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Modeling the management structure for greenhouse gas effects and their impacts on the hydrological cycle in cities

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RESUME

The complexity of cities and the challenges of sustainable planning and management require processes to be treated from a systemic perspective, which, in this study, were carried out using the concept of urban metabolism and modeling of system dynamics. Thus, a model was investigated and proposed to evaluate the effects of Greenhouse Gases (GHG) emissions on climate change and their impacts on the hydrological cycle in a hydrographic basin, addressing economic, social and environmental issues. The structured model makes it possible to visualize the cascade effect of the processes, leading to the observation of the necessary responses, in order to understand their effects, in a systemic, flexible and transparent way. The possibility of creating different scenarios through the dynamic model enables simulations of the present and the future that can be tested to facilitate physical interventions and strategic actions, helping in decision-making processes and in the formulation of public policies in cities.

KEYWORDS: Urban metabolism; system dynamics; climate change; water resources.

1 INTRODUCTION

Contemporary urban spatial planning and management are dominated by Cartesian, linear and mechanistic thinking, operated via fragmented strategies. This is most notably observed in policy development processes and the lack of communication among public stakeholders. This type of thinking is contrary to the reality of urban phenomena, which are complex and nonlinear (SANTOS; TONIOLO, 2010; PEREIRA, 2013). In an attempt to change this paradigm, systems thinking has emerged, based on the assumption that reality cannot be analyzed in isolation but must be rather approached holistically to understand and explain complex phenomena synergistically.

Within systems thinking, there is the concept of urban metabolism, an approach (or modeling strategy) aimed at facilitating the description and analysis of material and energy flows within cities. This is not a new concept; the first ideas that human activities alter biophysical processes, by analyzing the dynamic relationships between humans and nature, can be traced back to Karl Marx and Friedrich Engels in the 19th century (PINCETL; BUNJE; HOLMES, 2012; FOSTER; CLARK, 2016). Later, due to industrialization and the use of fossil fuels such as coal, Scottish biologist Sir Patrick Geddes initiated an ecological critique of urbanization in 1885, becoming the first scientist to attempt an empirical description of urban (and social) metabolism on a macroeconomic scale through experimental urbanization studies, establishing a physical budget for urban energy and material production (MACDONALD; PETERSON, 2007).

It was only in 1965 that the term "urban metabolism" was used by Abel Wolman in his work "Metabolism of the Cities," where he developed a model using a hypothetical city with one million inhabitants, allowing the determination of resource input and waste output rates (KENNEDY et al., 2007). This study helped demonstrate there are physical limitations to the natural resources we use in our daily lives, and their frequent use can lead to waste accumulation and environmental problems. In fact, Kennedy et al. (2007) defined urban metabolism as "the total sum of the technical and socioeconomic processes occurring in cities, resulting in growth, energy production, and waste disposal."

Many urban metabolism researchers use a systemic-dynamic model as the basis for an accounting framework (FERRÃO; FERNANDEZ, 2013), but it is also possible to create systemic-dynamic models, using the appropriate tools to represent processes within urban metabolism. These models can be used to simulate future scenarios of urban metabolism as a result of physical interventions and policies, aiding in decision-making processes regarding the urban environment.

One useful application of urban metabolism metrics is its ability to quantify greenhouse gas (GHG) emissions (KENNEDY et al., 2010). The actual emissions of carbon dioxide, methane, and other GHG emitted directly from a city are legitimate components of urban metabolism and are major contributors to climate change. The impacts caused by climate change, as a result of GHG emissions, include increased water scarcity and the risk of flooding, associated with declining water quality for example.

From a systemic perspective, using the concept of urban metabolism and the dynamic systems approach, the aim of this study was to investigate and propose a management framework for evaluating the effects of GHG emissions and their impacts on the hydrological cycle, considering the consequences of extreme hydrological variations due to climate change.

1.2 Urban Metabolism and Systemic Thinking

Cartesian urban planning is based on functionality and the rational organization of urban space, which often leads to spatial segregation and political and socio-spatial tensions. This approach aims to generate a standard of normality through public intervention. Contrastingly, systemic urban planning, according to Morin (2005), operates within the realm of diversity and takes a systemic perspective on urban dynamics. It considers all the political, social, economic, cultural, and technological connections and interrelations involved in the urban environment.

According to Barcellos and Barcellos (2004), the connections are of complex nature, demanding that the root causes of problems are identified, creating an opportunity to modeling techniques using computer simulations. Without this holistic view and the ability to generate future scenarios, solutions implemented in the short term, without considering the complexity of factors involved, can lead to new problems.

In contrast, some studies address different aspects of urban problems: flood risks (WINSEMIUS *et al.*, 2016; ARNELL; GOSLING, 2016); water system management (QIAN *et al.*, 2020; XU *et al.*, 2019); epidemiological impacts of flooding (ASHBOLT, 2018; VINET, 2017); flood-related mortality (JONKMAN, 2005; ALDERMAN, *et al.*, 2012); or water quality (BEACH *et al.*, 2016; ALSAN; GOLDIN., 2019). Environmental risks and vulnerability are often quantified using empirical and statistical approaches (BECCARI, 2016; FUCHS *et al.*, 2007) rather than physical models (KUSAKA *et al.*, 2012; MASSON *et al.*, 2013). Most of them, however, do not rely on an interdisciplinary (systemic) approach that explains the social, economic, and physical processes that interact city-wide. Instead, they are often limited to one or a few closely related scientific fields. The distinctions between the characteristics of Cartesian and systemic views are summarized in Table 1.

Table 1 – Characteristics of the Systemic and Cartesian View

	Systemic view	**Cartesian Vision**
Vision	Holistic	Fragmented
Interconnection	Events are interconnected	Events analyzed separately
Perception	Structure influences behavior	Reaction to events
Thinking	Circular	Linear
Complexity	Dynamics	Focus on details
Performance	On causes and leverage points	In Effects
Focus	Perception of the resistant dynamics of the system	Result
Relation	Perceive yourself as the agent causing your own problems	Look for culprits

Source: Adapted from Gratuliano, 2012.

Until the 1970s, urban metabolism was influenced by the General Systems Theory developed by Bertalanffy in works published between 1950 and 1968, (BOTELHO; SILVA, 2004). According to Bertalanffy (1992), after reaching its peak in the 1970s, urban metabolism was forgotten in the 1980s because it was believed that "market" research alone created a complete and effective model of economic management. However, this process, besides not being able to provide comprehensive answers to market dynamics, also excluded social and environmental issues.

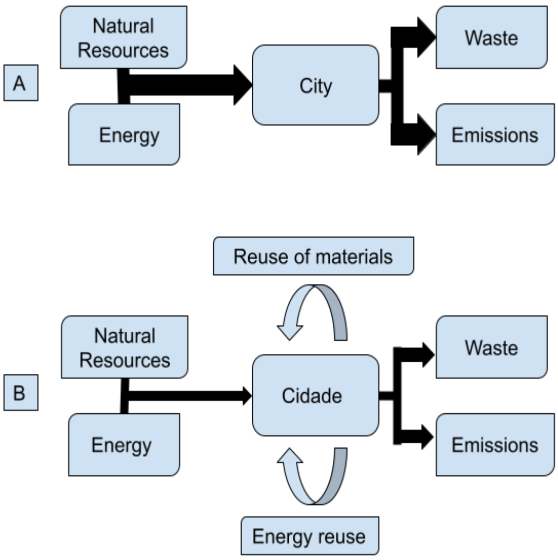
Systemic and integrated planning, as described by Rueda (1999), is a management model that relates urban metabolism, land use planning, and its operation in the system-environment unit. According to the author, it is necessary to think about the management models of our cities to maintain a balance with the environment that assures our future. Further, urban planning defines spaces and their occupancy densities, reflecting in water demand, sewage production, solid waste generation, and soil sealing that affects urban drainage management. Therefore, land use is a potential factor influencing services disregarding integration with other components (TUCCI, 2013).

As sustainability is becoming increasingly prominent (ROSEN, 2018), one of the main functions of urban metabolism is to assess and monitor the sustainability of cities and regions worldwide, collecting important information on energy efficiency, material cycling, waste management, and urban infrastructure (PINCETL, BUNJE, and HOLMES, 2012; DIJST et al., 2018; MUÑOZ and NAVIA, 2018).

Abel Wolman's work, previously mentioned, considered a city as analogous to an ecosystem and described how materials and energy flowed through the system, much like organisms in an ecosystem consume resources such as sunlight and food. As a consequence of this material flow within the city, products are created, and waste is generated. Thus, research on urban metabolism focuses on the sources and consumption of resources, their cycle within the system, and the production of waste (NIZA, 2009).

In the 1990s, Girardet laid the foundations of industrial ecology, using information from Wolman and his linear metabolism (Figure 1A), proposing a cyclical urban metabolic model (Figure 1B) because he realized that a linear sequence of environmental resource input from a city to its production of products and waste did not accurately emulate how real organisms influence the Earth's life support system (GIRARDET, 1990).

Figure 1. A. Linear metabolism –a large amount of resources and energy are consumed in urban processes and a large amount of waste is generated; B. Circular metabolism –there is the reuse and recycling of materials and energy, helping to reduce the extraction of resources and the production of waste and emissions.



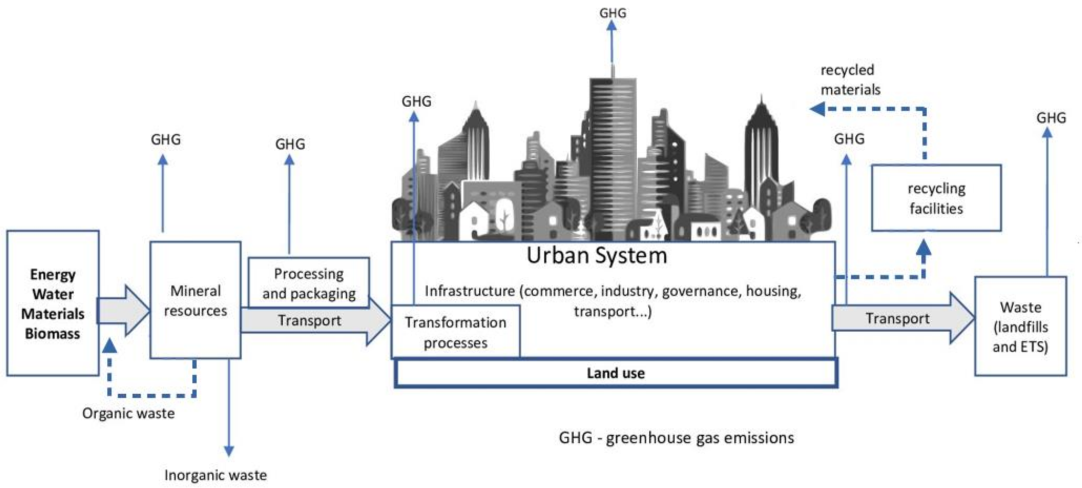
Using urban metabolism as a framework provides an effective way to obtain information on energy efficiency, material recycling, resource and waste management (KENNEDY et al., 2007), as well as to understand the characteristics of the urban system's infrastructure.

One of the primary methods for assessing urban metabolism is based on the analysis of material and energy flows, tracking the processes of input, storage, transformation, and output (HENDRIKS et al., 2000). Initially, it is necessary to survey and account for all flows and then create a balance of matter and energy. Then, with a sufficient amount of statistical data, the method is able to monitor resource flow over time in the urban system (BRUNNER, 2004). Using real data or historical series of greenhouse gas emissions, climate changes, and water resources, it is possible to generate scenarios and analyze the current conditions and trends of the analyzed data, resulting in future projections. For example, regarding water capture and consumption in a metropolis, it can generate comparability over time and provide decision-makers with information to develop action plans and guidelines to enhance the sustainability of cities.

1.3 Greenhouse Gas (GHG) Emissions and Climate Change

Regarding greenhouse gas emissions (GHG), the increasing demand for energy (fossil fuels) remains the most significant contributor to their emission (ERICKSON and LAZZARUS, 2013; ALOLA, BEKUN, and SARKODIE, 2019), and GHGs originating from human activities are the most significant factors for observed climate changes since the mid-20th century (IPCC, 2022). From a sustainability concept, urban metabolism is very useful in assessing the various conditions of greenhouse gas emissions in an urban system (Figure 2).

Figure 2. Material flow diagram and GHG emissions steps



The emissions of GHG, following the guidelines of the IPCC (Intergovernmental Panel on Climate Change), are calculated by multiplying an activity level by an emission factor. For example, GHG emissions generated by supplying electricity to a community are calculated by multiplying the community's consumption level by the GHG intensity of regional, state, or national electricity supply. Emission factors for fuels used in heating, transportation, or industrial combustion are well-established in the national GHG inventory report and are based on the combustion properties of each fuel. While calculations are more complex in some sectors (e.g., waste) for urban GHG inventories, urban metabolism parameters essentially provide the necessary measures of activity levels (KENNEDY et al., 2010).

A significant portion of anthropogenic CO2 emissions, the primary greenhouse gas source responsible for global warming, comes from the combustion of fossil fuels, primarily coal, oil, and natural gas. This occurs because the burning of coal or oil combines carbon with oxygen in the air to produce CO2, with additional consequences from deforestation, land-use changes, soil erosion, and intensive agriculture. Over the last decade (2009-2018), 42% of global fossil CO2 emissions came from coal, 34% from oil, 19% from natural gas, and the remaining 5% from cement production and other minor sources (PETERS et al., 2019; RITCHIE and ROSER, 2019).

In Brazil, in 2021, gross emissions of carbon dioxide equivalents (GtCO2 and GWP-AR5) amounted to 2.4 billion tons, contributing 3.2% to the world's emissions, making this source the 7th largest contributor, with China, the USA, Russia, and India being the largest contributors (SEEG, 2023). Figure 3 presents Brazilian GHG emissions data by economic sector for the years 2010 and 2020 (SEEG/BR, 2021), with a national growth of 9.5%, while globally, there was a 7% reduction.

According to Potenza et al. (2023), the largest contributing sector to emissions was land-use changes, accounting for 49%, with 998 million tons, primarily due to deforestation and wildfires in the Cerrado and the Amazon, emitting 1.19 billion tons gross in 2019—more than the entire country of Japan (POTENZA et al., 2023). Further, the second largest contributing productive sector was agriculture with 29%, mainly due to the expansion of the cattle herd, with gross emissions of 601 MtCO2e. The energy sector contributed 18% with 435

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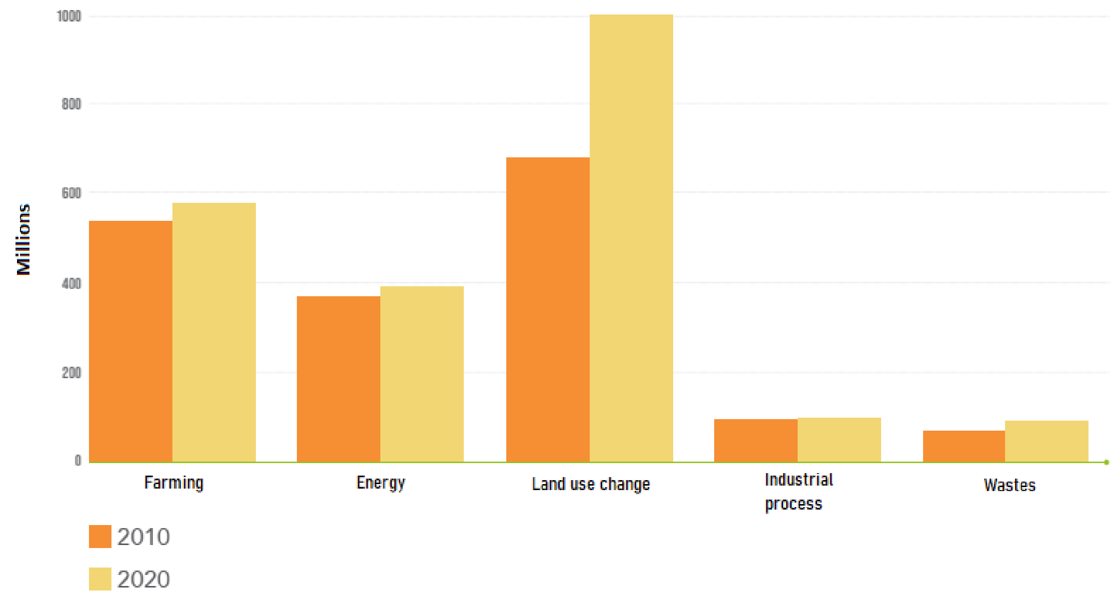
MtCO2e, and industrial processes accounted for a total of 108 MtCO2e, which is roughly equivalent to the waste sector, representing 4% of gross emissions (91 MtCO2e). The energy sector saw the highest increase in emissions since 1973.

Brazil also has one of the highest *per capita* emissions in the world, at 10.2 tons gross, while the global average is 6.7 t (SEEG, 2021). This could be explained by the fact that the carbon intensity in the economy has increased. However, the generated wealth is lower, as emissions primarily come from largely illegal sectors that generate little or no per capita income. In 2020, the pandemic exacerbated this situation: in 2019, the country generated $1,199 per ton of CO2e emitted, but this value dropped to $1,050 in 2020. Between 2003 and 2011, there was an increase from $538 to $1,032 in GDP generated for each ton, but since then, the country has been losing efficiency. The world's average is $1,583 of GDP generated per ton of CO2 emitted (SEEG, 2021).

Globally, the industrial sector, including the production of metals, chemicals, and manufacturing, accounts for 5.6% of emissions. The transport sector contributes 15.9%, construction 5.5%, agriculture 11.7%, land-use changes and forestry produce 6.5%, waste accounts for 3.1%, and the burning of other fuels contributes 2.9% (RITCHIE and ROSER, 2019).

Figure 3. Brazilian GHG emissions by economic activity in the periods of 2010 and 2020.



Source: Adapted from SEEG/Br-Gas Emission Estimation System (2021).

GHGs are major contributors to environmental and health problems, including global warming and climate change, which remain the most significant environmental issue for the international community (ALOLA, 2019). In this context, greenhouse gas emissions continue to pose a significant threat to the environment and humanity as they directly affect climatic conditions, which, in turn, lead to complex impacts on water systems, especially in urban areas.

1.4 Climate Change and Water

The relationship between water, energy, and climate is as important as it is complex (PARDOE et al., 2018). Climate change has the potential to disrupt the relatively stable climate in which civilization was built and compromise the security of water, food, and energy systems (MISRA, 2014). Over time, the effects of global warming due to the accumulation of human-generated greenhouse gases (GHG) in the atmosphere have become more evident (THOMPSON, 2010; LEE and KIM, 2017). In 2018, major GHGs such as carbon dioxide, methane, and nitrous oxide reached record levels, with the average global concentration of carbon dioxide for the year reaching 407.4 parts per million, the highest historically recorded, corresponding only to ice core data dating back 800,000 years (LINDSAY, 2020). In order to understand how human activities will influence climate in the future, it is essential to recognize changes that have already happened, like the shifts in global drought patterns, for example.

Water is one of the primary ways through which the population will first and most strongly experience the effects of climate change, given the likely changes in precipitation patterns and river runoff (ANA, 2016). In addition to being essential for life on the planet, water is also a driver of many climate change-related impacts (e.g. water scarcity and storms) for society and, particularly, for economic sectors like energy, transportation, and agriculture (JIMÉNEZ-CISNEROS et al., 2014).

Based on studies conducted by the IPCC (2022), the projection of potential impacts of climate change on water resources indicates that Brazil will experience different effects depending on the region, with a potential intensification of aridity conditions in the central region of the Northeast and in the southern Amazon, which could transition from a humid tropical climate to a sub humid tropical climate. There is also a relative consensus on increased precipitation and surface runoff in the southern region of the country. For the Southeast and Central regions of Brazil, studies have not reached convergent trends for precipitation. In addition to the effects on surface waters, climate change is expected to affect groundwater recharge rates, renewable groundwater resources, and aquifer levels (ANA, 2016). In some regions, drought periods are more intense and prolonged, such as in the Northeast, where the last drought lasted from 2010 to 2017, making it the longest monitored period since 1845 (MARTINS et al., 2017).

Anthropogenic climate change is one of the major water stressors, which, combined with non-climatic driving forces (such as population growth, economic development, urbanization, land use, or natural geomorphic changes), also challenges the sustainability of water resources by either reducing water supply or increasing demand (JIMÉNEZ-CISNEROS et al., 2014; OKELLO et al., 2015; PEREIRA; FREITAS, 2017). Changes in the hydrological cycle resulting from these climate changes can lead to various impacts and risks. Since water is a locally variable resource, vulnerabilities to related risks, such as floods and droughts, differ among regions. Studies conducted by Ghazal et al. (2014) show that rainfall events in Tehran, Iran, have become more sporadic, with the average rainfall decreasing, but the intensity of these rains has increased significantly. In Brazil, research by Zilli et al. (2016) has demonstrated that extreme rainfall events in the state of São Paulo have increased, leading to more frequent flooding.

Climate change is altering rainfall patterns in Brazil, particularly in the Southeast, with an average increase in both the volume of water and the average number of rainy days in the state of São Paulo. There are estimates of reduced average precipitation volume for the coming years in Rio de Janeiro and Espírito Santo, with concentrated events occurring over fewer days but with extreme intensities.

The development of dynamic models (combining climate factors, water balances, and socioeconomic information) is essential for monitoring water stress and increasing water demand (VÖRÖMASTY et al., 2000). Regarding dynamic models, Marvel et al. (2019) argue that they can predict droughts will become more frequent and severe as temperatures rise, potentially leading to food and water shortages, impacts on human health, destructive wildfires, and conflicts among people competing for resources.

According to a report by the World Meteorological Organization (WMO) in conjunction with the United Nations (UN), for the reduction of climate-related disaster risks, 45% of deaths in the past 50 years (1970-2019) were caused by natural disasters, accounting for 74% of all economic losses. More than 11,000 reported disasters were attributed to climate events, resulting in just over 2 million deaths and $3.47 trillion in losses. Over 91% of the deaths occurred in developing countries (DOURIS; KIM, 2021).

In Brazil, studies by the National Center for Monitoring and Alerts of Natural Disasters (Cemaden), in partnership with the Brazilian Institute of Geography and Statistics (IBGE), using data from the 2010 Census, projected that 9.5 million Brazilians live in high-risk areas (2018). In 2010, over 8.2 million people lived in these areas, totaling nearly 2.5 million residences at risk of climate disasters. Cemaden and IBGE data indicate that 75% of families living in these regions are in areas prone to landslides, while 25% reside in places at risk of floods, flash floods, and other phenomena. Cemaden and IBGE also note that among the people living in high-risk areas in Brazil, 17.8% are elderly, children, or belong to other vulnerable age groups (IBGE, 2018).

A technical study by the National Confederation of Municipalities (CNM) indicates that between 2013 and 2023, 27% (16,366) of disasters in Brazilian municipalities were related to rainfall, while droughts affected 41% (24,078) of people. Table 1 presents data on damages and losses caused by disasters, exclusively related to rainfall and droughts in Brazil between 2013 and 2023, excluding disasters related to fires and infectious and parasitic diseases.

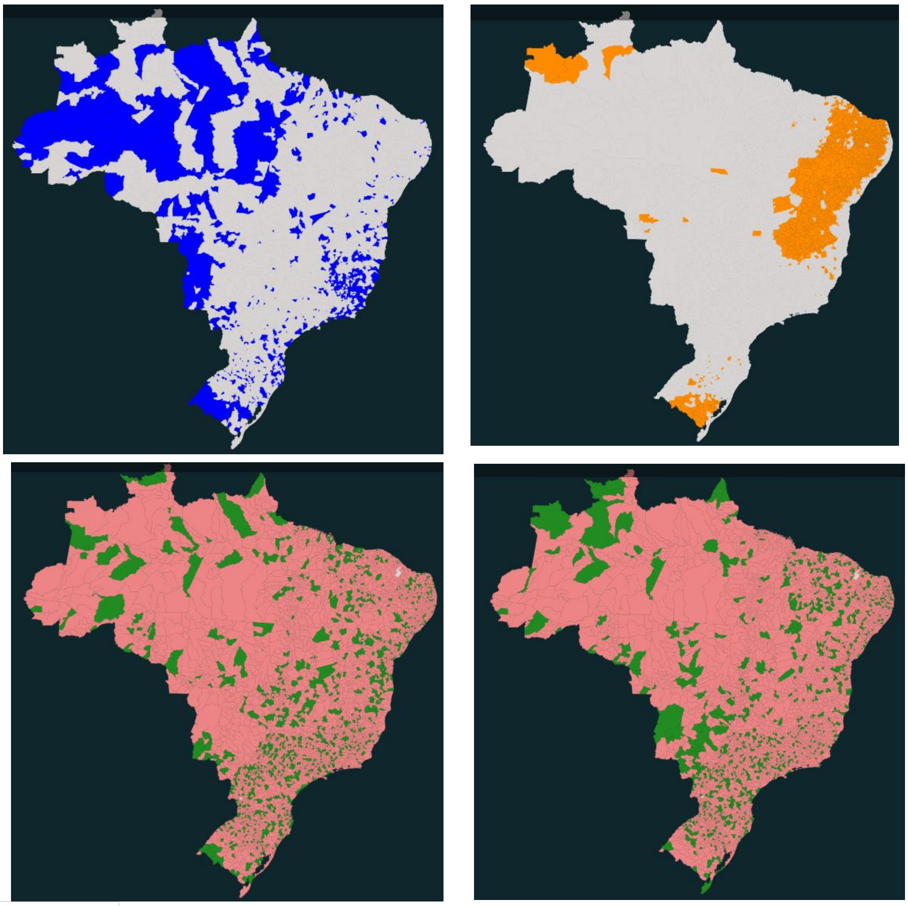
Table 1. Damage and losses caused by disasters in Brazil between 2013 and 2023

Year	Total people affected	Homelessness	Displaced	Deaths**	Damages (BRL$)
2013	14968534	133984	427044	155	1,532,530,400
2014	13024208	93744	320862	93	40,924,936
2015	17314279	91245	386251	85	22,338,291,787
2016	26219264	17377	109878	75	34,556,971,520
2017	58018712	42379	271491	64	34,555,663,836
2018	48677805	26800	93469	59	34,758,426,044
2019	32714231	75232	227233	356	25,348,202,372
2020	84856989	102122	309118	203	39,075,640,062
2021	48086097	93046	453391	277	52,217,519,664
2022	37428966	123849	820497	532	105,012,980,724
2023*	4777399	8382	64386	98	24,085,146,743
Total	**386086484**	**808160**	**3483620**	**1997**	**372,005,092,991**

* Data for 2023 refers to the months of January and February.
** Data refers only to deaths due to rain, there is no information on deaths due to droughts. R$ - billions of reais.
Source: CNM, 2023.

The National Secretariat for Civil Protection and Defense defines displaced persons as those who have had to leave their homes temporarily or permanently due to preventive evacuation, destruction, or severe damage caused by a disaster and who do not necessarily need shelter provided by the system. Homeless individuals are defined as those who, being displaced, require shelter provided by the government. Many Brazilian municipalities lack risk prevention systems, such as mapping their critical areas (Figure 4c) or flood control master plans (Figure 4d). As a result, actions are taken to repair damages when they should be implemented preventively. Figure 4 shows the Brazilian regions affected by extreme flood (a) and drought (b) events.

Figure 4. a) regions affected by floods; b) regions affected by droughts; c) municipalities with mapping of risk areas and; d) municipalities with flood prevention master plans.



SOURCE: CNM, 2023.

2 SYSTEM DYNAMICS AS A METHODOLOGICAL APPROACH

Understanding urban metabolism (FORRESTER, 1969, 1989) requires an investigation of the cities' socio-economic, political, technological, and cultural variables. In this context, evaluating urban vulnerability to climate change is an emerging research topic, as evidenced by projects like ARCC Water (Adaptive and Resilient Water Systems, Climate Change), Hydro-conflicts and Human Security (CLICO), and Modelling Analysis of Climate Change Mitigation (ADVANCE) (Tyndall Centre, UK), Assessing climate-led social-ecological impacts and opportunities for resilience pathways in the EU bioeconomy, Copernicus for Urban Resilience in Europe, Climate Change Impacts on Migration and Urbanization, and Sustainable Integrated Management FOR the NEXUS of water-land-food-energy-climate for a resource-efficient Europe (Potsdam Climate Change Institute, Germany), and the Impact of climate change on human health (CDC/Centers for Disease Control and Prevention, USA).

System dynamics is an approach to understand the nonlinear behavior of complex systems over time using stocks, flows, internal feedback loops, table functions, and time delays (RAHIM et al., 2017). System dynamics (SD) is a methodology and mathematical modeling technique for framing, understanding, and discussing complex issues and problems. Originally developed in the 1950s by Jay Forrester to help corporate managers improve their

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understanding of industrial processes, SD is currently being used across the public and private sectors for policy analysis and design (RADZICK and TAYLOR, 2008).

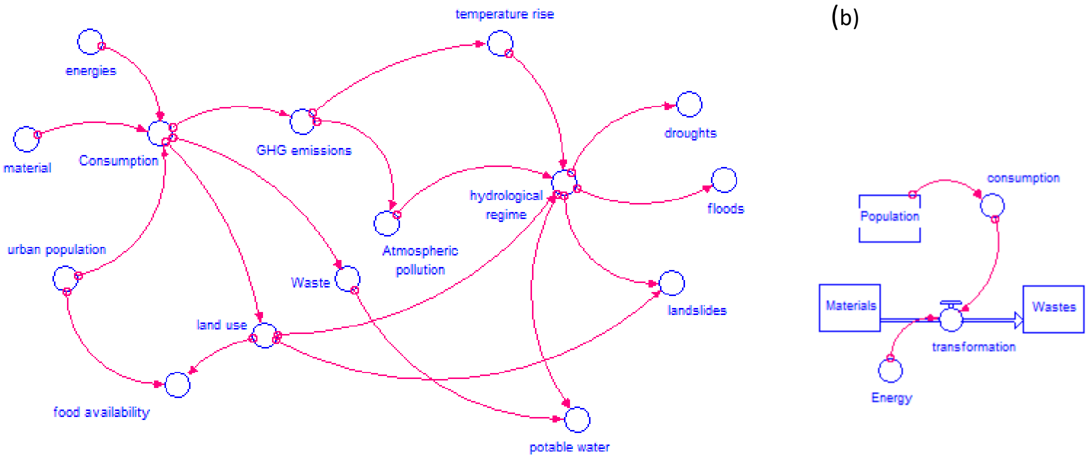
System dynamics has found application in a wide range of areas, including population dynamics, agricultural (RAHIM et al., 2017), ecological and economic systems, which often strongly interact with one another. Computer software is used to simulate a system dynamics model of the situation under study. Running "what-if" simulations to test specific policies in this model can greatly aid in understanding how the system changes over time. System dynamics is very similar to systems thinking and constructs the same causal loop diagrams of systems with feedback. However, system dynamics typically goes further and uses simulation to study system behavior and the impact of alternative public policies (STERMAN, 2000).

Systems can be initially represented by causal diagrams (Figure 5a) to facilitate the visualization of the process. To create a model, the use of process diagrams (Figure 5b) with representations of stocks (indicated by boxes), variables (circles), and flows (arrows) is necessary.

Figure 5. Schematic example of a dynamic system to analyze urban processes.
(a) causal diagram for visualizing the processes and
(b) diagrams of flows, stocks and variables of a dynamic model.

(a)

(b)



The causal diagram helps visualize the cascading effect of urban growth, with an increase in material and energy consumption, consequently leading to increased greenhouse gas (GHG) emissions and other pollutants, as well as an increase in waste production. Systemic models allow us to identify the relationships between driving forces, pressures, states, and impacts, enabling us to see what responses are necessary for each of the processes involved.

3 PROPOSAL AND FEASIBILITY OF MODEL APPLICATION

Unfortunately, urban planning projects are often proposed and implemented without the necessary integration, without assessing the future consequences of these projects, and without considering, for example, which transportation systems are directly related to GHG emissions. Misguided decisions in urban planning can lead to disastrous effects (INNES; BOOHER, 2018).

When confronted with the complexity of cities and viewed through a systemic lens, it becomes evident that many environmental, social, economic, cultural, and political relationships are interconnected. A city represents a complex dynamic system with a large number of components and complex interconnections, therefore, the issue of the effects caused by climate change (due to GHG emissions and their relationship with water resources) cannot be adequately addressed by linear models, demanding the implementation of systemic thinking (KUZNEKOVA; ROMAGNOLI, 2014).

When starting to establish a sustainable urban system in relation to water-related impacts and the effects of climate change, it is necessary to identify the main causal factors and the relationships and loops that connect the entire system. This involves an examination of pre-existing data to analyze the present and project the future. Based on this identification, proposals can be drawn to increase the system's resilience to urban water-related adversities.

Actions such as water conservation, improving water efficiency in landscapes, elaboration of city plans, water infrastructure, identifying alternative water sources, planning for drought emergencies, and planting drought-resistant crops will help prepare for future droughts and climate change.

Dynamic urban processes and their interconnection between different concepts and approaches should be studied together. These concepts and approaches include urban metabolism, urban resilience and vulnerability, and system dynamics modeling to address complex issues of multidimensional changing systems.

While linear models for statistical forecasting depend on equations developed ex-post, i.e., after observations; dynamic systems aim to first determine the system's structure, which consists of positive and negative relationships between variables, feedback loops, system archetypes, and delays (STERMAN, 2000, WOLSTENHOLME, 2003), followed by ex-ante projection, in which the future states of the system are replicated from the dynamic model (WINZ et al., 2009).

Figure 6 presents a systemic method, which, despite having compartmentalized boxes, are interconnected. The model is structured into five subdivisions (frames): The first focuses on environmental sanitation, including the GHG production chain and the contamination of urban waters with impacts on urban life (both are placed in the same frame because they are the primary objects of the model). The second subdivision of the frame covers water resource usage, navigation cases, and power generation. The third frame addresses environmental impacts resulting from emissions and climate changes, droughts, and alterations in rainfall patterns. The fourth frame encompasses social impacts, and the fifth and final frame deals with economic impacts. These subdivisions are merely a visual aid to organize the processes because in a systemic process, interactions occur without boundaries.

The model addresses economic issues, encompassing losses and seeking to present sources of financing for new initiatives aimed at preserving and recovering existing water resources. Regarding social issues, the model considers aspects such as population growth, responsible for increasing demand, and sanitation problems involving water quality and

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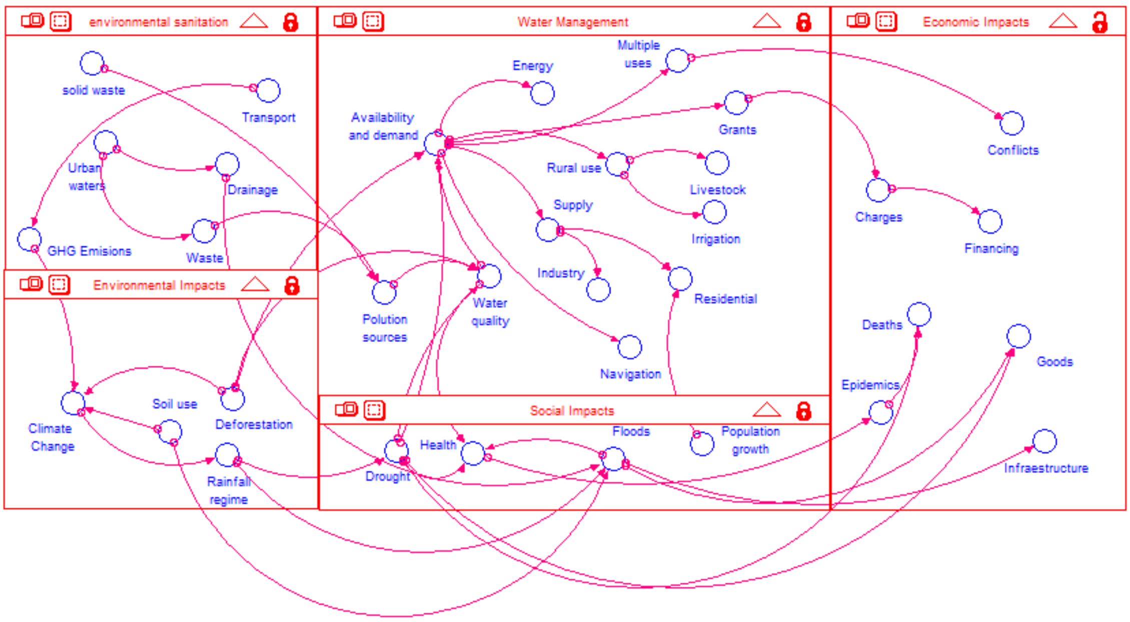
resulting floods. According to Duran-Encalada et al. (2016), dynamic models are able to to combine physical and socio-economic behavioral aspects in a systematic and flexible manner, providing transparency for decision-makers and users. Using dynamic modeling creates different scenarios that can be tested to facilitate detailed water management planning.

Another aspect addressed in the model is changes in rainfall patterns. These modifications can alter the availability and quality of water resources for urban supply (VOLSCHAN JUNIOR, 2011). In the case of droughts, in addition to the immediate reduction in surface water flow, there is also a decrease in aquifer recharge, compromising the reservoirs' storage capacity (ROSENZWEIG et al., 2011). On the opposite extreme, intense and concentrated rainfall over a short period of time generates sudden runoff, leading to floods, and a decline in water quality due to the transportation of sediments and contaminants into water bodies. The IPCC suggests climate change may reduce water quality due to interactions between high temperatures and precipitation variations (IPCC, 2022). Also addressed in the model are GHG emissions resulting from energy production and transportation, which also lead to changes in climate and rainfall patterns.

The dynamic system methodology focuses on capturing the structure of a complex situation in terms of the interactions between its elements. By using dynamic systems to model different scenarios, it becomes possible to test different models to facilitate planning engagement.

Figure 6. Schematic model in systemic causal loop format for evaluating water management in river basins, based on urban metabolism with visualization of the processes involved.



From the interactions between the elements of the model, it is possible to establish indicators for generating and monitoring scenarios. For example, you can relate increased GHG emissions to increased storms (or human actions) leading to increased flooding. The generated graphs are tailored to the user's specific interests to monitor what matters most.

The major concern evidently primarily results from increasing GHG emissions, and they will continue to raise growing concerns due to socioeconomic conditions (IPCC, 2022; FIEDLER, 2018). Other possible actions to reduce water-related impacts, such as implementing green infrastructure for managing stormwater or increasing energy efficiency in buildings, can improve a city's resilience to drought. These measures will be more effective when combined with reductions in the emission of GHG, minimizing the ultimate magnitude of climate change.

Decision-makers face multiple challenges when attempting to define strategies to adapt to climate change. They need to assess vulnerabilities in different communities and regions, identify opportunities and barriers for adaptation, and deal with complex social and ecological processes. The proposed solutions need to be planned for the long term, considering the profound uncertainty lying in the future. Solutions must be anticipated, even if they are implemented in only one of the many possible scenarios and may never be put into practice. Simulating scenarios from dynamic models helps address this complexity, allowing for incremental adaptation and long-term planning. It facilitates scheduling and prioritizing future decisions, providing flexibility by including various possible management and planning options.

4 FINAL CONSIDERATIONS

According to the IPCC (2022), the main risks climate change imposes to cities regard exacerbating existing issues related to energy supply, food production and distribution, water resource distribution, waste production and removal, and increased susceptibility to pandemics. Extreme weather events, such as increased storm frequency and rising sea levels, pose significant risks to urban populations, particularly those living in vulnerable areas.

Douris and Kim (2021) point out that only half of the WMO members have early warning systems for risks, and there are critical gaps in climate and hydrological observation networks in many countries. Many people are exposed to disaster risks due to the increasing number of extreme events, population growth, and occupation of vulnerable areas. Therefore, planning and managing cities from a predictive and sustainability perspective must be based on dynamic and systemic outlooks, with a focus on future visions. This approach should aim to support public policies and urban management according to socio-environmental needs and the constant transformations in cities.

To address the various aspects and consider the numerous factors involved in the complex relationships of cities, convergent approaches and innovative concepts are needed to incorporate current and future challenges in urbanization. The complexity of cities requires a systemic approach to deal with their processes, considering multiple environmental, social, economic, cultural, political, and institutional interconnections. These connections require integrated initiatives, which, in this study, were based on the concepts of urban metabolism and dynamic system modeling to address the complex issues involved in multidimensional processes of urban transformation related to GHG emissions.

This work considers that systemic thinking seeks to understand phenomena synergistically, while the concept of urban metabolism, as an approach, facilitates the description and analysis of material and energy flows, involving the interrelations of social, economic, political, technological, and cultural variables city-wide.

Through the lens of sustainability, one of the relevant applications of the urban metabolism approach is its ability to assess the different greenhouse gas (GHG) emission conditions in an urban system. These emissions are legitimate components of urban metabolism that directly influence climatic conditions and, consequently, have complex effects on urban water systems.

The study, design, and definition of environmental management models that combine climate factors, water balances, and socio-economic information is essential to understand the numerous socio-environmental interferences caused by extreme water variations (droughts, floods, scarcity). These models also consider the dynamic relationship between water supply and demand by society, accompanied by the effect of GHG on climate change. From a systemic perspective, adopting the concept of urban metabolism and the dynamic systems approach, this management model was conceived to evaluate the effects of GHG emissions on climate change and their impacts on the hydrological cycle. Supported by a systemic method, the model is structured in the management of water resources, environmental sanitation, and related impacts (environmental, social, economic), enabling a complex analysis of the interactions between element from the model and physical and socio-economic behavioral aspects in a systemic and dynamic way. This model is intended for urban planning and environmental management processes.

The ability to create different urban metabolism scenarios through a dynamic model (such as the one developed in this study) allows for future simulations and results that can be tested to facilitate physical interventions and strategic actions, aiding decision-making processes and the formulation of public policies in cities. Another advantage of dynamic modeling is that it can be easily adapted to the specificities of certain regions where it may be applied, and it can be applied regionally or locally.

In this way, this work emphasizes its purpose of studying, developing, and providing the a management model based on the urban metabolism concept (with a dynamic systems approach for analyzing the effects of GHG emissions). This aims to contribute to other emerging research in the future, supporting water management and urban planning in cities.

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