Urban Form and Energy Consumption in Wastewater Management: Case Study of Ahmedabad

Srushti Thakur[1*], Mona Iyer[2], Palak Patel[3], Sachin S[3], Rajan Rawal[4]

[1] *Student, Faculty of Planning, CEPT University, Ahmedabad, Gujarat, India,*
Email id: srushti.pg191000@cept.ac.in / t.srushti95@gmail.com
[2] *Professor, Faculty of Planning, CEPT University, Ahmedabad*
[3]*Research Associate, CARBSE, CEPT University, Ahmedabad*
[4]*Senior Advisor, CARBSE, CEPT University, Ahmedabad*

Abstract: Municipal services account for 4% of the total electricity consumption in India. In wastewater management value chain, 40% - 80% of the operational expenditure is on electricity. Conventionally, energy efficiency studies and interventions focus on electro-mechanical aspects of pumping assets. This research assesses and establishes empirical relationships between urban form parameters like built-up area, pumping station command area, ground coverage, topography etc with energy consumption at sewage pumping stations in Ahmedabad city. This shall inform city planners in planning energy efficient wastewater systems while preparing spatial plans and simulating energy consumption for new areas based on urban form. Efficient energy consumption would result in cost saving. Research gives indications towards horizontal versus vertical expansion of cities to move towards sustainable development goals like clean water and sanitation, affordable and clean energy and climate action. This would certainly require inputs on other aspects of city planning like land costs, transportation networks.

Keywords: *Wastewater management; Energy efficiency; Energy consumption; Urban form; Urban planning; Sustainable cities*

INTRODUCTION

Need of the study

India was the third largest energy consumer in entire world after China and USA (U.S.E.I.A., 2020). As per (IEA, 2020, p. 20), in the fiscal year 2017-18 total primary energy supply (TPES) of India was 882 Mtoe with maximum energy being generated by coal followed by oil. The total final consumption (TFC) was 591.2 Mtoe which has increased by 50% from 2007 till 2017 (IEA, 2020). Electricity constituted around 26% of the total final consumption for the year 2017 to 2019 (NITI Ayog, 2020). Electricity is an important input while delivering municipal services. Municipal services like water pumping, sewage treatment and street lighting accounted for consumption of around 4% of the total electricity consumption in India where only 10% of the total sewage generated gets treated (AEEE, 2019; Never, 2016). Thus, this research focuses on assessing the relationship between urban form parameters and energy consumption at sewage pumping stations in Ahmedabad city so as to give inputs to the existing planning tools in developing energy efficient and integrated spatial plans while simulating energy consumption for development of the new areas in the city.

Analysis of literature review

The literature review is intended to analytically identify the broad categories of the parameters impacting the energy consumption in wastewater management, understanding the relationship between the parameters and energy consumption while managing the wastewater. As studied by (Jia et al., 2019; USEPA, 2000)operation and maintenance cost of wastewater pump is directly proportional to number of pumps, lifting height of the pump and flow rate of wastewater through the pump. The power cost accounts for 80% - 90% of the total operation and maintenance cost of pumps. Thus, it can be inferred that electricity consumption is directly proportional to volume of wastewater pumped at sewage pumping station, number of pumps and the height to which it is lifted. As per (Rao, 2011) wastewater volume and characteristics depend on building types, infrastructure, land use, population density. Thus, it is safe to state that the city level electricity consumption for pumping and treating the wastewater is directly dependent on urban form parameters which influences the volume and characteristics of wastewater. Landuse and landcover affects the water consumption and thus affects the wastewater generation (ESMAP, 2014). The research conducted by (Jia et al., 2019), tested 200 random configurations of wastewater / rainwater management systems and urban form attributes in a virtual city to establish the relation while decoupling the results from location-specific characteristics. The main observation of this study was that as compared to sprawl pattern, compact form has positive impact in reduction of energy consumption for water and wastewater management. Guidelines given by (CPHEEO, 2012) suggests that the wastewater generation rate for designing of wastewater drain shall be different for each of the land use. Thus, it can be stated that wastewater generation depends upon water consumption, which is actually decided by the urban form of the city. As discussed in (Asarpota & Nadin, 2020), the density of land and property use, the mix of function, the relationship between urban form and transport infrastructure, the availability of green space, and passive energy-efficient design are the most impactful factors for developing energy efficient urban form in cities.

As per (CPHEEO, 2013), sewage pumping stations are provided for pumping sewage from deeper sewer to shallower sewer, conveying sewage to treatment plant or outfall, collecting sewage from remote locations. As per (ADB, 2010), flat terrain puts a constraint on conveyance of sewage through gravity flow. Sewerage zones i.e., command area of sewage pumping station is marked based on the topography and other features like natural and administrative boundaries, existing network. As energy consumed by a pump varies with the lifting height i.e., contour difference between sewage collection and disposal points. Thus, it can be inferred that topography and command area play a vital role in deciding energy consumption.

Most of the studies available focussed on electromechanical assets and thus there are very few studies available that establish the relationship between urban form parameters and city level energy consumption in wastewater management systems even though the urban form parameters play a vital role in deciding volume of wastewater generation, pollutant load of wastewater which eventually affects the energy consumption. Thus, this research is aimed at providing the direct relationship between energy consumption at sewage pumping stations and some of the urban form parameters like command area, ground coverage, built-up area. This research also focuses on impact of residential building typology, topography, seasonal variation and city's growth pattern on energy consumption at sewage pumping station.

STUDY AREA

Ahmedabad is a district headquarter located in central part of Gujarat state. Ahmedabad Municipal Corporation (AMC) has total area of 466 Sq.km comprising 6 zones divided into 64 administrative wards (AMC, 2016) as shown in Figure 1. As per development plan 2021 prepared by (AUDA, 2010), maximum area lies under residential zone, followed by in industrial zone, institutional zone, commercial zone.

As per (AMC, 2020), an existing sewerage system in AMC covers 95% of the total current population. Sewage is managed by 2,588 km long sewerage network with 65 nos. of sewage pumping stations and 12 nos. of sewage treatment plants having total capacity of 990 MLD. Out of the 65 sewage pumping stations 28 sewage pumping stations and 9 terminal sewage pumping stations are monitored through centralised SCADA. Out of the 28 sewage pumping stations, 20 sewage pumping stations are analysed for this study based on data availability. As shown in Figure 1, only 2 sewage pumping stations lie in western part of AMC and 18 lie in eastern part of AMC.

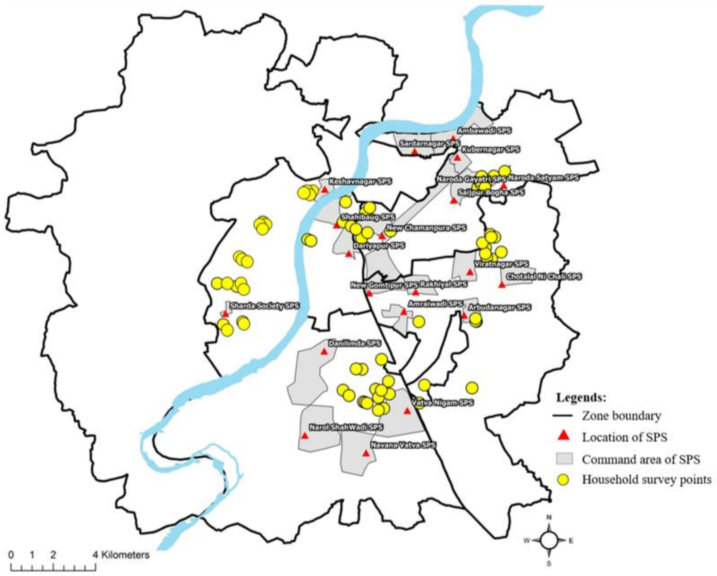


Figure 1 Google earth imagery of AMC with location of sewage pumping stations, command area and household survey points

Source: Prepared by authors, 2021

MATERIALS AND METHODOLOGY

Various parameters influencing energy consumption in wastewater management were identified through literature review. Based on availability of data and time, impact of 8 parameters namely command area of sewage pumping station, ground coverage, built-up area, residential building typology, pattern of city growth, seasonal variation and topography is studied. Table 1 shows the various categories of data required for the analysis.

Sewerage network map is received from drainage department of AMC, command area of sewage pumping stations is marked based on the direction of wastewater flow given in sewerage network map. The electricity consumption data is received from centralised SCADA whereas the shapefiles of urban form parameters are received from CEPT foundation studio, 2019. Wastewater generation rate is arrived at based on rate of water consumption. To assess the typology-wise water consumption rate, household survey is conducted. Average rate of water consumption for a typology was calculated based on the details like household size, capacity of storage, frequency of filling the storage units, depth of filling the storage units collected from household survey. Household survey was conducted in 80 households in AMC area covering 20 samples each for detached, semi-detached, row-houses and apartment typology as shown in Figure 1. Out of the 80 samples, 20 samples are collected from western part of AMC and remaining 60 samples are collected from western part of AMC as 10% of the sewage pumping stations assessed lie in eastern AMC and 90% of the sewage pumping stations assessed lie in western AMC.

Table 1 Data collection matrix

Sr. No.	Data Category	Details collected
1	Sewerage network map	a) Location of sewage pumping station, terminal sewage pumping station and sewage treatment plant

		b) Direction of the flow of sewage in the network and diameter of sewerage pipeline
2	Electricity consumption at sewage pumping stations	a) Daily electricity consumption at sewage pumping stations for 3 seasons of year 2020 i.e., monsoon (July and August), winter (December and January) and summer (April)
3	Details of urban form parameters	a) Shapefile of AMC boundary, zone boundaries, ward boundaries, district boundaries
		b) Shapefile of building footprint, road centreline, plot lines with land use, building use and building height marked
4	Wastewater generation rate	a) HH size per typology
		b) Capacity of storage units, frequency of filling the storage units, depth of filling for storage units

Source: Prepared by authors, 2021

RESULTS AND DISCUSSION

It was observed that electricity consumption at sewage pumping station is primarily a function of the volume of wastewater received at sewage pumping station and topography of the area. Urban form parameters play a vital role in deciding the wastewater volume. Thus, this research studies an influence of urban form parameters like command area of sewage pumping station, ground coverage, built-up area, residential building typology and pattern of urban growth on electricity consumption at sewage pumping station. In addition to urban form parameters, it also studies the impact of seasonal variation, water consumption pattern and topography on the electricity consumption at sewage pumping station.

Relationship between volume of wastewater and electricity consumption at sewage pumping station

To assess the relation between electricity consumption and wastewater volume and to arrive at a generalized equation for Ahmedabad city, average monthly volume of wastewater pumped at 20 sewage pumping station is plotted against average monthly electricity consumption at 20 pumping station as shown in Figure 2Figure 1 (a). The graph shown in Figure 2 (a) demonstrate strong positive correlation as the coefficient correlation is 0.89 (> 0.8).

This suggests that, for a fixed lifting height at a sewage pumping station if the wastewater volume received increases, then the electricity consumption would also increase. 65% of the sewage pumping stations assessed for this study pumps less than 320 million litres of wastewater with monthly electricity consumption as less than 25,000 kWh. Danilimda sewage pumping station shows the anomalous behaviour as the electricity consumption at Danilimda sewage pumping station is 2.5 times more than the generalized trend observed as marked in Figure 2 (a).

Relation between command area of sewage pumping station and electricity consumption at sewage pumping station

Command area of the sewage pumping stations assessed lie in the range of 0.2 sq.km. to 4.0 sq.km. out of which 55 % of the sewage pumping stations have command area less than 1.5 sq.km. To assess the relationship between command area of sewage pumping stations and average monthly electricity consumption at sewage pumping stations the graph shown in Figure 2(b) is plotted. This graph demonstrates moderately positive correlation between command area and electricity consumption at sewage pumping station with correlation co-efficient as 0.65 (lies between 0.3 to 0.7). This indicates that with an increase in the command area of the pumping station, the electricity consumption would increase moderately.

The pumping stations with high command area would possibly consume more electricity while pumping wastewater. This explains that, if the location of sewage pumping stations is kept constant and the command area is increased then the existing pumps would require more electricity to pump the increased volume of wastewater from more distance. This parameter also gives indication towards dependency of electricity consumption on wastewater network length and spread.

Relation between ground coverage in command area of sewage pumping station and electricity consumption at sewage pumping station

Ground coverage is the ratio of sum of the building footprint area (including projections of buildings) of all the buildings in respective command areas to the total command area. It is represented in percentage for this study. Ground coverage gives an indication of the ground area that is covered by building footprint and it denotes the density of building footprints in an area. The ground coverage of the command areas assessed in this study varies from 18% to 51%. 55% of the command areas of the sewage pumping station studied have ground coverage in the range of 25% to 42% which results in monthly electricity consumption of less than 25,000 kWh. The graph shown in Figure 2 (c) demonstrates weak positive correlation between ground coverage with electricity consumption at sewage pumping stations. This indicates that electricity consumption isn't much influenced by the ground coverage as ground coverage is a measure of only building footprint area.

Relation between built-up area in command area of sewage pumping station and electricity consumption at sewage pumping station

Built-up area is calculated as product of building footprint area of the building and number of floors in a building for all the buildings in the command area. Command areas of the 55% of sewage pumping stations have built-up area of less than 1,00,00,000 sq.ft. and monthly electricity consumption below 30,000 kWh per month.

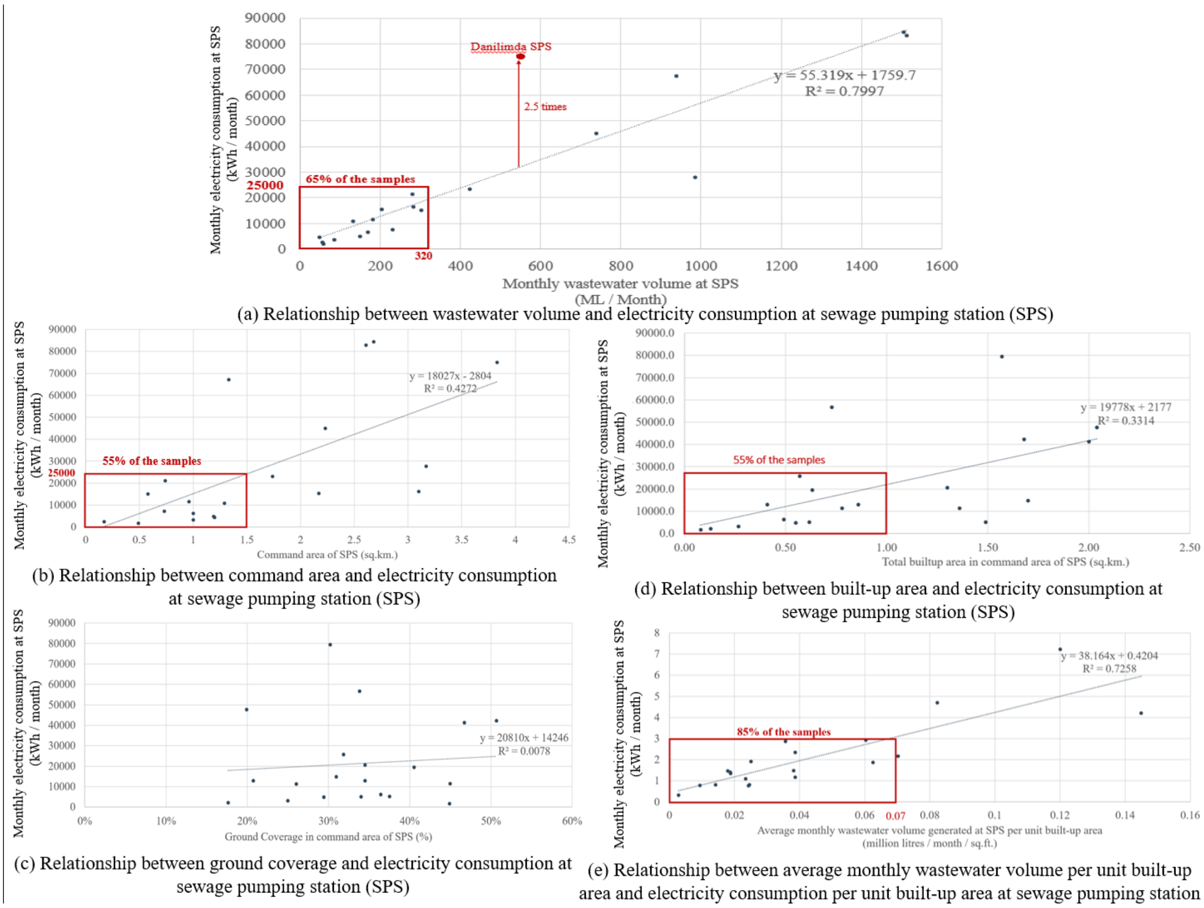
The graph shown in Figure 2 (d) demonstrates a moderately positive correlation between total built-up area in command area of sewage pumping station and monthly electricity consumption at sewage pumping station with correlation coefficient of 0.576. This means that with increase in total built-up area in a command area the monthly electricity consumption at sewage pumping station also increases. Built-up area demonstrates stronger correlation with monthly electricity consumption at sewage pumping station than ground coverage as built-up area is an indicator of number of floors and floor space constructed per floor.

The graph shown in Figure 2 (e) demonstrate a strong positive correlation between rate of wastewater volume generation per unit built-up area with rate of electricity consumption at sewage pumping station per unit built-up area in a command area with 85% of the samples having rate of wastewater volume generation as less than 0.07 million litres per month per sq.ft. of built-up area corresponding to monthly electricity consumption as less than 3 kW per sq.ft. of built-up area.

Impact of water consumption pattern on the rate of wastewater generation in a residential building typology

The average rate of per capita water consumption for a building typology was arrived after knowing the water storage capacity, frequency of filling the water storage and the depth of filling, household size for residential building typologies namely detached, semi-detached, row houses and apartments through household survey conducted for the study in year 2021.

It was observed that rate of per capita water consumption is more than 135 LPCD for detached and apartment typology whereas for semi-detached and rowhouse typology it is around 120 LPCD. As per the guidelines given by (CPHEEO, 2013), for planning and deigning sewers the wastewater volume is considered as 90% of the total water consumption in a city. Thus, the per capita wastewater generation rate is comparatively higher for detached and apartment as compared to semi-detached and rowhouse building typology. This parameter signifies the impact of standard of living on wastewater generation rate.



(a) Relationship between wastewater volume and electricity consumption at sewage pumping station (SPS)

(b) Relationship between command area and electricity consumption at sewage pumping station (SPS)

(d) Relationship between built-up area and electricity consumption at sewage pumping station (SPS)

(c) Relationship between ground coverage and electricity consumption at sewage pumping station (SPS)

(e) Relationship between average monthly wastewater volume per unit built-up area and electricity consumption per unit built-up area at sewage pumping station

Figure 2 Relationship urban form parameters impacting volume of wastewater and electricity consumption at sewage pumping stations

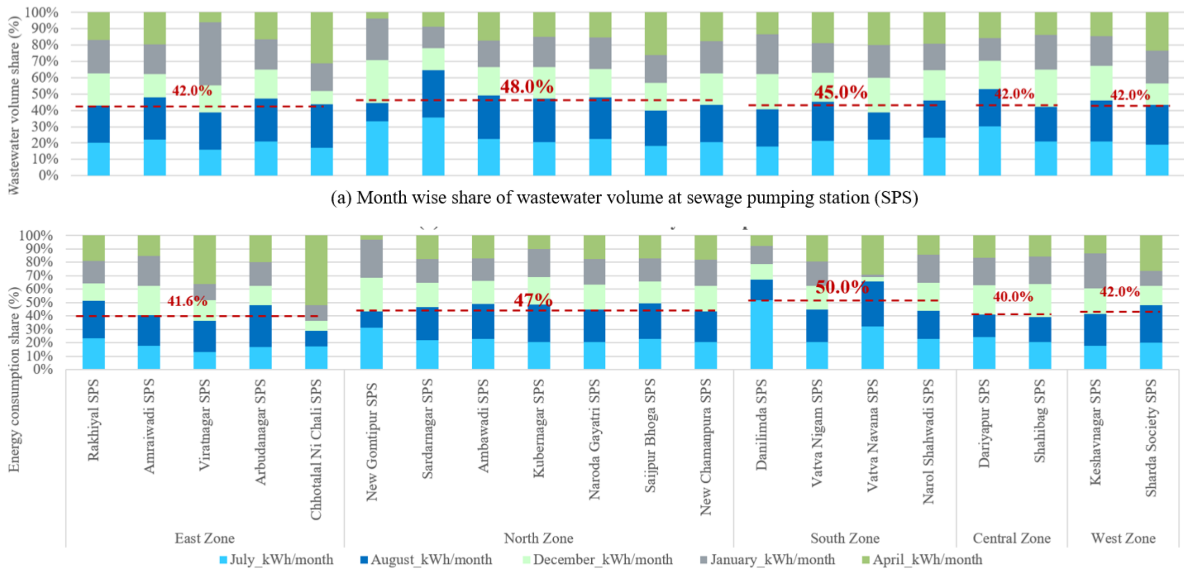
Source: Prepared by authors, 2021

Impact of seasonal variation on electricity consumption at sewage pumping station

Apart from urban form parameters discussed above seasonal changes play a vital role in deciding volume and characteristics of wastewater and thus also impact electricity consumption. Seasonal variation in wastewater volume could be due to variation in water supply pattern, variation in water consumption pattern or due to mixing of stormwater with wastewater. This analysis is based on the wastewater volume and electricity consumption data for three seasons namely, summer (April), winter (December and January) and monsoon (July and August).

Assuming that the wastewater volume received at sewage pumping station remains constant in spite the season. Then the ideal share of wastewater volume received at sewage pumping station in a month could be 20% of the total wastewater volume received in the five months. But, as shown in Figure 3 (a), the combined share of wastewater volume received at sewage pumping stations in north and south zones is more than 40% i.e., 48% and 45% respectively. The respective share of electricity consumption in north and south zones in monsoon months is 47% and 50% as per the graph shown in Figure 2Figure 3 (b).

As observed from the map shown in Figure 3 (c), in eastern part of AMC, north zone and south zone faces waterlogging more intensively than east zone. In AMC, during monsoon season, in waterlogged areas stormwater is bypassed into the wastewater network through the manholes present on roads. Thus, it can be inferred that addition of stormwater into existing wastewater network in the monsoon season increases the wastewater quantity by 3% to 6% at some of the sewage pumping stations which results in increase in electricity consumption by 6% to 8%.



(a) Month wise share of wastewater volume at sewage pumping station (SPS)

(b) Month wise share of electricity consumption sewage pumping station (SPS)

Figure 3 Impact of seasonal variation on electricity consumption at sewage pumping station
Source: Prepared by authors in March 2021 based on electricity consumption at sewage pumping station received from centralized wastewater SCADA

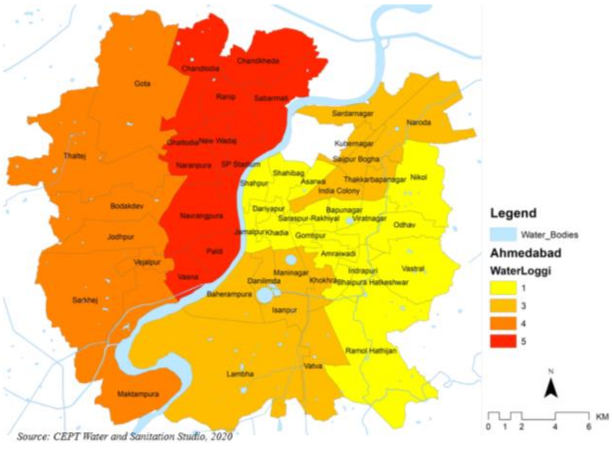


Figure 4 Water logging intensity map for AMC
Source: Water and Sanitation Studio, CEPT University, 2020

Impact of topography of the area on electricity consumption at sewage pumping station

95% of the command areas of sewage pumping stations have contour difference in the range of 2m to 6m. Command area of Danilimda sewage pumping stations has comparatively the highest contour difference (upto 10 m) and electricity consumption as shown in Figure 5. Command area of Danilimda sewage pumping stations is the highest i.e., 3.83 sq.km. among the sewage pumping stations assessed where 55% of the sewage pumping stations have command area less than 1.5 sq.km. In addition to this, electricity consumption at Danilimda sewage pumping stations was observed to anomalously high as discussed above in Figure 2 (a). Thus, it can be inferred that electricity consumption at Danilimda sewage pumping stations is anomalously high as it pumps wastewater from command area which has the maximum contour difference and larger span area.

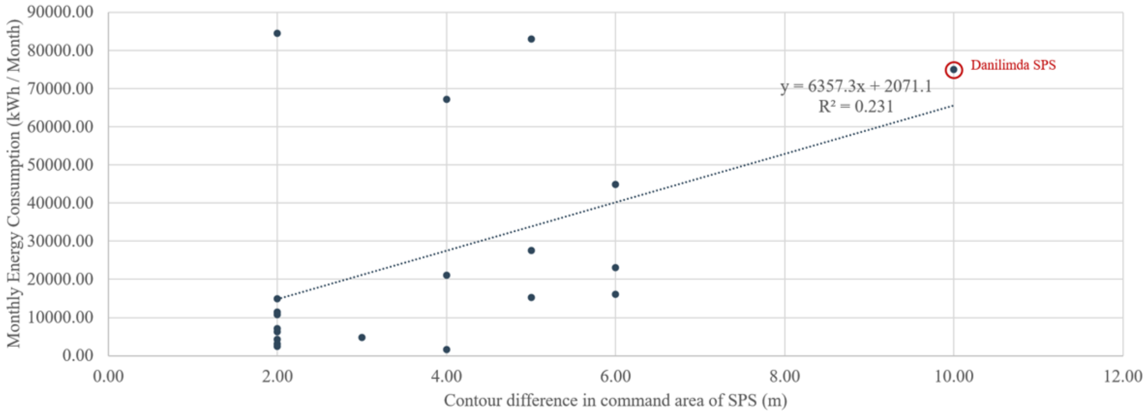


Figure 5 Impact of topography on electricity consumption at sewage pumping station
Source: Prepared by authors, 2021

CONCLUSIONS

Literature review certainly gave the indications towards relation between urban form and electricity consumption in wastewater management value chain but this research has derived the empirical equations to precisely predict the electricity consumption at sewage pumping station. From the analysis presented above it can be concluded that electricity consumption at sewage pumping station doesn't solely depend upon one parameter whereas it is due to the combined effect of various parameters. It may happen that the impact of one the parameter might be more significant than the other parameters depending on the other characteristics of the cities. Ahmedabad being the flat terrain the impact of topography was proved to be less severe as compared to the impact of volume of wastewater on the electricity consumption at sewage pumping stations. The volume of wastewater was found to be impacted by various urban form parameters but this research is focussed on developing empirical relation between electricity consumption at sewage pumping station and urban form parameters namely command area, ground coverage, total built-up area and residential building typology. The influence of command area and built-up area was more than that of ground coverage for Ahmedabad as command area defines the spatial extent of wastewater pumping and built-up area defines the total usable area by for residing in city whereas ground coverage is measure of ground area consumed for a structure. The finding from the research can be used by city planners while making integrated and electricity efficient development plan. It would also help urban local bodies in addressing the sustainable development goals.

Application of the findings of the research on city's growth pattern

As per scenario 1 represented in Figure 5 (a), when the command area is doubled the energy consumption also doubles and scenario 2 represented in Figure 5 (b), when the built-up area is doubled, energy consumption increases by 1.3 times. This is due to the higher impact of the command area on energy consumption at sewage pumping stations than that of the built-up area on energy consumption at sewage pumping stations. The findings of the research are explained in Figure 5 (c) and illustrated in Figure 5 (d) to simplify the complexity due to an interplay of various urban form parameters impacting the energy consumption at sewage pumping stations.

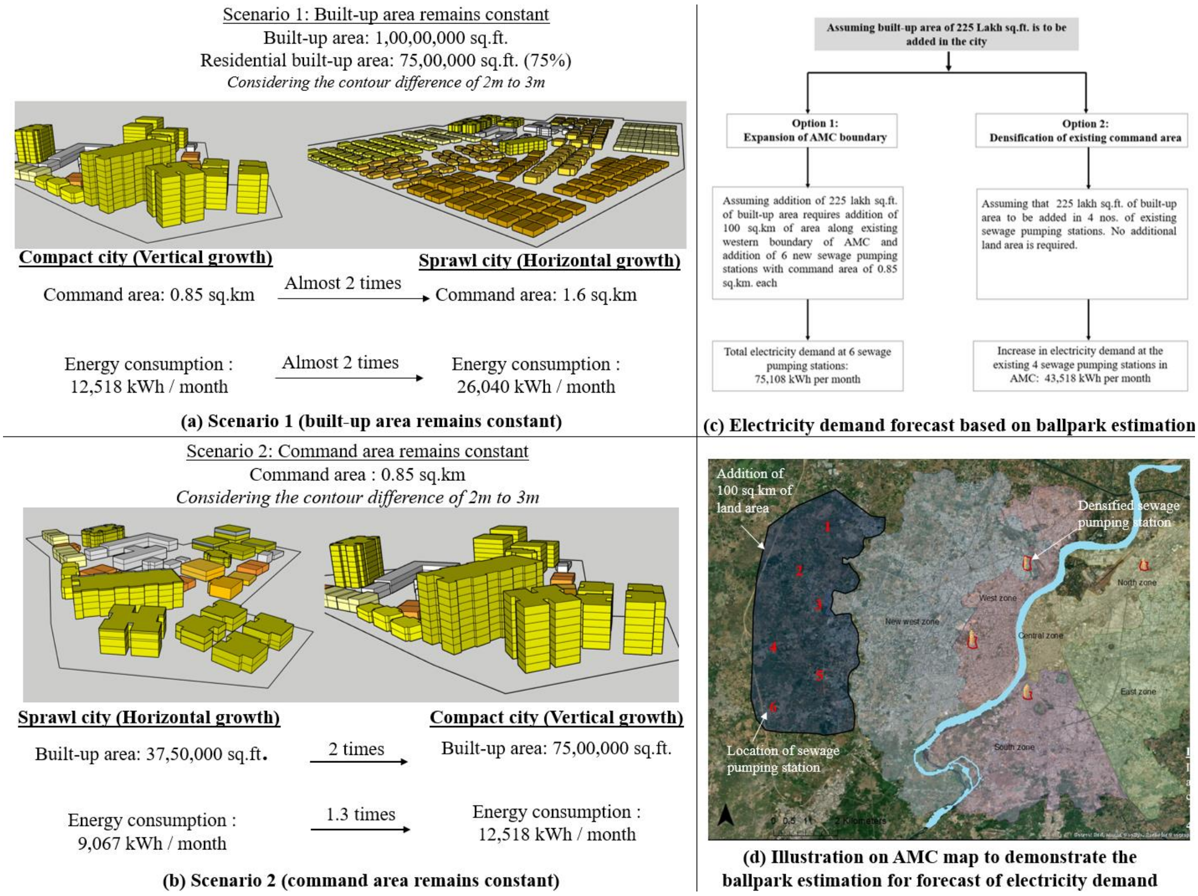


Figure 6 Comparison of horizontal vs vertical growth

Source: Prepared by author based on the findings of the research

Figure 6 (c) explains the options for city growth considering 225 lakh sq.ft. of built-up area is to be accommodated in the city. In option 1, to accommodate additional built-up area, land of 100 sq.km. is required. Whereas in case of option 2, the additional built-up area is accommodated by densifying existing command areas. Electricity consumption in case of option 2 is 42% of the electricity consumption in case of option 1. This confirms that in such case electricity demand would lower by 42% and the subsequent electricity cost saving would be Rs. 34 lakh per annum (considering cost of electricity as Rs. 9 per unit), if the existing command areas are densified with instead of expanding the city horizontally. Thus, it can be stated that compact cities are more electricity efficient than sprawl city in case of wastewater management at sewage pumping stations.

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