology	1	2		3	0.6667	0
Geology	0.5	1		1.5	0.3334	
	Geological faults	**Flood plains**				
Geological faults	1	1.67		2.67	0.625	0
Flood plains	0.6	1		1.6	0.375	
	Road Network	**Waste Centre**				
Road Network	1	1		2	0.5	0
Waste Centre	1	1		2	0.5	
	Residential	**Historical places**				
Residential	1	3		4	0.75	0
Historical places	0.33	1		1.33	0.25	

APPENDIX B

Classification of candidate sites according to PCD guidelines.

PCD Guidelines	**Amount of MSW (tonnes/day)**			
	10 to 50	50 to 100	100 to 300	300 to 500
	Land requirement (ha)			
	2.4 to 11.2	11.2 to 20.8	20.8 to 52.8	52.8 to 99.2
District	Candidate site			
Chana	CS2, CS3, CS5	CS9, CS10, CS12	-	-
Na Thawi	-	-	-	-
Sabayoi	CS1, CS4	CS13	-	CS16
Thepha	CS6, CS7, CS8	CS11	CS14	CS15, CS17, CS18

APPENDIX C

The suitable candidate sites area in hectares.

District	Candidate site	Area in hectares	Candidate site	Area in hectares
Chana	CS2	2.89	CS9	11.34
	CS3	3.29	CS10	12.92
	CS5	4.02	CS12	15.66
Na Thawi	-	-	-	-
Sabayoi	CS1	2.75	CS13	17.51
	CS4	3.70	CS16	94.75
Thepha	CS6	7.50	CS14	29.11
	CS7	9.82	CS15	79.26
	CS8	9.96	CS17	103.35
	CS11	13.75	CS18	124.51

APPENDIX D

Paper based questionnaires used for experts' interviews

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RESEARCH QUESTIONNAIRE

Topic **Selection of Municipal Solid Waste Landfill Site using GIS**

Please rate your impression of the importance of each of the following question below. Your valuable opinion and rating will help at greater extent in this research especially in prospective technique i.e. Analytic Hierarchy Process (AHP) which will be used for further evaluation.

Analytic Hierarchy Process (AHP)

AHP is a structured technique for organizing and analyzing complex decisions, based on mathematics and psychology. In AHP developed by Saaty (1980), a complex decision problem is decomposed into simpler decision problems to form a decision hierarchy. When developing a hierarch, the top level is the ultimate goal which in this case is municipal solid waste landfill site selection. After the decomposition stage is completed, cardinal rankings for criteria are determined, which is done by pairwise comparisons. Therefore, experts scoring, and opinions will play a key role in this approach.

The Fundamental Scale for Pairwise Comparisons Introduced by Saaty (1980)

Intensity of importance	Definition	Explanation
1	Equal importance	Two elements contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favor one element over another
5	Strong importance	Experience and judgment strongly favor one element over another
7	Very strong importance	One element is favored very strongly over another
9	Extreme importance	The evidence favoring one activity over another is the highest order of affirmation
2, 4, 6, 8	Intermediate values	Used to represent compromises between the preferences in weights 1, 3, 5, 7, and 9

Please score your response from the mentioned scale

1. **Following technologies are being using for the treatment of municipal solid wastes across the world. According to your opinion which technique is generally high suitable in southern part of Thailand?**

S.No.	Technology	Score
I.	Thermal conversion	
II.	Biological conversion	

2. **Due to high contents of organic materials, more than 50% containing high percentage of moisture in municipal solid wastes. According to your opinion which technology is most appropriate for southern part of Thailand?**

S.No.	Technology	Score
I.	Anaerobic digestion	
II.	Landfill gas to energy	
III.	Incineration	
IV.	Gasification	
V.	Pyrolysis	
VI.	Refuse-derived fuel (RDF)	

3. **According to your opinion which technology/technologies given in the table cause/causes less pollution and environment friendly?**

S.No.	Technology	Score
I.	Anaerobic digestion	
II.	Landfill gas to energy	
III.	Incineration	
IV.	Gasification	
V.	Pyrolysis	
VI.	Refuse-derived fuel (RDF)	

4. **Comparing different criteria/factors with each other. According to your opinion which criteria should be given more significance in selection of municipal solid waste landfill site?**

Remarks:

Morphology: The study of forms, structure and shapes of landforms i.e. slope, elevation and soil texture.

Environment: Environment is everything that is around us. It can be living or nonliving things. It includes physical, chemical and other natural forces. Living things live in their environment. They constantly interact with it and adapt themselves to conditions in their environment. But here environment means to protect groundwater table, aquifer and surface water and avoid those regions where floodplain and geological faults are expected.

Socio-economic: The study of social and economic factors to better understand how the combination of both influences something i.e. land use, public places etc.

S.No.	Criteria/factors	Score
I.	Morphology	
II.	Environment	

S.No.	Criteria/factors	Score
I.	Morphology	
II.	Socio-economic	

S.No.	Criteria/factors	Score
I.	Environment	
II.	Socio-economic	

5. **Considering morphological criteria in selection of municipal solid waste landfill site while comparing different combination of parameters with each other. According to your opinion which one should be given more priority?**

Remarks:
Slope: A slope is the rise or fall of the land surface. Slope is the measure of steepness or the degree of inclination of a feature relative to the horizontal plane. Slope is typically expressed as a percentage, an angle, or a ratio.
Elevation: The altitude of a place above sea level or ground level.
Soil texture: Soil texture (such as loam, sandy loam or clay) refers to the proportion of sand, silt and clay sized particles that make up the mineral fraction of the soil.

Morphology (Criteria)

S.No.	Parameters	Score
I.	Slope	
II.	Elevation	

S.No.	Parameters	Score
I.	Slope	
II.	Soil texture	

S.No.	Parameters	Score
I.	Elevation	
II.	Soil texture	

6. **Considering environmental criteria in selection of municipal solid waste landfill site, according to your opinion which parameter should be given more significance?**

Remarks:

Hydrogeology: Hydrogeology is the part of hydrology that deals with the distribution and movement of groundwater in the soil and rocks of the Earth's crust (commonly in aquifers).
Geology: Geology involves studying the materials that make up the earth, the features and structures found on Earth as well as the processes that act upon them.
Aquifer: An aquifer is an underground layer of water-bearing rock. Water-bearing rocks are permeable, meaning that they have openings that liquids and gases can pass through. Sedimentary rock such as sandstone, as well as sand and gravel, are examples of water-bearing rock.
Groundwater table: The groundwater table is the depth at which the ground below is saturated with water. The groundwater table rises or falls depending on rainfall, plants absorbing water and topography.
Surface water: Surface water is water on the surface of the planet such as in a river, lake, wetland, or ocean.
Geological fault areas: A fault is a crack in the Earth's crust where compressional or tensional forces cause relative displacement of the rocks on the opposite sides of the fracture. Faults may be vertical, horizontal, or inclined at any angle.
Flood plain: A flood plain is flat or nearly flat land adjacent to a stream or river that experiences occasional flooding when the river becomes too full.

Environment (Criteria)

S.No.	Parameters	Score
I.	Hydrogeology	
II.	Geology	

Hydrogeology (Sub-criteria)

S.No.	Parameters	Score
I.	Aquifer	
II.	Groundwater table	

S.No.	Parameters	Score
I.	Aquifer	
II.	Surface water	

S.No.	Parameters	Score
I.	Groundwater table	
II.	Surface water	

Geology (Sub-criteria)

S.No.	Parameters	Score
I.	Geological fault areas	
II.	Flood plain	

7. **Considering socio-economic criteria in selection of municipal solid waste landfill site, according to your opinion which parameter should be given more importance?**

Remarks:
Accessibility: Accessibility means route that should be easy to access and do not obstruct public transport i.e. road network, waste production center.

Waste production center: It is a place where waste and recyclables from many different sources are brought together for transporting to recycling centers, waste processors or to landfill.

Socio-economic (Criteria)

S.No.	**Parameters**	**Score**
I.	Accessibility	
II.	Public places	

S.No.	**Parameters**	**Score**
I.	Accessibility	
II.	Land use	

S.No.	**Parameters**	**Score**
I.	Public places	
II.	Land use	

Accessibility (Sub-criteria)

S.No.	**Parameters**	**Score**
I.	Road network	
II.	Waste production center	

Public places (Sub-criteria)

S.No.	**Parameters**	**Score**
I.	Residential areas	
II.	Historical places	

8. **The below listed parameters are according to different literature reviews. Therefore, I would like to confirm these parameters by taking your valuable opinion for "Selection of municipal solid waste landfill site using GIS". Please comment in "Experts valuable opinion" box if the selection range is not appropriate according to southern Thailand.**

S.No.	**Parameters**	**Selection range**
I.	Slope	$<10^{o}$
II.	Elevation	<40 meter (m)
III.	Distance from surface water	>1000 m
IV.	Distance from residential areas	>1000 m
V.	Distance from historical places	>1000 m
VI.	Distance from waste production centers	<500 m
VII.	Distance from road network	200-1000 m
VIII.	Land use	Grassland/Unused land
IX.	Distance from ground water table	>40 m
X.	Aquifer	Rocks of old age (Impermeable)

XI.	Soil texture	Clay
XII.	Flood plain	Non-flooded area
XIII.	Geologic fault areas	>500 m

Experts valuable opinion

APPENDIX E

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Full length article

Municipal solid waste landfill siting using an integrated GIS-AHP approach: A case study from Songkhla, Thailand

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ABSTRACT

The determination of suitable landfill sites has become indispensable in recent years as the global generation of waste has increased and the use of unsuitable landfill sites results in negative impacts on the ecosystem. This study demonstrates a scientific approach in identifying appropriate landfill sites. The study includes morphological, environmental and socio-economic factors to achieve its objective. Geographic Information System (GIS) and Analytic Hierarchy Process (AHP) were combined in order to analyze data obtained from online portals and government institutions, with a recent study of waste production centres being provided by the Regional Environmental Office. To illustrate the method, a case study from Thailand was used. Expert judgement was solicited over 13 landfill site selection criteria. This study identified an area of 560.59 ha as very highly suitable for landfill sites, 993.19 ha as highly suitable and 180.72 ha as moderately suitable, with the remaining parts of the study area being unsuitable for landfill sites. This research has the potential to influence future waste management policies by assisting stakeholders in landfill siting in a manner that reduces negative impacts on the environment.

1. Introduction

Municipal Solid Waste Management (MSWM) is a matter of great concern around the world from environmental, morphological and socio-economic perspectives (Demesouka et al., 2013; Turcott Cervantes et al., 2018). The effective management of municipal solid waste (MSW) is a big challenge for local authorities and planners due to rapid industrialization, growing populations and land scarcity (Khan et al., 2018). Effective waste management systems that can provide reliable services, are required to deal with increasing amounts of solid waste, as many current systems have failed to respond to the demand (Sukholthaman and Shirahada, 2015). The MSW services are generally observed as natural monopolies and so, among other reasons, are characterized by reduced incentives towards productive efficiency and innovation (Perotto et al., 2008; Sim□es et al., 2010).

Regulation in the waste sector is a matter of increasing interest for researchers and practitioners. Various countries are establishing their own regulatory authorities (e.g., Italy, Romania, Portugal, Brazil). In several countries, waste services are paid for by users and the occurrence of several market failures points to the need for a 'visible hand' (i.e., a regulator) to correct and mitigate them (Sim□es and Marques, 2012). During the last decade, the *3Rs* concept, encompassing reduce, reuse and recycle, has been promoted and implemented in various countries. However, its success is constrained by a lack of state regulation and enforcement, as well as by limited stakeholder participation. The evaluation of performance, especially the use of benchmarking, can play a vital role to invert this tendency (Sim□es et al., 2010). In Thailand which faces such issues with its MSWM system, an integrated sustainable waste management (ISWM) concept has been developed to address some issues with MSWM. However, questions

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remain relating to financing and the application of appropriate technology, which requires a huge investment (Chanhthamixay et al., 2017).

Complex and ambiguous regulations in Thailand are a burden on financing MSWM. Under the Public Health Act B.E. 2535 (1992) (PHA), Local Administrative Units (LAUs), such as municipal governments are responsible for collecting and disposing of MSW. On the other hand, the Public Health Act (PHA) permits LAUs only to bill the collection cost to MSW producers. According to the guidelines in the Enhancement and Conservation of the National Environmental Quality Act B.E. 2535 (1992), the disposal costs are to be recovered. However, only those LAUs which are more acquainted with the PHA, enforce and collect MSW collection fees and use this fee to cover collection and disposal costs (Challcharoenwattana and Pharino, 2016).

The regulations and guidelines for solid waste management also specify the requirements for private sectors operators. However, the bidding processes for the selection of landfill operators is typically questionable. Also, formal representation of private sector stakeholders in the waste-related decision making process is unclear. Solid waste management is covered by several regulations, and the regulatory framework has recently been improved by the enforcement of a new National Cleanliness and Orderliness Act in 2017. However, extended producer responsibility (EPR) regulations, forcing manufacturers to recall and recycle their products at the end of their useful life cycle are missing. Nevertheless, there are also some implementation guidelines for certain aspects of waste management, such as detailed actions for crisis provinces, or environmental impact assessment for waste treatment facilities. However, guidelines on increasing recycling rates, extending collection services or improving environmental standards are lacking (Chanhthamixay et al., 2017).

According to Gbanie et al. (2013), MSW contains of food waste, durable and non-durable goods, containers and packaging, yard trimmings and miscellaneous organic waste from household, commercial and industrial sources. Alternatively, waste is any substance that an individual throws or intends to throw away, as defined by the European Commission in the Waste Framework Directives of 1975. However, this definition is subjective since what may be regarded as *waste* as opposed to a *resource* may depend on the context. In this article, waste is considered as being materials derived from households, public places, commercial outlets and institutions that are deemed useless.

The delineation of disposal sites is one of the most significant steps in the disposal of MSW. Modern MSWM practices include waste reduction, the recycling and reuse of waste, energy and materials recovery, incineration and safe landfilling (Makarichi et al., 2018). Regardless of the approach, it is impossible to eliminate all forms of waste and a better way to handle waste is through the implementation of methods that ensure the minimum impact of waste on the environment (Khan and Faisal, 2008).

Much research has been conducted over the past two decades on solid waste management. Lima et al. (2018) discussed the potential of gas production from landfill sites in Brazil while Augusto et al. (2019) examined landfill leachate issues and their treatment in Spain and Khan et al. (2018) investigated the optimal siting of waste-to-value-added facilities, mainly suitable sites for landfills. Moreover, choosing an appropriate landfill site can substantially minimize the technical and environmental challenges involved in waste disposal. Landfilling, although found at the bottom of waste management hierarchy (waste reduction, reuse, recycling, composting and landfilling), is an integral part of the waste management chain (Gbanie et al., 2013). It is best suited to wastes that cannot be reused or recycled (Dijkstra et al., 2018; Seshadri et al., 2016) as it is one of the simplest and most economical processes for storing MSW (Samadder et al., 2017).

In common with other developing countries, MSW is a critical issue in Thailand with the potential to cause detrimental impacts to the environment and public health. In a recent report by the Pollution Control Department (PCD), Thailand was noted to have produced 27×10^6 tonnes of MSW in the year 2016 (PCD, 2017). Environmental impacts such as air pollution, soil and water contamination and climate change are alarming for Thailand because most of its MSW is disposed of in open dumpsites. The placement of waste facilities for the treatment or landfilling of residual waste near public places is a major issue, which decision-makers have to address against a background of social opposition, a phenomenon known as *not-in-my-backyard* (NIMBY) (Demesouka et al., 2019). Nevertheless, morphological and economic factors need careful assessment prior to embarking on the opening of new landfill facilities with a view to minimizing their costs as well as maximizing their productivity. Therefore, a thorough investigation of waste disposal sites is essential in a developing country such as Thailand.

Recently, the Geographic Information System (GIS) has emerged as a convenient tool for use in landfill site-selection studies. GIS is a computer-based decision support system with the capacity to manage, analyze and display geospatial reference data (Khan et al., 2018). Further, multi-criteria decision making (MCDM) is a well-known technique for resolving complex decision-making problems in waste-disposal site selection (Demesouka et al., 2019). Saaty proposed the analytic hierarchy process (AHP) as a type of MCDM technique under which a problem is decomposed in the form of a hierarchy, where the goal remains at the top (Saaty, 1990). In the study described in this paper, the goal was to identify as the determination of ideal landfill locations. A combined GIS-AHP approach has been favourited by various researchers for landfill-site selection, including Demesouka et al. (2013), who evaluated the suitability of potential MSW landfill sites in northeast Greece by applying GIS combined with AHP and compromise-programming methods. Chabuk et al. (2016) selected a landfill site for Babylon, Iraq using a GIS and AHP process, while Spigolon et al. (2018) used an AHP approach in a GIS environment for the siting of sanitary landfills and the optimization of the transportation of municipal solid waste in S□o Paulo, Brazil. In addition, Uyan (2014) determined the location of a solid waste disposal site for Konya, Turkey, and Khodaparast et al. (2018) investigated MSW landfill siting in Qom city, Iran, both using GIS and AHP while Barakat et al. (2017) evaluated landfill sites in Morocco with GIS based Boolean and AHP models. GIS-AHP has therefore been proven to be a powerful tool in evaluating potential landfill sites. However, studies on the selection of MSW landfill sites using an integrated GIS-AHP approach in tropical regions have been limited. Also, the current landfill site selection system in Thailand is costly, time consuming and they are often selected randomly without any proper survey taking place. The study described will provide a cost effective, time saving and scientific process for the selection of landfill sites in tropical nations like Thailand to ensure that sites comply with both international and national guidelines.

To the best of the authors' knowledge, no previous study has been conducted in the study area to determine potential locations for landfill sites using the AHP approach with GIS. The only study (by Charusiri and Ladachart, 2008) in Songkhla province considered the geological barriers to landfill site selection but only considered the physical properties while not taking into account an AHP approach along with morphological, environmental and socio-economic considerations. Moreover, at present some of the existing open landfill sites in the study area are claimed to be having negative impacts on surrounding populations. Therefore, this study aims to remedy the shortcomings of that previous study by considering landfill-site selection in four major districts of Songkhla by applying the MCDM technique under a GIS environment, with the study taking into account the international literature on the subject as well as the opinion of experts familiar with local conditions, in order to achieve its objective. Finally, the candidate sites were compared to the national guidelines published in Thailand, by the Pollution Control Department (PCD, 1998).

After this introduction, this article is ordered as follows. Section 2 describes the materials and methods, including criteria selection, the significance of various criteria and the application of GIS-AHP. Section

3 presents and discusses the results achieved by this study and finally, section 4 presents the main conclusions.

2. Materials and methods

2.1. Study area

Songkhla is a province in southern Thailand, with its location around 7.1988° N and 100.5951° E, having an area of 7394 km^2 and a population of more than 1.4 million people. The province borders Malaysia to the south and therefore hosts many tourists each year. As, a result Songkhla province generates many hundreds of tonnes of waste each day, including an increasing amount of waste from the southernmost districts of Songkhla, Chana, Thepha, Na Thawi and Sabayoi, all of which have large land areas and populations and together generate about 228 tonnes of MSW per day (Buranasing, 2015). A survey in 2015 noted that these wastes are composed of food (60%), plastic (25%), glass (5%), gardening waste (5%), paper (2%), polystyrene (2%) and metal (1%) (REO, 2016a) similar to waste composition collected from Prince of Songkla University, Hatyai, Songkhla which has been reported in Thai Reserach Fund (TRF) document grant no. TRG 5880268. Some of the existing waste disposal sites in those locations were selected manually, therefore, bringing health challenges to residents nearby. Because of this, people have become susceptible to the NIMBY phenomenon, a recent example of which was in Chana, where people opposed the establishment of a waste transfer station. Public confidence can only be regained based on a comprehensive scientific study endorsed by the local administration. Therefore, the case study for this research is focused on the four southernmost districts of Songkhla, namely, Chana, Thepha, Na Thawi and Sabayoi, as shown in Fig. 1, where the problem of waste disposal site selection is quite severe.

2.2. Methodology overview

Fig. 1 shows the different steps involved in this study. The first stage of the research was the collection of data which were accessed from different online portals and government institutions. The second stage was the selection of criteria based on international literature, national legislation and expert judgment. The third stage was MCDM based on a GIS-AHP approach. The fourth stage was the selection of suitable locations for the siting of landfills.

2.3. Data collection

The main objective of this study was to evaluate suitable locations for siting MSW landfills. To this end, up-to-date data was collected from various online portals and government institutions and, the most recent data for waste production centres was provided by the Regional Environmental Office in Songkhla (REO, 2016b) with groundwater table and aquifer data being obtained from the Department of Groundwater Resources in Songkhla, (DGR, 2018). The data relating to surface water, the road network, soil texture, residential areas and land use were acquired from the Land Development Department (LDD, 2014) and a topographic map defining slope and elevation contour lines was obtained from the Royal Thai Survey Department (RTSD, 2018). For floodplain data, the Thailand Flood Monitoring System online portal was accessed (GISTDA, 2018) and the locations of historical places and geological fault area data was obtained from the Southern Regional Center of Geo-Informatics and Space Technology Development Agency and the Department of Mineral Resources, Thailand, respectively. All the criterion data sets used in this study, their formats and sources are described in Table 1.

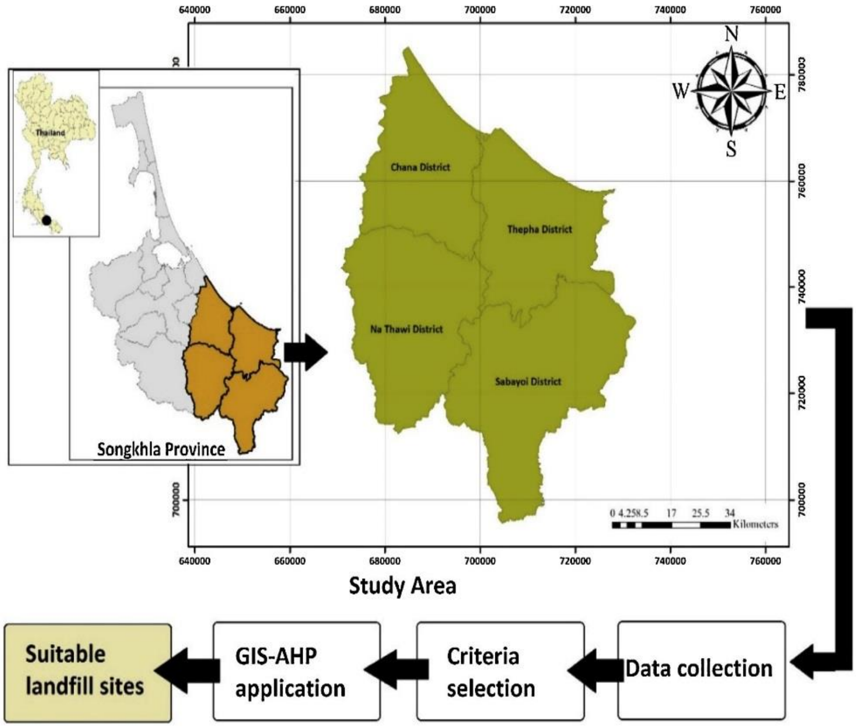

Fig. 1. Methodology overview and study area.
(adapted source: (Ali et al., 2019)).

Table 1
Data sets, formats and sources.

Dataset	Format	Spatial resolution	Source of data	Edited source
Slope	Raster to Vector conversion	30 m	Royal Thai Survey Department, 1999 (RTSD, 2018).	Southern Regional Center of Geo-Informatics and Space Technology Development Agency, Prince of Songkla University (PSU) (2017) (FEM, 2017).
Elevation	Raster to Vector conversion	30 m		
Surface water	Vector	500 m		
Road network	Vector	500 m		
Soil texture	Vector	500 m	Land Development Department, 2002 (LDD, 2014).	
Residential areas	Vector	500 m		
Land use	Vector	500 m		
Aquifer	Vector	250 m	Bureau of Groundwater Resources Region 12 (Songkhla), 2018 (DGR, 2018).	
Groundwater table	Excel, X, Y Coordinates	GIS Spatial Interpolation		
Geological fault areas	Vector	250 m	Department of Mineral Resources, 1985 (DMR, 2016).	
Floodplain	Vector	100 m	Geo-Informatics and Space Technology Development Agency (GISTDA, 2018).	
Waste production centres	Excel, X, Y Coordinates	Imported to GIS	Office of Environment Region 16 (Songkhla), 2016 (REO, 2016).	
Historical places	Vector	500 m	Southern Regional Center of Geo-Informatics and Space Technology Development Agency, PSU 2017 (FEM, 2017).	

2.4. Criteria selection

The selection of criteria is an important part of the evaluation process in any site selection project as the sites' reliability will mainly depend on these factors. Therefore, various criteria were selected after discussions with regional experts and consulting relevant international literature (Al-Hanbali et al., 2011; Bosompem et al., 2016; Chabuk et al., 2016, 2017; Delgado et al., 2008; De Feo and De Gisi, 2014; Guiqin et al., 2009; Kontos et al., 2005; Motlagh and Sayadi, 2015; Nas et al., 2010; Ramjeawon and Beerachee, 2008; Şener et al., 2011, 2010; Spigolon et al., 2018). In this study, thirteen input map layers were produced, where the main criteria were categorized into three groups, covering morphological, environmental and socio-economic factors. The first group is concerned with the morphological characteristics and the soil texture of the study area. These criteria are considered to ensure that threats due to groundwater pollution such as leachate contamination are minimized as well as reducing landfill construction and operation costs (Demesouka et al., 2013). The second group, environmental criteria should be the main concern in landfill siting. Environmental criteria are very significant because various contaminants are released to the environment from MSW landfills via landfill leachates or landfill gases, and these present a major threat to the surrounding environment, with the potential to cause permanent damage to environmental quality (Krčmar et al., 2018). The third group, socio-economic criteria concern the study area's ecology, the aim being to prevent aesthetic and economic damage to candidate sites due to MSW landfills (Demesouka et al., 2019). Additionally, because of the large area occupied by landfills, land scarcity might impact the development of human society and ecosystems (Akinjare et al., 2011; Ready, 2010).

2.5. Morphological perspective

2.5.1. Slope and elevation

Slope and elevation are the two main parameters to be considered in the construction of a landfill site (Kontos et al., 2005). Land surface with steep slopes and high elevation is inappropriate for landfill sites (Şener et al., 2010). Guiqin et al. (2009) and Kahraman et al. (2018) stated that very steep slopes will entail higher excavation costs. Landfill sites having excessively steep slopes would cause difficulties during construction while too flat a surface would have an impact on runoff drainage (Nas et al., 2010). Land slopes between 0° and 10° have been suggested as being appropriate for the construction of landfill sites (Chabuk et al., 2017; Effat and Hegazy, 2012; Şener et al., 2011, 2010). The term elevation refers to the altitude above sea level, which will vary from area to area. Previous studies (Chabuk et al., 2016; Şener et al., 2010) have employed limits of greater than 2000 m and 17 to 23 m for elevations in Turkey and Iraq respectively. Due to high transportation costs, landfill sites far above sea level are unsuitable. On the contrary, landfill sites located near sea level present a high risk of flooding and water body infection (Demesouka et al., 2013).

Therefore, finally, areas with a slope greater than 15° were considered to be unsuitable while areas having only a slight slope of less than 5° were considered as very highly suitable. Similarly, elevations above 120 m were considered as unsuitable while elevations below 40 m were considered as very highly suitable in this study (see Fig. 2(a) and (b)). A digital elevation model (DEM) of the study area was formed using data acquired from the Royal Thai Survey Department, Thailand. The slope and elevation maps were prepared using ArcGIS software. Further details are included in Table A1 in the Appendix.

2.5.2. Soil texture

The soil has a substantial effect on the amount of groundwater recharge that can penetrate into the ground, and hence on the ability of pollutants to move vertically into the unsaturated zone. Silt and clay are composed of fine particles which can decrease the relative soil permeability and can confine the movement of pollutants (Lee, 2003). Highly

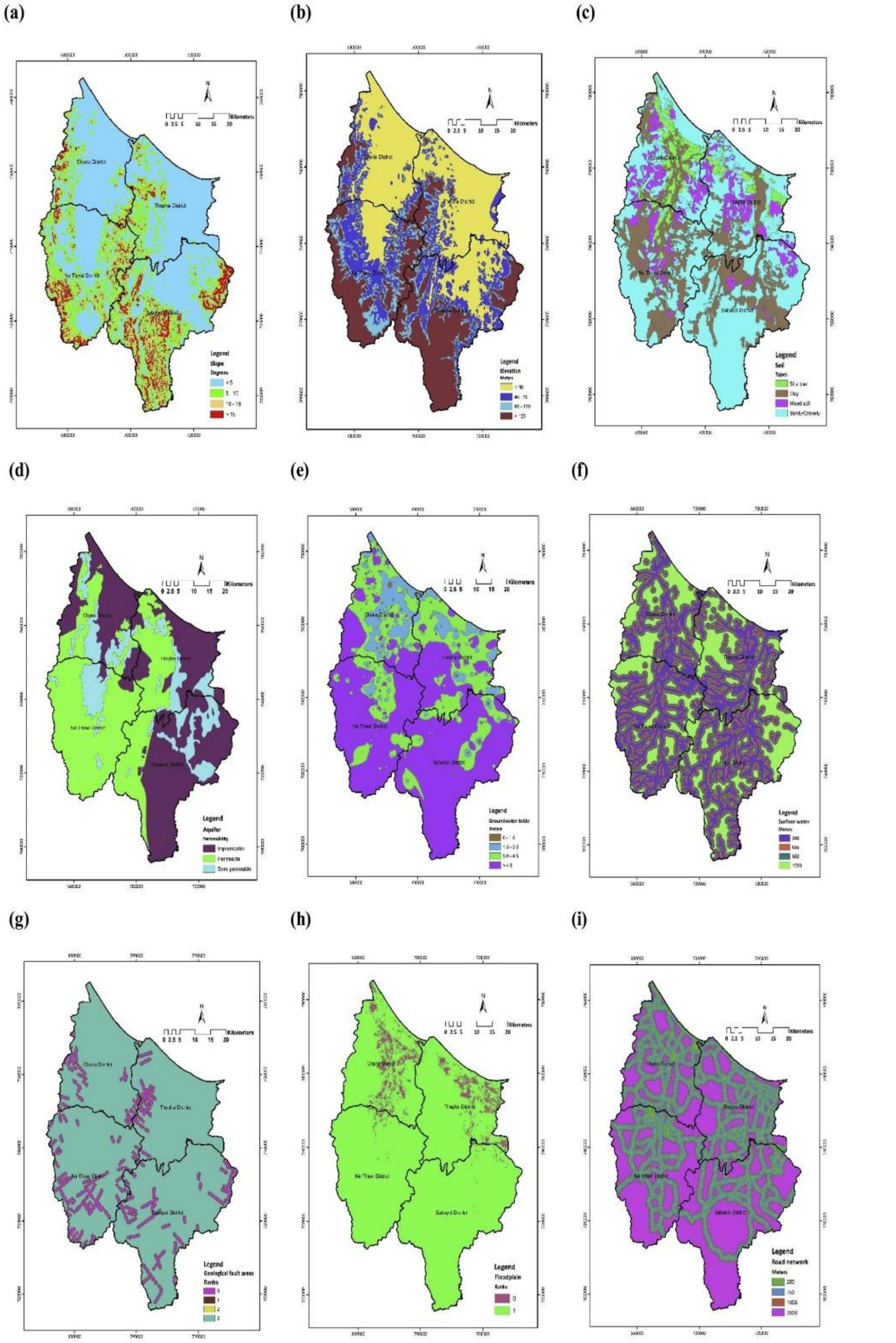

Fig. 2. (a) Slope, (b) elevation, (c) soil texture, (d) aquifers, (e) groundwater table, (f) surface water, (g) geological fault areas, (h) floodplain, (i) road network, (j) waste production centers, (k) residential areas, (l) historical places, and (m) land use.

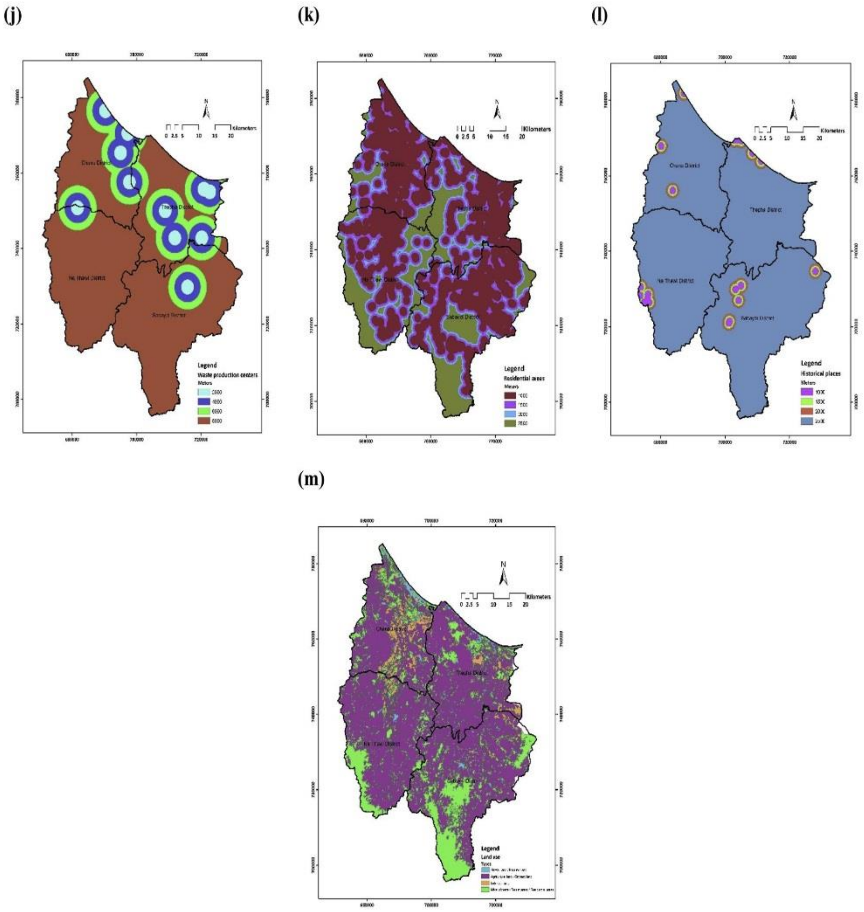

Fig. 2. (*continued*)

permeable soil, such as sand and sandy loam, are therefore unsuitable while low permeability soils, such as, clay and clay loam are suitable, and relatively low to medium permeability soil such as sandy clay are fairly suitable for landfills (Aydi et al., 2013; Bahrani et al., 2016). Sharifi and Retsios (2004) reported that clay-rich soil (possibly, more than 50% clay), high soil thickness and very low permeability soil (preferably 0.05 m/day or less) should be considered for landfill site construction. Sandy soil should not be selected for landfill sites because of the very high porosity and high-water permeability rate which can allow landfills to affect the quality of the water in the area. (Motlagh and Sayadi, 2015) meanwhile, suggested that the best soil texture is silty clay followed by silty sand.

Therefore, a soil texture map of the study area was obtained from the Land Development Department of Thailand and based on the judgment of local soil experts, four soil type layers were identified with silty clay, clay and mixed soil being ranked as very highly suitable, highly suitable and moderately suitable, respectively, while sandy and gravelly soils were considered to be unsuitable in this study, as can be seen in Fig. 2(c). Further details are included in Table A1 in the Appendix.

2.6. Environmental perspective

2.6.1. Hydrogeology

2.6.1.1. Aquifers. It is important to locate a landfill in areas with a low groundwater contamination risk. Groundwater contamination from landfills is determined by several factors including the permeability of aquifer units and the aquifer properties. In the present study, an aquifer map of the area was provided by the Department of Groundwater Resources, Songkhla, which showed that the area had, seven aquifer units based on assessments by local geologists. These seven aquifer units are defined as carboniferous metasedimentary, colluvial deposits, granitic, Lampang, old terrace deposits, triassic carbonate, and floodplain deposits. Lampang has a high potential for water absorption due to the preponderance of sand and was classified as permeable. Colluvial deposits and old terrace deposits contain sand, gravel and clay from old river deposits and have limited water absorption potential. These aquifer units were classified as semi-permeable. Carboniferous metasedimentary, granitic, triassic carbonate and floodplain deposits are impermeable because of the clay, rock and shale content and were considered as being highly suitable for the location of landfill sites (see Fig. 2(d)). Further details are included in Table A1 in the Appendix.

2.6.1.2. Groundwater table. According to the Pollution Control Department (PCD, 1998), a landfill site should be placed in an area where the groundwater level is sufficiently low, and sites at high groundwater level areas require a special design. For this study, an inverse distance weighting (IDW) interpolation approach to the water level data was used to determine the depth of the groundwater table. The data for 671 existing wells provided by the Department of Groundwater Resources were evaluated to establish the groundwater table, and groundwater depth readings from the study area were used in analyzing the potential landfill sites. Groundwater depth ranges from 0 to 1.5 m, 1.5 to 3 m and 3 to 4.5 m were determined as unsuitable, moderately suitable and highly suitable, respectively. Depths below 4.5 m were determined as very highly suitable in this study as shown in Fig. 2(e). Further details are included in Table A1 in the Appendix.

2.6.1.3. Surface water. Landfills produce leachate and poisonous gases. Therefore, landfill sites should not be located near any surface water such as ponds, lakes, rivers and streams (Alavi et al., 2013; Colvero et al., 2018; Demesouka et al., 2019; Gbanie et al., 2013; Kahraman et al., 2018; Motlagh and Sayadi, 2015; Nas et al., 2010; Simsek et al., 2014). A minimum buffer zone of 300 m should be sustained for any kind of natural or man-made water body, including wetlands as stated by the Pollution Control Department (PCD, 1998) and, the suitability of locations for landfills increases with increasing distance from water sources (Motlagh and Sayadi, 2015). Hence, a buffer zone of 300 m was adopted for any surface water and any area providing a buffer zone of fewer than 300 m from surface water was considered unsuitable, between 300 m to 600 m and 600 m to 900 m were considered moderately suitable and highly suitable, respectively, and greater than 900 m was considered to be very highly suitable as shown in Fig. 2(f). Further details are included in Table A1 in the Appendix.

2.6.2. Geology

2.6.2.1. Geological fault areas. It is not recommended that landfill sites be located in areas with active geological formations or other subsurface topographies, as reported by the Pollution Control Department (PCD, 1998). Thus, areas with dormant or active faults are considered inappropriate for landfill construction (Eskandari et al., 2012). Avoiding faults plays a major role in the prevention of pollution that might be caused by seismic activity (Gorsevski et al., 2012). Groundwater may be contaminated due to leachate as fault areas increase the permeability of rocks (Moeinaddini et al., 2010). The seismic risk and possibly unstable land area are significant factors for decision makers when considering the siting of a landfill (Demesouka et al., 2013). Further, areas subject to active or potentially active landslides are not feasible for landfill sites (Motlagh and Sayadi, 2015). Landfill sites should be placed at a location distant from fault lines to reduce the possibility of natural disasters (Kahraman et al., 2018). Therefore, a buffer zone of 300 m was allowed around geological fault areas, as can be seen in Fig. 2(g). Areas less than 300 m distant were considered as unsuitable; those between 300 m and 400 and 400 m and 500 m distant were considered as moderately suitable and highly suitable, respectively, while areas greater than 500 m distant were considered to be very highly suitable in this study (see Fig. 2(g)). Further details are included in Table A1 in the Appendix.

2.6.2.2. Floodplain. According to the Pollution Control Department (PCD, 1998), any area where frequent or periodic flooding occurs is unsuitable for a landfill site. To avoid the threat of overland drainage pollution, a landfill should not be located near to a floodplain (Lin and Kao, 2005). Areas located in the 100-year floodplain are therefore inappropriate for landfills since the floodplains of major rivers may represent a risk to the stability of the waste dumped in the landfill. Hence, landfills should not be placed within 300 m of a major river (Bagchi, 2004; Şener et al., 2010; Simsek et al., 2014). However, the floodplains of secondary streams can be used for landfills by constructing an embankment (Bagchi, 1994). For this study, the alluvial plains of major rivers were considered to be unsuitable and the remaining areas as suitable as shown in Fig. 2(h). Further details are included in Table A1 in the Appendix.

2.7. Socio-economic perspective

2.7.1. Accessibility

2.7.1.1. Road network. Many researchers have recommended a 1000 m buffer zone for the location of a landfill site from the road network (Al-Hanbali et al., 2011; Baban and Flannagan, 1998; Chang et al., 2008; Delgado et al., 2008). However, in view of high transportation costs, landfill sites should not be located too distant from the road network and the suitability ranking of sites declines the further they are from the road network (Kahraman et al., 2018; Uyan, 2014; Yal and Akgün, 2014). Therefore, linkage of the landfill site to the existing road network by a permanent road is indispensable. The road should be 5 m wide for small operations and 6 to 8 m wide for larger landfills (Ersoy et al., 2013). In addition, garbage trucks should not obstruct traffic streams (Guiqin et al., 2009). In this study, since a buffer zone of 250 m around road networks is required by the Department of Highways, a distance greater than 1000 m was considered as very highly suitability while distances of less than 250 m were considered as unsuitable as can be seen in Fig. 2(i). Further details are included in Table A1 in the Appendix.

2.7.1.2. Waste production centres. The economic feasibility of a candidate landfill site is a significant factor since the proximity of a landfill site to waste production centres will reduce transportation costs (Guiqin et al., 2009; Kahraman et al., 2018). Hence, siting a landfill in areas too distant from the waste production centres is entirely unacceptable since it would entail long distance to be travelled by garbage trucks (Demesouka et al., 2013). In this study, the distances between all the candidate landfill sites, existing landfills and the waste production centres were analyzed. The existing landfill and waste production centre data were obtained from the Regional Environmental Office, Songkhla and it was concluded that candidate landfill sites near to existing landfills and waste production centres would be highly suitable. A distance of less than 2000 m was considered as very highly suitable and greater than 6000 m was considered as unsuitable in this study (see Fig. 2(j)). Further details are included in Table A1 in the Appendix.

2.7.2. Public places

2.7.2.1. Residential areas. This criterion is very important due to the NIMBY phenomenon and is the factor primarily responsible for restricting the number of suitable sites for siting landfills. The proximity of a landfill site to a residential area entails various environmental issues such as human health, land prices and future urban development (Kahraman et al., 2018; Nas et al., 2010; Şener et al., 2010). According to European legislation, landfill sites at a distance of less than 500 m from residential areas are unacceptable (Demesouka et al., 2019, 2013; Gorsevski et al., 2012). In addition, previous studies (Chabuk et al., 2016; Ersoy and Bulut, 2009; Nas et al., 2010; Şener et al., 2010; Uyan, 2014) and the judgment of local experts consulted in this study suggested that landfill sites should not be located within 1000 m of residential areas. For this reason, in this study, a buffer zone of 1000 m was adopted around residential areas to avoid public opposition. A buffer zone of less than 1000 m and greater than 2000 m were evaluated as unsuitable and very highly suitable, respectively, as shown in Fig. 2 (k). Further details are included in Table A1 in the Appendix.

2.7.2.2. Historical places. The study area contains some historical sites including mountain tunnels, temples, national parks and waterfalls. According to the Pollution Control Department (PCD, 1998), any

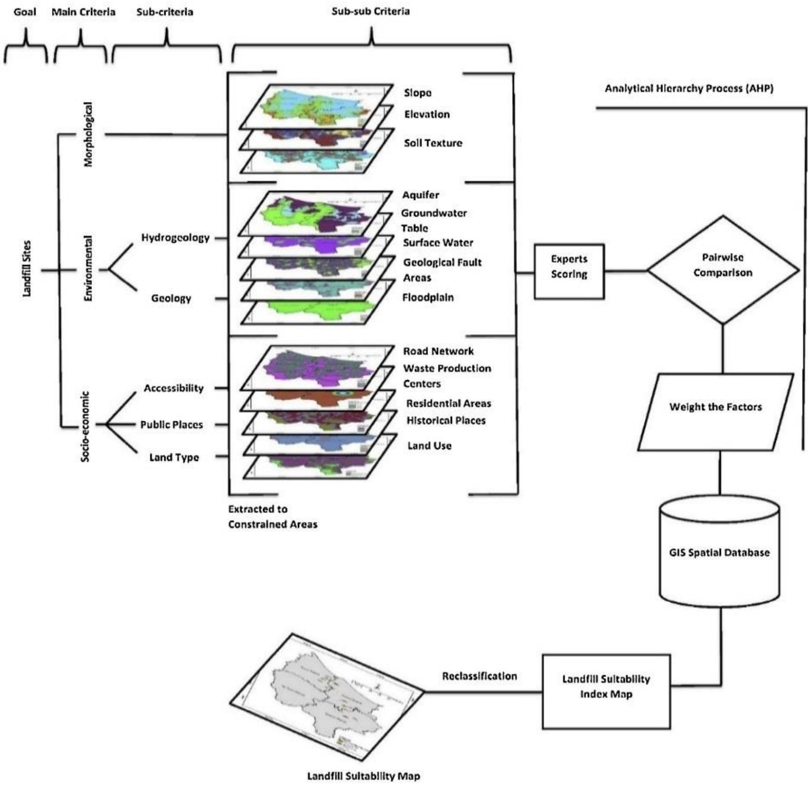

Fig. 3. Flowchart of the methodology.
(adapted source (Şener et al., 2011)).

ancient monument as defined under the Ancient Monuments, Relics, Antiques and National Museum Act of 1961 is unsuitable for landfill sites. Moreover, the construction of landfill sites at a distance of less than 1000 m from historical places is prohibited by the PCD and is also not recommended in the international literature (Chabuk et al., 2016; Kahraman et al., 2018; Uyan, 2014; Yildirim, 2012). Hence, buffer zones of 1000 m around all historical places were allowed based on GIS software data. A buffer zone of less than 1000 m was evaluated as unsuitable and one greater than 2500 m was evaluated as very highly suitable in this study, as can be seen in Fig. 2 (l). Further details are included in Table A1 in the Appendix.

2.7.3. Land type

2.7.3.1. Land use. Land use portrays the human use of the land and the natural environment. Land use classes include forest, agricultural, residential, industrial, military and archaeological areas (Simsek et al., 2014). Gorsevski et al. (2012) used land use categories of water, forest, and barren and agricultural land whereas (Alavi et al., 2013) classified land use as residential, agricultural, industrial and unused land. However, Kontos et al. (2005) distinguished agricultural and pasture lands while Chabuk et al. (2016) also considered orchards and unused lands as the most suitable areas for landfill siting. The aim of this criterion is to protect highly productive or underdeveloped areas and to ensure low capital costs. Thus, residential areas and mixed forests were considered inappropriate for siting landfills. and tourist areas were also regarded as unsuitable. Industrial areas play an important role in the development of a region and were classified as moderately suitable while agricultural and orchard lands were evaluated as highly suitable. Finally, in this study, the most highly suitable areas classified for landfill sites were grassland and pasture (see Fig. 2 (m)). Further details are included in Table A1 in the Appendix.

2.8. GIS-AHP application

Since the morphological, environmental and socio-economic criteria were diverse in nature, represented in different units and partially or totally contradictory, they were integrated using the MCDM technique and the GIS tool as have been applied by previous researchers for landfill site selection (Demesouka et al., 2019, 2013; De Feo and De Gisi, 2014; Gbanie et al., 2013; Motlagh and Sayadi, 2015). MCDM based on GIS is an intelligent technique from which valuable information can be obtained through the exploitation and conversion of spatial and non-spatial data, which can help in critical decision making, based on the judgment of decision makers (Chen et al., 2010; Gbanie et al., 2013; Sumathi et al., 2008).

In this study, the main aim of applying MCDM in a GIS environment was to identify the most suitable landfill sites. MCDM requires the assigning of weights to various criteria. Each criterion was assigned a weight based on the opinions of experts and stakeholders' familiar with the local situation, including consideration of the local MSWM scenario and the relative lack of organized scientific methods and technical skills available in the four districts studied. Previous studies have variously employed the judgment of two, three and five experts (Chang et al., 2008; Demesouka et al., 2013; Gbanie et al., 2013; Kahraman et al., 2018). However, in this study, a total of ten experts variously drawn from the local administration office and the provincial environmental agency as well as experts in the fields of civil engineering, soil science, mining and materials engineering and sociology were consulted, along with representatives of the operators of the waste-to-energy gasification power plant in Hat Yai and stakeholders in the study area. The experts' and stakeholders' rankings represented the importance of the various criteria to them. For example, for environmental scientists, environmental issues would be assigned first priority, whereas stakeholders and sociologists might prioritize issues such as waste disposal expenses and aesthetic places in the study area and civil engineers and soil science experts would emphasize the topographic conditions of the area since neglecting morphological criteria could ultimately lead to the failure of any landfill site project.

The weights for the main criteria, sub-criteria and sub-sub criteria (attributes) were calculated by using the AHP approach. AHP is an extensively recognized decision-making approach to evaluate data for the assessment of suitable landfill sites through the GIS tool. The AHP approach is executed in three basic steps (Saaty and Vargas, 2001). The first step involves the decomposition of the decision-making problem into a hierarchical structure, and for this study, the hierarchy of steps can be seen in Fig. 3. The next step in AHP is based on pairwise comparisons which are used to determine the weights for various criteria. The weight of a particular criterion is determined by ranking its importance and suitability. The evaluation of the pairwise comparisons is completed through expert judgment. The comparison of various criteria can be made using a 9-point scale defined by (Saaty, 1990) as shown in Table 2.

In this study, Saaty's 9-point scale was employed (Table 2). Ten experts familiar with the local conditions judged the criteria in order to derive a square matrix (Mx) for pairwise comparison of the various criteria applicable in landfill site selection is expressed in Eq. (1):

$$Mx = \begin{bmatrix} C_{11} & C_{12} & C_{13} & \dots & C_{1n} \\ C_{21} & C_{22} & C_{23} & \dots & C_{2n} \\ C_{31} & C_{32} & C_{33} & \dots & C_{3n} \\ \dots & \dots & \dots & \dots & \dots \\ C_{n1} & C_{n2} & C_{n3} & \dots & C_{nn} \end{bmatrix} \tag{1}$$

$Mx = [Cij]\ \forall\ i, j = 1,2,3, \dots n$ for n criteria that influence the ultimate objective of the study, where, Cij demonstrates the relative importance of the criteria Ci over Cj and the reciprocal will be Cji or $1/Cij\ \forall\ i \neq j$ and $Cii = 1$ (Saaty, 1990). Therefore, the main criteria, sub-criteria and sub-sub criteria were evaluated using the matrix as in Eq. (1). Subsequently, weights were calculated by normalizing the individual eigenvectors associated with the principle eigenvector of the reciprocal ratio matrix. Finally, the ranking values of all the criteria were normalized to '1'. The final weights used for landfill site selection in the study area using the AHP approach on the basis of the experts' judgments are shown in Table 3 whereas the AHP pairwise comparisons can be seen in Table B1 in the Appendix.

The final step was to check the consistency ratio. Inconsistencies may occur due to the involvement of expert judgment. To check the level of inconsistencies, a measure known as the consistency ratio (CR) was introduced by (Saaty, 1990) and has been widely applied in previous research dealing with MSWM applications (Chabuk et al., 2016, 2017; Eskandari et al., 2015; Gorsevski et al., 2012; Khan et al., 2018; Moeinaddini et al., 2010). The mathematical form for the calculation of CR is represented by Eq. (2):

$$CR = \frac{CI}{RI} \tag{2}$$

where CI is the consistency index and RI the random index or mean consistency index, which depends on the matrix size (Şener et al., 2011; Ying et al., 2007). The mathematical formulation for the calculation of the CI is described by Eq. (3):

$$CI = \frac{\lambda max - n}{n - 1} \tag{3}$$

where λmax is the principle eigenvalue and n is the matrix size ($n \times n$) in a pairwise comparison. The RI values utilized for different matrix sizes are given in Table 4 (Donegan and Dodd, 1991).

Generally, the CR should be maintained at less than 0.10 in order to maintain the consistency of the matrix (Şener et al., 2010) and, a CR greater than 0.10 indicates inconsistency in the experts' judgments which require re-evaluation. The CR in this research for morphological, environmental and socio-economic criteria were 0.05, 0.03 and 0.02, respectively, all of which were below 0.10 which indicates that the weights assigned were appropriate. According to (Saaty, 1993), the CI can be improved by keeping the number of factors in a group small, maintaining the homogeneity of factors within each group and better understanding the problem.

The calculated weights of the various criteria were aggregated using the weighted linear combination (WLC) technique based on MCDM and the GIS tool. In this study, the ArcGIS 10.3.0 tool using the WLC technique was used to combine the multiple map layers and their different weights. This technique has been extensively used in previous studies of landfill site selection (Gbanie et al., 2013; Gorsevski et al., 2012; Motlagh and Sayadi, 2015; Shahabi et al., 2014). A base map of 500 m was used for the entire data set in order to bring the distinct data layers into a common spatial resolution. For suitability analysis, a 4-point scale was used to rank the various criteria where 3 represented very highly suitable, 2 represented highly suitable, 1 represented moderately suitable and 0 represented unsuitable, as shown in Table A1 in the Appendix. Thereafter, the multiple map layers with different weights were overlaid using the GIS overlay tool. The weights of the various criteria were summed to calculate the total suitability by using the following mathematical Eq. (4):

$$SI = \sum w_i s_i \tag{4}$$

$w_i =$ the weight of criterion i, $s_i =$ standardized suitability score of criterion i and $SI=$ suitability index for the area. This permitted the merging of the distinct data layers to achieve the stated objective and the results of the study are presented in the next section.

3. Results and discussion

This was the first-ever study to identify ideal landfill sites in the four southernmost districts of Songkhla province, Chana, Na Thawi, Sabayoi

Table 2
Pairwise comparison scale in AHP (Saaty, 1990).

Intensity of importance	Definition	Explanation
1	Equal importance	Two attributes preferred equally
2	Weak or slight	Judgement indicates weak favoring of one attribute over another
3	Moderate importance	Judgement slightly favored one element over the another
4	Moderate plus	Judgement moderately favored one element over the another
5	Strong importance	Judgement strongly favored one element over the another
6	Strong plus	Judgement slightly more than strongly favored one element over the another
7	Very strong or demonstrated importance	Judgement very strongly favored one over the another
8	Very, very strong	Judgement very, very strongly favored one over the another
9	Extreme importance	Extreme preference of one attribute over the another

Table 3
Significance weights of main criteria, sub-criteria and sub-sub criteria.

Main criteria	W1	Sub-criteria	W2	Sub-sub criteria	W3	Final weight
Morphological	0.2231	Slope	0.3515	Slope	1	0.0784
		Elevation	0.3222	Elevation	1	0.0719
		Soil texture	0.3261	Soil texture	1	0.0727
Environmental	0.4958	Hydrogeology	0.6666	Aquifer	0.1527	0.0504
				Groundwater table	0.4318	0.1427
				Surface water	0.4154	0.1373
		Geology	0.3333	Geological fault areas	0.625	0.1033
				Floodplain	0.375	0.0619
Socio-economic	0.2809	Accessibility	0.3005	Road network	0.5	0.0422
				Waste production centers	0.5	0.0422
		Public places	0.4757	Residential areas	0.75	0.1002
				Historical places	0.25	0.0334
		Land type	0.2237	Land use	1	0.0628

Key: W1: weight of layer 1, W2: weight of layer 2, W3: weight of layer 3, Final weight = W1*W2*W3, CR: consistency ratio ≤ 0.1.

Table 4
RI values for different matrix sizes (Donegan and Dodd, 1991).

n	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0.00	0.00	**0.58**	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.59

and Thepha. In total, thirteen parameters were selected within the headings of morphological, environmental and socio-economic perspectives based on regional experts' judgments and guidelines derived from relevant literature, to investigate the most suitable areas for landfill sites within the four districts of Songkhla as shown in Fig. 1, by applying MCDM in a GIS environment. Each criterion was assigned weights on the basis of experts' judgments using the AHP approach.

Based on the scoring by the experts. this study found that groundwater table was the most significant criterion for landfill site selection in terms of the environmental perspective with a weight of 0.1427 (14.27%) and this factor has also been considered as posing environmental health risks in previous studies (Wang et al., 2018). The experts assigned a weight of 0.1373 (13.73%) to surface water, which was the next most significant criterion within the environmental perspective. with geological fault areas being the third most significant criterion with a weight of 0.1033 (10.33%). Under the economic perspective, residential areas were given a weight of 0.1002 (10.02%) and were considered to be the most crucial criterion, due to the NIMBY syndrome (Demesouka et al., 2019). Under the morphological perspective, slope, soil texture and elevation were assigned weights of 0.0784 (7.84%), 0.0727 (7.27%) and 0.0719 (7.19%), respectively as the three most significant factors.

Thus, based on the judgment of the experts familiar with the local conditions, the dominant criterion in the study area was judged to be the environmental perspective with a total weight of 0.4958 (49.58%), followed by the socio-economic perspective with a total weight of 0.2809 (28.09%) with the morphological perspective being judged to be less important with total weights of 0.2231 (22.31%).

The weight values obtained were used to produce a map for each criterion using the ArcGIS analysis tool, and the field calculator and overlay union of the ArcGIS analysis tool were used to create a final suitability map (Fig. 4). The landfill suitability index (LSI) was used to calculate the suitability for the siting of landfills in the study area after the screening out of restricted areas. The range of the LSI was between 2.00184 and 3.05589. In order to understand the scale easily, an equal interval classification method was used to divide the range of attribute values into sub-ranges of equal proportion. The landfill suitability values of the study area were grouped into three classes: very highly suitable (3.05589 to 2.70454), highly suitable (2.70454 to 2.35319) and moderately suitable (2.35319 to 2.00184).

The results show that out of a total area of 302944.51 hectare (ha), 180.72 ha (0.06%) of the study area is moderately suitable, 993.19 ha (0.33%) is highly suitable and 560.59 ha (0.19%) is very highly suitable for landfill siting. The remaining 301,210.01 ha (99.43%) is unsuitable for landfill siting as shown in Table 5. This study, therefore, found that 560.59 ha of the study area can be considered as very highly suitable for landfill sites taking into consideration the morphological, environmental and socio-economic factors. According to this table, Chana had 53.47 ha of very highly suitable for landfill siting, Sabayoi had 121.80 ha, while Thepha had 385.31 ha of very highly suitable land for landfill sites. On the other hand, Na Thawi was found to be entirely unsuitable for the construction of landfill sites.

Based on the land requirement guidelines for landfill capacities recommended by the Pollution Control Department (PCD, 1998), as shown in Appendix Table C1, eighteen candidate sites designated from CS1 to CS18 are appropriate for landfill siting. Thepha was found to be very highly suitable for landfill siting having a total of eight candidate sites. These sites meet all the requirements of the guidelines of the Pollution Control Department on the basis of the amount of MSW (tonnes/day) and the land requirement (hectares). In Thepha, candidate sites CS6, CS7 and CS8 could accommodate 10 to 50 tonnes/day of MSW, candidate site CS11, 50 to 100 tonnes/day, candidate site CS14, 100 to 300 tonnes/day, while candidate sites CS15, CS17, CS18 could deal with 300 to 500 tonnes/day of MSW and all, are therefore appropriate for landfill sites. On the other hand, Sabayoi has four candidate landfill sites comprising CS1 and CS4 which could accommodate 10 to 50 tonnes/day MSW, CS13, 50 to 100 tonnes/day and CS16. 300 to 500 tonnes/day of MSW. Similarly, Chana has six candidate sites: CS2, CS3, CS5 which could accommodate 10 to 50 tonnes/day, and CS9, CS10, and CS12, 50 to 100 tonnes/day of MSW. However, there were no candidate sites in Na Thawi which met the aforementioned guidelines. Further details are shown in Appendix Table C1 and Appendix Table D1, and the final suitability map is presented in Fig. 4.

4. Conclusions

Landfill site selection is an important and difficult task which involves a high degree of complexity in balancing the morphological, environmental and socio-economic perspectives. This study developed an MCDM technique that was applied in a GIS environment to investigate the best location for landfill sites in the four southernmost districts of Songkhla province, Chana, Na Thawi, Sabayoi and Thepha.

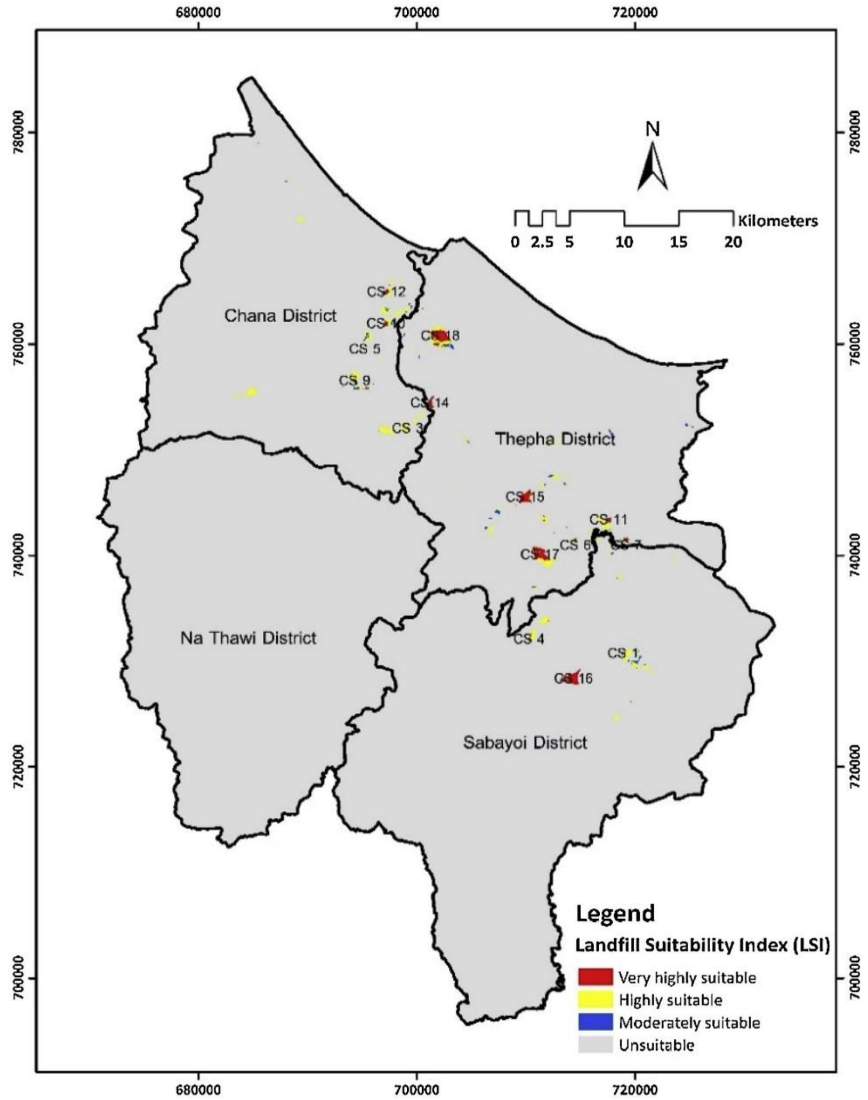

Fig. 4. Landfill suitability map.

Table 5
Area-based suitability classes of the total study area.

District	Very highly Suitable (ha)	Highly suitable (ha)	Moderately suitable (ha)	Unsuitable (ha)	Total area (ha)
Chana	53.47	394.66	47.58	62,265.88	62,761.60
Na Thawi	–	–	–	78,389.58	78,389.58
Sabayoi	121.80	191.41	28.60	95,470.99	95,812.81
Thepha	385.31	407.11	104.54	65,083.55	65,980.52
Total	560.59	993.19	180.72	301,210.01	302,944.51

Key: ha: hectare.

On the basis of expert judgment and previous international studies, morphological, environmental and socio-economic criteria were scrutinized. Using the AHP approach the weights of various criteria were calculated which were used to construct thirteen input map layers which were then synthesized using the GIS tool to produce a final suitability map through overlay analysis.

In addition, the authors also concluded that landfilling is the most common practices for solid waste disposal in developing countries, however, the concept of landfill tax in these countries has been limited. Introduction of landfill sites taxes would make it a costly waste management option, which would help in reducing the amount of waste going to landfills. Application of landfill sites taxes would encourage the households to increase the efforts of recycling their wastes as through unit-based pricing system, the municipal authorities would charge the household for high landfill costs. Furthermore, the landfill sites tax policy would promote prevention and recycling to enhance its effectiveness as well as introducing high landfill tax could increase the financial attractiveness of waste-to-value technologies to landfilling.

This study found eighteen candidate sites that are suitable for landfill siting, with eight candidate sites in Thepha, six candidate sites in Chana, and four candidate sites in Sabayoi, which are all very highly suitable. However, Na Thawi district contained no suitable landfill sites based on the suitability criteria employed. The study was also used to show that the siting of some of the existing open landfill sites in the four districts could pose a severe risk to the health of the communities living nearby as environmental safety measures have been previously breached. This methodology can be adapted by including more criteria in landfill site selection, considering environmental health risks, contaminants in soil and water using the spatial interpolation tools from GIS, and thus uncertainty can be reduced. In future analysis, participatory GIS (PGIS) approach would be beneficial in dealing with landfill siting since PGIS would provide a platform for the public in the decision making process. Furthermore, additional data layers could be obtained and measured from topography using geomorphometric analysis.

Therefore, the findings of this study are likely to be capable of resolving issues relating to potential landfill sites in the future since the method adopted in this study is scientific in its approach and is an effective tool for decision makers, planners and stakeholders in deciding where to site landfills. Moreover, this method permits the decision makers to accomplish decision analysis functions and can help to them to solve waste management issues in tropical regions like Thailand and the method presented in this study can also be reproduced for potential landfill siting in other parts of the world.

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Appendix A

Table A1
Suitability ranking of factors.

Factors	Ranges	Suitability ranking
Slope (degree)	0-5	3
	5-10	2
	10-15	1
	> 15	0
Elevation (m)	0-40	3
	40-80	2
	80-120	1
	> 120	0
Soil texture	Silty clay	3
	Clay	2
	Mixed soil	1
	Sandy / Gravelly	0
Aquifer	Carboniferous metasedimentary	Impermeable
	Granitic	Semi-permeable
	Triassic carbonate	Permeable
	Floodplain deposits	
	Colluvial deposits	
	Old terrace deposits	
	Lampang	
Groundwater table (m)	> 4.5	3
	4.5-3	2
	3-1.5	1
	1.5-0	0
Surface water (m)	> 900	3
	900-600	2
	600-300	1
	< 300	0
Geological fault areas (m)	> 500	3
	500-400	2
	400-300	1
	< 300	0
Floodplain	Non-floodplain	3
	Floodplain	0
Road network (m)	> 1000	3
	1000-750	2
	750-250	1
	< 250	0
Waste production centres (m)	< 2000	3
	2000-4000	2

(continued on next page)

Table A1 (*continued*)

Factors	Ranges	Suitability ranking
	4000-6000	1
	> 6000	0
Residential areas (m)	> 2000	3
	2000-1500	2
	1500-1000	1
	< 1000	0
Historical places (m)	> 2000	3
	2000-1500	2
	1500-1000	1
	< 1000	0
Land use	Grassland / Pastureland	3
	Agricultural land / Orchard land	2
	Industrial area	1
	Mixed forests / Tourist areas / Residential areas	0

Appendix B

Table B1
AHP pairwise comparison.

	Morphological	Environmental	Socio-economic	Sum of rows	Final weight	CR
Morphological	1	0.5	0.75	2.25	0.2231	0.0086
Environmental	2	1	2	5	0.4958	
Socio-economic	1.33	0.5	1	2.83	0.2809	
	Slope	Elevation	Soil Texture			
Slope	1	1.4	0.83	3.23	0.3515	0.0530
Elevation	0.71	1	1.25	2.96	0.3222	
Soil Texture	1.2	0.8	1	3	0.3261	
	Aquifer	Groundwater table	Surface water			
Aquifer	1	0.4	0.33	1.73	0.1527	0.0327
Groundwater table	2.5	1	1.4	4.9	0.4318	
Surface water	3	0.71	1	4.71	0.4154	
	Accessibility	Public Places	Land use			
Accessibility	1	0.8	1.2	3	0.3005	0.0273
Public Places	1.25	1	2.5	4.75	0.4757	
Land use	0.83	0.4	1	2.23	0.2237	
	Hydrogeology	Geology				
Hydrogeology	1	2		3	0.6667	0
Geology	0.5	1		1.5	0.3334	
	Geological faults	Flood plains				
Geological faults	1	1.67		2.67	0.625	0
Flood plains	0.6	1		1.6	0.375	
	Road Network	Waste Centre				
Road Network	1	1		2	0.5	0
Waste Centre	1	1		2	0.5	
	Residential	Historical places				
Residential	1	3		4	0.75	0
Historical places	0.33	1		1.33	0.25	

Key: CR: consistency ratio.

Appendix C

Table C1
Classification of candidate sites according to PCD guidelines.

PCD Guidelines	Amount of MSW (tonnes/day)			
	10 to 50 Land requirement (ha)	50 to 100	100 to 300	300 to 500
	2.4 to 11.2	11.2 to 20.8	20.8 to 52.8	52.8 to 99.2
District	Candidate site			
Chana	CS2, CS3, CS5	CS9, CS10, CS12	–	–
Na Thawi	–	–	–	–
Sabayoi	CS1, CS4	CS13	–	CS16
Thepha	CS6, CS7, CS8	CS11	CS14	CS15, CS17, CS18

Key: CS: Candidate site, ha: hectare.

Appendix D

Table D1
The suitable candidate sites area in hectares.

District	Candidate site	Area in hectares	Candidate site	Area in hectares
Chana	CS2	2.89	CS9	11.34
	CS3	3.29	CS10	12.92
	CS5	4.02	CS12	15.66
Na Thawi	–	–	–	–
Sabayoi	CS1	2.75	CS13	17.51
	CS4	3.70	CS16	94.75
Thepha	CS6	7.50	CS14	29.11
	CS7	9.82	CS15	79.26
	CS8	9.96	CS17	103.35
	CS11	13.75	CS18	124.51

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APPENDIX F

Conference certificate

CERTIFICATION OF ATTENDANCE

This certifcate is awarded to

Ismail Kamdar

for presentation on

"Selection of Municipal Solid Waste Disposal Site
for Ban Phru, Thailand Using GIS"

in ASSURING SUSTAINABILITY via University
with Research: Towards a sustainable development
(ASSURE 2018) International Conference

23th January 2018
Ranong Room Siam Oriental Hotel
Hatyai, Songkhla, Thailand

Banchong Witthayawirasak

Assoc. Prof. Dr. Banchong Witthayawirasak
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VITAE

Name Mr. ISMAIL KAMDAR

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Educational Attainment

Degree	Name of Institution	Year of Graduation
Bachelor of Science in Electrical (Power) Engineering	COMSATS Institute of Information Technology, Abbottabad, Pakistan	2016

Scholarship Awards during Enrolment

Interdisciplinary Graduate School (IGS) Grant No. IGS Contract no.074-282263

Awarded Endowment Fund Scholarship for bachelor's study in Electrical Power Engineering at COMSATS University Islamabad, Abbottabad Campus, Pakistan │ 2012 – 2016.

Work – Position and Address

Trainee Electrical Engineer in Islamabad Electric Supply Company (IESCO) June 2016 – May 2017 (12 months).

List of Publication and Proceeding

Journal Publications

(As the first author)

Ismail Kamdar, Shahid Ali, Adul Bennui, Kuaanan Techato & Warangkana Jutidamrongphan* (2019). Municipal solid waste landfill siting using an integrated GIS-AHP approach: A case study from Songkhla, Thailand. Resources, Conservation and Recycling. (Impact Factor 7.044; ISI Science Citation Index Expanded) https://doi.org/10.1016/j.resconrec.2019.05.027

Ismail Kamdar, Dilawer Ali, Juntakan Taweekun*, Warangkana Jutidamrongphan & Kuaanan Techato (2019). A review study on municipal solid waste management and waste to energy technologies. International Journal of Integrated Engineering (IJIE). (SCOPUS) (Accepted)

Conference proceedings

Ismail Kamdar, Juntakan Taweekun & Kuaanan Techato: “Title: Selection of municipal solid waste disposal site for Ban Phru, Thailand using GIS” at Assuring Sustainability via University with Research: Towards a sustainable development (ASSURE 2018) International Conference, 23 January, Ranong Room Siam Oriental Hotel, Hat Yai, Songkhla, Thailand.

Ismail Kamdar: Attended International Conference on Energy Systems and Environmental Management (ESEM 2018) on 22nd June 2018, Golden Crown Grand Hotel Hat Yai, Songkhla, Thailand.