



Article

Estimating Potential Methane Emission from Municipal Solid Waste and a Site Suitability Analysis of Existing Landfills in Delhi, India

Chander Kumar Singh *, Anand Kumar and Soumendu Shekhar Roy

Department of Energy and Environment, TERI University, New Delhi 110070, India; anand.everst@gmail.com (A.K.); imssroy@gmail.com (S.S.R.)

* Correspondence: chanderkumarsingh@gmail.com or chander.singh@teriuniversity.ac.in; Tel.: +91-965-021-0123

Received: 16 August 2017; Accepted: 20 September 2017; Published: 25 September 2017

Abstract: The management of rapidly growing municipal solid waste (MSW) is one of the major challenges in developing countries. The current study also estimates the suitability of a site through a geographical information system using multi-criteria decision analysis (MCDA) for landfill sites in National Capital Territory (NCT). The results of the suitability index indicate that only 58.7 km² of the land is suitable for the construction of landfill sites, while 194.27 km² of the total area is moderately suitable. The existing three landfill sites that are currently functional and used by government organizations as landfills are found to be moderately suitable. A large fraction of MSW is disposed in landfills, which emit one third of the total anthropogenic methane (CH₄) and are considered an important contributor of Green House Gases (GHGs) to the atmosphere. Thus, there is a need for the proper estimation of GHG emission from landfills, specifically CH₄, which contributes 20% of the GHGs that contribute to global warming. The current study aims to estimate the CH₄ emission from landfills in the NCT, Delhi, India using GHG inventory guidelines from the Intergovernmental Panel on Climate Change (IPCC). The CH₄ emission from landfills has doubled from 31.06 Gg/yr from 1999 and 2000 to 65.16 Gg/yr from 1999 and 2000 to 2015. The generation of CH₄ from MSW is strongly correlated ($R^2 = 0.58$) with the Gross State Domestic Product (GSDP), which is an indicator of wellbeing.

Keywords: municipal solid waste; landfill; methane; site suitability; geographical information system (GIS)

1. Introduction

India has seen a tremendous increase in its urban and semi-urban population in the last few decades. The percentage of the population in urban areas has increased from 27.8% to 31.16% from 2001 to 2011 as per the Census of India conducted in 2011. Rapid population growth with unplanned urbanization has led to several basic infrastructure problems such as water supply, storm water logging, and sewerage, along with the management of solid wastes generated in the rapidly developing cities of India. Municipal solid waste (MSW) is typically defined as the waste materials originating from domestic, commercial, and public areas such as gardens, street sweeping, and drain silts, which, in the long run, might cause environmental and public health problems [1–3]. Due to changes in lifestyle and increase in per capita income, the generation of MSW has increased, and its proper disposal and management has become a major challenge for government and non-government organizations [3,4]. The collection of MSW is challenging due to a lack of resources, improper infrastructure, lack of community participation, and awareness. The uncollected waste gets disposed in an inappropriate area, which affects the environment as well as the aesthetics of the surroundings. Several ways to manage MSW have been suggested, including recycling, reduction at source, and incineration [5,6]

but the most common and traditional practice for the disposal of MSW is landfill. The random and unscientific selection of landfill sites may create a threat to the environment, humans, and adjacent aquatic bodies, including groundwater. It has been argued that the information about the geology, hydrology, landuse and landcover (LULC), along with the understanding of the landfill site, is most important before the selection of suitable landfill sites [7]. Households are the largest source of solid waste generation in Delhi [8], and the compliance to rules regarding MSW management is very low [9].

The selection of sites for the proper construction of landfills is important as it adversely affects the regional and global environment. A recent incident took place at a landfill site in Delhi on 1 September 2017, when a 50 m high mound of landfill collapsed, killing some people. The geographical information system (GIS) along with multi-criteria decision analysis (MCDA) provides a suitable approach to solve the complications which might be encountered during the decision-making process [10–13]. Remote sensing and GIS can be used as to identify the cost-effective, environment friendly and easily accessible or transportable area for landfill [13]. MCDA supports the decision maker with its specialty in ranking a known set of alternatives by comparing them with other variables based on how they perform relative to each criterion. Multi-Criteria Decision-Making (MCDM) determines a preference among a set of variables. The decision-maker's preferences depend upon the relative importance of the options according to a number of "criteria", which are identified by experts or stakeholders. The integration of spatial data using GIS-based MCDM for site suitability has been recognized as an important analytical tool in the environmental decision-making process for formulating and addressing the spatial issues of challenging decision objectives [14].

In decision making processes, a large set of feasible alternatives are always involved, which makes it more difficult for users as conflicts and inadequate decisions are always involved [15–17]. Both value and utility based models are based on mathematical functions, which assist in decision making based on their preferences. Multi-attribute value theory (MAVT), multi-attribute utility theory (MAUT), and the analytic hierarchy process (AHP) are the most common approaches. In comparison to other methods, the AHP has gained importance in terms of being interactive, allowing the automatic calculation of priorities and inconsistencies, and providing several ways to process a sensitivity analysis. The AHP is widely used for suitability analysis, natural resource management, and environmental planning, but still it has limitations, especially in terms of rank reversal, i.e., when a new alternative is added or an old one is deleted in the course of a new operations research or decision-making process [18].

Studies have been conducted using AHP for suitable site selection for potential groundwater zones [19,20], landfill sites selection [13], city planning [21], treatment plant allocation [13,22], and the conservation of natural resources [23].

Significant amounts of leachates generated during the decomposition of wastes have the potential to contaminate groundwater aquifers [24]. These leachates increase the acidity of the soil [24–26] and also initiate the mobilization of heavy metals present into the landfill wastes. Landfills are also considered as the one of the major sources of Green House Gases (GHGs). It has also been estimated that landfills are among the third major anthropogenic source of GHGs, including carbon dioxides (CO_2) and methane (CH_4) [27–29]. The high concentrations of CH_4 have tendency to replace oxygen in the surrounding atmosphere and increase human health risks. Once MSW is deposited into the landfill, it goes through anaerobic decomposition process, and, due to the activity of methanogens, CH_4 is emitted into the atmosphere [4,30]. CH_4 is one of the most important GHGs as it has a high global warming potential, i.e., 28 times higher than CO_2 [4]. According to an estimate by Global Methane Initiative, the concentration of CH_4 is expected to be 8.59 Gt CO_2 -eq (CO₂-eq) by 2020 and was recorded as 6.88 Gt CO_2 -eq in 2010 [31]. There are some established methods that have been used by researchers to determine the concentration of CH_4 emitted from landfills [27,32].

With the above background, an effort has been made to assess the suitability of landfill sites in one of the fastest growing cities and the national capital of India, Delhi, and to estimate the CH_4 emission from the existing landfills in the study area.

2. Study Area

2.1. Geographical Location

This study has been conducted in the National Capital Territory (NCT) of India, Delhi, which is situated between $28^{\circ}23'17''$ N– $28^{\circ}53'00''$ N latitude and $76^{\circ}50'24''$ E– $77^{\circ}20'37''$ E longitude (Figure 1). The study area covers around 1480 km^2 of the total area, with an altitude varying from 213 m to 305 m from the mean sea level. The study area is the part of Gangetic alluvial plain, and, based on the average rainfall value (714 mm), it is classified as a semi-arid climatic zone. The Yamuna River passes through the eastern part of the study area, and geologically the area is composed of older alluvium, newer alluvium, channel alluvium, aeolian surface, and quartzite with inter bedded schist [14]. The city is growing rapidly, and the population of the city has increased from 13.8 million to 16.7 million from 2001 to 2011 (Census of India, 2011), out of which 91% of the total population stays in the urban and peri-urban areas.

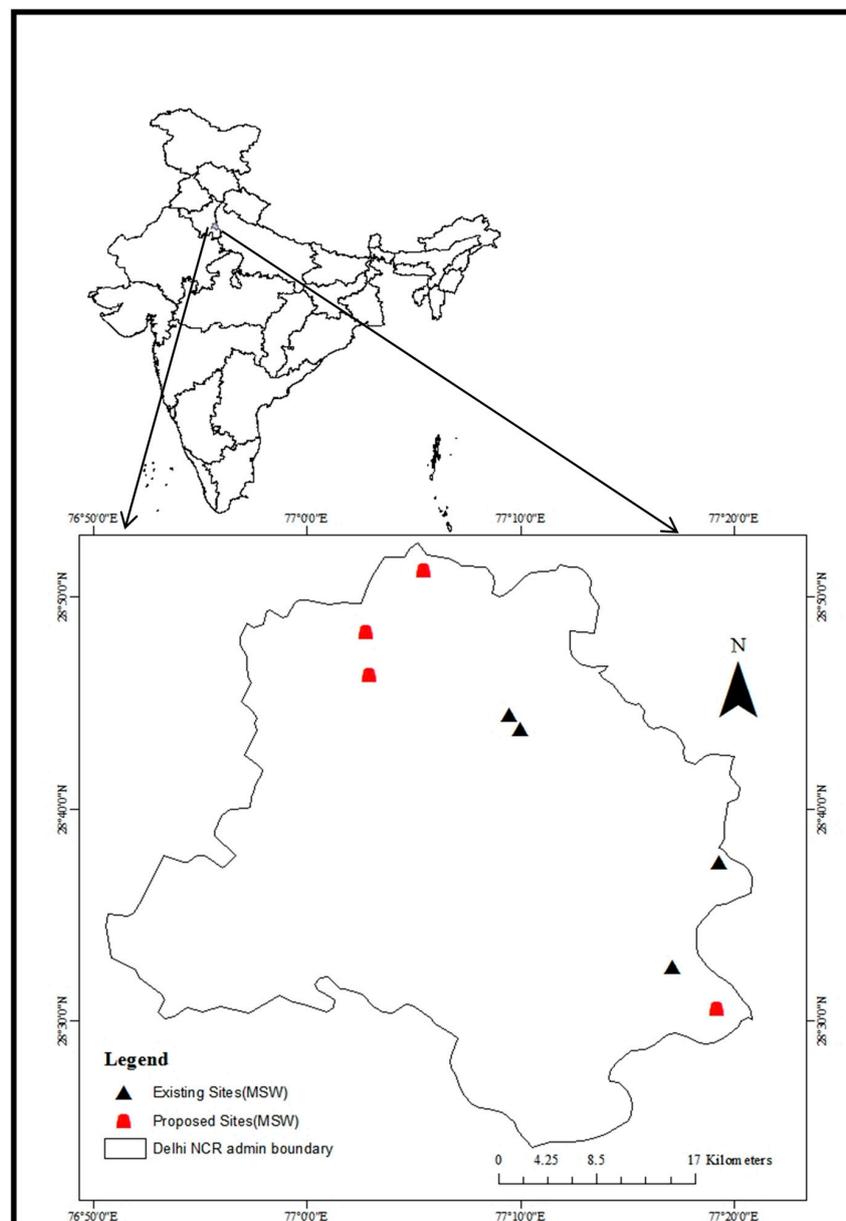


Figure 1. Study area map.

2.2. Status of Municipal Authority in Delhi

The management and disposal of MSW in Delhi is mostly taken care of by Municipal Corporation of Delhi (MCD), the New Delhi Municipal Corporation (NDMC), and the Delhi Cantonment Board (DCB). MSW from the larger part of the study area is managed by MCD, and this covers around 95% of the total geographical area, i.e., 1390 km², of which 43% is urban areas, and rest of the areas are under the NDMC and the DCB. There are already three landfill sites in Delhi, named Bhalsawa, Ghazipur, and Okhla, with total areas of 161,874 m², 283,280 m², and 129,499 m², respectively, which serves 50.3%, 30.8%, and 18.9% of the total population of the city.

In 2004, it was reported by MCD that 56.6% of the total waste generated was residential waste, followed by 18.3% from shopping centers, 9.6% from vegetable markets, 9% from industries, 6.8% from construction sites, and 1.9% from hospitals. The physical composition of the waste comprises 38.6% biodegradable waste, 5.6% paper waste, 6% plastic wastes, 34.7% inert materials, and 13.9% non-biodegradable wastes [15]. These landfill sites are almost saturated, and the illegal disposal of waste continues in these landfills. In addition to this, there are three waste to energy conversion plants at Timarpur, Ghazipur, and Narela which altogether produce electricity at 52 MW/day. One integrated MSW plant of 4000 Tons Per Day (TPD) has been developed at Narela-Bawana, which is currently operating at 2000 TDP.

3. Methodology

3.1. Landfill Site Suitability

In order to assess the suitability of a landfill site in the study area, ten thematic layers are considered, including the distance from the road, the distance from a railroad, the distance from water bodies, the distance from urban areas, the distance from protected land, the slope, and the soil generated using f ArcGIS 10 (ESRI, Redlands, CA, USA) and ERDAS Imagine 9.3 (ERDAS, Inc., Madison, CA, USA). Out of these thematic maps, the slope was generated from a Shuttle Radar Topographic Mission (SRTM) Digital Elevation Model (DEM). The soil map of the study area was obtained from the National Bureau of Soil Survey and Land Use Planning and converted into digital format. Landuse/Landcover was generated using the Landsat-8 dataset [33]. The satellite dataset was geometrically corrected and projected in a Universal Transverse Mercator and datum WGS84 projection system. The road, railways, protected land, urban areas, and water bodies were extracted from the LULC layers, and a buffer was created around each of these extracted classes. Supervised classification using a maximum likelihood classifier was carried out to classify the Landsat image.

The details of the thematic layers used are given in Table 1.

Table 1. Source of data used in site suitability study.

S.No	Data	Source
1	Digital Elevation Model	United States Geological Survey-Earth Explorer
2	Landsat-8 Data	USGS-Earth Explorer
3	Soil Data	Soil Survey of India
4	Road	Open Street Map
5	Rail	Open Street Map
6	Protected land	Landuse/Landcover derived from Landsat 8 image
7	Urban Area	Landuse/Landcover derived from Landsat 8 image
8	Water bodies	Landuse/Landcover derived from Landsat 8 image
9	Slope	Shuttle Radar Topographic Mission Digital Elevation Model

In comparison to other MCDA processes, AHP is considered much easier and more effective in processing both qualitative and quantitative data [34]. The scope of subjectivity is also neutralized in deciding the weightages by using a pair-wise comparison matrix. The method breaks the problem

into its components, which are the variables determining the nature of the study; in our case, the distance from respective parameters such as roads, railways, and water resources. These factors are then constructed hierarchically, with assigned numerical values according to their subjective relevance, to determine relative participation of each factor in arriving at a decision [35]. The relative importance of one factor over another creates a comparison matrix in which each factor is rated against every other factor.

Expert's opinions were solicited for assigning suitable weights. Saaty [36] suggests that suitable weights should be assigned based on the expert's opinion; thus, experts' opinions were solicited for assigning weights to individual thematic layers. A total of 15 scientific experts and policy makers working in the field of municipal solid waste management were consulted, and their opinions were asked on the relative importance of the variables they considered important for management and site suitability of MSW. The policy makers in particular were also consulted for their comments and views about the relative importance of the influencing themes and their features. The experts provided weights for the selected thematic maps and their features on Saaty's scale. The weights calculated for each thematic map were the results of a pairwise comparison of each map based on their relative importance to the suitability of the site for MSW. Table 2 shows the result of the pairwise comparison of each map. The consistency ratios of the assigned weights for the thematic layers and their attributes are found to be less than 10% and thereby suggest that the assigned weights are consistent.

Table 2. Weightage of factors influencing the suitability of landfill sites.

Criteria	Distance	Ranking	Gradient of Suitability	Weightage %
Distance from road	<500	1	Highly suitable	10.55
	500–1000	2	Suitable	
	1000–1500	3	Moderate	
	>1500	4	Unsuitable	
Distance from rail	<500	1	Highly suitable	6.95
	500–1000	2	Suitable	
	1000–1500	3	Moderate	
	>1500	4	Unsuitable	
Distance from water bodies	<500	4	Unsuitable/restricted	35.05
	500–1000	3	Moderate	
	1000–1500	2	Suitable	
	>1500	1	Highly suitable	
Distance from Urban	<500	4	Unsuitable/restricted	23.75
	500–1000	3	Moderate	
	1000–1500	2	Suitable	
	>1500	1	Highly suitable	
Distance from protected land	<500	4	Unsuitability/restricted	15.9
	500–1000	3	Moderate	
	1000–1500	2	Suitable	
	>1500	1	Highly suitable	
Slope	0–9 Degree	1	Highly Suitable	3.188
Soil	Loam	2	Suitable	4.613
Total				100

The factor distance map and the constraints distance (threshold) will thus generate weighted overlay as thematic maps for the AHP. For the AHP model, the final result includes the weights of the derived factors, the class weights, and a calculated consistency ratio (CR). In the AHP method, an index of inconsistency, known as the consistency ratio (CR), is used to indicate the probability that the matrix judgments were randomly generated [36,37].

$$CR = \frac{CI}{RI} \quad (1)$$

where RI is the average of the resulting consistency index depending on the order of the matrix given by Saaty (1980) and CI is the consistency index and can be expressed as:

$$CI = \frac{\lambda_{\max} - n}{n - 1} \quad (2)$$

where λ_{\max} is the largest or principal eigenvalue of the matrix and can be easily calculated from the matrix and n is the order of the matrix. The consistency ratio (CR) is a ratio between the matrix's consistency index and random index and, in general, ranges from 0 to 1. A CR value of 0.1 or less is a reasonable level of consistency [17]. A CR above 0.1 requires revision of the judgment in the matrix due to the inconsistent treatment of particular factor ratings. The land fill site suitable for dumping solid waste is thus within 0.1 of the CR obtained.

The factors used in this study to identify the suitable landfill sites are the distance from the road, railway, urban areas, water bodies, and protected land; soil; and slope. The distance buffer map and the suitability map have been prepared using ArcGIS 10.

3.2. Estimation of CH_4 from Landfill

Among the available methods for the estimation of CH_4 from the landfill, the simplest one was provided by Bingemer and Crutzen in 1987 [38] and revised by the Intergovernmental Panel on Climate Change (IPCC) in 1996. It is a mass balance approach, which provides the actual emission from the landfill, and it is widely used in cases in which detailed data is not available. The estimates of this default method are based on a set of constant empirical parameters. The equation for the calculation of CH_4 from MSW is as below [39].

$$CH_4 \text{ (Gg/yr)} = (MSW_T \times MSW_F) \times MCF \times DOC \times DOC_F \times F \times \left(\frac{16}{12} - R \right) \times (1 - OX) \quad (3)$$

where, 1 Gg/yr is equal to 1000 tons/yr.

MSW_T is the total amount of solid waste generated (Gg/yr) as per the estimates of the Central Pollution and Control Board (2015). MSW_F is the fraction of MSW that reaches landfill sites. In this study, we assumed that 70% of the total MSW reaches the landfill and the rest has been lost either in recycling, reuse, or other alternatives. The MSW_F values have been adopted from the IPCC report and other studies conducted in the region [39]. MCF is the methane correction factor, which has been adopted from the IPCC 1996 for South-Asian countries. DOC is the degradable organic carbon, which can be calculated using the following equation:

$$DOC = 0.4A + 0.17B + 0.15C + 0.3D \quad (4)$$

where A is paper, cardboard, and rags; B is leaves, straw, and others; C is fruits and vegetable wastes; and D is woods. The values have been considered from a study conducted over the landfills in Delhi by Chakraborty et al. in 2011. The values for A , B , C , and D are taken as 6.6, 6.0, 46.3, and 3.8, respectively [40].

DOC_F is the value of dissimilated fill gas, which is considered to be 0.77 for a temperature of 35 °C [33,39]; F is the fraction of methane gas, considered to be 0.5; R is the recovered methane gas, which is considered to be 0 for this study, as provided by IPCC 1996 for the South East Asian countries; and OX is the oxidation factor, which is the amount of oxidized methane on the top layers, where an ample amount of oxygen is present. However, it reduces the total quantity of methane generated from the landfills, and, as there is no factor assigned, we have assumed it to be 0.

IPCC has identified two types of uncertainties in the model. However, it is helpful to use IPCC estimates in regions where the availability of data is a problem [27,39–42].

- (1) Uncertainty in the model: The modified methodology assumes that the waste disposal is not incremental, i.e., a constant amount is added each year and the methane emission accounts for the same year. Thus, temporal increment at the landfills is not accounted for in calculation; therefore, the methane emission is overestimated. The amount of waste disposed is a highly sensitive parameter in default methodology.
- (2) Uncertainty in the data used in the model: The data required for the estimation of methane emission might have uncertainties. In this methodology, uncertainties in the estimates of MSW_T and MSW_F would be responsible for higher uncertainties in the total methane emission estimates. The model is also sensitive to parameters such as waste composition; DOC content is sensitive to small variations in the assumed values of DOC, which thus change the overall methane emission.

4. Results and Discussion

4.1. Site Suitability of Landfills

4.1.1. Land Use/Land Cover (LULC)

The LULC of the study area has been prepared to discriminate between various land use classes and their spatial extent in the study area. Altogether 11 LULC classes were delineated in the study area (Figure 2). Built up land is found as the most dominant class, which covers around 43.1% of total study area, followed by fallow land (25.2%), cropland (15%), sparse vegetation (6.1%), dense vegetation (3.0%), open lanes (1.8%), rocky land (2.4%), and water bodies (1.5%) and very small areas of sediment (0.1%) and wetlands (0.14%) were also found. The LULC map of the study area provides a better idea of the allocation of landfill and other waste management options. With rapid population growth, people move towards the outskirts of the city for open space so LULC provides an idea about the places that might be extended as land resources for the proper management of MSW in the future by providing suitable landfill sites.

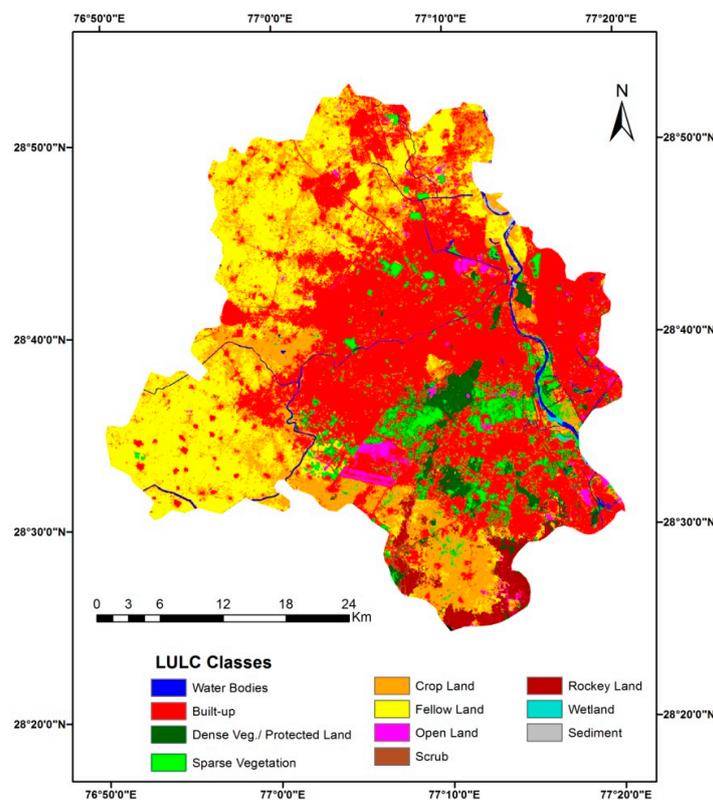


Figure 2. Land use/Land cover map of the study area.

4.1.2. Slope and Soil Characteristics

Slope is another important aspect in selecting suitable landfill sites for proper excavation. The appropriate slope for the construction of a landfill is considered to be 0% to 12% as a steep slope (>12%) is not appropriate for the landfill and will increase the runoff rate and decrease the infiltration [11]. Due to the high runoff speed, contaminants from the landfill might travel long distances, while the lesser slopes also reduce the cost of landfill construction. A slope map of the study area indicates that most of the region has slopes ranging from 0% to 12%, which is suitable for the construction of landfills (Figure 3). For landfills, soil is also one of the important parameter as leachates from the landfill might infiltrate and contaminate the groundwater. It is reported that the majority of the soil in Delhi is dominated by coarse loamy soil [14]. Loamy soil is considered suitable for the construction of a landfill [11].

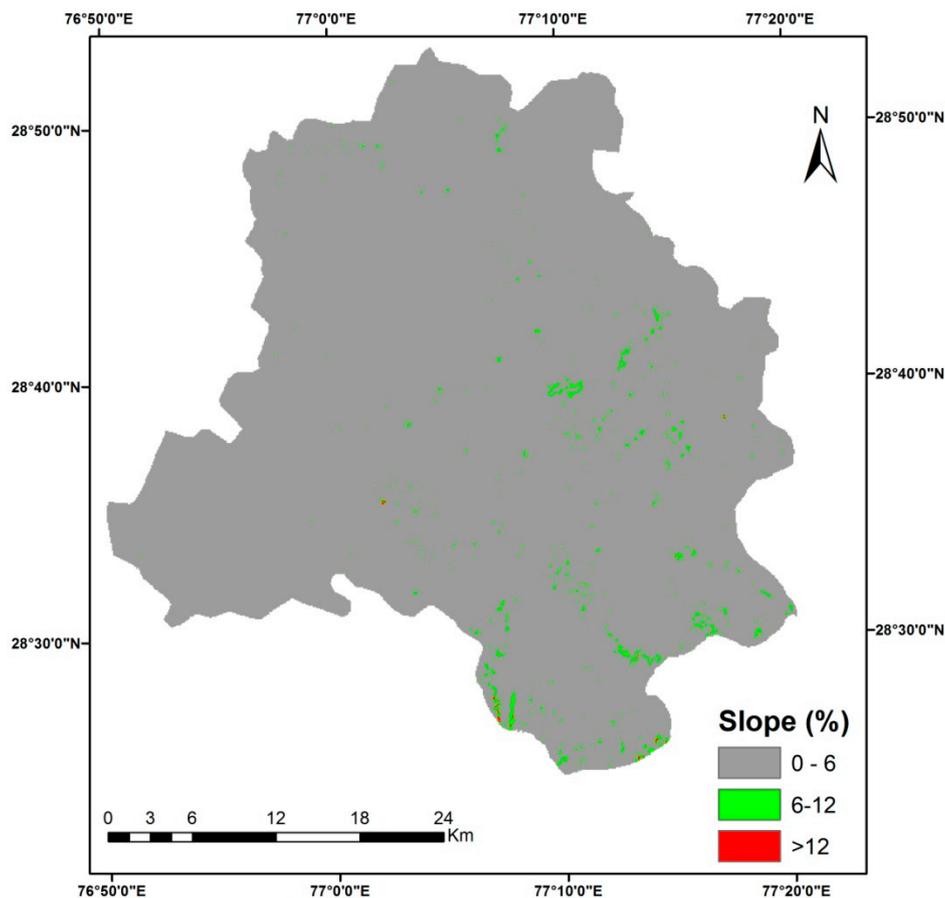


Figure 3. Slope map of the study area.

4.1.3. Distance Buffer Map

The distance buffer has been created using the spatial analyst tool in Arc GIS from network data extracted from LULC and verified through open street maps (Figure 4a–e). The distance proximity has been analyzed for road, rail, and surface water bodies, including rivers, streams and water logged areas. The distance buffer map provides the range of highly suitable to restricted areas for the construction of a suitable landfill. The minimum or restricted distance in the buffer is considered a constraint for a suitable landfill site. The nearest distance from the road and rail network is considered highly suitable for the construction of a landfill as this will reduce the cost of transportation. The distance analyses for roads and railways are calculated as <500 m, 500 m to 1000 m, 1000 m to 1500 m, and >1500 m (Table 2) and range from highly suitable to unsuitable with increasing distance (Figure 4f–j). For surface water

bodies and urban areas, the distance buffer map is prepared as <500 m, 500 m to 1000 m, 1000 m to 1500 m, and >1500 m and ranges from unsuitable to highly suitable with increasing distance as the surface water bodies near the landfills are more vulnerable to contamination and landfills affect their aesthetic beauty.

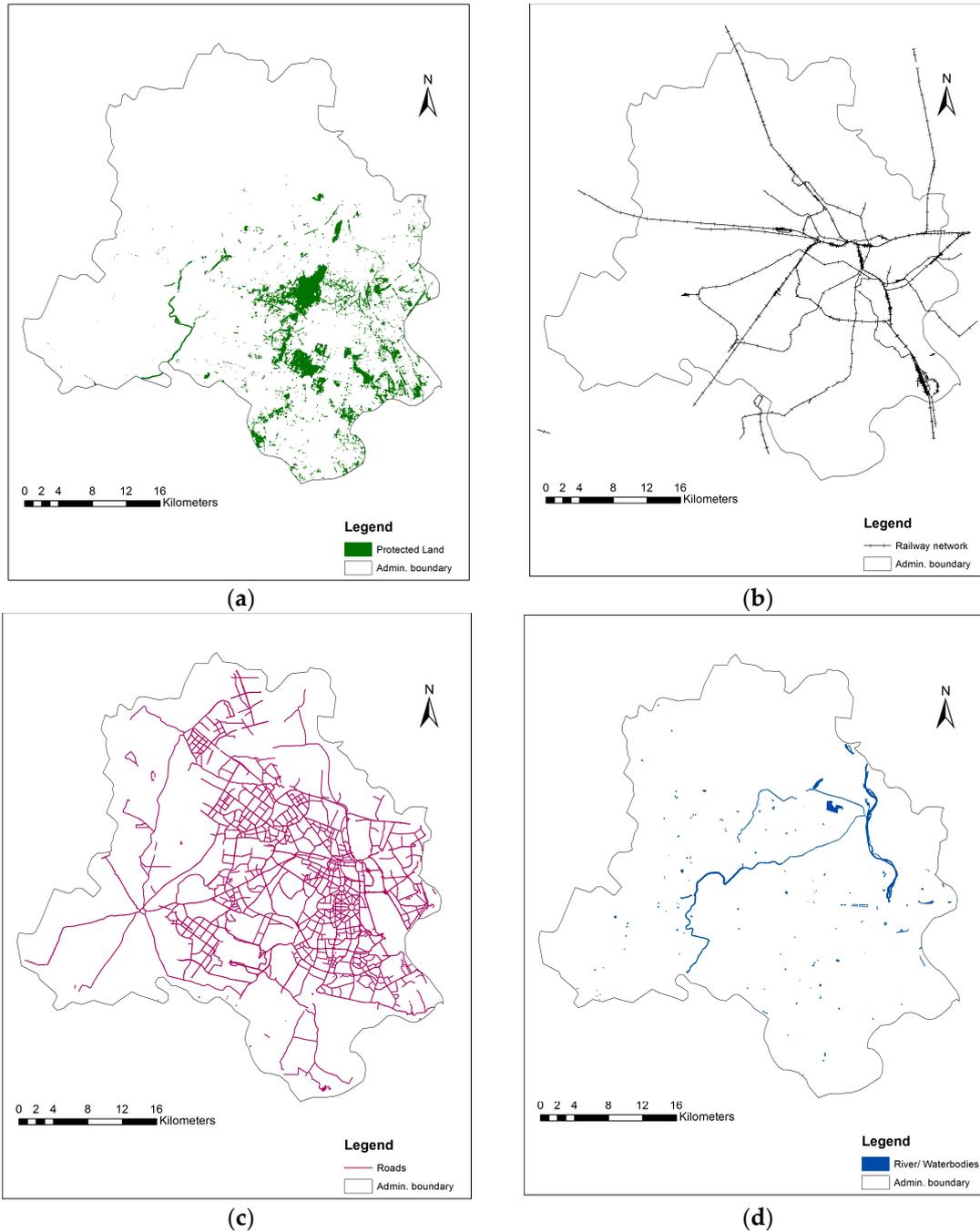


Figure 4. Cont.

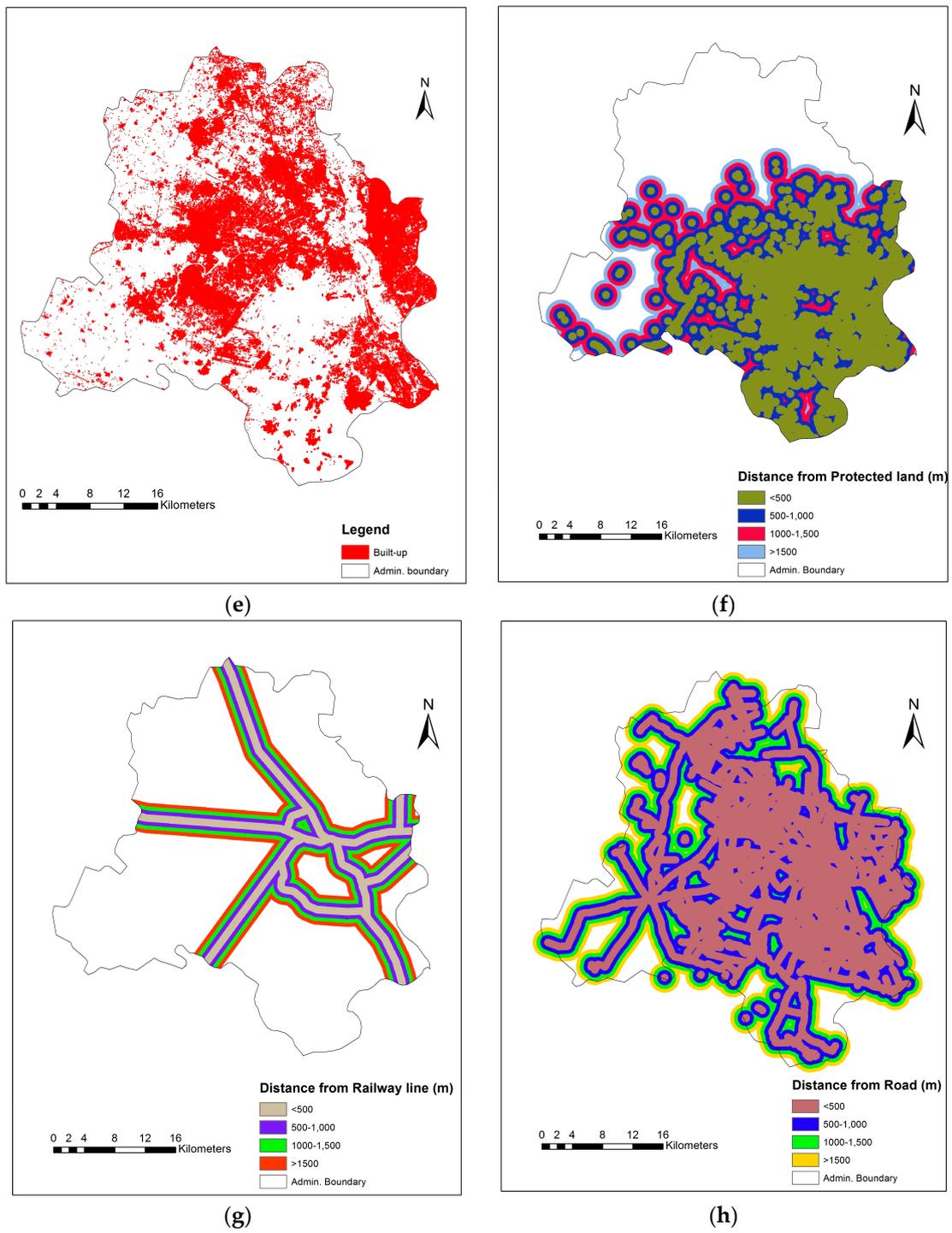


Figure 4. Cont.

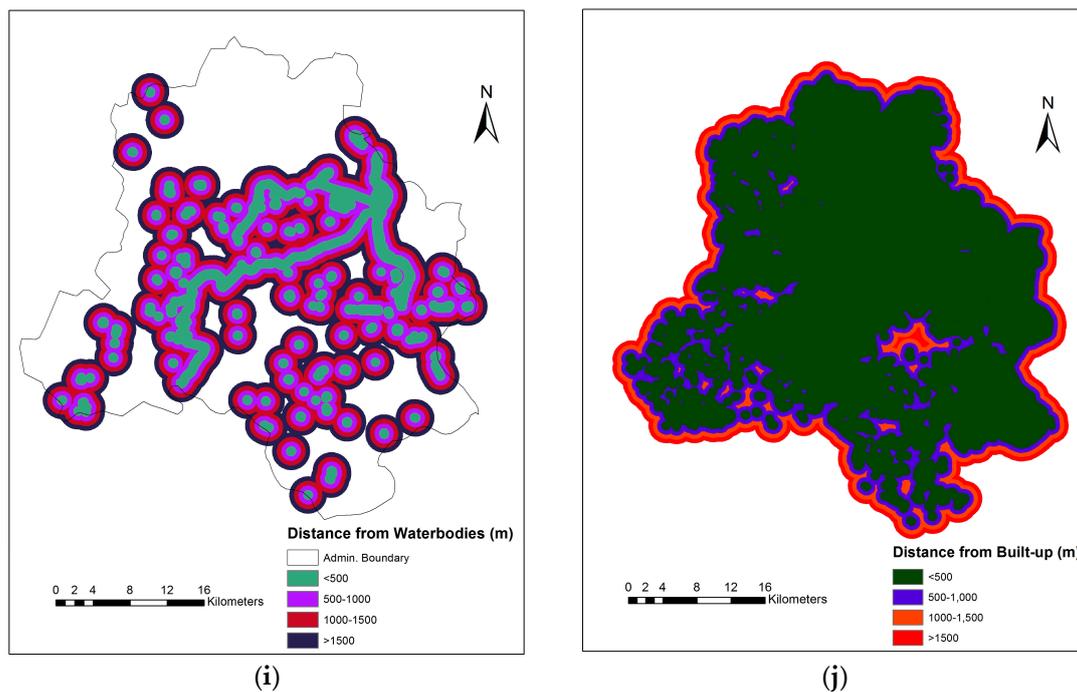


Figure 4. (a–e) Network map of all the factors; (f–j) Distance Buffer map of all the factors.

4.1.4. Overlay and Final Suitability Map

The selection of a suitable landfill site involves a comprehensive analysis of the environmental and socio-economic impact. Based on the likely impacts on the surrounding environment and their importance, weights have been assigned to all the parameters considered in this study (Table 3). The relative importance of one factor over another creates a comparison matrix in which each factor is rated against every other factor. The weights have been assigned based on a pairwise comparison on seven point scale. This comparison of all the factors is further standardized to check the influence of one factor in the MCDM, considering that the units and parameters are of different scales for different factors (Table 4). From the respective weight of the factors of suitability, a comparison matrix was created in the AHP model, and pairwise importance was assigned relative to the other factors, which was further verified using a consistency ratio to assign a suitable location for the landfill site (Table 5).

Table 3. Pairwise matrix for all the factors.

Pairwise Matrix							
Factors	Distance Water Bodies	Urban	Protected Land	Distance Road	Distance Rail	Soil	Slope (%)
Distance Water bodies	1.00	2.00	3.00	4.00	5.00	6.00	7.00
Urban	0.50	1.00	2.00	3.00	4.00	5.00	6.00
Protected land	0.33	0.50	1.00	2.00	3.00	4.00	5.00
Distance Road	0.25	0.33	0.50	1.00	2.00	3.00	4.00
Distance Rail	0.20	0.25	0.33	0.50	1.00	2.00	3.00
Soil	0.17	0.20	0.25	0.33	0.50	1.00	2.00
Slope (%)	0.14	0.17	0.20	0.25	0.33	0.50	1.00
Total	2.59	4.45	7.28	11.08	15.83	21.50	28.00

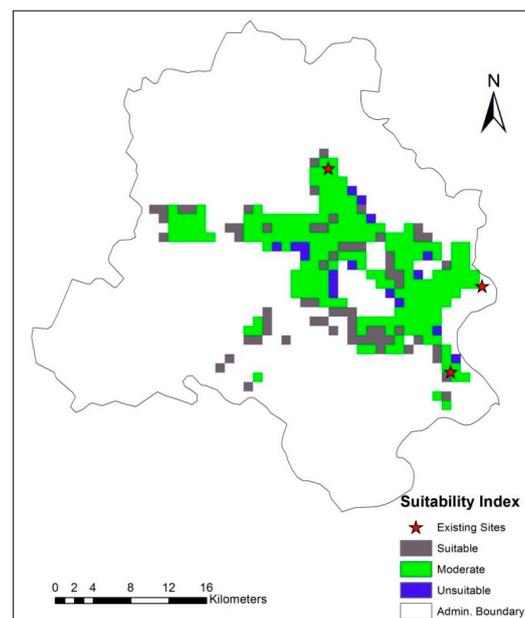
Table 4. Standardization of comparison matrix.

Factors	Distance Water Bodies	Distance from Urban Area	Distance Protected Land	Distance from Road	Distance from Rail	Soil	Slope (%)	Weights	Weights %
Distance Water bodies	0.386	0.449	0.412	0.361	0.316	0.279	0.250	0.351	35.051
Distance from Urban	0.193	0.225	0.275	0.271	0.253	0.233	0.214	0.238	23.754
Distance Protected land	0.129	0.112	0.137	0.181	0.190	0.186	0.179	0.159	15.901
Distance from Road	0.097	0.074	0.069	0.090	0.126	0.140	0.143	0.105	10.548
Distance from Rail	0.077	0.056	0.045	0.045	0.063	0.093	0.107	0.070	6.960
Soil	0.064	0.045	0.034	0.030	0.032	0.047	0.071	0.046	4.613
Slope (%)	0.055	0.038	0.027	0.023	0.021	0.023	0.036	0.032	3.189
Total								1	100

Table 5. Results from the analytic hierarchy process (AHP) matrix.

S.No	Results of AHP Matrix	Values
1	No. of factors (N)	7
2	Maximum principle Eigen vector (λ_{\max})	7.1965716
3	Consistency Index (CI)	0.0327619
4	Relative Index (RI)	1.32
5	Consistency Ratio (CR)	0.0248196

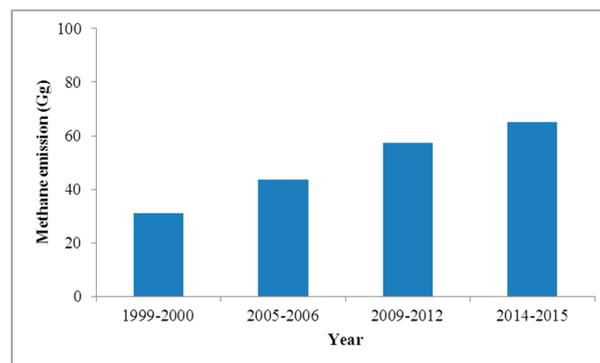
The suitable sites for landfill are depicted, where the classes occur as gradients of suitability from extremely restricted to highly suitable sites. The consistency ratio (CR) is found to be 0.02, which is acceptable and well below 10%, and it signifies the reciprocal matrix. The available areas are represented in the final map (Figure 5), and it has areas lying under categories from suitable to unsuitable. It has been found that only 58.7 km² of the land is suitable for the construction of landfills, while 194.27 km² of the area is moderately suitable for landfills. All three sites that are currently used by the municipal corporations as landfills are found to be in the unsuitable or moderately suitable category. The 58.7 km² of suitable land is spatially distributed in the study area. The highly suitable sites for landfill construction in Delhi are not available, while there are few patches in the central and eastern part of the study area that are suitable to moderately suitable for landfill construction.

**Figure 5.** Final suitability map for landfill site with existing landfills in Delhi.

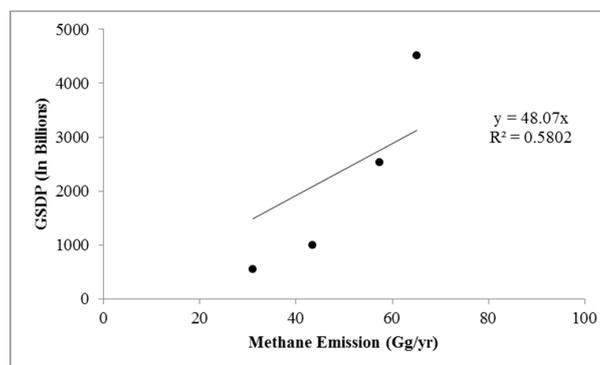
4.2. Environmental Impacts of Landfills and CH₄ Emission

The rapid increase in the production of MSW is a major challenge that has been faced by Delhi in the past few years. Properly constructed landfills are one of the prime factors for the management of solid waste all around the globe. However, MSW poses a serious threat to the surrounding environment, including surface and groundwater, air, and soil, if not managed and monitored properly. The extent of the threat from the landfill depends on the quantity and composition of the wastes, the distance from the sites, the local environmental conditions, i.e., temperature and humidity, the hydrology and geological settings, the degree of compactness, etc. Once the biodegradable organic waste is decomposed by the bacteria, the pH of the system is reduced, which leads to the mobilization of heavy metals in leachates, and these leachates mix with the groundwater system during the recharge process, which alters the quality of groundwater in nearby aquifers. High concentrations of ions, including nitrate, chloride, sulfate, heavy metals, i.e., Zn, Cu, Fe, Ni, Fe, and cations, have been reported in aquifer system near the Bhalswa landfill, located in one of the most urbanized areas of Delhi. Srivastava et al., in 2008, concluded that the leachates from the landfill are one of the prime sources of the enrichment of the aforesaid contaminants [24].

Landfills also affect the ambient air quality as the gas emitted from the landfill consists of GHGs, which are responsible for regional and global alterations in the ambient environment. The results of current study suggest that there has been a continuous increase in CH₄ production by landfills in Delhi. During the period from 1999 to 2015, the amount of CH₄ increased from 31.06 Gg/yr to 65.16 Gg/yr, which is more than double the CH₄ generated in 1999 to 2000. The temporal trend is shown in the Figure 6a. The result of the CH₄ emission calculated by Chakraborty et al. in 2011 for 2007 to 2008 is 45.7 Gg/yr, which approximates what we observed in our estimates for 2005 to 2006, namely, 42 Gg/yr.



(a)



(b)

Figure 6. (a) Trend of CH₄ emission from landfill; (b) Correlation of the Gross State Domestic Product (GSDP) and CH₄ generation.

Landfills remain active for longer durations, even after their closure, and emit GHGs. The timescale for waste management and climate change are very similar to that for climatic changes so that an increase in temperature might alter the biological waste reduction process, including composting and the anaerobic decomposition of wastes. Whereas changes in precipitation patterns might also affect the MSW management and make it difficult for the institutions involved in MSW management, in last few years, the population of Delhi has experienced a transition in terms of the developmental and industrial activity around the city, which has triggered rapid population growth and settlement in the city.

The increasing trend in the population is reported in census reports from the government, and the results of the study indicate that the MSW CH₄ emission is positively correlated with the population growth and the total gross state domestic product (GDSP) with $R^2 = 0.58$ (Figure 6b). Similar observations are also reported by others as it is believed that high per capita income and GDSP/GDP (where GDP is gross domestic product) is the prime factor that indicates higher human activity and leads to the increased production of MSW [4].

5. Conclusions and Recommendation

In past decades, the rapid population growth, along with urbanization, has created a massive amount of MSW all around the globe. A large fraction of MSW is disposed in landfills, which are important sources of greenhouse gas emissions, especially CH₄ which has high global warming potential. In this study, the results indicate that the amount of CH₄ generated from landfills is increasing every year, and it has doubled in last 15 years. We found that the generation of GDSP, MSW, and CH₄ is strongly correlated, and a change in lifestyle has increased the per capita MSW and CH₄ emissions. However, the methods adopted to calculate the CH₄ emission are not very appropriate and contain many assumptions based on the default values for the South Asian countries that have been used in the model, which might restrict an accurate assessment. The existing landfill sites that have been used for the disposal of the waste are almost saturated, as governments report, and there are only much less suitable sites available. Apart from this, the results from this study suggest that a geospatial approach improves the decision-making process for the selection of suitable landfill sites. It might reduce the cost and time and leads to the proper management of solid waste.

Acknowledgments: The authors acknowledge the TERI University, Geoinformatics Laboratory for providing the software's for data interpretation and analysis. The authors also state that they haven't received any funding for the work and has developed the database on available resources at TERI University.

Author Contributions: Chander Kumar Singh and Anand Kumar conceived and designed the study; Chander Kumar Singh identified the methodology; Chander Kumar Singh, Anand Kumar and Soumendu Shekhar Roy analyzed the data; Soumendu Shekhar Roy contributed analysis techniques in GIS; Chander Kumar Singh wrote the paper. All authors have read and approved the final manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Rajkumar, N.; Subramani, T.; Elango, L. Groundwater contamination due to municipal solid waste disposal—A GIS based study in Erode City. *Int. J. Environ. Sci.* **2010**, *1*, 39–55.
2. Zhu, D.; Asnani, P.U.; Zurbrugg, C.; Anapolsky, S.; Mani, S. *Improving Solid Waste Management in India: A Sourcebook for 740. Policy Makers and Practitioners*; WBI Development Studies; World Bank Institute, The World Bank: Washington, DC, USA, 2008; pp. 739–741.
3. Government of India. Solid Waste Management Rules. Available online: <http://www.moef.nic.in/content/so-1357e-08-04-2016-solid-waste-management-rules-2016> (accessed on 11 August 2017).
4. Du, M.; Peng, C.; Wang, X.; Chen, H.; Wang, M.; Zhu, Q. Quantification of methane emissions from municipal solid waste landfills in China during the past decade. *Renew. Sustain. Energy Rev.* **2017**, *78*, 272–279. [CrossRef]
5. Tchobanoglous, G.; Kreith, F. *Handbook of Solid Waste Management*; McGraw-Hill: New York, NY, USA, 2002.

6. Sastry, D.B.S.S.R. *Composition of Municipal Solid Waste-Need for Thermal Treatment in Present Indian Context*; Ramky Energy & Environment Ltd.: Hyderabad, India, 2012.
7. Ghobadi, M.H.; Taheri, M.; Taheri, K. Landfill site selection with GIS-based multi-criteria evaluation technique. A case study in Béni Mellal-Khouribga Region, Morocco. *Environ. Earth Sci.* **2017**, *76*, 413. [[CrossRef](#)]
8. Municipal Corporation of Delhi. *Feasibility Study and Master Plan for Optimal Waste Treatment and Disposal for the Entire State of Delhi Based on Public Private Partnership Solutions*; Municipal Solid Waste Characterisation Report; Municipal Corporation of Delhi: Delhi, India, 2004; Volume 6.
9. Central Pollution Control Board. *Status Report on Municipal Solid Waste Management*; Central Pollution Control Board: Delhi, India, 2013.
10. Gemtzi, A.; Tsihrintzisz, V.A.; Christouc, O.; Petalab, C. Use of GIS in siting stabilization pond facilities for domestic wastewater treatment. *J. Environ. Manag.* **2007**, *82*, 155–166. [[CrossRef](#)] [[PubMed](#)]
11. Finn, M.P.; Usery, E.L.; Scheidt, D.J.; Jaromack, G.M.; Krupinski, T.D. An Interface between the Agricultural Non-Point Source (AGNPS) Pollution Model and the ERDAS Imagine Geographic Information System (GIS). *Geogr. Inf. Sci.* **2006**, *12*, 9–20. [[CrossRef](#)]
12. Twumasi, Y.A. Use of geo-spatial data for sustainable management of solid waste in Niamey, Niger. *J. Sustain. Dev. Afr.* **2000**, *8*, 203–215.
13. Pandey, P.C.; Sharma, L.K.; Nathawat, M.S. Geospatial strategy for sustainable management of municipal solid waste for growing urban environment. *Environ. Monit. Assess.* **2011**, *184*, 2419–2431. [[CrossRef](#)] [[PubMed](#)]
14. Mallick, J.; Singh, C.K.; Al-Wadi, H.; Ahmed, M.; Rahman, A.; Shashtri, S.; Mukherjee, S. Geospatial and geostatistical approach for groundwater potential zone delineation. *Hydrol. Process.* **2015**, *29*, 395–418. [[CrossRef](#)]
15. Talyan, V.; Dahiya, R.P.; Sreekrishnan, T.R. State of municipal solid waste management in Delhi, the capital of India. *Waste Manag.* **2008**, *28*, 1276–1287. [[CrossRef](#)] [[PubMed](#)]
16. Cowen, D. GIS versus CAD versus DBMS: What are the differences? *Photogramm. Eng. Remote Sens.* **1988**, *54*, 1551–1555.
17. Malczewski, J. GIS-based multicriteria decision analysis: A survey of the literature. *Int. J. Geogr. Inf. Sci.* **2006**, *20*, 703–726. [[CrossRef](#)]
18. Ishizaka, A.; Labib, A. Review of the main developments in the analytic hierarchy process. *Expert Syst. Appl.* **2011**, *38*, 14336–14345. [[CrossRef](#)]
19. Abdalla, F. Mapping of ground water prospective zones using remote sensing and GIS techniques: A case study from the Central Eastern Desert, Egypt. *J. Afr. Earth Sci.* **2012**, *70*, 8–17. [[CrossRef](#)]
20. Avtar, R.; Singh, C.K.; Shashtri, S.; Singh, A. Identification and analysis of ground water potential zones in Ken-Betwa River linking area using remote sensing and GIS. *Geocarto Int.* **2010**, *25*, 379–396. [[CrossRef](#)]
21. Sharma, L.K.; Pandey, P.C.; Nathawat, M.S. Assessment of land consumption rate with urban dynamics change using geospatial techniques. *J. Land Use Sci. Taylor Francis.* **2011**, *7*, 135–148. [[CrossRef](#)]
22. Ratnapriya, E.A.S.K.; De Silva, R.P. Location optimization of wastewater treatment plants using GIS: A case study in Upper mahaweli Catchment, Sri Lanka. In *Proceedings of the Applied Geoinformation for Society and Environment*; Stuttgart University of Applied Sciences: Stuttgart, Germany, 2009; pp. 20–25.
23. Ananda, J.; Herath, G. A critical review of multi-criteria decision making methods with special reference to forest management and planning. *Ecol. Econ.* **2009**, *68*, 2535–2548. [[CrossRef](#)]
24. Srivastava, S.K.; Ramanathan, A.L. Geochemical assessment of groundwater quality in vicinity of Bhalswa landfill, Delhi, India, using graphical and multivariate statistical methods. *Environ. Geol.* **2008**, *53*, 1509–1528. [[CrossRef](#)]
25. Taylor, G.; Berggren, D.; Bergkvist, B.; Folkenson, L.; Ruhling, A. Soil acidification and metal solubility of forest of southern Sweden. In *Effect of Atmospheric Pollution on Forest, Wet Land and Agricultural Ecosystem*; Hutchinson, T.C., Meena, K.M., Eds.; NATO ASI Series; Springer: Berlin, Germany, 1987; Volume G16, pp. 347–359.
26. Shivhare, R.L.; Pandey, G.S. Effluent–effluent interaction. Corrective effects in some tannery combination of effluent. *Indian J. Environ. Health* **1996**, *38*, 233–238.
27. Oonkay, H.S. *Literature Review: Methane from Landfills Methods to Quantify Generation, Oxidation and Emission*; Oonkay: Apeldoorn, The Netherlands, 2010.

28. Kirschke, S.; Bousquet, P.; Ciais, P.; Saunoy, M.; Canadell, J.G.; Dlugokencky, E.J.; Bergamaschi, P.; Bergmann, D.; Blake, D.R.; Bruhwiler, L.; et al. Three decades of global methane sources and sinks. *Nat. Geosci.* **2013**, *6*, 813–823. [[CrossRef](#)]
29. Scheehle, E.; Godwin, D.; Ottinger, D.; DeAngelo, B. *Global Anthropogenic Non-CO₂ Greenhouse Gas Emissions: 1990–2020; Revised Version*; Report No. 430-R-06-003; U.S. Environmental Protection Agency: Washington, DC, USA, 2006.
30. Themelis, N.J.; Ulloa, P.A. Methane generation in landfills. *Renew. Energy* **2007**, *32*, 1243–1257. [[CrossRef](#)]
31. GMI. International Best Practices Guide for Landfill Gas Energy Projects. 2012. Available online: <http://www.globalmethane.org/tools-resources/tools.aspx#three> (accessed on 20 August 2017).
32. Intergovernmental Panel on Climate Change (IPCC). *Report of the Twelfth Season of the Intergovernmental Panel on Climate Change*; IPCC: Mexico City, Mexico, 1996.
33. USGS Earth Explorer. Available online: <https://earthexplorer.usgs.gov/> (accessed on 10 July 2017).
34. Moeinaddini, M.; Khorasani, N.; Danekar, A.; Darvishefat, A.A.; Zeinalyan, M. Siting MSW landfill using weighted linear combination and analytical hierarchy process (AHP) methodology in GIS environment (case study: Karaj). *Waste Manag.* **2010**, *30*, 912–920. [[CrossRef](#)] [[PubMed](#)]
35. Saaty, T.L.; Vargas, L.G. *Models, Methods, Concepts and Applications of the Analytic Hierarchy Process*; Kluwer Academic Publishers: Norwell, MA, USA, 2001. [[CrossRef](#)]
36. Saaty, T.L. *Multicriteria Decision making: The Analytic Hierarchy Process*. McGrawHill: New York, NY, USA, 1980.
37. Satty, T.L. Homogeneity and clustering in AHP ensure the validity of the scale. *Eur. J. Oper. Res.* **1994**, *72*, 598–601. [[CrossRef](#)]
38. Bingemer, H.Q.; Crutzen, P.J. Production of methane from solid waste. *J. Geophys. Res.* **1987**, *87*, 2181–2187. [[CrossRef](#)]
39. Kumar, S.; Gaikwad, S.A.; Sekdar, A.V.; Kshirsagar, P.S.; Singh, R.N. Estimation method for national methane emission from solid waste landfills. *Atmos. Environ.* **2004**, *38*, 3481–3487. [[CrossRef](#)]
40. Chakarborti, M.; Sharma, C.; Pandey, J.; Singh, N.; Gupta, P.K. Methane emission estimation from landfills in Delhi: A comparative assessment of different methodologies. *Atmos. Environ.* **2011**, *45*, 7135–7142. [[CrossRef](#)]
41. Shams, S.; Sahu, J.N.; Rahman, S.M.S.; Ahsan, A. Sustainable waste management policy in Bangladesh for reduction of greenhouse gas. *Sustain. Cities Soc.* **2017**, *33*, 18–26. [[CrossRef](#)]
42. Kumar, S.; Mondal, A.N.; Gaikwad, S.A.; Devotta, S.; Singh, R.N. Qualitative assessment of methane emission inventory from municipal solid waste disposal sites: A case study. *Atmos. Environ.* **2004**, *38*, 4921–4929. [[CrossRef](#)]



© 2017 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>).