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Assessing the demand of solid waste disposal in urban region by urban dynamics modelling in a GIS environment

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Abstract

The twentieth century saw a dramatic increase in the production of urban solid waste, reflecting unprecedented global levels of economic activity. Despite some efforts to reduce and recover the waste, disposal in landfills is still the most usual destination. However, landfill has become more difficult to implement because of its increasing cost, community opposition to landfill siting, and more restrictive environmental regulations regarding the siting and operation of landfills. Moreover, disposal in landfill is the waste destination method with the largest demand for land, while land is a resource whose availability has been decreasing in urban systems. Shortage of land for landfills is a problem frequently cited in the literature as a physical constraint. Nonetheless, the shortage of land for waste disposal has not been fully studied and, in particular, quantified. This paper presents a method to quantify the relationship between the demand and supply of suitable land for waste disposal over time using a geographic information system and modelling techniques. Based on projections of population growth, urban sprawl and waste generation the method can allow policy and decision-makers to measure the dimension of the problem of shortage of land into the future. The procedure can provide information to guide the design and schedule of programs to reduce and recover waste, and can potentially lead to a better use of the land resource. Porto Alegre City, Brazil was used as the case study to illustrate and analyse the approach. By testing different waste management scenarios, the results indicated that the demand for land for waste disposal overcomes the supply of suitable land for this use in the study area before the year 2050. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

Urbanisation is one of the most evident global changes in the world. In the last 200 years, world population has increased six times, and the urban population has multiplied 100 times (Radzicki, 1995). The rapid urban growth has exerted heavy pressures on land and resources contained within the area surrounding cities, and resulted in serious environmental and social problems.

Ideally, for a system to sustain itself renewable resources must not be used faster than the rate at which they can be regenerated, non-renewable resources must not be used faster than the rate at which they can be substituted for, and pollution must not be generated faster than the rate at which the system can absorb it. However, urban population has been consuming land and resources and producing wastes and pollution at a high and increasing rate.

The twentieth century and particularly the period post Word War II saw a dramatic increase in the production of urban solid waste, reflecting unprecedented global levels of economic activity. The demand for land to dispose of this waste increases proportionately.

The growing concern for environmental issues and the goal of sustainable development have moved the management of solid waste to the forefront of the public agenda. Legislation and regulations have been introduced in local and national levels to guide waste management, and techniques for appropriate waste treatment and disposal have been developed. Moreover, strategies for sustainable waste management have emphasised the need to minimise waste production, increase waste recovery and reduce the use of landfill.

Nowadays, there is a general agreement on the best practices for sustainable management of urban solid wastes, and there are isolated experiences throughout the world applying these principles. However, the goal of sustainable waste management seems far from being reached. Reduction of waste production is still more a hope than an achievement in most countries. The net waste production increases as population grows, and the per capita generation of waste is also increasing, particularly in developing countries (The World Bank, 1999). Waste recovery processes have been applied successfully but, as shown in Table 1, the amounts of wastes being diverted to these processes are generally small. Disposal in landfills is still the most usual destination.

Nonetheless, landfill has become more difficult to implement because of its increasing cost (especially because of the transport to distant sites), community opposition to landfill siting, and more restrictive environmental regulations regarding the siting and operation of landfills. Moreover, landfill is the waste destination method with the largest demand for land, while land is a resource whose availability has been decreasing in urban systems.

Table 1
Waste disposal methods in developed nations (% by weight)

Country	Landfilling	Incineration	Composting	Recycling
NSW/Australia	82	2.5	0	15.5
Canada	80	8	2	10
France	45	42	10	3
Germany	46	36	2	16
Greece	100	0	0	0
Ireland	97	0	0	3
Italy	74	16	7	3
Netherlands	45	35	5	16
Portugal	85	0	15	0
Spain	65	6	17	13
UK	88	6	0	6
USA	67	16	2	15

Source: Environment Protection Agency, 1995; Williams, 1998.

Shortage of land for landfills is a problem frequently cited in the literature as a physical constraint. Nonetheless, shortage of land for waste disposal has not been fully studied and, in particular, quantified.

In this paper, we described a method we have developed to quantify the relationship between the demand and supply of suitable land for waste disposal over time, using a geographic information system and modelling techniques.

1.1. Waste management models

The whole activity of managing solid waste destinations involves determining type, capacity and location of facilities for waste treatment and disposal, as well as their scheduling, based on environmental and health regulations, economic reliability and social acceptability for both present and future contexts.

Many operational models have been created over the last few decades to assist in developing more efficient solid waste management programs. One typical issue addressed by these models is the search for best configurations for waste management systems that involve the best combination of waste facilities (usually landfill, incineration, recycling and/or composting) or the best flow of waste through a certain group of facilities at a certain moment of time. The economic optimisation functions in these models include costs (operation and/or transportation) and revenues from the sale of energy, organic compost, and recycled materials. Examples are the models developed by the University of California at Davis (Lawver et al., 1990) and Morris (1990).

With the increasing awareness of environmental issues and the pressure to reduce pollution risks associated with waste management, environmental factors were introduced into some waste management models. According to state of the art review on solid waste management models developed by McDonald (1996), Chang was the first to explicitly incorporate environmental costs. His model determines the capacity and location of solid waste management facilities required to minimise the net present value of all costs minus benefits. The constraints include mass balance considerations, capacity limitations, financial concerns, air pollution control, and leachate impacts (Chang et al., 1996). The model developed by Daskalopoulos et al. (1998) identifies the optimal combination of technologies for the handling, treatment and disposal of municipal solid wastes according to economic and environmental criteria. These criteria are the rate of energy consumption, the rate of emission of greenhouse gases to the atmosphere, and the net economic cost of the operations involved (operation costs minus revenues). The environmental criteria are translated into corresponding associated costs and the final comparison is made on a total cost basis. The importance of each of these evaluation criteria can be weighted in order to comply with the particular objectives of the waste management policy adopted. Technical constraints include the economically feasible upper limits for recycling, composting or incineration for each fraction of waste.

Other characteristic issues that waste management models deal with is selection of facility sites. Erkip and Kirca (1990) and Movassaghi (1992) used network analysis to find the best site in terms of minimum cost for transfer stations and incinerators with energy recovery. Siddiqui et al. (1996) developed a methodology to find the best locations for siting landfills based on physical and environmental characteristics using a geographic information system. Lober (1995) addressed the NIMBY (not in my backyard) phenomenon, which expresses the increasing community opposition to facility siting. The innovation of this model is the spatial representation of social criteria by transforming a range of distances between population concentrations and a waste facility into a map of attitudes of opposition towards the facility.

Some models dealt with the scheduling of waste management programs and facilities. Lund (1990) developed a linear programming model to evaluate different recycling options as an alternative to landfilling. The model also determines a least-cost lifetime for the landfill, considering the recycling costs and the benefits of deferring landfill closure and future replacement costs. Jacobs and Everett (1992) developed a model to determine the optimal operation of consecutive landfills while incorporating recycling programs. They present a linear optimisation model that can indicate the landfill use characteristics throughout the planning horizon for the system. Everett et al. (1993) improved on the earlier model by incorporating composting facilities.

According to the United Nations Conference on Environment and Development in 1992 (Agenda 21), which has been guiding the formulation and implementation of strategies for sustainable development worldwide, environmentally sound waste management must go beyond the mere safe disposal of wastes, and be focused on minimising waste and maximising reuse and recycling of waste. Results from the use of the existing solid waste models, however, usually favour landfills as the optimum way to treat wastes (Daskalopoulos et al., 1998). It suggests that these models might be inappropriate for the concept of sustainable waste management. It seems that there is a gap between the goals of sustainable waste management and the outcomes of the existing waste management models.

In studying the development of solid waste model development over the last few decades it is possible to observe that most of the existing models are static (consider only the present time) and seek for optimum solutions (best facility locations, capacities, expansion and/or combination patterns) in terms of minimum economic cost. Only a few models include environmental factors and use trade-offs between the economic and environmental objectives, or consider time as an important factor.

Di Nino and Baetz (1996) took an innovative approach to the interface between sustainability, urban form, municipal solid waste management infrastructure (waste collection), and environmental impacts. In his work the relationship is dynamic since, with time, urban areas experience growth. How this growth is spatially located, and at what density, will dictate the extent to which the collection system is affected and the resultant air emissions from the vehicles. By comparing different types of urban form (spread and nodal), the results showed that urban form strongly affects the solid waste infrastructure and the environmental impacts of air pollution. The collection of waste in a spatially concentrated city (nodal) generates less air pollution than in a spread city, since the distances to transport the waste to disposal sites are generally shorter. This work suggests the importance of linking the search for sustainable waste management systems to the dynamics of cities of which the system is part.

The approach taken in the present study aims to explicitly deal with the dynamic interrelation between the urban system and the waste management system. It is based on the following considerations: (a) wastes are consequences of the urban system at a certain moment (population, urban infrastructure, people behaviour, etc.); and (b) the urban system is dynamic (changes with time) and its dynamics influences the dynamics of waste production and management.

1.2. Interrelation between urban dynamics and waste management

The idea of the close relationship between the urban and waste management systems and the need for long-term planning assessment can be demonstrated through the use of landfills. The waste management systems applied in most cities in the world are dominated by landfills, even where there are recycling, composting and combustion facilities. This is due to the low economic cost of landfills and their ease of implementation, for example their independence of the behaviour of citizens, unlike source reduction and recycling. However, of all waste facilities landfills have the largest demand for land. This demand has been increasing with the increase in waste production. On the other hand, land is a resource whose availability has been decreasing in urban systems. Indeed, space, or urban land, is a limited resource and also is a market good with increasing value. Thus there is a serious problem of the contradictory behaviour of the supply and demand functions for land in cities with time (Fig. 1).

Leao et al. (1999) explored some aspects of the dynamic interrelations between the built and natural urban environments, and the waste management system (Fig. 2).

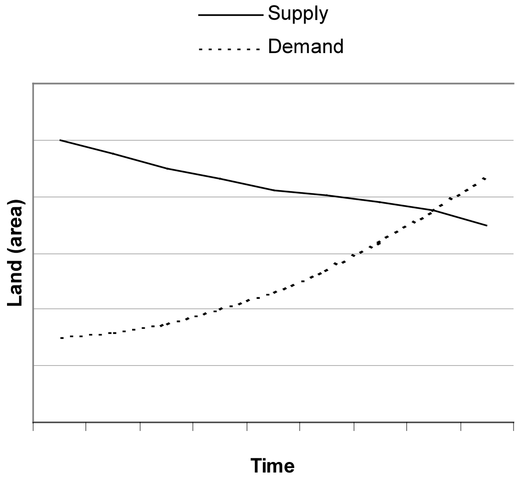
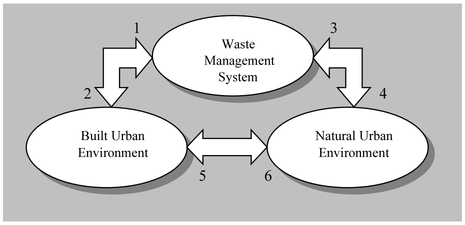


Fig. 1. Hypothetical functions of demand and supply of land for landfill over time.



	INTERRELATIONS
1	The built environment configuration influences the waste management sector. Increasing population leads to increasing waste generation. Also, the spatial distribution of the urban land uses affects the availability of land for waste treatment and disposal facilities, as well as the suitability of the available land. For example, the accessibility to transport networks and proximity to residential districts or environmentally protected areas are important factors to be considered in suitability assessment of land for the allocation of waste facilities.
2	A particular waste management system configuration can also affect future urban land use configuration. However, this effect is much weaker than the opposite one. For example, the location of a waste facility (landfill or incinerator) generates in its neighbourhood disamenities and a low potential for land use change into a residential use. On the other hand, a waste facility can generate a decrease in the land value in its neighbourhood; It can lead to a high potential to land use change into industrial use, since this activity needs large parcels of urban land and is less sensitive to the effects of waste facilities.
3	Physical characteristics, such as geology, topography, and hydrology, and their environmental conditions influence the waste management system. Waste treatment and disposal processes can cause environmental damage, such as water and soil contamination and air pollution. Because of this, the selection of appropriate type and site of waste facilities is extremely important. The environmental assessment of land suitability for waste facilities encompasses the evaluation of the physical characteristics.
4	The waste management system affects the physical characteristics of city, as waste treatment and disposal processes can generate pollution, and hence, can affect adversely the environment. However, appropriate site selection and the use of appropriate technologies for waste treatment and disposal make this effect weaker than its opposite.
5	Physical characteristics and their environmental conditions influence the land use configuration. High land areas, for example, can be considered as a topographic barrier to urban occupation. Regions susceptible to flooding have the same effect. On the other hand, proximity to water bodies can be viewed as an amenity that attracts residential use. This effect is strong only in the beginning of settlements.
6	The urban land use configuration affects the physical characteristics of the city. The activities of urban land uses generate outputs that affect adversely the environment, such as liquid wastes, solid wastes, and toxic gases. Moreover, sprawling urban land uses cause loss of natural and agricultural lands.

Fig. 2. Interrelations between the built and natural urban environments and the waste management systems.

Actually, the pace and pattern of urban growth is recognised as one of the most critical barriers to sustainable development. Urban development is replacing undeveloped land at an unprecedented rate, leading to general environmental degradation, since the land surrounding built urban areas contains various resources vital for the needs of human society, both for present and future generations. These resources include agricultural lands, ground water recharge areas, landscape amenity values, recreational areas for urban populations and the developable land needed to support expanding urban populations, economic activities and infrastructure.

Therefore, long-term monitoring and simulation of the growth of urban systems is an important component of planning toward sustainable development. Monitoring serves as a basis for the understanding of urban dynamics and for the measurements of the progress of systems towards sustainability. Simulation allows decision-makers to forecast alternative and comparable future states. The authors did not find in the literature any quantitative study or model that considered the spatial and temporal dynamic of urban growth as a component for the management of the destination of solid wastes.

1.3. Urban growth and simulation/monitoring techniques

Various theories and methodologies have been developed for the monitoring and simulation of urban growth. During the 1950s and 1960s research on urban modeling was directed towards building large scale urban models (LSUMs). They were elaborate mathematical models for urban and regional planning applications that boomed in a period characterised by the introduction of computers in planning and the emergence of new academic fields such as operations research, urban economics and regional science (Lee, 1994). The LSUMs were severely criticised because they tried to replicate too complex a system and serve too many purposes at the same time, and the information provided was too coarse to be useful to most policy makers (Wegener, 1994).

Since the early 1970s, new scientific and technological developments such as the concepts of complexity, self-organisation, chaos and fractals have considerably changed the fields of spatial modelling and urban planning. As a result a new breed of models has been developed, based on the fact that, by definition, in a chaotic system small changes at the micro-level can result in dramatic and unpredictable changes at the macro-level (bottom-up approach; Couclelis, 1997).

Cellular Automata (CA) is one of the new concepts and techniques introduced in urban modeling. According to Engelen et al. (1995), CA provides the key to a dynamic modeling and simulation framework that allows the integration of socio-economic with environmental models, and that operates at a geographical base. Furthermore, Itami (1994) says that CA models are conceptually clearer, more accurate, and more complete than conventional mathematical systems. This is due to the clear correspondence between physical and computation processes and because they are based on transition rules that are simpler than complex mathematical equations, but produce results which are more comprehensive.

There are some examples of applications of CA-based models on simulation of spatial urban dynamics. Clarke and Glaydos (1998) developed a temporal urban mapping model able to reproduce long-term urban growth process (100 years). The application and testing of the model in some important American cities have successfully demonstrated the utility of integrating historical maps with remotely sensed data and related geographic information to dynamically map urban land characteristics. Wu (1998) presented a model developed through the integration of geographic information system (GIS), cellular automata (CA), and multi-criteria evaluation/analytical hierarchical process (MCE/AHP). The main contribution of Wu's model is the introduction of a decision-making process into the simulation process, resulting in distinctive spatial forms based on various growth strategies and urban planning options. Engelen et al. (1995, 1997) designed an automaton to represent urban land use dynamics, and used it to forecast effects of climate changes on a small island. It is a good example of the rich possibilities of linking cellular based models of urban growth to urban environmental issues.

All these models show that such a modelling technique can help planners and policy makers to design more effective policies, better tuned both to specific local needs and to overall socio-economic and environmental constraints. They suggest that CA-based models can be an adequate system to be used in the context of sustainable development, and also to the management of urban solid waste.

2. Model design

2.1. The study problem

Static models provide optimum solutions for the present situation. However, because of the long-term nature of the operation of waste management systems and the dynamics of the urban system during this period, strategies considered optimum for the present may become unsustainable in the future. A dynamic approach for waste management should provide sustainable solutions. Nonetheless, temporal and spatial dimensions of the urban solid waste disposal issue have not been approached in an integrated manner.

The approach taken in the present study is based on the spatial dynamics of the urban system and its influences on the dynamics of waste production and management. In other words, it is necessary to deal with the interrelation between the urban system (built and natural) and the waste management system (which is itself an urban sub-system), and the dynamic nature of both systems. This dynamic interrelation will be analysed in terms of the progression of the supply and demand of suitable land for landfill over time in a growing city (relations 1 and 3 of Fig. 2). Since land is a limited resource, measuring its decreasing availability for waste disposal in urban areas is essential if physical constraints and more realistic costs of landfilling are to be incorporated into a planning system.

2.2. The solution method

The solution suggested here explicitly deals with the spatial and temporal dimensions of solid urban waste disposal. The proposed methodology combines an urban growth model with a land suitability model, and estimates of waste production and demand of land for waste disposal under alternative waste management scenarios. The objective is to determine the changing relationship between the supply and demand of land for waste disposal in an urban area. Fig. 3 shows the proposed design for the system.

2.2.1. Projections of urban growth

This module forecasts the future spatial distribution of urban land use in the study area by the use of a cellular automata (CA)-based model developed by Clarke and Glaydos (1998). This model can simulate 100-year projections of urban growth process based on calibrated parameters from historical data. It simulates future urban sprawl, which is characterised by non-developed areas being progressively converted into urban developed areas.

CA are discrete dynamic systems whose behaviour is completely specified in terms of local relations. They are composed of four elements: cells, states, neighbourhood rules and transition rules. *Cells are* objects in any dimensional space that manifest some adjacency or proximity to one another. Each cell can take on only one *state* at any one time from a set of states that define the attributes of the system. The state of any cell depends on the states and configurations of other cells in the *neighbourhood* of that cell. And finally, there are *transition rules* that drive changes of state in each cell as some function of what exists or is happening in the neighbourhood of the cell (Batty et al., 1997). The idea of cellular automata is closely associated with that of microscopic simulation in which the behaviour at a local scale gives rise to an emerging global organisation.

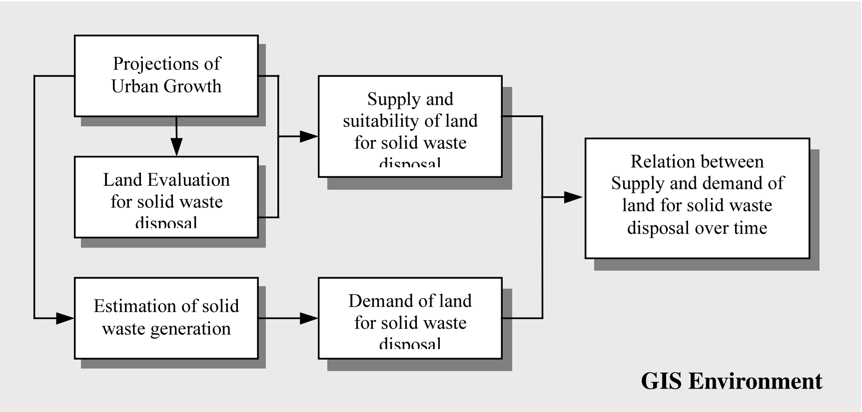


Fig. 3. System to measure the relationship between the supply and demand of land for waste disposal in urban areas over time.

Data inputs for Clarke's model include: (a) a digital elevation model; (b) a layer showing the initial or seed configuration of urban areas, plus as many additional historical layers as possible, to calibrate the model; (c) as many historical transportation layers as possible, which the model reads and uses sequentially as their year of construction is reached; and (d) a layer of excluded areas unlikely or impossible to urbanise, such as parks, water bodies and wetlands. The model considers two cells states, which are urban or non-urban (vacant).

The state transitions are governed by nine parameters—five growth factors and four self-modification factors. The growth factors are: a *diffusion coefficient*, which determines the overall dispersiveness of the distribution of single grid cells and the movement of new settlements outward through the road system; a *breeding coefficient*, which determines the likelihood of a newly generated detached settlement beginning its own growth cycle; a *spread coefficient*, which controls how much normal outward 'organic' expansion takes place within the system; a *slope resistance factor*, which decreases the likelihood of settlement extending up steeper slopes; and a *road gravity factor*, which has the effect of attracting new settlements along the existing road system.

The self-modification factors generate more realistic growth patterns, since without them the model would produce linear or exponential growth. The parameters *critical high growth* and *critical low growth* increase or decrease the diffusion, breed, and spread coefficients. The parameters *boom* and *bust* imitate the tendency of an expanding system to grow even more rapidly or to cause growth to decreases as it does in a depressed or saturated system. Other effects of self-modification are an increase in the road-gravity factor as the road network enlarges, and a decrease in the slope resistance factor as the percentage of land available for development decreases.

The model operates as a set of nested loops: the outer control loop repeatedly executes each growth 'history', retaining cumulative statistical data, while the inner loop executes the growth rules for a single 'year'. The growth rules evaluate the properties of the cells and their neighbours (whether or not they are already urban, what their topographic slope is, how close they are to a road). The decision to urbanise is based on the growth rules as well as a set of weighted probabilities that encourage or inhibit growth. The calibration involves finding the best combinations of the five growth parameters, which regulate the rate and nature of the types of growth, and defining the four growth constants, which affect self-modification. The calibration process uses historical data and a trial-and-error process to determine the best factor values.

There are 13 measures to test statistically the degree of fit between the model's output and the historical data. Three important measures are: (a) the r^2 *fit* between the actual and predicted number of urban pixels; (b) the r^2 *fit* between the actual and the predicted number of edges in the images (pixels that have contact between urban and non-urban on any side); and (c) the r^2 *fit* between the actual and predicted number of separated clusters in the urban distribution. These measures are computed as averages of multiple runs.

In the prediction phase, the model produces annual probability images of urban growth using the Monte Carlo iterations. In these images, the higher the value, the more likely urbanisation is. The probability values are classified by range in six classes (<50, 50–59, 60–69, 70–79, 80–89, and 90–100%), and identified by colours.

According to Clarke and Glaydos (1998), the applications of the model shown that the approach can produce useful results. It has successfully replicated past urban expansions in a regional scale and over a long period. The Washington/Baltimore case study, for example, presented high values of fit for the simulation results. The *r^2 fit* between the actual and predicted number of urban pixels was above 0.96. More information about the model can be found at: http://www.ncgia.ucbs.edu/projects/gig/

2.2.2. Land evaluation for solid waste disposal

Land evaluation is the process of assessment of land performance when the land is used for specified purposes. The logical basis that makes land evaluation possible and useful are: (a) land varies in its physical and human-geographic properties, and this variation affects land uses; (b) the variation is in part systematic, so that the variation can be mapped; and (c) the behaviour of the land when subjected to a given use can be predicted with some degree of certainty, depending on the quality of data on the land resource and the depth of knowledge of the relation of land to land use.

According to Rossiter (1996), land evaluation is an instrument to inform the process of allocation of land uses to land areas, and thus can be used to search for rational land use planning and appropriate and sustainable use of natural and human resources.

The land evaluation process assesses the suitability of land mapping units for specific land use types. The procedure starts by determining the land requirements for the land uses under analysis. They are the necessary conditions of the land for successful and sustained implementation of a specific land utilisation type. They are the *demand* side of the land use equation: what the use requires of the land. Subsequently, the evaluation process involves measuring or estimating the land characteristic values for the land unit (field survey, laboratory measurements, remote sensing, predictive modelling, etc), and combining these land characteristics values into land quality values. Land qualities express the ability of the land to fulfil specific requirements for the land use under analysis. They are the *supply* side of the land use equation: what the land can offer to the use. The process is concluded by matching the land quality values with land use requirements, and by combining these land quality values into land suitability classes.

The land evaluation method in the present study assesses the land suitability of available non-developed urban land over time for urban solid waste disposal (landfill). The method excludes inappropriate areas and classifies the remaining areas according to their suitability for that specific land use. The calculation of the land suitability is made through the integration of factors and constraints that describe physical, economic and social characteristics of the land parcels of the study area. Based on the studies developed by Lane and McDonald (1983), Lober (1995), Siddiqui et al. (1996), Leao (1997), these are some criteria used in land evaluation for landfill: (a) topography (slope); (b) type of soil; (c) accessibility (distance to the road network); (d) distance to water bodies and flooding areas; (e) distance to parks and areas of environmental protection; (f) distance to airports; (g) distance to urban areas (related to costs of transport and community opposition); (h) minimum area requirement; (i) depth of the ground-water table; (j) type of rock underground; (k) availability of soil material to cover wastes.

The integration of the criteria is based on multi-criteria (Eq. (1)) and multi-objective (Eq. (2)) assessment methods (Eastman et al., 1993).

$$S_{\mathrm{k}} = \left(\sum_i f_i w_i \prod_j r_j \right)_{\mathrm{k}} \tag{1}$$

$$\underline{S} = \sum (S_{\mathrm{k}} \cdot w_{\mathrm{k}}) \tag{2}$$

where, S_{k} is suitability of land for landfill for objective k (k = environmental, social and/or economic); $(f_i)_{\mathrm{k}}$ is factor i for objective k; $(w_i)_{\mathrm{k}}$ is weight of the factor i for objective k; $(r_j)_{\mathrm{k}}$ is constraint j for objective k (take value 0 or 1); $\underline{S}$ is multi-objective suitability; w_{k} is weight of the objective k.

The land suitability of the study area changes over time as urban area sprawls. In order to describe the temporal behaviour of the land suitability for landfill the average suitability of the available and suitable land for each period is calculated (Eq. (3)).

$$\overline{\mathrm{Suit}}_t = \left(\frac{\sum_{i,j} s \cdot a}{A} \right)_t \tag{3}$$

where, Suit_t is average land suitability of the available and suitable land for landfill at time t (values between 1 and 10), s is land suitability for landfill at time t and location i, j (values between 1 and 10); a is area of the parcel ij with land suitability s (area of the grid cell resolution). A is total available and suitable land for landfill at time t.

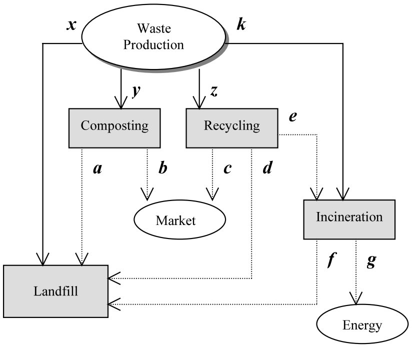
2.2.3. Characterisation of urban solid waste management systems

The present study focuses on the destination of wastes. The emphasis in on how much waste is produced, which part of this waste is going to be sent to landfill over time, and the area required to dispose of this waste in landfill.

The characterisation of scenarios for the management of the waste involves:

(a) Definition of the combination of methods for treatment and disposal of urban solid waste, such as recycling, composting, incineration and landfill (Fig. 4). Reduction of waste production can also be considered.

(b) Estimation of the future waste production, based on historical data and



Material Balance:

$$\textit{Produced waste }(PW) = xL + yC + zR + kI \qquad [4]$$

$$\textit{Landfilled waste }(LW) = xL + aC + dR + fI \qquad [5]$$

$$\textit{Recovered waste }(RW) = bC + cR \qquad [6]$$

$$\textit{Incinerated waste }(IW) = kI + eR \qquad [7]$$

Fig. 4. Components and productive outputs for an integrated municipal solid waste system.

trends, existing projections, existing or hypothetical policies and plans, characteristic of the study area.

(c) Calculation of the amount of waste to be sent to landfill over time using the system defined in item (a) (Eq. (5), Fig. 4).

(d) Estimation of the area requirement to dispose the waste in landfill over time for a system. It can be developed through the use of an index of *area/tonne of waste* characteristic of the study area (density of the waste, type and height of landfills, etc).

3. Application

3.1. Description of the study area

Porto Alegre City, located in the south of Brazil, has an area of 47 750 ha and a current population of 1.3 million. The city is limited on the west by the Guaiba river, and on the other sides by counties that encompass the metropolitan region which Porto Alegre is the core city (Fig. 5).

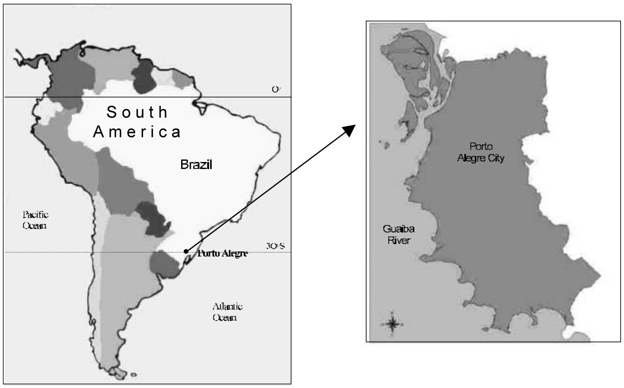
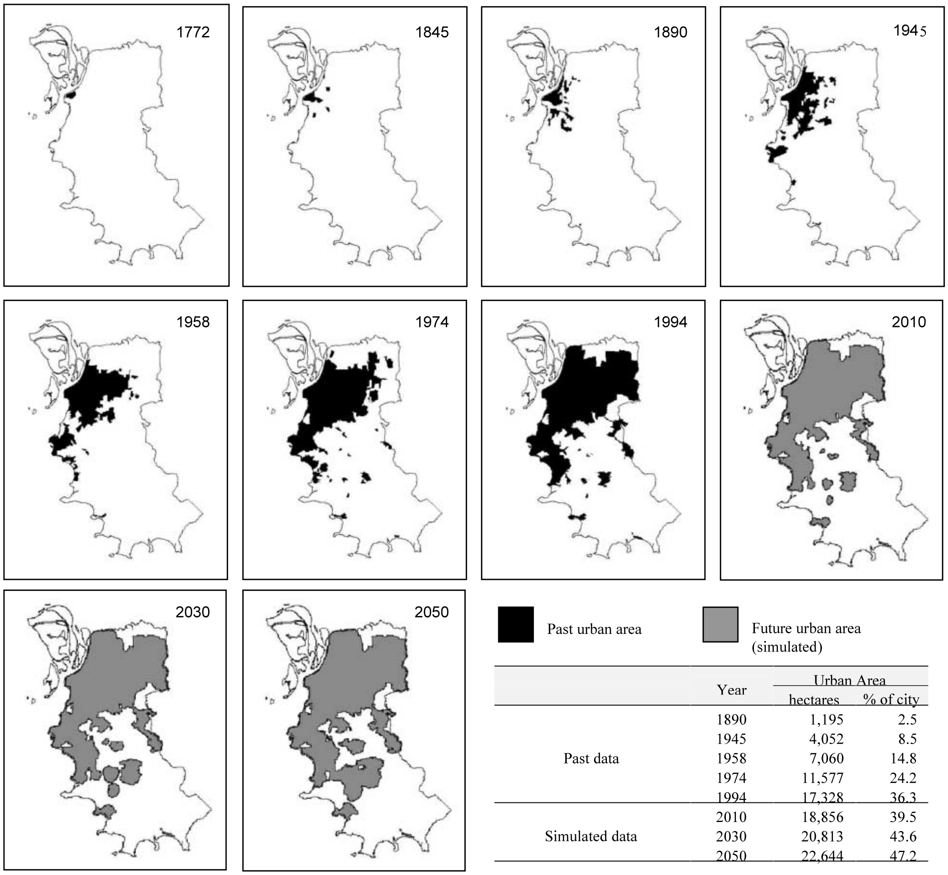


Fig. 5. Study area: Porto Alegre City, Brazil.



	Year	Urban Area hectares	Urban Area % of city
Past data	1890	1,195	2.5
	1945	4,052	8.5
	1958	7,060	14.8
	1974	11,577	24.2
	1994	17,328	36.3
Simulated data	2010	18,856	39.5
	2030	20,813	43.6
	2050	22,644	47.2

Fig. 6. Maps of urban sprawl in Porto Alegre City—historical and simulated information.

During the twentieth century the population of Porto Alegre grew almost 23 times. There was a rapid population increase from the 1940s to the 1980s, and a lower rate during the 1990s. Projections estimate progressively lower rates of population growth for the next decades (METROPLAN, 1999).

The increasing population has been accompanied by a significant urban sprawl (Fig. 6). During the last century the built urban area increased 13.5 times.

A policy for waste management has been applied in Porto Alegre since 1988. It involved recovering areas degraded by waste dumping, siting and implementing new landfills, and opening recycling and composting units, together with environmental education programs.

The current situation in the city is that the waste diversion by recycling and composting is still very low and that there is a shortage of suitable land available for landfill. Recently, disposing of the waste in the surrounding cities of the metropolitan region has been considered as a solution. However, there are some administrative and political difficulties in that option, and also a high cost associated with the transport of waste to distant disposal sites.

Table 2
Statistic indexes for the evaluation of the quality of the simulation

Index	Description	Value for the simulation in Porto Alegre (0–1)
R^2 population	Least square regression score for modelled urbanisation compared with actual urbanisation for the control years	0.9836
Edge r2	Least square regression score for modelled urban edge count compared with actual urban edge count for the control years	0.9719
R^2 clusters	Least square regression score for modelled urban clustering compared with known urban clustering for the control years	0.9492

Population indicates number of urban pixels.

3.2. Simulation of urban sprawl

Fig. 6 presents the urban configuration (form and extent) of Porto Alegre. Historical maps (1890–1994) were used to calibrate the model to the specific reality and dynamic of the study area. The historical transportation network, excluded areas (parks, wetlands and water bodies) and topography were also used for the calibration process. The maps for the period 2010–2050 in Fig. 6 are part of the results of the simulation process of urban sprawl into the future. Only the areas with Monte Carlo probability higher than 70% were considered as being converted into urban land use.

The predictions are consistent. As shown in Table 2, the statistical indexes for the assessment of the quality of the urban growth simulation process presented high values. Moreover, the spatial configuration of the future urban growth generated by the model fits with the existing descriptive and qualitative projections about where the future urban sprawl in Porto Alegre is more likely to happen (Souza and Muller, 1997). Finally, the model predictions match the estimates of a continued urban growth with progressively lower rates for Porto Alegre.

3.3. Supply and suitability of land for urban solid waste disposal

Table 3 describes the criteria used to assess the availability and suitability of land for landfill and also presents the weights for the multi-criteria and multi-objective assessment. The land evaluation criteria used in the present study include some of the most important physical characteristics a site should have, in order to be suitable for waste landfilling. The chosen criteria required available data that could be mapped and treated within a geographic information system environment.

Table 3
Factors and constraints for land evaluation for solid waste disposal

Objectives	Weight	Criteria	Level of suitability				
			Unsuitable (constraint)	Low suitability	Medium suitability	High suitability	Weight
Environmental (static)	0.60	Protected areas	Parks + 300 m	–	–	–	–
		Slope	> 20%	15–20%	10–15%	< 10%	0.20
		Water bodies	< 200 m	200–500 m	500–1000 m	> 1000 m	0.45
		Soil	Soils with bad drainage within areas vulnerable to flooding	Soils with low permeability and with seasonal elevation of the underground water table	Thin layer soils that offer risk of aquifer contamination	Soils with medium or high permeability and with deep underground water table level	0.35
		Road network	Roads + 50 m	–	–	–	–
Social (dynamic)	0.40	Urban area	< 1000 m	–	1000–2000 m	> 2000 m	–

Table 4
Integration of all static and dynamic factors/constraints for each period of time

Year	Level of suitability (ha/year)				Availability of land	Average suitability (1–10)[a]
	Unsuitable	Low	Medium	High		
1890	43 668	876	2599	622	4097	6.50
1945	44 709	598	2170	416	3184	6.47
1958	45 263	539	1664	300	2503	6.42
1974	46 651	374	919	123	1416	6.34
1994	46 688	274	706	98	1078	6.31
2000	46 740	261	667	98	1026	6.31
2010	46 859	250	564	92	906	6.30
2020	46 970	233	471	92	796	6.29
2030	47 061	215	405	85	705	6.28
2040	47 128	203	359	75	637	6.28
2050	47 189	184	328	65	577	6.27

[a] Average suitability of the suitable land available for landfill.

Moreover, a minimum area requirement of 20 ha was considered as a spatial constraint.

Table 4 presents the results of the multi-criteria and multi-objective land evaluation for Porto Alegre. By integrating all the factors and constraints for each period of time, it results in information as such the area for each level of suitability in Porto Alegre over the period of time under analysis.

3.4. Projections of urban solid waste generation

Urban solid waste in this study includes all non-hazardous waste produced by urban activities, such as household, commercial, construction, and non-toxic industrial waste.

The future urban solid waste generation in the study area was obtained in the Master Plan for Solid Waste of the Metropolitan Region of Porto Alegre (METROPLAN, 1999 Volume III). This study involved an estimate of the urban solid waste generation in the Metropolitan Region of Porto Alegre for the period 1997–2050. The increase of the solid waste generation is considered being caused by two factors: (a) the growth of population; and (b) the increase of the per capita rate of waste generation.

The population growth was estimated based on a logistic function for the natural growth combined with an S-shaped function for the migrations. The per capita waste generation was considered increasing in progressively lower rates, until reach stability by the year 2010 (Fig. 7).

The amount of waste generated in Porto Alegre during the study period were then obtained by multiplying the population of each year (inhabitants) by the per capita rate of waste generation for the same year (kg per inhabitants per day) (Fig. 8).

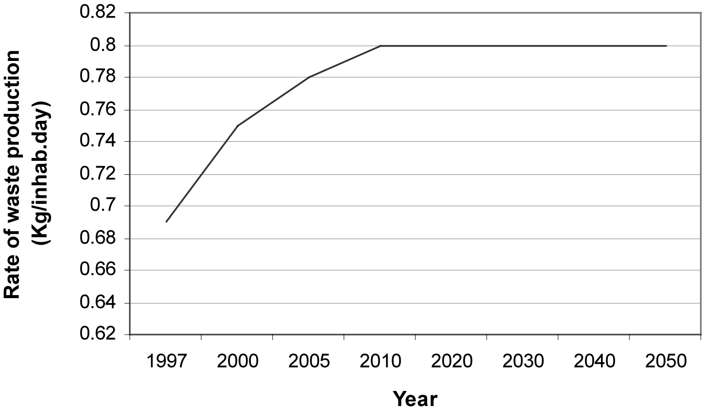


Fig. 7. Evolution of the per capita rate of solid waste generation in Porto Alegre.

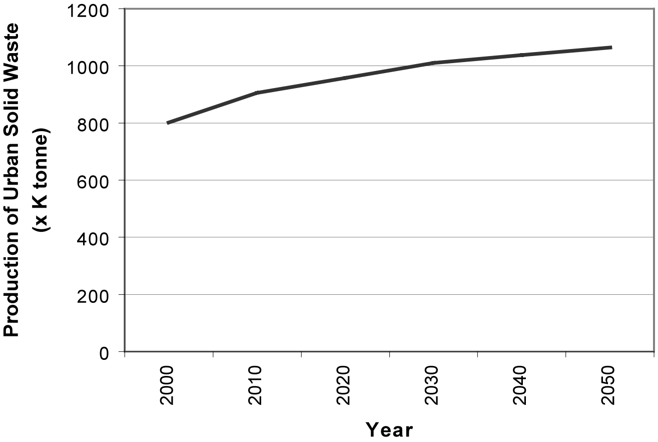


Fig. 8. Projections of urban solid waste production in Porto Alegre over time (2000–2050).

3.5. Alternative scenarios of urban solid waste management

Three scenarios of waste management were developed to investigate the demand for waste disposal land (Table 5). Scenario A is the worst-case, where all the waste is sent to landfill during the whole period 2000–2050. Scenario B tries to reproduce the existing waste management regime of the city. It includes progressively increasing rates of recycling and composting that result in a reduction of 10% of the waste to be disposed in landfills. Scenario C is an optimistic system that includes higher rates of waste recovery and a decreasing per capita rate of waste production. In comparison with scenario A, scenario C results in a reduction of 25% of the amount of waste to be disposed in landfills.

Fig. 9 presents the cumulative amount of urban solid waste to be sent to landfill in Porto Alegre for each waste management scenario during the period 2000–2050.

Table 5
Waste management scenarios

	Landfill	Recycling	Composting	Reduction
Scenario A	100%			
Scenario B	90% (waste not recovered)	Increases progressively from 0.5 (current rate) to 3% during 2000–2050	Increases progressively from 5 to 10% during 2001–2020	
Scenario C	75% (waste not reduced or recovered)	Increases progressively from 0.5 (current rate) to 10% during 2000–2050	Increases progressively from 5 to 20% during 2001–2050	10% reduction in the per capita rate of waste production during 2000–2050

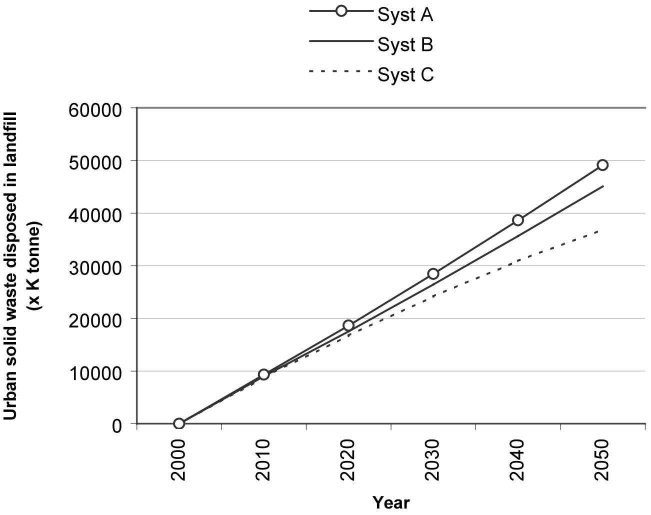


Fig. 9. Cumulative amount of urban solid waste to be disposed in landfill for different waste management systems.

3.6. Demand of land for urban solid waste disposal

Based on the current technology used in the study area, there is a need of 1.43 m^3 of landfill space for each tonne of waste disposed. According to Walquil et al. (METROPLAN, 1995), a standard height of landfill to be used in calculations of land demand for waste disposal varies between 10 and 20 m for cities with a waste production up to 1000 tonnes per day. Considering the characteristics of most of the available areas for landfill, as well as the height of some existing landfills in the

Table 6
Demand of land for waste disposal in Landfill in Porto Alegre for the period 2000–2050

Waste management Option	Amount of waste for landfill (M tonne)	Demand of land for landfill (ha)
Scenario A	49.1	702
Scenario B	45.1	644
Scenario C	36.9	527

study area (7 m at the Zona Norte landfill, and 25 m at the Santa Tecla landfill) an average height of 10 m for landfills was adopted. Therefore, the area demanded for waste landfilling is 0.143 m^2/tonne (or 1.43×10^{-5} ha/tonne). Table 6 presents the demand of land for waste disposal in landfill for the period 2000–2050 for the three different waste management systems proposed.

3.7. Relation of supply and demand of land for urban solid waste disposal in landfill

According to the results of the methodology developed, there is not enough suitable land available for disposal of the urban solid waste in Porto Alegre for the period 2000–2050 for most of the waste management scenarios analysed. For the Scenarios A and B, the demand of land for landfill overcomes the supply of land suitable for that use before the year 2050. Scenario C reaches this point just after 2050.

Fig. 10 presents the curves of demand and supply of land suitable for landfill for each one of the waste management systems under analysis. Also it shows the availability of land over time considering land being consumed over time for waste disposal.

For Scenario A, the supply of land is entirely used by the year 2044. By the end of the study period there is a deficit of 125 ha (20% of the required area). Scenario B postpones this date for the year 2046 by recovering 10% of the waste through recycling and composting. In 2050 the land deficit is 67 ha, 10% of the land requirement. Finally, Scenario C, which reduces by 25% the amount of waste sent to landfill during the study period, finds in the study area the land requirements for landfill. This scenario would fill the available land by the year 2054.

It is important to highlight that the actual availability of land for landfill can be significantly lower than the amount shown in Table 4. A more complete land evaluation should consider other characteristics, such as more detailed analysis of soil, ground-water level, current and future land uses, economic use of the land (agriculture, mining, etc.), vegetation, price of the land, etc. Since of most of these criteria demand large scale mapping, studies usually apply them on small areas earlier selected by general criteria, such as those in Table 3.

The Agency for Planning of the Metropolitan Region of Porto Alegre (Metroplan) developed two studies for selection of areas for landfill. The first phase of the study, developed in 1995, mapped inappropriate areas for landfill in the Metropolitan region of Porto Alegre through the use of general constraints in a GIS environment. The second phase, developed in 1998, applied a more complete set of criteria able to eliminate some more areas and classify the remaining areas into levels of suitability. The latter phase was performed in part of the metropolitan region of Porto Alegre, involving five of the 24 counties of the region (Porto Alegre City was not included). The results showed that 7% of the area suitable for landfill in the five counties from the first phase assessment are actually unsuitable for landfill and that 50% of the same area presented very low suitability values (METROPLAN, 1995, 1998).

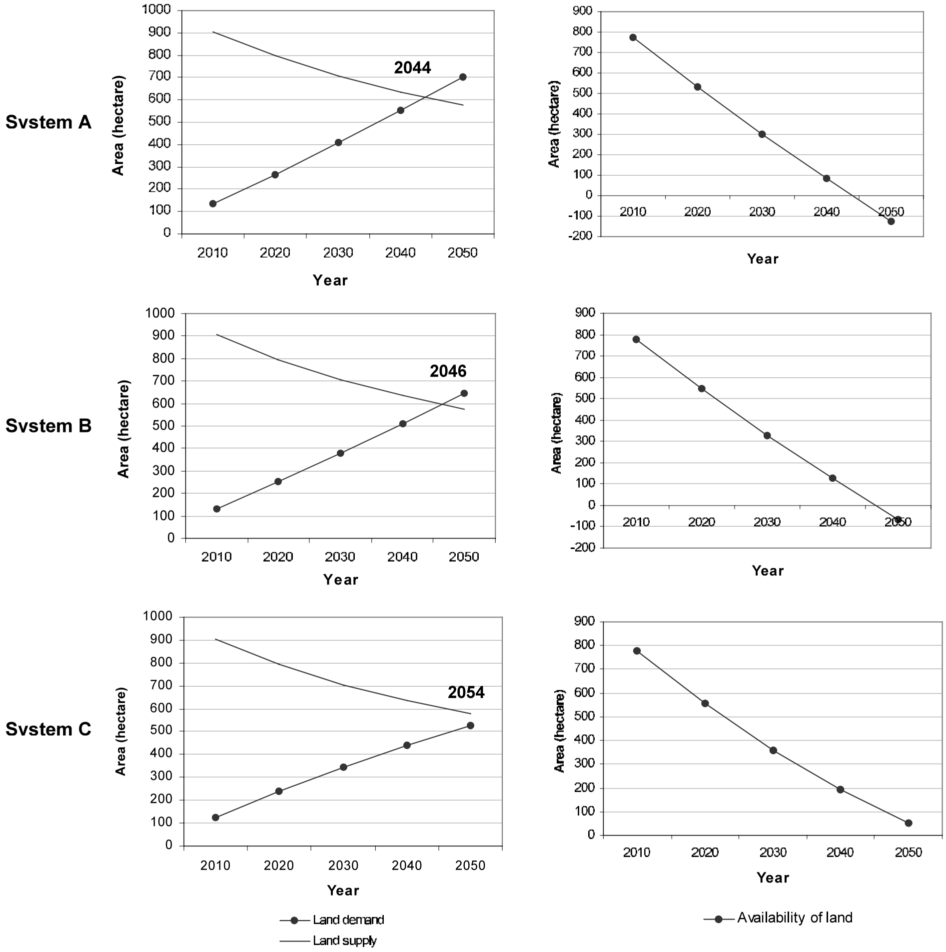


Fig. 10. Relation supply to demand and availability of land for waste disposal for the waste management systems.

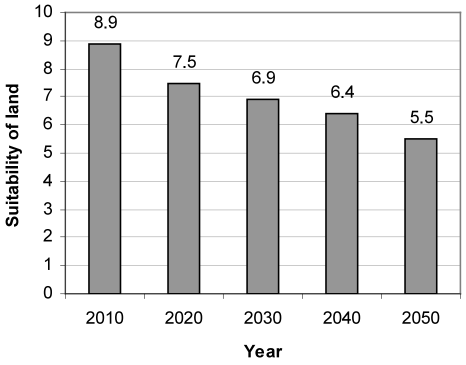


Fig. 11. Changing suitability of the best land available for waste disposal needs under Scenario C.

3.8. Level of suitability of the available land for landfill over time

The average suitability of the total available landfill areas presents low suitability values for all dates and does not change significantly over time. It has decreased slightly from 6.50 in 2000 to 6.27 in 2050 (Table 4).

The adoption of land for landfill is not, however, a single one-step process. New landfill sites would need to be opened on a semi-continuous basis, e.g. every 10 years. In order to model this on-going process, for every period of 10 years the most suitable land available is allocated for landfill progressively according to the demand of the period and the waste management system under analysis. Initially, in 2010, a landfill was allocated in the best area according to the suitability assessment for this year. This area is then eliminated from the map of available land for landfill in 2020. The area requirement for landfill for the year 2020 is then allocated in the parcel with the best suitability value for the period. And so on, until the year 2050.

This analysis resulted in a significant decrease in the suitability of the land being used. For the Scenario C (the only scenario with supply of suitable land until the end of the study period, 2050), for example, the best land available for disposal of waste during 2000–2010 had a suitability of 8.9. This suitability, however, decreased progressively to a minimum value of 5.5 by 2050 (Fig. 11).

This decreasing suitability shows that the areas to be used for landfill are going to become progressively less appropriate. This has consequences on the costs of the system, as well as in the risks for the environment and the community. Low suitability results, for example, from the use of areas whose soil presents low suitability, or areas near to water bodies. It makes necessary the use of more sophisticated operations and devices to assure environmental protection, which leads in turn to higher costs. Also, low suitability can result from the use of land close to residential areas, which might lead to strong public opposition.

4. Conclusions

The complexity and dynamics of urban evolution has created difficulties for the management of urbanised spaces and in the maintenance of urban quality of life. Indeed, the traditional planning system, mostly based on policies that are transitional and focused on the short-term, has failed in that task. This situation plus the recent challenge imposed by the goal of sustainable development, makes a new approach to urban planning and management essential. As sustainability is a long-term commitment, such an approach should be not only efficient in the present but also sustainable in the future. It should focus on the concept of possible future trajectories and on the measures necessary to lead the system along a more desirable path. It will involve the development of new planning tools, with more sophisticated and efficiently organised methods for monitoring the evolution of the urban system and its future prospects and performance.

The treatment and disposal of wastes is one of the central themes of sustainable development. The main emphasis of the present study was to consider explicitly the destination of the urban solid wastes in the context of urban development and sprawl. It has been developed by: (a) evaluating the impact of urban sprawl on the availability of land for waste disposal over time; (b) evaluating the impact of urban sprawl on the suitability of land for landfilling over time; and (c) evaluating the impact of population growth in terms of potential waste generation and the temporal relationship between demand and supply of land for landfilling.

Based on projections of population growth, urban sprawl and waste generation, and by testing different waste management scenarios, the method can allow policy and decision makers to measure the extent of the problem of shortage of land for landfill into the future, and can provide information to guide the design and schedule of programs to reduce and recover waste, and can potentially lead to a better use of the land resource.

The present study approached the interrelation between urban development and waste management. Nonetheless, the two sides of the issue, demand and supply of land were treated differently. The demand for land for landfill was manipulated through the analysis of different scenarios of waste management. The impact of recovering wastes and reducing the waste production was tested. The supply of land, however, was obtained by a simulation model that projects the future based on historical trends. It is possible to improve this analysis by testing how different strategies for urban growth can affect the supply of land for landfill. These strategies can consider, for example, policies for reducing urban sprawl or stimulating the urban growth in certain earlier defined areas. Links between modelling and policy generation, such as those developed by Wu (1998) could be very valuable in this context.

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