

Original Research Paper

Measuring Intra-City Eco-Efficiency Variations of Urban Infrastructures in Jeddah

Mohammed Aljoufie and Alok Tiwari

Department of Urban and Regional Planning, King Abdulaziz University, Saudi Arabia

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Corresponding Author:

Mohammed Aljoufie
Department of Urban and
Regional Planning, King
Abdulaziz University, Saudi
Arabia
Email: maljoufie@kau.edu.sa;
aljoufie@itc.nl

Abstract: Saudi cities are experiencing construction booms linked to urban infrastructure services and the Kingdom's second largest city, Jeddah, is not an exception. As these booms are associated with urban expansion and rapid population growth, the major challenge confronting urban planners is the ensuring of resource efficiency given the offered infrastructure. In fact, reducing the consumption of resources and the impact of consumption on the environment is a serious concern with respect to the improved value of sustainable urban development as well as society. This paper attempts to measure intra-city spatial eco-efficiency variations of the major urban infrastructures of Jeddah. These infrastructures include water supply, public transportation, social businesses, energy consumption, solid waste generation and green areas, all of which are assumed to be offered as a skeleton for upcoming urban environmental plans that will then lead to the reconfiguring, retrofitting or replacing of infrastructures in the city, thus driving it towards a green economy.

Keywords: Urban Infrastructure, Eco-Efficiency, Retrofitting, Green Economy

Introduction

Measuring or assessing (Kuosmanen, 2005) is the secret to established management practices. Measuring the sustainability of cities contributes to overall good city management as sustainability indicators and composite indices are recognised as effective tools for policy making (Singh *et al.*, 2009).

Assessing eco-efficiency inspires urban planners and decision makers to search for the least costly and most environmentally friendly alternatives available (Ribarova *et al.*, 2013). While urban environments drive economic development, their avid hunger for growth combined with their size, results in an alarming increase in resource consumption in dense areas of cities (Schaffer and Vollmer, 2010).

In fact, sustainability does not prevent resource consumption, but rather, it aims to efficiently consume resources. While material and resource flows are inherent to and incurred by the cities' infrastructure, eco-efficiency is the indicator to promote transformation towards sustainability. However, there is a considerable lack of research regarding the development of this indicator. In particular, there is a considerable absence in the literature

on the development of such an indicator to analyse intra-city eco-efficiency variations in urban infrastructures.

Sustainability of Urban infrastructure is crucial for urban environment (Choguill, 1996) because they regulate flow of natural and artificial resources consumed in the urban areas. The eco-efficiency of urban infrastructure has significant importance with respect to rapidly urbanising and globalising cities such as Jeddah, where urban infrastructure development choices made today determine the success of cities to deliver services to its stakeholders while growing competitively within a protected environment for decades to come (UNESCAP, 2011).

Hence, this paper attempts to develop a measure for intra-city spatial eco-efficiency of selected urban infrastructure amenities in Jeddah such that the amenities can be strategically planned to offer sustainable reconfiguring and retrofitting.

Eco-Efficiency of Urban Infrastructure: Theoretical Background

Brunt land Commission suggested sustainable development as a development paradigm that aims to

meet the needs of the present generation without compromising the capabilities of future generations (WCED, 1987). Saudi cities have recently begun focusing on sustainability because of the increasing awareness that economic growth usually comes at the cost of environmental impact, such as the consumption of the earth's resources has surpassed the earth's available resources. In 2012, the UAE launched 'The Arab Green Economy Initiative', which guides their economy from a virtual to a real sustainability perspective (UNDP, 2012). The environmental and climate changes impact related burdens as the production and consumption of resources call for a more efficient use of environmental resources. The concept of eco-efficiency was initially developed as a business link to sustainability (Schaltegger and Sturm, 1990; Freeman *et al.*, 1973). It was later adopted by the WBCSD (2000) with the slogan, 'doing more with less' or 'creating more value with less impact'. Eco-efficiency suggests a substantial change from non-sustainability to sustainability (Mickwitz *et al.*, 2006). Eco-efficiency offers solutions such as optimising resource values by reducing the use of resources and thereby reducing the environmental impact. Eco-efficiency promotes the development of a cyclic economy that is resource conservative in nature rather than a traditional linear economy that consumes resources and produces waste

(Byström, 2012). A paradigm shift from conventional environmental reporting to sustainability reporting or eco-efficiency reporting, which comprises the Triple Bottom Line (TBL)-social, economic and environmental aspects- has been evidenced in the last few years (Fet, 2003). Eco-efficiency reporting advises cities' economies to reconfigure their infrastructure towards a low-carbon transition plan (Bulkeley *et al.*, 2014).

Methodology

Study Area

Jeddah is the second largest city in the Kingdom of Saudi Arabia with a population of 3.4 million in 2014. The population is expected to grow to over 5 million by 2029 (JM, 2009), when the city will then rank 5th, based on size, among all Arabian cities (UN-HABITAT, 2012a). Jeddah is located on the west coast of the Kingdom in the middle of the eastern shore of the Red Sea and it is surrounded by the plains of the Tahoma to the east (Fig. 1). Being a coastal city, its location is more environmentally sensitive to the kingdom. Furthermore, the city is experiencing a transition as many mega infrastructural amenities designed to provide the city's residents a better quality of life are either provisioned for or planned.

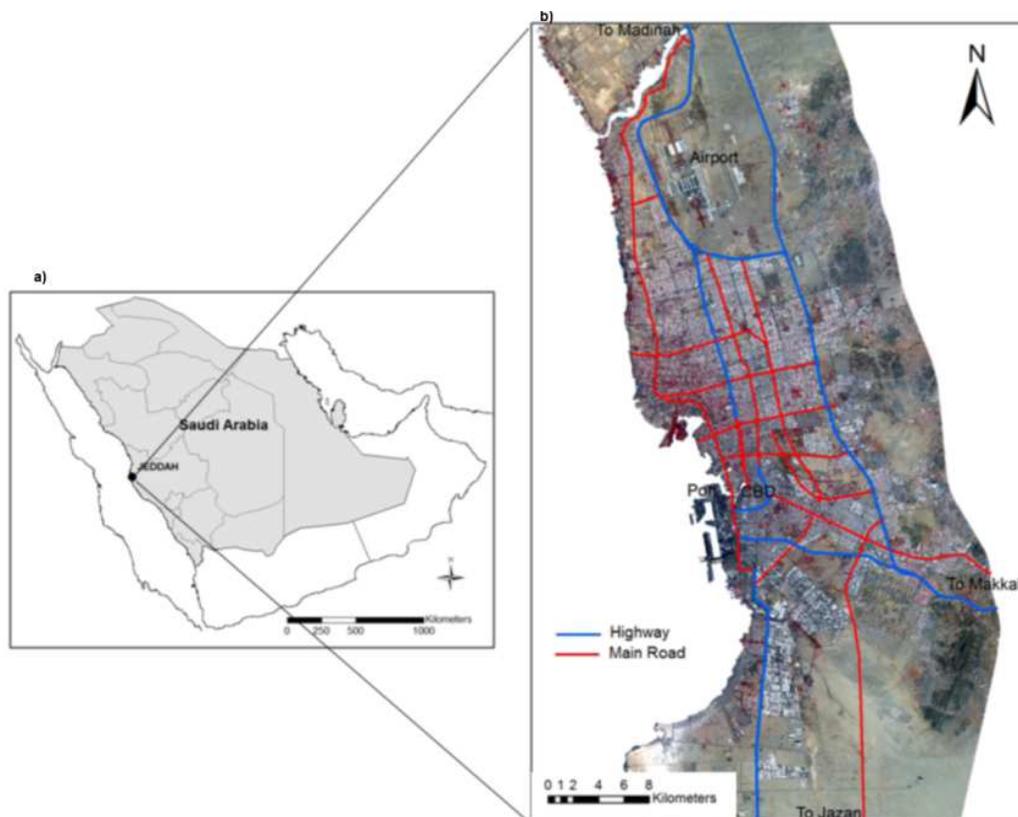


Fig. 1. (a) Geographic location of Jeddah (b) Jeddah city

Jeddah's history, location and unique role in relation to Hajj have contributed to shaping its urban form and demographic profile. Attracting migrant workers and pilgrims from the entire Islamic world, the city is perceived as a place of opportunity. The rapid growth in population (natural and migratory) in the last four decades has coincided with the Kingdom's enormous increase in wealth, which, in turn, has resulted in Jeddah's unprecedented rate of physical expansion. The urban area of Jeddah has exceeded the current capacity of its infrastructure, thus leading to structural problems with respect to city's ability to provide adequate water, sewage and roadways. This growth has also left the city with a number of structural challenges, including numerous areas of vacant land as well as a dependency on private cars for transportation.

Data Collection and Preparation

In this study, six key urban infrastructure resources have been chosen in varying units to determine environmental cost, namely, water, energy, solid waste, green cover, public transport and social business areas (mall in the case of Jeddah). These constitute major urban infrastructure, all of which are pertinent for environmental betterment and improved quality of life in a city.

The analysis was conducted at the district level because of the homogenous character of districts in Jeddah. A simple random sampling technique was applied to obtain household level water, energy and solid waste related data at the district level. The remaining infrastructure data, including green infrastructure, public transport route length and social business areas, were first extracted from satellite imageries in conjunction with secondary data. A GIS-based approach was then used to disaggregate the extracted data regarding green infrastructure, public transport route length and social business areas at the district level.

Eco-Efficiency Indicators

Though numerous indicators have been recommended by scholars and agencies to measure sustainability and eco-efficiencies (Singh *et al.*, 2009) the UN (2009) adheres to the following equation:

$$Eco - efficiency = \frac{Environmental\ Cost}{Economic\ Output}$$

As previously indicated herein, environmental cost may refer to pollution emissions, resources used or costs associated with environmental burden, while economic output can be expressed in value added through benefits, units of product or service or costs associated with environmental burden. In this study, environmental cost

refers to urban infrastructure resources used, while the economic output refers to the service area expressed as per hectare (10,000 square meters) of land parcel.

Hence:

$$Eco - efficiency = \frac{Infrastructure\ resource\ uses}{Service\ area} \quad (1)$$

After computing the eco-efficiency of each infrastructure resource at the district level, the resources were categorised on the basis of natural breaks (jenks) and a weight was assigned to each infrastructure resource ranging from very low (0) to very high (5).

Accordingly, to calculate the eco-efficiency for public transport (EEtr):

$$EEtr = \frac{Length\ of\ public\ transport\ routes\ in\ meters}{Geographical\ area\ of\ district\ in\ hectares} \quad (2)$$

Allocated weights for public transport eco-efficiencies (EEtr) are depicted in Table 1.

To calculate the eco-efficiency for water supply (EEwt):

$$EEwt = \frac{Water\ supply\ in\ kilo\ liters}{Geographical\ area\ of\ district\ in\ hectares} \quad (3)$$

Allocated weights for water supply eco-efficiencies (EEwt) are presented in Table 2.

To calculate the eco-efficiency for energy (electricity):

$$EEen = \frac{Electricity\ consumption\ in\ kilowatt\ Hours}{Geographical\ area\ of\ district\ in\ hectares} \quad (4)$$

Allocated weights for energy eco-efficiencies (EEen) are presented in Table 3.

To calculate the eco-efficiency for solid waste generation (EEsw):

$$EEsw = \frac{Daily\ solid\ waste\ generation\ in\ quintals}{Geographical\ area\ of\ district\ in\ hectares} \quad (5)$$

Allocated weights for solid waste generation eco-efficiencies (EEsw) are presented in Table 4.

To calculate the eco-efficiencies for green infrastructure (EEgi):

$$EEgi = \frac{Green\ area\ in\ square\ meters}{Geographical\ area\ of\ district\ in\ hectares} \quad (6)$$

Allocated weights for green infrastructure eco-efficiencies are presented in Table 5 (EEgi).

Table 1. Assigned Weights for Public Transport Eco-efficiencies (EEtr)

Weighted score	Category	Length of public transport routes (in meters) per hectare of land
1	Very low	0.0 to 2.8
2	Low	2.8 to 10.0
3	Moderate	10.0 to 19.0
4	High	19.0 to 35.0
5	Very high	35.0 to 57.0

Table 2. Assigned Weights for Water Supply Eco-efficiencies (EEwt)

Weighted score	Category	Water Supply (in kilolitres) per hectare of land
1	Very low	75.4 to 103.8
2	Low	45.2 to 75.4
3	Moderate	14.9 to 45.2
4	High	6.1 to 14.9
5	Very high	0.5 to 6.1

Table 3. Assigned Weights for Energy Eco-efficiencies (EEen)

Weighted score	Category	Electricity supply (in kilowatt hours) per hectare of land
1	Very low	329.0 to 454.0
2	Low	197.0 to 329.0
3	Moderate	65.3 to 197.0
4	High	22.7 to 65.3
5	Very high	0.0 to 22.7

Table 4. Assigned Weights for Solid Waste Generation Eco-efficiencies (EEsw)

Weighted score	Category	Amount of solid wastes generated daily (in quintals) per hectare of land
1	Very low	47.0 to 65.0
2	Low	28.0 to 47.0
3	Moderate	13.0 to 28.0
4	High	3.8 to 13.0
5	Very high	0.0 to 3.8

Table 5. Assigned Weights for Green Infrastructure Eco-efficiencies (EEgi)

Weighted score	Category	Green area (in square meters) per hectare of land
1	Very low	0.0 to 71.2
2	Low	71.2 to 175.4
3	Moderate	175.4 to 336.8
4	High	336.8 to 663.9
5	Very high	663.9 to 1141.0

Table 6. Assigned Weights for Social Businesses Eco-efficiencies (EEsb)

Weighted score	Category	Area of malls (in square meters) per hectare of land
1	Very low	0.0 to 130.0
2	Low	130.0 to 210.0
3	Moderate	210.0 to 303.0
4	High	303.0 to 559.0
5	Very high	559.0 to 1265.0

To calculate the eco-efficiency for social businesses (EEsb):

$$EEsb = \frac{\text{Area of malls in square meters}}{\text{Geographical area of sistrict in hecatres}} \quad (7)$$

Allocated weights for social businesses eco-efficiencies (EEsb) are presented in Table 6.

Table 7. Classified City-level Eco-efficiency Index

EEI	Eco-efficiency
1	Very low
2	Low
3	Moderate
4	High
5	Very high

After determining the infrastructure resource eco-efficiencies, a composite index was developed at the district level. The index depicts the overall spatial sustainability performance of a district. Then, after calculating the sustainability performance, the following formula is applied:

$$EEI_i = \frac{\Sigma (EE_{tri} + EE_{wti} + EE_{gii} + EE_{eni} + EE_{swi} + EE_{sbi})}{C_{ui}} \quad (8)$$

where, EEI_i is the eco-efficiency index for the 'i'th district; EE_{tri} , EE_{wti} , EE_{gii} , EE_{eni} , EE_{swi} and EE_{sbi} are the weighted eco-efficiencies for the 'i'th district for public transport, water supply, green infrastructure, energy, solid wastes and social businesses, respectively; and C_{ui} denotes the number of classes of the urban infrastructures.

Additionally, a city-level eco-efficiency index was created and classified to denote district level variations of eco-efficiencies for Jeddah as depicted in Table 7.

It is statistically noteworthy, as evidenced in Table 7, that the highest possible eco-efficiency in a district is '5', while the lowest is '1'.

Results

Sustainable infrastructure ensures the prosperity of a city (UN-HABITAT, 2012b), while huge environmental resource consumption and limited availability of green and open spaces hampers carrying capacities in urban areas (Mitlin and Satterthwaite, 1996). Accordingly, measuring eco-efficiency becomes more important for the sustainable planning of a city's environment. The findings of this study with respect to eco-efficiency of a city are as follows.

Eco-Efficiency of Public Transport

The importance of an efficient public transport system is not debatable and the need to develop such a system is crucial for decreasing the carbon footprint of a city. However, such development is lacking in Jeddah, as Aljoufie *et al.* (2013) have indicated the dominance of the car as a means of transportation and a decline in the emphasis placed on public transportation. The share of daily car trips in Jeddah was 96% in 2012. Conversely, public transportation, walking and cycling jointly represented only 4% of the total trips in the city (AECOM, 2012). At present, adequate public transport is available in only a few districts. Figure 2 shows the district level eco-efficiency of public transportation infrastructure in Jeddah. Of the 70 reporting districts in Jeddah, 25 do not have a single meter of public

transportation routes, while only three districts-Al Sabeel, Al Balad and Al Sahefah have transportation routes of more than 35 kilometres per hectare, which is considered very high with respect to eco-efficiency. The districts that demonstrate high eco-efficiency are located in the city centre. District level eco-efficiency of public transport infrastructure is presented in Table 8.

The factors that likely obstruct the sustainable development of public transportation in Jeddah include poor service offered by the current public transportation system, cheap fuel prices, cheap automobiles and low social acceptability. Non-motorised transport modes, such as walking and cycling, are also not well received in the city because of the adverse climate conditions and the absence of adequate supporting road features (secured pedestrian sidewalks and bicycle tracks).

Eco-efficiency of Water Supply

Water is both an economic and an ecological resource (Huang *et al.*, 2013) and in urban areas, the demand for this resource ensues due to the use of alternative hydro-systems (Grimm *et al.*, 2008). Figure 3 and Table 9 show the district level eco-efficiency of water supply in Jeddah. It is noted that eco-efficiency of water supply is high and very high, cumulatively, in approximately 55.7% of the districts located in the urban peripheries where there are new districts and low population density. On the other hand, the eco-efficiency of three districts concentrated in Jeddah's city centre was very low.

Urbanisation consistently increases water-related environmental vulnerabilities, which include water pollution, urban floods, the depletion in the quantity and quality of groundwater, etc. Jeddah's groundwater is highly polluted because of high concentrations of nitrates resulting in the water being declared unusable. The daily water consumption of Jeddah is 1 million cubic meters, 85% of which is supplied through a piped distribution system while the remaining 15% is supplied via water tankers. The analysis further reveals that per capita water consumption averages 190 liters per day and ranges from 90 liters in the lowest use cases to 275 liters in the highest use cases. Unaccounted for water due to leakage and other factors is 30%, which is equal to 191 thousand cubic meters per day (Al-Sefry and Sen, 2006), a factor that negatively affects the eco-efficiency of the water supply. It is further noteworthy that the entire water supply of the city is cycled through hydrocarbon fuelled desalination plants. This means that the consumption of water in the city is, in essence, the indirect consumption of fossil fuel. Undoubtedly, continuing to supply water in this manner will

increase the negative environmental impacts and impede the greening of the city's economy. Eco-efficiency of Water infrastructure is also crucial because of its multiplier effects which can be either of

positive or negative, for instance if water is consumed in an inefficient way it could lead problems for wastewater infrastructure hampering city's sustainability (Beck and Cummings, 1996) more adversely.

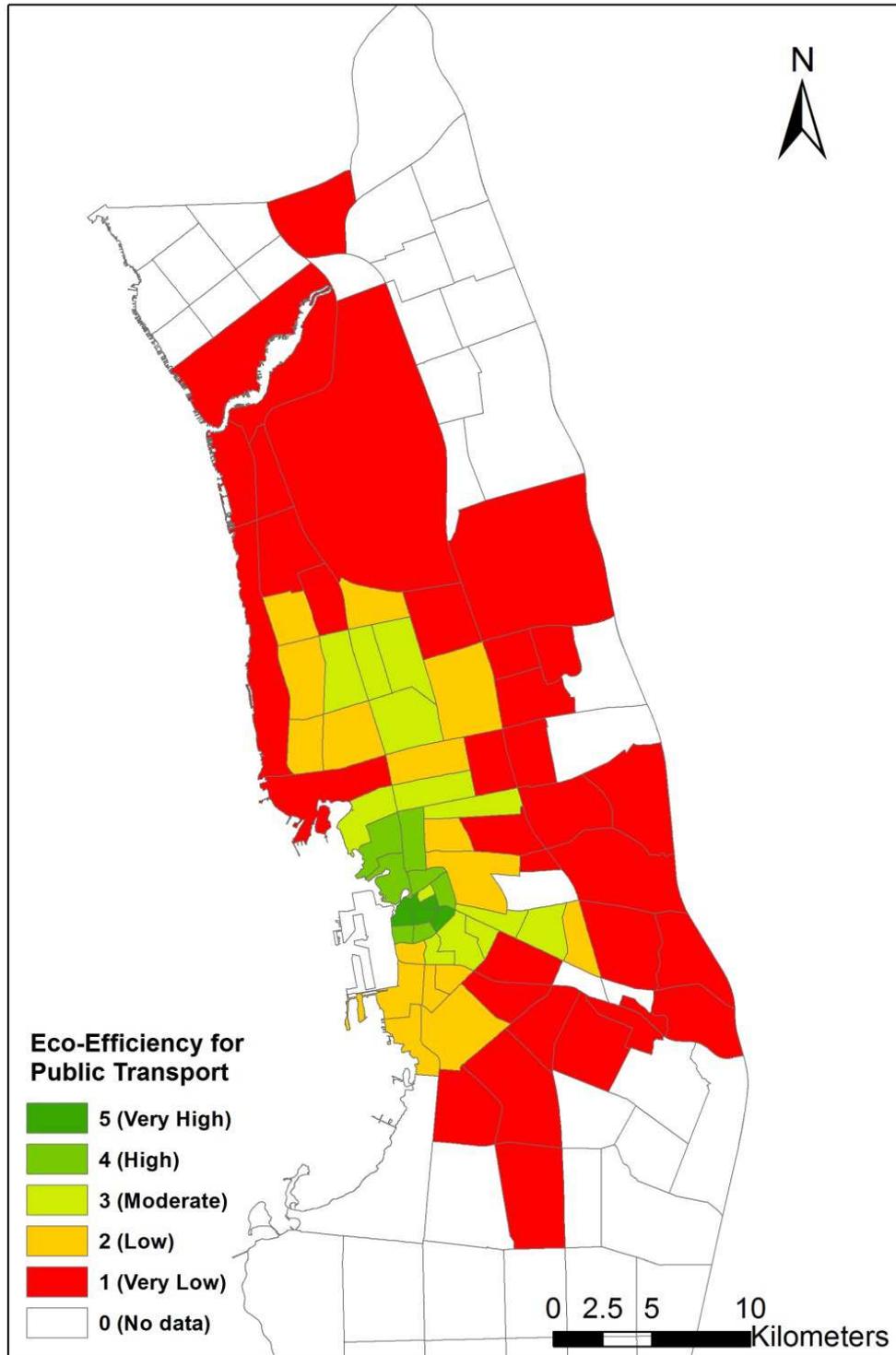


Fig. 2. Eco-efficiency for public transport

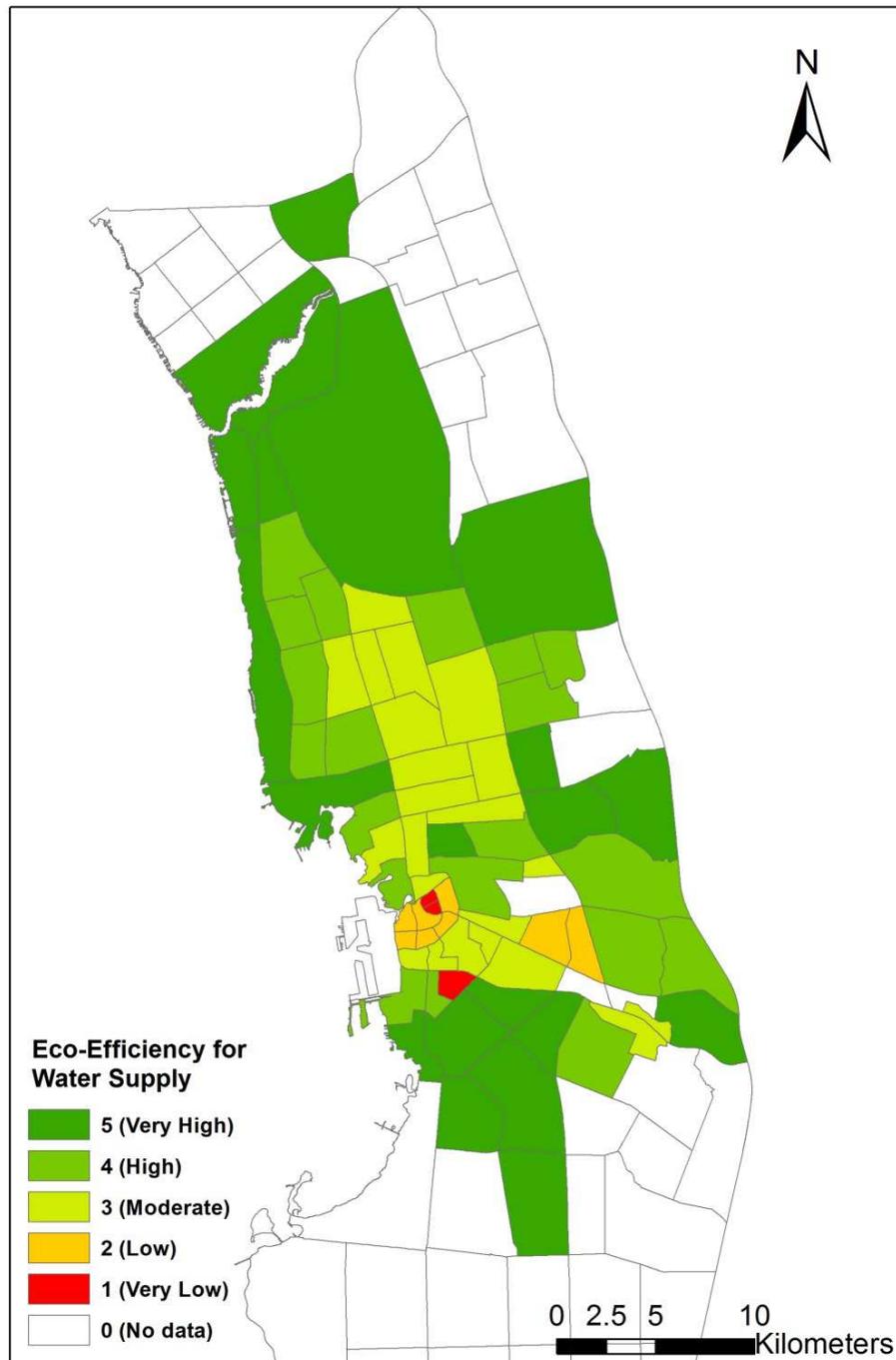


Fig. 3. Eco-efficiency for water supply

Table 8. District level eco-efficiency of public transportation routes in Jeddah

EE _{tr}	No. of districts	%
Very low	34	48.6
Low	14	20.0
Moderate	13	18.6
High	6	8.5
Very high	3	4.3
Total	70	100.0

Table 9. District level eco-efficiency of water supply in Jeddah

EE _{wt}	No. of districts	%
Very low	3	4.3
Low	6	8.6
Moderate	22	31.4
High	19	27.1
Very high	20	28.6
Total	70	100.0

Eco-Efficiency of Green Infrastructure

Kambites and Owen (2006) defined green infrastructure as the connected networks of multifunctional, predominately unbuilt space that supports both ecological and social activities and processes. As such, green infrastructure is multifunctional as it can solve many urban problems almost simultaneously. For example, it can absorb carbon emissions from automobiles, contribute to environmental improvements, enhance urban health, sustain place making and leisure activities, decrease the urban heat island effect, increase social cohesion and interactions, etc. Because of the many potential benefits, urban

professionals' concern regarding green infrastructure has increased in recent years (Krellenberg *et al.*, 2014, Schäffler and Swilling, 2013, Alberti *et al.*, 2003).

Figure 4 and Table 10 depict the district level eco-efficiency of green infrastructure in Jeddah. It is evidenced that very low and low eco-efficiencies are dominant in Jeddah, while high and very high eco-efficiencies comprise collectively a low percentage. Thus, there is a significant need for green infrastructure in most of the districts of Jeddah. Unfortunately, however, green infrastructure in Jeddah faces many challenges, two of which are the arid climate and the lack of water, both of which deter the development of green infrastructure in the city.

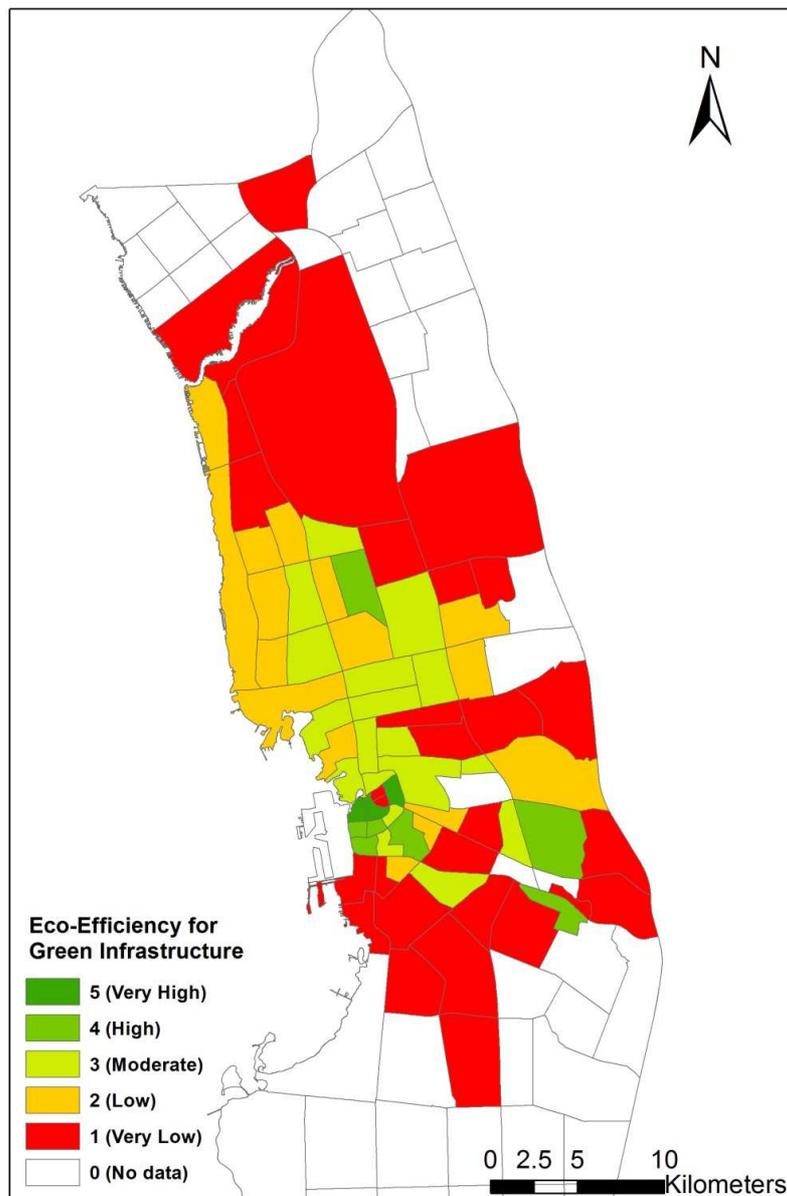


Fig. 4. Eco-efficiency for green infrastructure

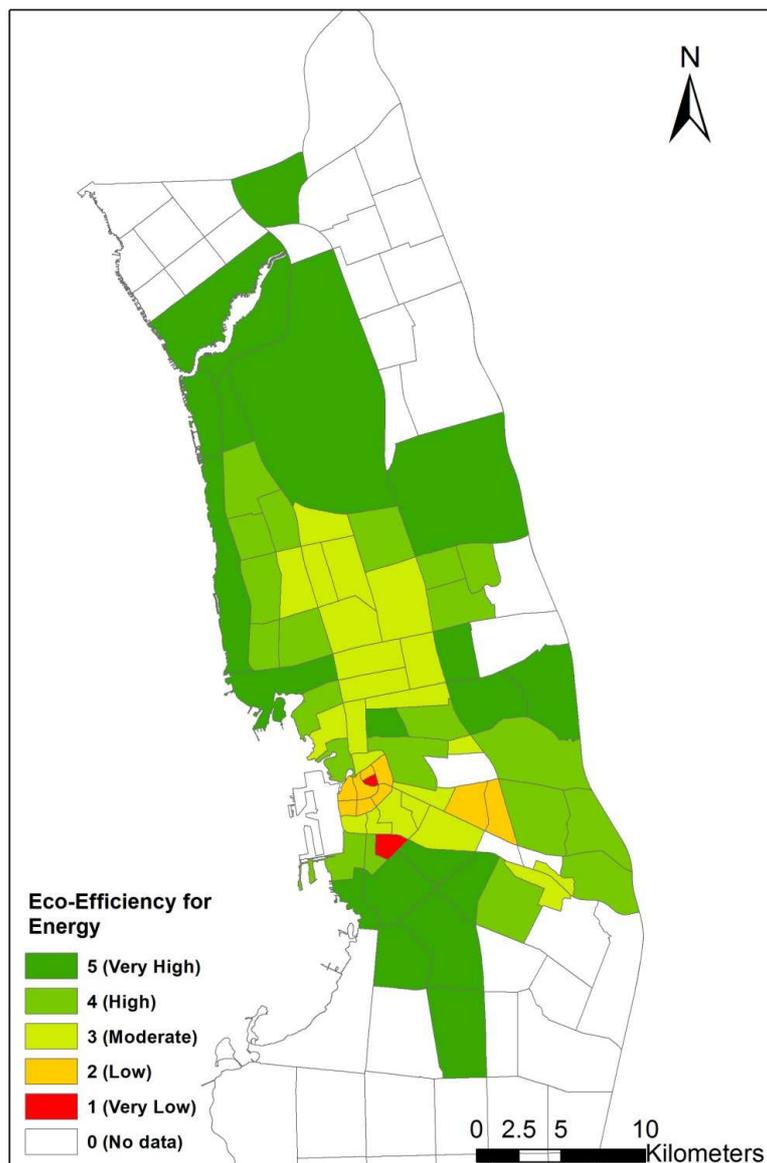


Fig. 5. Eco-efficiency for energy

Table 10. District level eco-efficiency of Green Infrastructure in Jeddah

EE _{gi}	No. of districts	%
Very low	28	40.0
Low	16	22.9
Moderate	18	25.7
High	6	8.6
Very high	2	2.8
Total	70	100.0

Eco-Efficiency of Energy Infrastructure

Similar to water supply, electricity supply in Jeddah depends on hydrocarbon based fuels. As most of the electricity is used for air-conditioning, the production and consumption of electricity in the city generates higher

carbon emissions, which translate into a larger ecological footprint. With respect to Beijing, Zhang *et al.* (2013) proposed the expansion of green spaces as a tool for energy savings and emissions reduction.

Table 11 and Fig. 5 indicate high consumption of electric energy in 20 districts, thus leading to an extremely low eco-efficiency, while eco-efficiency is comparatively very high in 19 districts of the city. It is noted that low, very low and moderate eco-efficiencies are concentrated in the city centre of Jeddah and in the highly dense areas of the city. The rationalisation of energy consumption in conjunction with climate conditions are the main challenges facing energy infrastructure not only in Jeddah but in all Saudi cities.

Eco-Efficiency of Solid Wastes

Massive amounts of municipal solid waste and its improper handling and management negatively impacts human and environmental health as well as sanitation in many of the world's cities (Da Silva *et al.*, 2005; Diaz *et al.*, 2005; Rotich *et al.*, 2006; Rouse, 2006). Urbanisation, rapid population growth and unsustainable resource use patterns in cities has worsened the problems associated with the proper handling of the solid wastes generated by cities

(Suocheng *et al.*, 2001). The average amount of daily per capita generated solid waste in Jeddah is 1.2 kilograms, though its spatial generation varies.

Figure 6 and Table 12 depict the district level eco-efficiency of solid waste generation in Jeddah. The eco-efficiency of solid wastes was found to be very low in two districts of Jeddah where generated waste equalled more than 47 quintals per hectare of land, while it was below 3.8 quintals per hectare of land in 20 districts. Recycling and solid waste management are the main challenges facing solid waste generation in Jeddah.

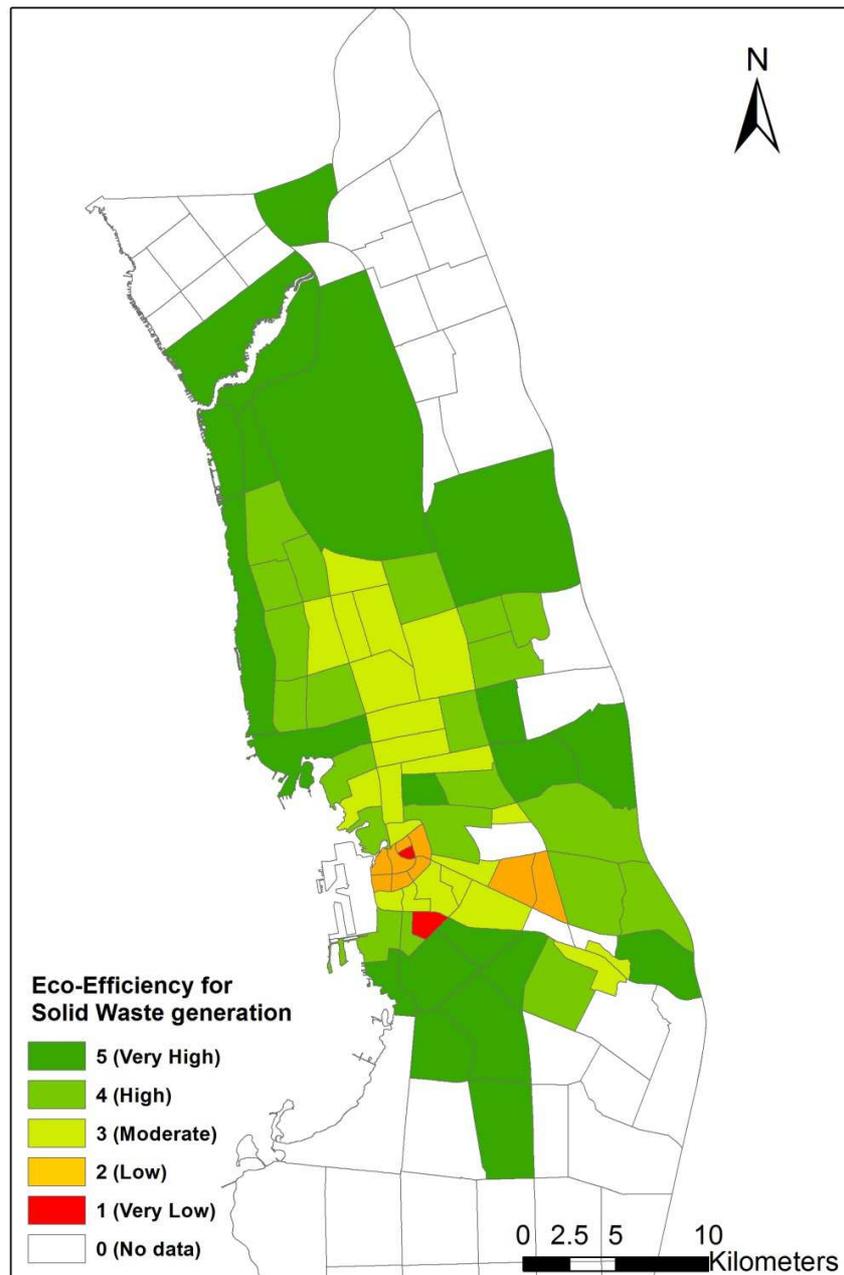


Fig. 6. Eco-efficiency for solid waste generation

Table 11. District level eco-efficiency of Energy Infrastructure in Jeddah

EE _{en}	No. of districts	%
Very low	2	2.9
Low	7	10.0
Moderate	22	31.4
High	20	28.6
Very high	19	27.1
Total	70	100.0

Eco-Efficiency of Social Business

Malls are now inseparable features of any city environment. As such, they offer a social space especially for the families and children within the city's boundaries.

Hence, their efficiency or sufficiency is worth measuring. Richard *et al.* (1989) concluded that malls are the most preferred place for social interaction and shopping and accordingly, these social business areas offer improved quality of life and prosperity to city residents.

Figure 7 and Table 13 depict the district level eco-efficiency of social businesses in Jeddah. The social businesses in approximately 85% of Jeddah's districts demonstrate low eco-efficiency, whereas three districts receive an eco-efficiency rating of very high. There is an unequal distribution as well as a dispersed pattern of moderate to very high eco-efficiency with respect to social businesses in Jeddah, which is escalated by the absence of a strict urban centre hierarchy in Jeddah.

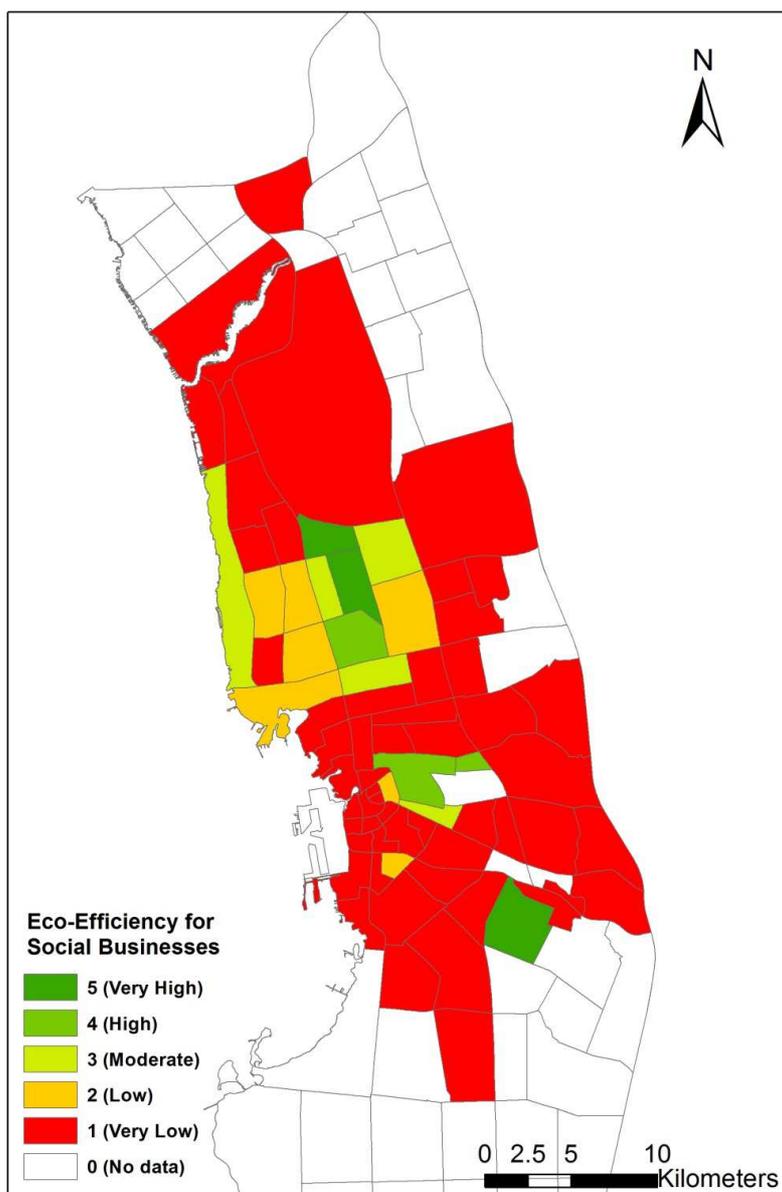


Fig. 7. Eco-efficiency for social businesses

Table 12. District level eco-efficiency of solid waste generation in Jeddah

EE _{sw}	No. of districts	%
Very low	2	2.90
Low	7	10.00
Moderate	21	30.00
High	20	28.55
Very high	20	28.55
Total	70	100.00

Table 13. District level eco-efficiency of social businesses in Jeddah

EE _{sb}	No. of districts	%
Very low	51	72.9
Low	8	11.4
Moderate	5	7.3
High	3	4.2
Very high	3	4.2
Total	70	100.0

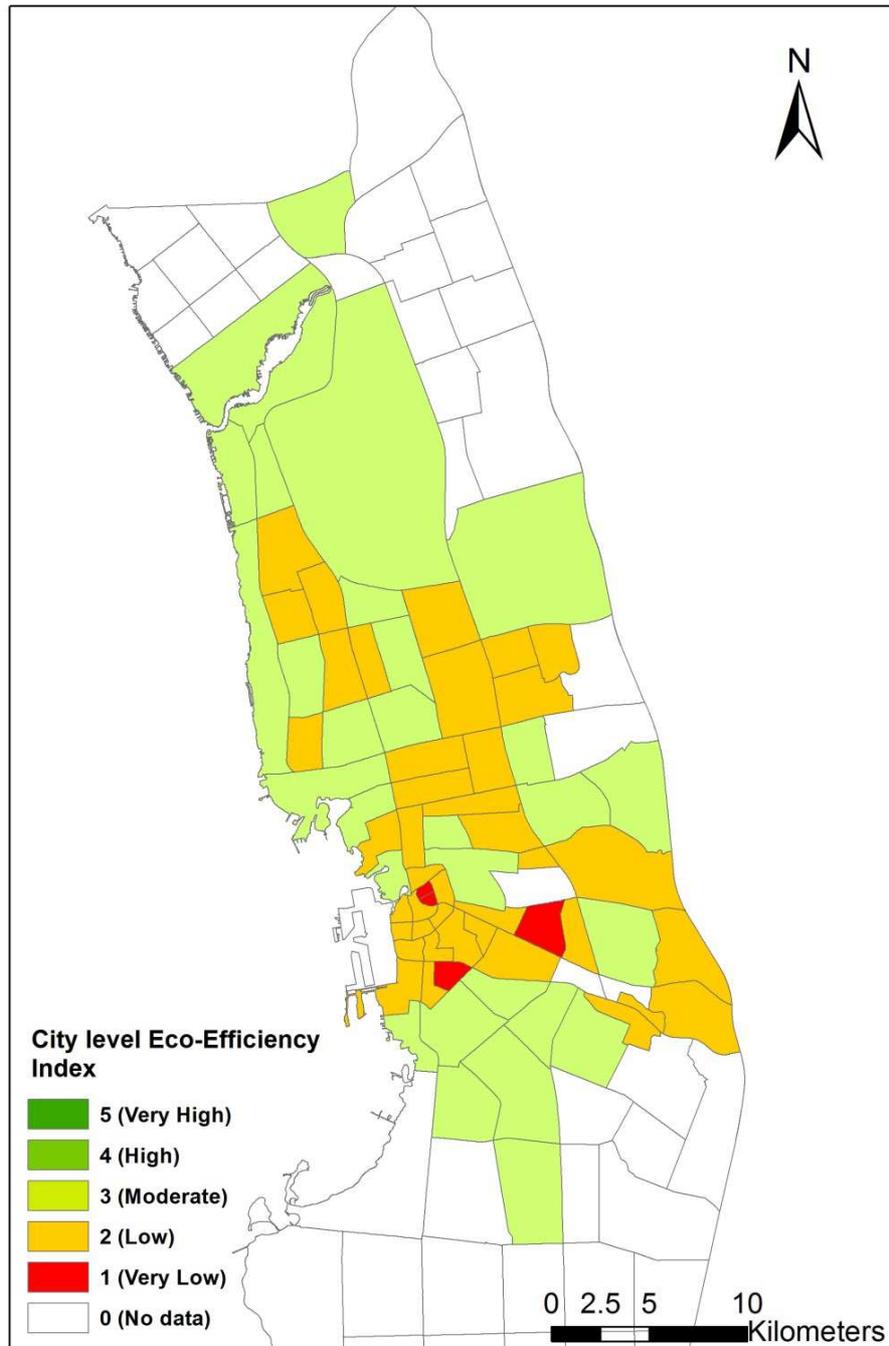


Fig. 8. City level eco-efficiency index

Table 14. District level eco-efficiency of social businesses in Jeddah

EE _{sb}	No. of districts	%
Very low	4	5.41
Low	40	54.05
Moderate	30	40.54
High	0	0.00
Very high	0	0.00
Total	70	100.00

Table 15. Relationship between population and urban infrastructure of Jeddah

Urban Infrastructure	Coefficient of correlation 'r' for population
Public transportation infrastructure	0.76
Social business area	0.05
Energy (Electricity) consumption	0.88
Solid waste management infrastructure	0.91
Green infrastructure	0.40
Water supply	0.85

Intra-City Eco-Efficiency Index

Figure 8 and Table 14 depict the intra-city eco-efficiencies of urban infrastructure resources in the various districts of Jeddah.

Table 14 indicates that the eco-efficiency of 5.41% of the districts of Jeddah was very low, while the eco-efficiency of the urban infrastructure of 54.05% of the districts was found to be low, an issue of serious concern for decision makers and planners. The eco-efficiency level in the remaining 40.54% of the districts in Jeddah was determined to be moderate. No districts in Jeddah were found to be highly or very highly eco-efficient.

Areas deemed to be very low with respect to urban infrastructure eco-efficiency were distributed in a rather dispersed pattern in the city centre and drawn areas. Low-efficiency areas were distributed throughout the city in highly dense locales, while moderate eco-efficient areas were distributed in the urban peripheries that were comprised of new, low-density districts.

Eco-Efficiency and Population Density

Although this paper attempts to measure eco-efficiencies in spatial reference, it must also determine if there exists a relationship between eco-efficiencies and population. To determine the measured 'r' (correlation coefficient), population serves as the independent variable (x) and the infrastructure resources serve as the dependent variables. As shown in Table-15, a strong relationship was found between a district's population and available transportation routes ($r = 0.76$), energy consumption ($r = 0.88$), waste generation ($r = 0.91$) and water consumption (0.85). On the other hand, no association was found between population and social business areas (0.05) and a weak association ($r = 0.4$) was found between population and green infrastructure availability.

A strong positive correlation between population and public transportation routes indicates that eco-efficiency increases as the population increases, while it decreases in terms of dense population in the case of energy use, water consumption and solid waste generation. No correlation between population and social business indicates that malls are not necessarily located in dense, deserted or newly expanded areas; hence, we cannot link a mall's eco-efficiency to population density. The weak association between population and green infrastructure reveals that eco-efficiency in reference to green infrastructure generally increases with the increase in population density, though there are exceptions.

Eco-Efficiency Applicability for Urban Infrastructure in Jeddah

Worldwide debates on sustainability indicate that eco-efficient, socially inclusive urban infrastructure is a prerequisite for building competitive and liveable cities (UNESCAP, 2011). Eco-cities such as Dongtan (China) and Masdar (UAE) are the first two global cities that promise to offer excellent eco-efficiency by ensuring a zero carbon level (Premlatha *et al.*, 2013). Though in a broad scenario, a closed materials cycle is likely difficult to enact in any city, this concept does not lead towards rejection but rather it encourages urban planners and decision makers to minimise resource waste, thereby lowering carbon emissions (Li, 2014) and to maximise their economic and environmental values by innovative urban designs and ideas. In this respect, eco-efficiency is a pathway that leads towards integrated resource management. Thus, this paper adopts a simpler method to compute eco-efficiency and it offers an inspiration - as simpler is better; it proves also to be easier for the residents of Jeddah.

Major barriers in Jeddah from an eco-efficiency perspective include the following:

Not only is there is a limited availability of public transportation routes, but public transportation is not perceived as a popular means of transportation among the city residents as it is not reliable and it is inadequate and uncomfortable. Nonetheless, it has been used widely by migrant workers because of it is a more affordable means of transportation. Thus, to address this problem, land uses in Jeddah should be well integrated with its transportation planning (Aljoufie, 2014). Further contributing to the problem is the fact that Jeddah is not a pedestrian friendly environment, a factor that negatively affects the city's liveability as walkability in a city not only improves its eco-efficiency, but it apparently also improves urban health and liveability (Shamsuddina *et al.*, 2012; Bhattacharyya and Mitra, 2013; Ariffin and Zahari, 2013). Walkability in a city supports a mass rapid public transportation system, which cumulatively contributes to a decrease in the carbon footprint and increase in eco-efficiency. The same is true for bicycle riding. Given the benefits of enhancing a city's walkability, Jeddah's strategic plan should include Transit Oriented Development (TOD) as it may contribute to achieving public transport linked eco-efficiency (Wey and Chiu, 2013). However, this must be supported by an efficient public transportation system in conjunction with restrictions on private vehicle use.

As water and energy in the city of Jeddah are acquired by hydrocarbons, their linear consumption can have a greater negative impact on the environment, which means a notable decrease in eco-efficiency. The arid climate of the city creates a greater demand on energy for air-conditioning, while increased water consumption produces a series of consequences including the generation of greater amounts of wastewater, which must be treated, thus using more energy. Hence, energy intensive (a special reference to fossil fuel) approaches to the provision and extension of the infrastructure is not sustainable. Accordingly, a holistic water and energy management approach is critical for Jeddah, A higher environmental cost is involved in seawater desalination which can be minimised by maximising renewable energy uses leading into improved eco-efficiency performance of both Water and Energy Infrastructure resources (Purnamaa *et al.*, 2005; García-Rodríguez, 2002).

The increased amount of solid waste generated in some districts is a critical factor that hampers environmental sustainability to a large extent as resource recovery, recycling, reducing and reusing is not often practiced in the city. Thus, separation (Mbiba, 2014) of solid waste at the source is vital as it results in 3R (reduce, reuse and recycle) actions.

Though social business areas in the city are adequately provisioned, there are variations at the district

level and many districts still require more social spaces to enhance their eco-efficiency. Thus, an efficient urban centre hierarchy system that promotes social justice is highly recommended.

Finally, eco-efficiency of green infrastructure is significant as Jeddah does not have an adequate amount, partly due to the challenges presented by the arid climate. The expansion of green spaces improves the eco-efficiencies of many infrastructure resources as it consumes organic waste after the recycling of solid waste and it contributes substantially to the cooling of the city, which leads to energy savings and promotes walkability in the city by providing shade and protection from the sun and arid weather while absorbing carbon emission from automobiles. Accordingly, the expansion of green infrastructure in Jeddah, implemented on a priority basis, offers multiple advantages.

Improvements in infrastructure resource efficiency are often considered the first step towards sustainable resource management (Hawken *et al.*, 2010; Von Weizsäcker *et al.*, 2009; Natalia and Kennedy, 2008). Adopting technological innovations, strengthening local institutions (Chan *et al.*, 2013) and enhancing the efficient capacity building are important strategies as Jeddah transitions towards eco-efficiency and low-carbon emission. As eco-efficiency in Jeddah cannot be planned and achieved in isolation, there is an urgent need to prepare an integrated strategic plan for the city to tackle the sustainability challenges that the city's infrastructure is currently facing.

Conclusion

Urban infrastructures in Jeddah are in a transitional phase as they continue to experience rapid growth. At this juncture, measuring the sustainability of these infrastructures with the help of eco-efficiency indicators has greater importance because eco-efficiency is vital for integrated and sustainable infrastructure resource management.

Eco-efficiency indicators at the city level were developed to measure the intra-city spatial eco-efficiency of selected urban infrastructure amenities in the city of Jeddah. Results indicate that low eco-efficiency dominates Jeddah's urban infrastructure and that there is an emerging need for an integrated strategic plan for the city to tackle sustainability challenges with respect to urban infrastructure, it paves the framework for the retrofitting, replacing and expansion of infrastructure whatever and wherever required.

Eco-efficiency paves the way for decoupling economic benefits from environmental improvements, which is a prerequisite to establishing a liveable and competitive city. Eco-efficiency intimates a notion for

urban planners, designers and policymakers to work together for the city's branding as a green place. Furthermore, it calls for more in-depth investigations regarding resource efficiency deficits.

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Author's Contributions

This work is an consequence of the complete cooperation of both authors.

Mohammed Aljoufie: Contributed in the planning of study, data collection, data exploration and presentation of GIS based thematic mapping. He wrote and reviewed the manuscript.

Alok Tiwari: Participated in the preparation and design of the study; data processing and analysis. He paid his efforts in the writing and the revision of the manuscript.

Ethics

The authors declare that this is an original research and do not have any ethical issues or copyrights conflict.

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