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Trends and dynamics of material and energy flows in an urban context: a case study of a city with an emerging economy

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Abstract

Background: Currently, most of the world's population lives in cities, and the rapid urbanization of the population is driving increases in the demand for products, goods and services. To effectively design policies for urban sustainability, it is important to understand the trends of flows in energy and materials as they enter and leave a city. This knowledge is essential for determining the key elements characterizing future urban growth and addressing future supply challenges.

Methods: This paper presents an analysis of the energy and material flows in the city of Bogotá over the time span from 2001 to 2017. Urban flows are also characterized in terms of their temporal evolution with respect to population growth to compare and identify the changes in the main input flows, wealth production, emissions and waste in the city.

Results: The results of the analysis are then compared with those for other selected large urban agglomerations in Latin America and worldwide to highlight similarities and make inferences. The results show that in Bogotá, there was a decrease in some of the material flows, such as the consumption of water and the generation of discharge, in recent years, while there was an increase in the consumption of energy and cement and in the production of CO_2 emissions and construction materials. Solid waste production remained relatively stable. With respect to the other large cities considered, we observe that the 10-year growth rates of the flows with respect to population growth are lower in Bogotá, particularly when compared with the other urban agglomerations in Latin America.

Conclusions: The findings of this study are important for advancing characterizations of the trends of material and energy flows in cities, and they contribute to the establishment of a benchmark that allows for the definition and evaluation of the different impacts of public policy while promoting the sustainability of Bogotá in the coming decades.

Keywords: Material flows, Environmental performance, Sustainability policy, Bogotá

Background

Many people live in cities, and statistics show that in 30 years, more than 60% of people will live in cities [1]; therefore, it is essential to achieve sustainability and to provide policy and decision makers with instruments for reducing the effects and impacts of current and future urbanization on the environment. In this context, it is important to understand and assess how energy and material flows feeding a city operate and are transformed to formulate and implement instruments that guarantee quality of life and a healthy environment.

According to the United Nations Environment Program (UNEP) [2], globally, cities occupy 3% of the Earth's surface, produce 80% of the gross domestic product, consume 75% of natural resources, produce 50% of solid waste and generate between 60 and 80%

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of greenhouse emissions. These figures have reached a critical point, and cities have become a pivotal focus for reducing GHG emissions and reducing the increase in the global temperature. However, as stated by COP 21 and the subsequent Paris Agreement, cities have the potential to improve their efficiency; for example, it is estimated that although global water consumption can be reduced by 30% and energy by 30–50%, these reductions would require an infrastructure investment of approximately 41 trillion dollars over the next 20 years [3]. Moreover, major global megacities are responsible for, on average, 9% of global electricity consumption and 13% of solid waste production, and they account for 7% of the global population and generate an important share of the gross domestic product [4]. Therefore, it is important to analyse different flows and the necessary production of goods, services and pollution to meet the requirements of the population and decrease environmental problems and impacts.

Policies for the sustainability and management of urban areas require an understanding of the demands of natural resource flows and the generated environmental impacts. Material flow analysis allows us to demonstrate how to generate a relationship between inputs and outputs that can promote eco-efficiency, which is essential for policy makers and decision makers aiming to formulate an urban policy that guarantees sustainability, productivity improvements and competitiveness [5].

In recent years, the analysis of urban flows has emerged as a reliable approach for analysing and designing urban sustainability policies [6]. Indeed, several studies have shown that at the urban level, identifying, analysing and evaluating the flows of materials involving the consumption of resources and energy are fundamental for determining the environmental effects and impacts of consumption and its transformations, the potential for urban resilience and the actions and/or options that can support urban sustainability over time in a differentiated manner [7–9].

Urban flows can be analysed based on two approaches to promote sustainable development challenges [10], as explained below. The first approach, research and decision support, involves the determination of urban flows and evaluates the following factors:

i. Urban biogeochemical processes, such as those studied by Pataki et al. [11] and Lin et al. [12], provide an important solution and opportunities to integrate biogeochemical science in the design and evaluation of urban infrastructure to generate synergies between environmental quality and food security through innovation and new technologies that reduce waste and pollution;
ii. The effects of the material and energy demands in cities suggest that the present patterns for energy and resources may lead to a reduction in and the scarcity of natural resources, thus degrading ecosystems and affecting the quality of life in urban areas; thus, some objectives are to promote energy and resource efficiency, to improve urban systems and to increase and sustain economic growth [13, 14];
iii. Biogeochemical and social operation interactions can be used to analyse how natural cycles and society can disturb the urban ecosystem and foster understanding of the urban ecosystem and the circular economy, among other factors; this approach is important for formulating governance and policies that promote sustainable development in cities. Various researchers, such as Prendeville et al. [15], who analysed these issues in six cities, and Czamanski and Broitman [16], who noted the importance of incorporating new innovation and structures that generate interurban migration patterns to achieve sustainable development, have analysed these elements.

The second approach involves solving sustainable development challenges through urban flows and aims to achieve the following goals:

i. Decoupling (to decrease the dependence of growth on the use of natural resources), for which studies have demonstrated that a decoupling effect seems to have occurred in G20 countries with strategies for emission control, energy consumption, and economic decoupling supported by diversification, a sustainable energy consumption mix and stable economic growth maintenance; the circular economy seeks to decouple global economic development from finite resource consumption [17, 18];
ii. Dematerialisation (consumption of fewer materials), which implies that the decrease in the intensity of material utilization depends on the increase in material circulation, the overall social interest in cleaner production and increased effectiveness in the use of existing inputs and raw materials [19, 20];
iii. Decarbonisation (consumption of less carbon) implies that urban transitions, through the reordering of the urban infrastructure and use of new technologies, can achieve high decarbonisation in the electricity sector; this concept involves new energy business models at the distribution level and new power distribution architectures [21, 22]. Another study analysed the carbon net-

works of eight global cities by tracking the carbon exchanges between various natural and economic components, and the results highlighted a synergy between urban decarbonization and carbon-containing resource system optimization, whereby carbon flows in cities can be effectively managed to achieve climate mitigation goals [23];

iv. The closing of material loops, for which Tomić and Schneider [24] and Patricio et al. [25] demonstrated that energy recovery from waste might suggest "closing the loop" in the total waste recovery process, and strategies such as industrial symbiosis, resource recovery or reuse can be good approaches to achieve material loop closure and decrease dependence on external sources. These studies are important, because they allow one to design indicators, to determine sustainability targets and to establish new strategies to establish resource efficiency policies and programmes.

The present study consists of a material flow analysis from the household perspective in Bogotá, a city located in an emerging economy, as an integrated approach considering the flows in and out of the city (the data are only for the urban area of Bogotá). These results are compared with those for other cities in Latin America to establish similarities and differences. Following Bai [26], this study provides value by combining material and energy budgets and pathways, material and energy intensities (per capita) and temporal and intersystem variations (for Bogotá and other Latin American cities) to determine trends and functional differences among cities. This analysis allows us to understand management and socioeconomic variances, establish political actions to improve urban environmental performance, decrease pollution and determine future potential relationships between inputs and outputs based on population behaviour and the requirement that quality of life and standards be maintained.

Bogotá is selected, because it is the capital of Colombia, a country with an emerging economy. Bogotá provides one quarter of the country's internal production; it has a high level of industrialization, is home to different productive activities and the highest population concentration in Colombia. In addition, many environmental challenges are being addressed in Bogotá. This type of study can serve as an input for the development of more effective programmes for sustainable development in Colombia's urban areas and those in similar countries.

The research questions that guide this paper are as follows: (i) What are the trends in material and energy flows in the selected city, and how do they change over time? (ii) How do material and energy flows vary in comparison with those in other Latin American countries? To resolve these questions, this study applies different flow analyses based on inputs and outputs, relationships with the gross domestic product and comparisons of flows in other cities through normalized data.

This study is based on a flow approach that aims to incorporate dynamics in terms of resource inputs and outputs, materials, and energy (e.g., [27, 28]). Material and energy analyses can quantify resource flows based on physical weight or volume considering the scale or the relationship between inputs and outputs through indicators [10, 29]. Therefore, the main material and energy flows that enter and leave Bogotá city are defined and quantified, offering a holistic view of the city´s activities to determine the productivity, efficiency and sustainability of this urban area [30].

In this research, trends and dynamics over time are analysed with the aim of determining the temporal evolutions of input and output flows over 10 and 17 years, with a focus on 2017. Data trends for Bogotá are also compared with the 10-year temporal trends in a selected number of large urban agglomerations in Latin America, which is a novel contribution of this study. The results indicate that Bogotá has generated sustainable processes while increasing its GDP and maintaining lower environmental pressure with respect to that in other cities; this result can serve as an input for the design of adequate policies according to international trends.

The main contributions of this study are as follows. (i) The trends and dynamics of material and energy flows in a city with an emerging economy are analysed through novel indicators and over different periods; (ii) The results for Bogotá are compared with those of other Latin American countries to comparatively assess sustainable performance. This work thus contributes to an analysis of flows and their effects on the environment from different approaches; in particular, studies related to energy and material flows are limited for emerging economies, especially those in Latin America.

This paper is structured as follows. Following this introduction, the second section describes the main characteristics of Bogotá, section three presents the data and variables used in this study, and the fourth section presents the results and the analysis. Finally, conclusions and future research directions are presented in Sect. 5, and Appendix A shows the main environmental policies implemented in Bogotá.

Case study

Bogotá is the capital of Colombia. The geological characteristics of Bogotá correspond to those of a high plateau. Bogotá has a diversity of high-productivity soils, and its subsoil is rich in groundwater that, in many cases, is used by industry or service providers. Pressure on the environment is directly due to an increase in the population, which grew by 27.9% in recent years (from a population of 6,302,000 in 2001 to a population of 8,064,000 in 2017). The indicators show that Bogotá is central to the economic, environmental and social development of Colombia, as it is the urban area with the highest population and density nationally. Bogotá contributes to the economy through production, concentrating on specialized productive sectors and contributing to aggregate value, which is reflected in exports. However, it is also the city with the highest assortment of imports and, in recent years, has improved its social performance by reducing poverty and inequality. These indicators support the importance of performing analyses of the sustainability of Bogotá, especially due to its importance and contributions to Colombia. Table 1 shows the important role that Bogotá plays in the Colombian economy: the city is home to approximately 16% of the population and contributes to 26% of the national GDP; more importantly, it represents 44% of the national value added while importing 48% of the goods of the entire nation. Overall, Bogotá is the main driver of the Colombian economy and has a comparatively low poverty index at the national level.

Methods and data description

This study evaluates material and energy flows in households in Bogotá over time using secondary information reported by different local statistical institutions as a systematic assessment of the flows and stocks of materials and energy within a city defined in space and time [33]. Material and energy flows are based on the laws of the conservation of mass and energy and account for inputs and outputs through urban systems [34]. The selection of data was determined based on availability, consistency and integrity to provide and guarantee reliable estimations of flow changes in the period selected.

Material and energy flows are the focus of this study, and quantitative procedures are defined for determining the flow of materials and energy through urban areas or cities using input/output methodologies, including both material and economic information. This approach captures the mass and energy balances in an urban area, where inputs (water + energy + grey cement) equal outputs (wastewater + emissions + solid wastes + construction waste) and is also based on the laws of thermodynamics. This method asks whether the flows of materials and energy are sustainable in terms of the environmental burden they create [35].

Data were collected using a survey specifically developed for investigating the urban metabolism of megacities and large urban agglomerations [36], including both input and output flows and the relationship between inputs (such as food, water, construction and other materials, raw materials, energy, capital, information, and people) and outputs (such as industrial products, goods, services, knowledge, waste, and emissions). Inputs are important, because they support and allow societal activities; urban functions within a city; the formation of urban stocks, such as infrastructure, housing, buildings, public spaces, green areas and parks; the production of products and services; and the management of entire urban areas. Outputs determine the magnitude, distribution, internal interactions and feedback of an urban system regulated by governance, policy, culture and individual and collective behaviours.

Table 1 Main indicators for Bogotá and Colombia in 2017

Indicator	Colombia	Bogotá	% Contribution of Bogotá
Population	49,291,609	8,064,000	16.36%
Economically active population (comprises all persons of either sex who supply labour during a specified time reference period for the production of economic goods and services, as defined by the United Nations System of National Accounts) [31]	24,787,801	4,609,000	18.59%
Gross domestic product (billion US dollars)	311,89	82,305	26.39%
GDP per capita (dollars)	6327	101,851	–
12-month variation in the Consumer Price Index (%)	4.6	4.1	–
Gross production (millions of dollars) year 2016	81,815,32	13,113.38	16.03%
Value added (millions of dollars) year 2016	29,691	5197.18	17.50%
Export value (millions of dollars; FOB values)	37,769.6	2472.3	6.5%
Import value (millions of dollars; CIF values)	46,075.7	22,166	48.1
GINI coefficient	0.508	0.498	–
Poverty index	26.9%	12.4%	–

Source: [32]

Temporal variation in the flows was captured by collecting data for the years 2001, 2005, 2010, 2015 and 2017. The variables and indicators used in this study were selected from the available household information provided by the city and used to establish the relationship between inputs and outputs over time. In addition, considering the growth of the city, intensities or measurements per capita were calculated from the population data for each of the analysed inputs and outputs and normalized variables.

Inputs and outputs include the following data, which are compared, and the corresponding trends are analysed over different time periods considering the relationships among absolute flows normalized based on inhabitant and household variables.

Inputs:

Water: Consumption in the household sector (m^3/year) and consumption per inhabitant per year (m^3/inhab/year). The data source is the water consumption database of the Secretary of Planning, District of Bogotá.

Energy: Consumption (electricity and natural gas) in the household sector (TJ/year) and consumption per inhabitant per year (TJ/inhab/year). The source is the database of energy of UPME and the Superintendency of Public Services.

Grey cement: Consumption per year in the household sector (ton/year) and consumption per inhabitant per year (ton/inhab/year). The source is the database of cement of the Secretary of Planning, District of Bogotá.

Outputs:

Wastewater: Generation of domestic discharge (m^3/year) and generation of domestic discharge per inhabitant per year (m^3/inhab/year). The source is the water consumption database of the Secretary of Planning, District of Bogotá.

Emissions: COx (ton/year), SOx, NOx and particulate matter PM10 (μg/m3) and COx (ton/inhab/year). The source is the database of emissions of the Environmental Observatory of Bogotá, and data are general and correspond to mobile sources.

Solid waste: Generation of domestic solid waste (ton/year) and domestic solid waste per inhabitant per year (m^3/inhab/year). The source is the solid waste database of the Secretary of Planning, District of Bogotá.

Construction waste: Generation for construction of household (ton/year) and generation per inhabitant per year (ton/inhab/year). The source is the solid waste database of the Secretary of Planning, District of Bogotá.

Together with these flows, data on policies related to water savings, energy, and mobility have been reviewed to better understand the temporal variation in the flows, with a focus on 10- and 15-year periods of growth in Bogotá to determine how policies have helped improve the performance of the city.

Moreover, the temporal variation in data is compared with that for other large Latin American urban agglomerations, and the data used for the present study are from previous urban metabolism studies (see [37–39] for full details) in which urban metabolism [6, 26] data were collected according to a specific multi-layered survey developed for large urban agglomerations [36].

Results

In this section, the trends and analysis of the flow of materials over different periods of time in the city of Bogotá are presented considering the main inputs and outputs at a general level and as components; the dynamics of growth and reduction are observed according to different pressures or actions on the environment or the greater awareness of city inhabitants. Following this analysis, the 10-year growth of Bogotá is compared with that of other large urban agglomerations, and differences and analogies are noted.

Temporal variation in flows over the period of 2001–2017

During the study period, the flows of materials and energy in the city of Bogotá increased, especially due to a population increase from 6,302,880 in 2001 to 8,064,000 in 2017, which represents an annual increase of approximately 100,000 inhabitants.

Figure 1 shows a comparison of the flow balance of materials and energy per capita for the period of 2001–2017 and depicts the increases in certain flows, especially energy, cement, CO_2 emissions and construction waste, reflecting the growth of the city. Through the design and application of public policy instruments at the urban level, e.g., dissemination and awareness campaigns [BIBs], reductions in flows such as those for water and wastewater generation were achieved, and the production of solid waste remained relatively stable. With regard to the input/output equilibrium of flows, Fig. 1 also shows that input and output flows of energy and water are in equilibrium, indicating that the distribution and collection infrastructures are efficiently managed.

A more detailed view is offered in Fig. 2, where the 10-year and 15-year growth rates are compared. It is interesting to note that flows fall into three categories: flows that grow, remain stable or decrease:

1) Significant increase (more than 50%): GDP, debris and cement, for both the 10-year and 15-year analyses, displayed close relationships with economic growth and increased construction activities in Bogotá.

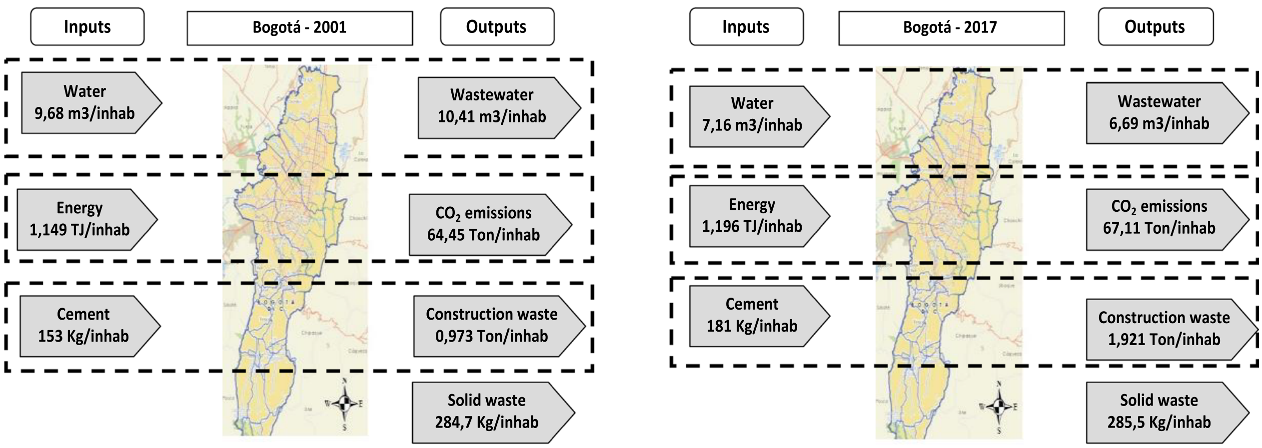

Fig. 1 Comparative analysis of the flow of materials through Bogotá in 2001 and 2017

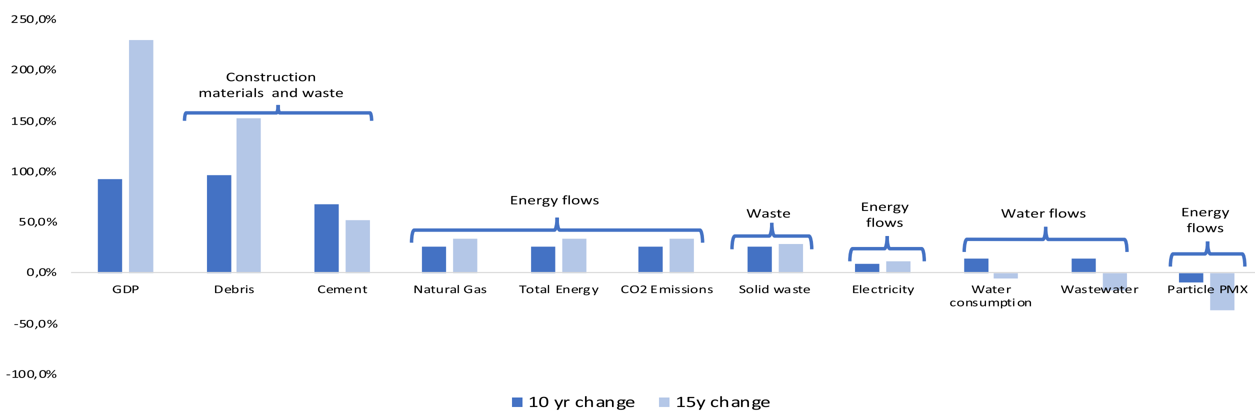

Fig. 2 Comparison of the 10-year and 15-year growth rates for the main inputs and outputs of Bogotá

2) Stable (between 0 and 50%): Natural gas, total energy, CO_2 emissions, solid waste, and electricity consumption flows have remained stable over time, indicating a decoupling between growth, use of energy and the generation of waste; notably, this type of decoupling is important for improving environmental performance.
3) Reduced (less than 0%): Water consumption, wastewater, and particle PMx flows were reduced by promoting awareness campaigns in the city to promote the efficient use of water and changes in fuels by improving fuel quality and reducing particulate emissions.

Considering the first category, it is interesting to note that the GDP experienced a significant increase over both 15 years (230%) and 10 years (92%), and in the same period, population and the use of resources and outputs increased to different levels; in addition, water (-5.2% in 15 years), wastewater (-17.8% in 15 years) and PMx emission (-9.2% in 10 years and -37% in 15 years) flows were significantly reduced. The only flows that are greater than 50% for both the 10- and 15-year periods are those related to the construction sector: debris and cement flows. In particular, debris experienced the most significant growth in 15 years, achieving an increase of 150%.

Considering the population as the main driver of urban expansion and urban flows, we show in Fig. 3 the elasticity of the metabolic flows with respect to the population. As expected, both 10-year and 15-year GDP values are well above 1 at 5 and 8, respectively. Such values are in line with those of other large urban agglomerations worldwide [37], and debris and cement elasticity reflect the important increase observed in Fig. 2. With regard to the other flows, it is interesting to note that natural gas, total energy, CO_2 emissions and solid waste display elasticity values between 1 and 1.4, while electricity, water consumption (15 years) wastewater (15 years) and

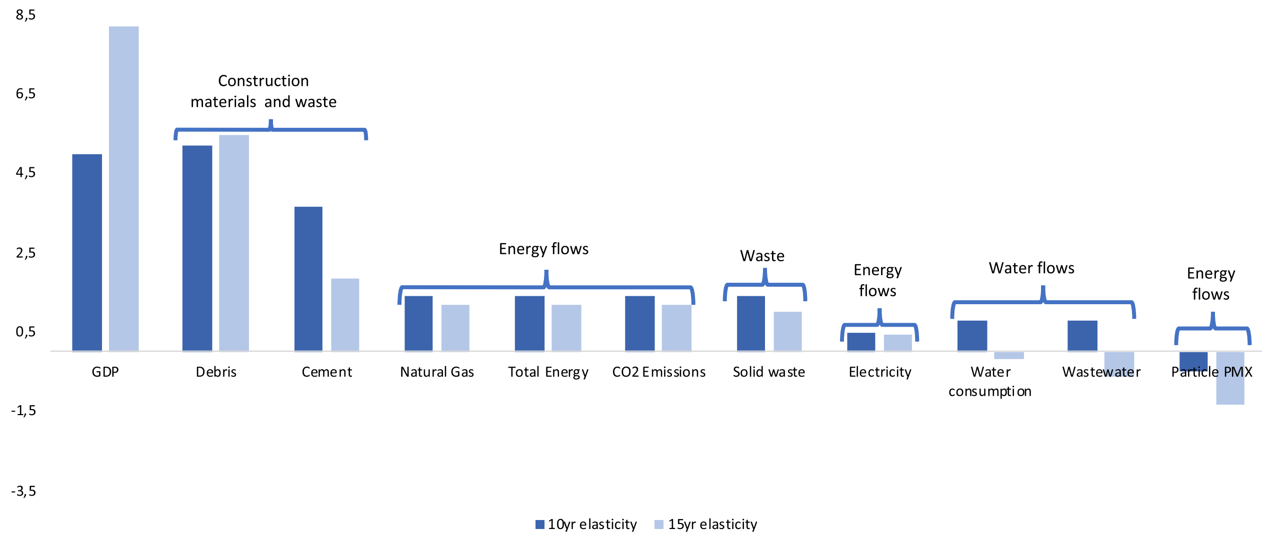

Fig. 3 Comparison of the 10-year and 15-year elasticity of flows with respect to population

particle PMX exhibit negative values or values less than 1.

These results indicate the importance of understanding the specific issues related to a sustainable urban transition at the local level, which implies a link between urban activities and urban planning. Musango et al. [29] and U4SSC [40] recommend the design and application of methods to calculate energy and material flows, ensuring a comparison for all cities in both developed and developing countries; this approach supports analyses of spatial and temporal issues related to urban flows; assessments of different effects of society from a transdisciplinary perspective; the use of dynamic models, which allows physical and social processes to be evaluated as key elements in urban planning and design interventions; improved eco-efficiencies, integrated urban management and development plans; and the promotion of social inclusiveness, among other processes.

In the following subsections, the paper discusses in detail the temporal variations in urban flows, highlighting the main actions implemented by the municipality to reduce the pressure placed by the city on the environment.

Trends in water consumption and wastewater production

In the urban sphere, water consumption is essential for different personal and business processes, and these processes generate wastewater; thus, these types of consumption maintain a direct relationship over the study period. In 2001, the total water consumption of the city was 61,014,567 m^3, and in 2017, the consumption was 57,811,956 m^3, indicating a decrease of 3,202,611 m^3 during these years. A similar situation was observed with wastewater; in 2001, 65,642,718 m^3 was produced, and in 2017, production was 53,988,449 m^3.

Figure 4 shows the trends in water flow and discharge per capita for Bogotá in different years of the study period, and there is a trend towards the more efficient use of this resource, leading to reduced discharge with consequent benefits for the environment.

These results are products of various public awareness campaigns to generate less waste and the adoption of water saving technologies that have resulted in the rational and efficient use of water based on integral management (quantity and quality) and the participation of all stakeholders with defined water requirements from profile consumption (e.g., differentiated tariffs) or specific programs; the main regulations are implemented by the Programme for the Conservation and Efficient Use of Water (Law 373:1997) and include national and local policies for the integral management of water resources, promotion of conservation, and the sustainable use of water (for additional details, see Appendix A).

These results concur with those of previous studies [41–43] in Spain, where according to the specific context, it is fundamental to formulate and apply a combination of measures and action plans that integrate pricing and non-pricing measures and educational campaigns to improve the efficient management of water resources at the household and industrial levels. Moreover, it is important to constantly evaluate the results and impacts of implemented measures to guarantee applicability and effectiveness.

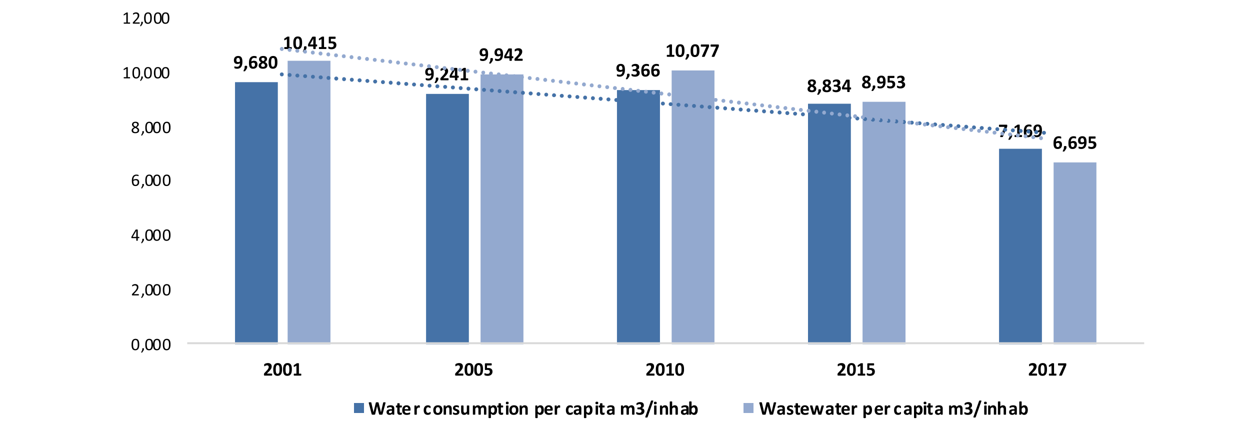

Fig. 4 Trends in water consumption and the generation of waste per capita in Bogotá from 2001 to 2017

In addition to the implementation of a communication campaign oriented towards the voluntary saving of water, in critical situations of drought due to climatic variability or maintenance of treatment plants, user associations indicate that in recent years, the gradual dismantling of subsidies and the increase in costs due to increased consumption have limited the payment capacity of low socio-economic strata [44], which has led to the reduced consumption of water and, therefore, less dumping and wastewater; these results demonstrate that to achieve efficient and sustainable use of water and decrease wastewater for population, it is necessary to implement integral policies and programs with collaboration and improve awareness among the stakeholders and users of water resources considering the relevant requirements and needs.

Trends in energy consumption and emissions generation

Energy consumption is vital for cities and is synonymous with development and progress. In the case of Bogotá, the two most important sources of energy for residential use are electricity and natural gas. The consumption of these two resources totalled 7,240,701.31 TJ in 2001 and 9,646,171.83 TJ in 2017, an increase of 33%.

Figure 5 shows the per capita energy consumption for Bogotá as a total of electricity and natural gas consumption. From 2001 to 2017, there was an increase in consumption, and in recent years, the reduction per inhabitant has remained stable.

In the case of electricity, per capita consumption has remained almost constant, especially in recent years, with a downward trend. In the case of natural gas, increases in consumption were evident until 2010, and then a reduction in consumption occurred, generating lower per capita consumption for this fuel; in recent years, slight increases have been observed. These results may be due to a new migration of users to electricity, mainly due to natural gas rationing or accidents that occurred.

In general, energy consumption in the residential sector of Bogotá has remained relatively stable, with minor

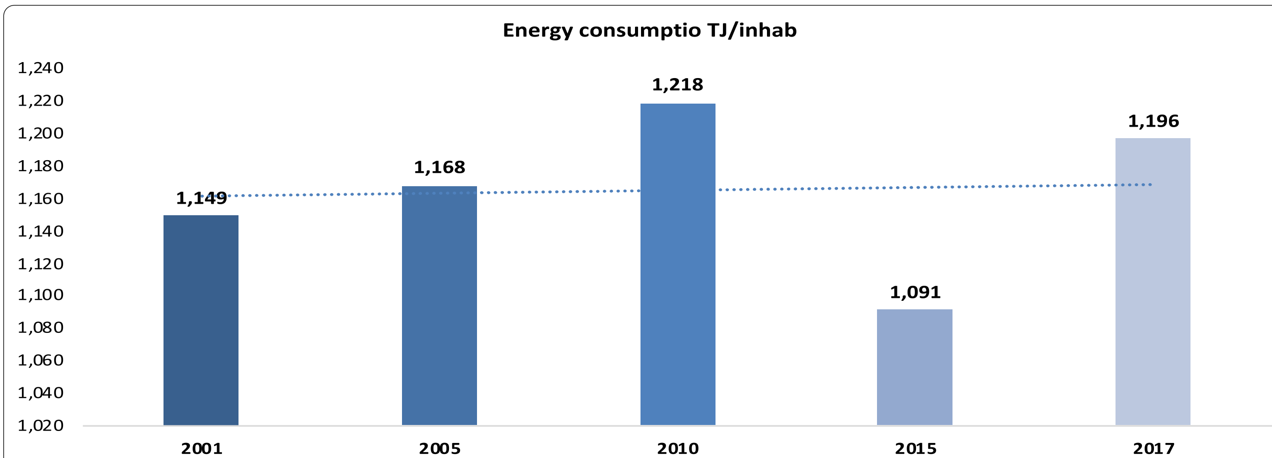

Fig. 5 Energy consumption per capita in Bogotá 2001–2017

increases in electricity consumption, and reductions in natural gas consumption; however, energy consumption has slightly increased in the last 3 years. These results may also be due to technological changes and increased awareness regarding the rational use of energy.

Other factors that contributed these results are the policies and regulations that were designed and applied to improve energy efficiency through the introduction of energy saving technologies and promote improved energy consumption habits through the Program for Rational and Efficient Energy Use (Law 697/2001) and action plans to achieve the energy goals of a country with priorities related to lighting, refrigeration and construction (for more details, see Appendix A). It is important to continue assessing and defining programs to improve energy use and decrease emissions considering user profiles and specific requirements related to electricity and natural gas consumption.

Policy makers and decision makers should evaluate the electricity demand to determine the main drivers of efficient construction design, sociodemographic and physical dwelling characteristics, network planning and strategic instruments, regulations, sociotechnical structures, and energy efficiency technologies and to capture the diversity of infrastructure characteristics, which could generate potential energy reductions and cost savings [45, 46].

As a result of energy consumption variations, emissions that generate air pollution increased. Table 2 shows the pollutant loads in the air in different periods. CO_2 emissions have increased slightly on average in recent years.

In addition, sulphur dioxide and nitrogen dioxide (expressed as annual average in μg/m^3) have shown similar trends and remained stable or decreased, and PM10 (expressed as μg/m^3) has generally decreased due to improvements in the quality of fuels. However, in Bogotá, the need to further improve the quality of fuels, especially in transport, has been acknowledged following the air quality alerts in 2019. Thus, it is important to analyse emission trends, consider the energy sources used by different sectors and identify alternatives for improving air quality in the city of Bogotá.

These results are consistent with the statement that improving urban air quality is one of the most demanding tasks facing policy makers worldwide, and it is important to determine the costs and benefits of measures that could lead to reductions in inefficient fossil fuel combustion and improvements in energy efficiency, which should reduce air pollutant emissions [47, 48]. In this context, local governments must analyse the situation and the potential for programmes to promote electrical mobility, improve fuel quality and provide sustained mobility in cities to decrease emissions and improve the air quality index.

Table 2 Air pollutant emissions in Bogotá 2001–2017

Air pollutant emissions	2001	2005	2010	2015	2017
CO_2 emissions per capita Ton/inhab	64.45	65.51	68.33	61.21	67.11
Annual average sulphur dioxide μg/m^3	NA	0.013	0.020	0.019	0.013
Annual average nitrogen dioxide μg/m^3	NA	0.026	0.038	0.035	0.024
Particulate matter PM10 μg/m^3	65	74	59	44	41

NA not available

Source: http://oab.ambientebogota.gov.co/es/listado-indicadores-por-recurso-natural

Trends in cement consumption and the generation of construction waste

In the urbanization process, a large amount of construction material is required, which in parallel generates construction waste that, in many cases, due to the mixtures used, is difficult to recover; alternatively, problems associated with landfill occupation and pollution are encountered. In 2001, the consumption of grey cement in the Bogotá was 962,000 tons, and in 2017, 1,461,000 tons were consumed, which was an increase of 52%. Regarding the generation of debris, in 2001 and 2017, 6,132,000 tons and 15,487,802 tons were generated, respectively, which represents a threefold increase over that span. Figure 6 illustrates the trends in cement consumption and construction waste generation per capita in the city of Bogotá for the study period.

Cement consumption per inhabitant has remained relatively constant, while the generation of construction waste per person in the city has increased, mainly due to the dynamics of new construction and the modification of existing construction during urban densification and expansion processes. In addition, in recent years, in cities, the demand for materials for periodic housing remodelling and industrial and commercial areas has increased, which may reflect an increase in this consumption pattern and added value by construction. Therefore, in the past decade, regulations have been designed and applied to ensure the adequate treatment and management of construction waste considering the role of stakeholders in the temporary and final disposal of construction waste, guidelines for the process and treatment of construction and demolition waste and a model for construction and demolition waste management (for more details, see Appendix A). These regulations have promoted improvements in construction waste management, the generation of

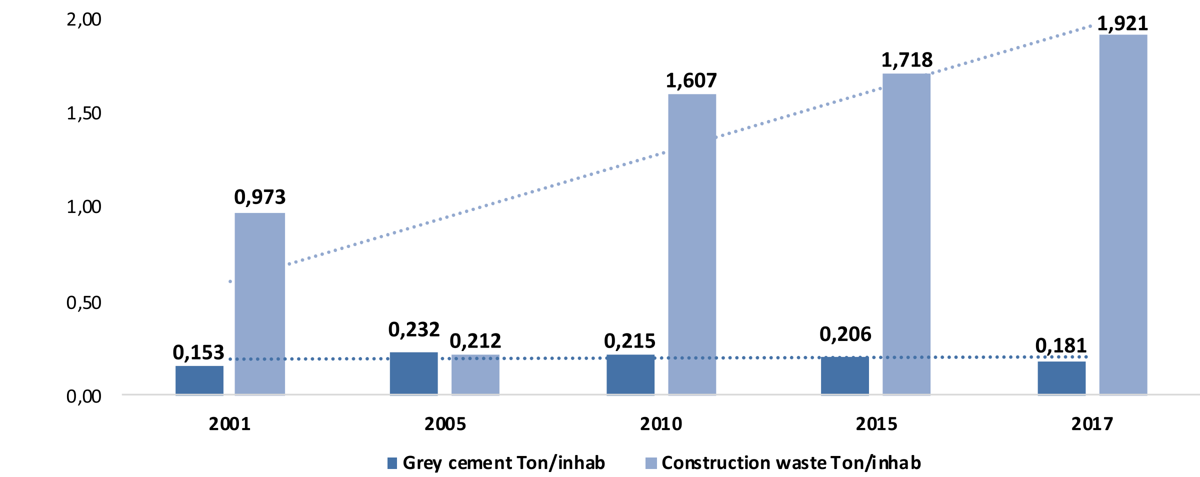

Fig. 6 Trends in cement consumption and the generation of waste construction per capita in Bogotá from 2001 to 2017

alternatives for final deposition and other uses and a decrease in environmental problems.

Moreover, construction waste can be recycled or reused as building materials through integrated waste management systems that can promote the sorting of waste, reductions in illegal dumping behaviour, financial subsidies from the government for waste recycling, and waste landfilling charges; this approach provides an opportunity for extracting economic and environmental benefits from waste, such as through reducing CO_2 emissions, energy use, natural resource use and illegal landfills [49, 50].

Trends in the production of solid waste

Another fundamental component that can ensure sustainability in urban areas is the management of solid waste. In Bogotá, in 2001, 1,794,430 tons of solid waste were generated, and in 2017, the amount was 2,295,821 tons, which is an increase of 28%. Figure 7 shows the per capita generation of waste in Bogotá for the study period; between 2001 and 2010, there was an increase in per capita waste generation, and in the last year of the period, a downward trend was achieved that could be attributed to increased awareness of the importance of reducing waste generation and contributing to recycling. This awareness was achieved through integrated solid waste management with respective guidelines by sector; this approach includes tariffs, recycling channels, strategies to decrease waste, and potential waste uses (for more details, see Appendix A). Promoting recycling management and decreasing waste disposal in landfills require improved control, monitoring and awareness.

According to the World Bank [51], managing waste is essential for achieving sustainable and liveable cities,

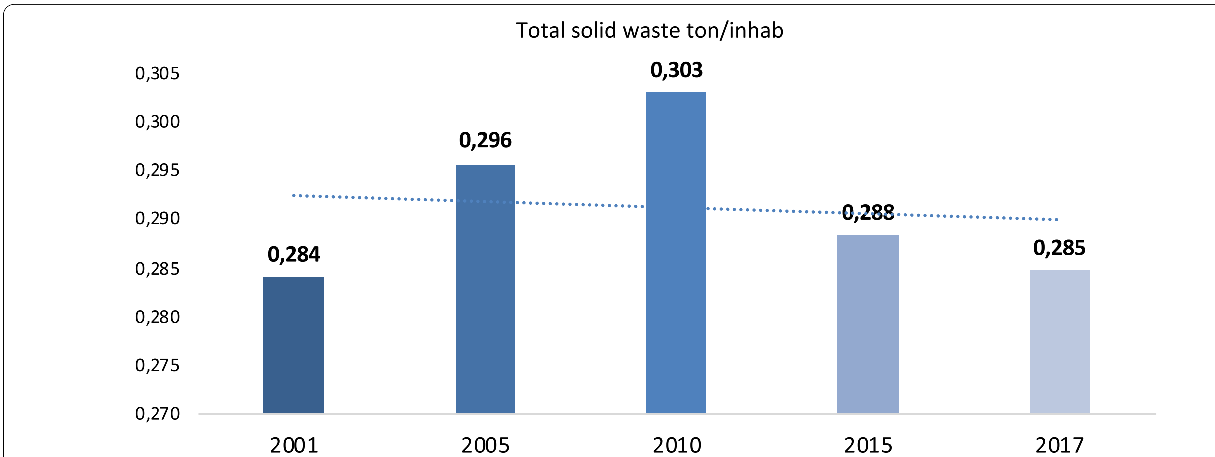

Fig. 7 Production of solid waste per capita in the city of Bogotá from 2001 to 2017

especially in developing countries. However, effective waste management is expensive (on average 20%–50% of municipal budgets) and complex. The main objectives of solid waste management include [52] developing new technologies, strategic innovations and monitoring tools; defining waste management scenarios, performing life cycle assessments and other modelling tasks; and establishing simulation tools and alternatives to enhance sustainable recycling and use of solid waste to achieve an integrated system characterized by efficiency, sustainability and social support.

Discussion

Results of this study show the dynamics of growth and reduction are observed according to different pressures or actions on the environment or the greater awareness of city inhabitants. Findings indicate the importance of understanding the specific issues related to a sustainable urban transition at the local level, which implies a link between urban activities and urban planning. Musango and U4SSC [29, 40] recommend the design and application of methods to calculate energy and material flows, ensuring a comparison for all cities in both developed and developing countries; this approach allows analysis of spatial and temporal issues in urban flows; assessment of different effects of society as a transdisciplinary study; the use of a dynamic model, which allows physical and social processes to be evaluated as key elements in urban planning and design interventions; improved eco-efficiencies, integrated urban management and development plans, and the promotion of social inclusiveness, among other suggestions.

These results show the importance of knowing the dynamics of the different flows of inputs and outputs in urban areas to determine how actions can be achieved when the population takes responsibility for their environmental impact. These results also illustrate how the population can be aware of pollution and environmental problems and how local actions take precedence to impact global indicators, improve the environment and contribute to the sustainability of the city. These actions take into account that urban activities and processes are managed at a sub-national level by municipal or city governments, and thus these governments must formulate effective actions and processes to simultaneously improve and strengthen resource efficiency and productivity and achieve sustainable development [29].

Main limitations of this study are the lack availability of data, where it is important to promote the acquisition of data, to compare trends and dynamics among cities and determine effects of different policies and programs to promote sustainability.

Table 3 Ten-year (2001–2011) growth in selected Latin American cities

	GDP	Population	Electricity	Total energy	Water
Mexico City	65.8	3.0	3.6	32.6	NA
Sao Paulo	179.5	10.9	49.0	42.2	23.9
Rio de Janeiro	98.0	9.6	103.6	51.5	41.5
Buenos Aires	109.3	11.7	39.2	18.2	NA
Lima	91.99	17.64	135.14	55.11	32.83
Bogota	92.1	18.5	8.4	25.6	14.6

Table 4 Ten-year (2001–2011) population elasticity in selected Latin American cities

	GDP	Electricity	Total energy	Water
Mexico City	21.8	1.2	10.8	NA
Sao Paulo	16.5	4.5	3.9	2.2
Rio de Janeiro	10.2	10.8	5.4	4.3
Buenos Aires	9.3	3.3	1.6	NA
Lima	5.2	7.7	3.1	1.9
Bogota	5.0	0.5	1.4	0.8

Comparison with large Latin American urban agglomerations

The 10-year variations in the energy and material flows of Bogotá are compared to those of other large urban agglomerations in Latin America: Mexico City, Sao Paulo, Rio de Janeiro, Buenos Aires, and Lima. To ensure data uniformity among the megacities investigated, data were collected from a previous study on the urban metabolism of megacities [37] based on the same survey used for Bogotá. Tables 3 and 4 report the percent growth and the flow elasticity with respect to the population. Elasticity is defined as the ratio of the percentage change in the quantity of a metabolic flow to the percentage change in the price of a particular benchmark parameter. In this case, we consider the population as a benchmark, meaning that it serves as the main guiding indicator for the comparison of metabolic flows, especially in fast-growing cities.

Elasticity values greater than 1, and in general, well above 5 and 6 (when considering other megacities), are of particular interest when considering sustainability and the efficient use of resources. In general, according to recent findings on megacities [38, 53], the super-linear scaling of flows with respect to population increases should not be surprising: cities are powerful drivers of economic growth, and in emerging and developing countries, in particular, they are regions of spatial accumulation that attract many people. In addition, especially in megacities with fast-growing economies, as is the case in Latin America, people are rapidly exiting the low-income bracket and joining the middle class, yielding increases in GDP and electricity consumption. Thus, individuals climb the energy ladder by shifting to more efficient energy sources, with electricity being at the top of the ladder. Liddle and Lung [38] found a direct link between electricity and GDP, and a further relationship between GDP and access to electricity share was reported by Stewart et al. [54]. In addition, switching to more efficient fuels for a significant part of the population may lead to the emergence of a rebound effect [55]. In particular, values over 70% have been observed in households in selected Chinese cities, while a rebound effect over 100% in Chinese megacity economies has been recently observed [56]. Therefore, as a first hypothesis, we could argue that the high elasticity values observed may be caused by a mix of socioeconomic factors, infrastructure improvements, and citizens' behaviours. Low-elasticity behaviours, on the contrary, may be explained by improvements in the efficient use of resources and the implementation of resource conservation policies and infrastructural factors that limit the expansion of the demand of a certain flow (e.g., lack of access to basic services). In the case of Bogotá, our hypothesis is that the rigidity of water and electricity is driven by conservation policies.

Bogotá experienced the highest population growth rate, 18.5% (in line with Lima), among the cities considered, with a value of approximately 10% for Buenos Aires, Rio and Sao Paulo and an overall range between 3% (Mexico City) and 18% (Lima and Bogotá) for all other cities. Excluding Mexico City, the population growth in the other major cities in the region was between 10 and 20% in the period considered. Despite this relative homogeneity, the observed metabolic flows exhibit consistent differences. Focusing on the energy sector, electricity consumption in Bogotá has generally remained stable, while that in Lima and Rio de Janeiro has increased. These figures are reflected in the elasticity value, which for Bogotá is 0.5, the only value below one observed in the table. This finding is particularly relevant from the perspectives of sustainability and resource conservation. Low elasticity values for resources mean that a city has been able to develop and increase its quality of life while reducing pressure on the environment. These findings also hold for total energy consumption. Table 3 shows values in the interval of 18–55%, with Bogotá plotting in the lower part of the interval.

From an economic perspective, the GDP displays consistent variability among the observed cities. The GDP of Bogotá increased similarly to those for Lima and Rio de Janeiro, and the elasticity values were significantly different: Bogotá had an elasticity of 5, while the other cities (excluding Lima) had higher values between 9 and 21, indicating that population growth in Bogotá was a weak trigger for economic growth (see Table 4).

Conclusions and future directions

This paper reports an analysis of the urban flows in Bogotá for the period of 2001–2017, and the fundamental elements needed to understand, where the main environmental problems are generated and what actions could be taken are identified.

The results show that at the city level, most of the flows increased under pressure from population growth and city densification/expansion. However, when reviewing the flows at the inhabitant level, greater efficiency is observed, which demonstrates that day-by-day, citizens are becoming more aware of consumption and the environmental problems that they can generate. During the study period, flows for the consumption of energy and cement and the generation of CO_2 emissions and debris increased in the city, and these trends are consistent with Bogotá's dynamics. In contrast, the reduction in water consumption, the creation of landfills and the production of solid waste were relatively stable. These findings are also confirmed by 10-year and 15-year growth analyses, indicating that the elasticity of the metabolic flows in relation to the population increase is either reduced or in a lower bracket when compared with those other large urban agglomerations in the Latin America region. Furthermore, a comparison of the 10-year growth of Bogotá with that of other cities highlighted significant differences, especially regarding metabolic flows.

This study demonstrates that urban systems present different opportunities for the development and application of strategies, plans and programmes for the efficient management of resources within the framework of integrated urban planning. In addition, the paper seeks to migrate from considering the linear behaviour of material flows to a more circular approach, where wastes are considered an economic resource with value that should be managed (recycle, reuse, and reduce) to decrease environmental problems [57] through actions, such as recyclable packing, energy and water savings, the promotion of ecological products, the reduction of emissions and waste, waste recovery, the evaluation of renewable and alternative energies, the use of low environmental impact consumer goods, dematerialisation, and the application of low-carbon processes, among others [58]; through this approach, the provision of various urban and public products and services to inhabitants and economic activities can be made sustainable. Thus, it is possible to promote changes in citizen rationalization and consumption patterns towards the best use of resources and reduce the generation of waste to strengthen various aspects of urban systems.

This study has potential limitations related to limited access to data and time constraints, because statistical offices produce data in variable forms and at different temporal scales, which may limit some evaluations of the impact of specific programs or instruments of public policy and some techniques that could be used to assess environmental performance for specific flows over time.

From the analysis presented here, public policy instruments should be prioritized that allow, at the macrolevel, impactful citizen actions in favour of sustainability and adequate urban environmental management based on a benchmark that allows the impact of different programmes that promote the care of the environment to be measured.

Future work will be devoted to better understanding the metabolic flows from a circular economy perspective based on a novel urban model that integrates urban metabolism with a life-cycle assessment [59].

Appendix A: Policies and regulations implemented to reduce environmental impacts

Table 5 shows different policies and regulations developed in Colombia and especially in Bogotá with the aim of fostering the rational and efficient use of natural resources and solid waste management. The policies listed here have improved the awareness of the population regarding the use and protection of natural resources, energy efficiency and the rational generation of solid waste.

Table 5 Main policies and regulations in Bogotá to improve environmental impacts

Resources	Policies and regulations
Water	Regulations are based on integrated management with a participatory approach that involves users, planners and decision makers at all levels
	Programs have been defined from a water demand characterization perspective (qualify and quantify) by different users and based on an analysis of consumption profiles to undertake actions aimed at changes that optimize water use and promote practices that favour the sustainability of ecosystems and reductions in contamination
	Law 373/1997: A programme for the conservation and the efficient use of water (a set of projects and actions for the efficient use of water)
	National Policy for Integrated Management of Water Resources/2010: with a special principle (6): "fresh water is considered a scarce resource and, therefore, its use will be rational and will be based on saving and efficient use"
	Decree 3570/2011: Integrated management of water resources to promote the conservation and sustainable use of water
	Decree 485/2011: The Bogotá District Plan for Water
	Signing of agreements with productive sectors of interest to promote efficient use of water
	Tariffs differentiated by water consumption guarantee based on the minimum subsistence and average consumption; higher consumption is associated with a higher cost per cubic metre
Energy	Policies and regulations on energy efficiency seek to ensure energy supply based on the adoption of new technologies and good consumption habits to optimize the management and use of available energy resources. Energy efficiency is a driver used to increase national productivity and competitiveness and is one of the main strategies for mitigating the environmental impacts of the energy chain
	Law 697/2001: The Program for Rational and Efficient Energy Use and other Forms of Non-conventional Energy
	Resolutions 180919/2010 and 41430/2015: Action plans to develop and apply energy efficiency goals and actions by priority consumption sector
	Priority programs: i. Residential: lighting, refrigeration, and construction; ii. Industrial sector: Boilers, lighting, driving force, cogeneration, combustion, energy management, ecolabel, cooling chain Transport: Technology reconversion, good practices, and transport means Service sector (government, services): lighting, refrigeration, public lighting, building, and air conditioning
Solid waste	Integrated solid waste management through the development of different programs and actions, such as the formulation of guidelines for waste management in different industrial sectors, an information subsystem to track and measure waste generation, recycling processes, and tariffs and other strategies to decrease waste management generation while increasing recycling and the potential use of discarded materials
Construction waste	Resolution 2397/2011: the entities, generators, transporters, exploiters and sites for the temporary and final disposal of construction waste are aligned, which allows appropriate management measures to be implemented in a city, resulting in reduced environmental impact
	Resolution 00715/2013: Technical–environmental guidelines for activities related to the use and treatment of construction and demolition waste
	Decree 586/2015: An efficient and sustainable model of construction and demolition waste management is adopted

Source: Ministry of Environment and Sustainable Development, UPME and the Bogotá District Environment Secretariat

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Authors' contributions
CIPM: conceived and designed analysis, wrote the paper, and performed analysis; WAP: contributed data or analysis tools and performed analysis; AF: wrote the paper and performed analysis; AC: contributed data or analysis tools and performed analysis. All authors read and approved the final manuscript.

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Availability of data and materials
The authors confirm that the data supporting the findings of this study are available within the article and the data that support the findings of this study are available from the corresponding author, upon reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
Potential conflict of interest exists. We wish to draw the attention of the Editor to the following facts, which may be considered as potential conflicts of interest, and to significant financial contributions to this work. The nature of potential conflict of interest is described: X No conflict of interest exists. We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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