Remote Sensing and complex urban systems: Contributions to the state of the art on the Heat Island and the monitoring of water quality

Sensoriamento Remoto e sistemas urbanos complexos: Contribuições para o estado da arte sobre o fenômeno de Ilha de Calor e o monitoramento da qualidade da água

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Abstract

The article starts from the premise that cities are constituted in complex systems, so that its study, through the systemic approach, encounters three difficulties. Among these, the availability of technological instrumentation applied to research and which favors the obtaining and analysis of reality data stands out. In this context, remote sensing techniques are inserted, which have been increasingly applied in urban studies. Thus, the present article aims to present the state of the art of the use of remote sensing in urban studies, having the phenomenon of the Heat Island and the monitoring of water quality as thematic focus. In methodological terms, this article is a narrative, non-systematic and qualitative review, carried out based on the analysis of the literature, from books and articles in international journals. It is expected that the present material will contribute to the updating of knowledge, as well as to highlight the importance of the topic addressed in the academic environment.

Keywords: Urban Planning. Susteainable Cities. Geotechnologies.

Resumo

O artigo parte da premissa de que as cidades se constituem em sistemas complexos, de modo que seu estudo, por meio da abordagem sistêmica, encontra três dificuldades. Dentre estas, destaca-se a disponibilidade de instrumentação tecnológica aplicada à pesquisa e que favorece a obtenção e análise de dados da realidade. Nesse contexto, estão inseridas as técnicas de sensoriamento remoto, cada vez mais aplicadas nos estudos urbanos. Assim, o presente artigo tem como objetivo apresentar o estado da arte da utilização do sensoriamento remoto em estudos urbanos, tendo como foco temático o fenômeno Ilha de Calor e o monitoramento da qualidade da água. Em termos metodológicos, este artigo é uma revisão narrativa, não sistemática e qualitativa, realizada a partir da análise da literatura, de livros e artigos em periódicos internacionais. Espera-se que o presente material contribua para a atualização de conhecimentos, bem como evidencie a importância do tema abordado no meio acadêmico.

Palavras-chave: Planejamento Urbano. Cidades sustentáveis. Geotecnologias.

Introduction

The year 2007 marks the first time that the urban population has outnumbered the world's rural population. Since then, the urban population has increased rapidly, reaching 4.2

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billion people in 2018, which corresponded to 55% of the total absolute world population. This number will continue to increase, so that, by 2050, it is expected that around 6.7 billion people will inhabit areas considered urban, which will correspond to a total of 68% of the absolute world population.

However, urban development was not accompanied by adequate planning in most existing cities, a fact that contributed to a generalized picture of urban crisis, marked by social, environmental, and economic problems. This situation is even more worrying in the urban areas of less developed countries, where the problems are deepened due to the late and accelerated urban transition process.

In view of the expected urban growth for the coming decades, which should be concentrated in the least developed and most populated regions of the planet, as well as in the face of growing global concerns about sustainability, new studies are needed to guide policies and urban planning, with the objective of building sustainable cities.

Cities can be considered as spatial organizations that result from interactions between different elements. In this way, they can be framed in the concept of complex systems, and for their analysis, it is necessary adequate technical instruments. In this context, the role of Remote Sensing as a tool of great importance to the study of urban phenomena and problems is highlighted.

In this sense, the present article aims to lecture about the potential of Remote Sensing application to urban studies. Thus, based on a narrative, non-systematic and qualitative review we sought to present the state of the art regarding the use of Remote Sensing in studies of the phenomenon of the Heat Island and the monitoring of water quality in urban areas (Cordeiro, 2007).

For this purpose, the article is organized in four sections, in addition to the present introduction. In the first, the urbanization numbers and some of the challenges to which these numbers point will be pointed out. The second section aims to talk about the relationship between the phenomenon of urbanization and sustainability, indicating some of the social, economic, and environmental impacts resulting from this relationship. The third section talks about the evolution of remote sensing and its potential for application to urban studies, focusing on studies of urban Heat Island and water quality monitoring. Finally, the fourth section presents the bibliographic references that supported this research.

Urbanization numbers and some of their challenges

The Population Division of the United Nations Department of Economic and Social Affairs has published, based on national statistics, reports with revised and updated estimates and projections of urban and rural populations in all countries of the world and of the main existing urban settlements.

The 2018 report presented estimates and projections of the total world population, urban and rural for the period from 1950 to 2050 (United Nations, 2018). According to the same, in 1950, the population residing in urban areas corresponded to 30% of the total population worldwide. Between this year and 2018, the world's urban population grew rapidly and, in 2007, that population became, for the first time, greater than the rural population.

Thus, between 1950 and 2018, the urban population grew more than four times, from 0.8 billion to 4.2 billion people, or, in percentage terms, from the aforementioned 30% to 55% of the total world population. The growth in the number of the world's urban population draws attention when one observes the time required for its increase by 1 billion people.

1959 was the first year to reach this mark and it took 26 years for the world's urban population to reach 2 billion people, corresponding to 1985. In 2002, after 17 years, the world's urban population reached 3 billion people and, in 2015, this population reached 4 billion people, thus needing only 13 years to reach that value.

This growth, however, did not take place in a homogeneous manner among the various existing countries and regions (Quaresma *et al*., 2017). Taking Brazil as an example, most of the problems faced in its large and medium-sized cities can be understood by the late, accelerated, and unequal way in which urban development in this country took place. According to Villela and Suzigan (1973), until the end of the 19th century, the Brazilian urban population was very low and showed little variation. In the period between the years 1890 and 1920, this population increased from 6.80% to 10.70% of the existing absolute population. However, in the following two decades, the index almost tripled, reaching 31.24% of the Brazilian population in 1940. The acceleration of this growth was also present in the following years, in such a way that, from 1940 to 1980, according to Scarlato (2005), it was found that the Brazilian urban population increased to 67.59%.

The evolution of these data shows that it took only 40 years for Brazil to transform itself, from a predominantly rural country, into a predominantly urban country. This situation differs from the realities of developed countries, which took more than a century to reach similar urbanization rates, like Belgium, whose urban population evolved from 31% in 1846, to 49% in 1900 and reaching 61% in 1970.

In addition to the more developed regions, characterized by a mostly urban population, and countries like Brazil, which were characterized by a late and accelerated process of urbanization, it is important to note that many less developed regions of the planet are characterized by presenting little less half of its total population still living in rural areas.

The urban population of these less developed regions has been growing considerably faster than those belonging to more developed regions. According to United Nations (2018), in 1950, the urban population of the most developed regions was 446 million inhabitants, and for the least developed regions, these values corresponded to 305 million inhabitants. This demonstrates that the urban population of the most developed regions represented 59% of the existing urban population on the planet, although such regions have only 32% of the total world population.

In the year 1970, this situation is reversed, and the urban population of the least developed regions now reaches 680 million inhabitants, against 674 million in the more developed regions. The difference then starts to grow rapidly and, in 2018, the urban population of less developed regions reached values higher than three times the values of the urban population of more developed regions, representing 3.2 billion inhabitants, against 1.0 billion inhabitants, respectively. That same year, the urban population of the least developed regions represented 76% of the world's urban population and 84% of the total world population.

Whereas, for the year 2050, the urban population of the most developed regions will be 1.1 billion inhabitants, corresponding to only 17% of the world's urban population, and whereas the absolute population of such regions will correspond to only 13% of the population absolute world, we can see the challenges that are imposed to urban studies in underdeveloped regions, since, according to projections made, it is estimated that, in 2050, the urban population of these regions will reach 5.6 billion. This value will correspond to 83% of the world's urban population, and such regions will also cover 87% of the absolute world population.

Other estimates in the report indicate that the pace of global urbanization is likely to slow down in the future. Thus, between the years 2018 and 2030, the world's urban population is expected to have an average annual growth rate of 1.7%, which is well below the average rates of 3.0%, 2.6% and 2.2 % referring to the periods from 1950 to 1970, from 1970 to 1990 and from 1990 to 2018, respectively.

Despite such a slowdown, projections made indicate that the world's urban population will continue to grow, reaching, in 2050, 68% of the existing absolute population, which will correspond to a total of 6.7 billion people. A number of factors are attributed as causes for such growth, among which, natural growth, migrations from rural to urban areas and the geographic expansion of pre-existing urban settlements.

Regarding the spatial attribute, the expansion of urban areas is, on average, twice as fast as the growth of the urban population, and the expected increase in urban land cover during the first three decades of the 21st century will be greater than the urban expansion accumulated throughout history (Seto *et al*., 2014).

Urbanization and sustainability

In view of the figures presented in the previous items, it is possible to observe that the urban environment has been constituted and has been strengthening as the main way of life for humanity. In addition, the data makes it possible to reflect on the relationships between urban areas and sustainability. In this sense, Kadhim, Mourshed and Bray (2016) observe that, despite being engines of economic prosperity and social development, in view of their ability to concentrate people and economic activities, cities always end up being characterized as urban environments unsustainable.

According to the aforementioned authors, the growth and expansion of cities without planning, or with poor planning, can generate long-term negative impacts on urban sustainability, affecting the various spatial scales that exist, from local to regional and national, and potentially also affecting the intergovernmental scale.

Among the predicted impacts, the authors cite those with negative consequences for the economy, such as the reduction in productivity of the main economic sectors; environmental degradation, which can be observed by atmospheric pollution, the formation of heat islands, as well as the increase in the phenomenon of urban floods; and negative social impacts, such as increased morbidity and mortality, losses in quality of life and segregation of neighborhoods and communities.

This dichotomy between urban development and sustainability impacts can also be seen in Hoornweg and Bhada-Tata (2012), for which urban areas, being responsible for about 80% of the Global Gross Domestic Product and, in view of their potential for expansion of population income, end up stimulating an increase in energy consumption and increasing greenhouse gas emissions. In addition, according to these authors, urban areas are responsible for the generation of about 1.3 billion tons of solid waste per year. This volume of waste is expected to increase to 2.2 billion tonnes in 2025 and the costs of its management are expected to reach 375.5 billion dollars. These authors point out that solid waste not collected contributes to other urban problems, such as floods, air pollution and impacts on public health.

Urban environmental problems are deepened when related to accelerated urbanization, such as that which took place in developing countries such as Brazil. According to Quaresma *et al.* (2017), the acceleration of the urbanization process, when not accompanied at the same pace by planning, resulted in negative impacts in the social, environmental, and economic spheres.

According to the same authors, in the social sphere, among the existing problems, social and spatial segregation stands out. Cities can be interpreted as a social and historical product, reflecting, in their configuration, the production relations of the society that created them. Thus, the class differences inherent in the capitalist mode of production materialize in spatial inequalities within cities, which often imply forms and processes of social and spatial segregation, such as slum.

About the environment, changes in use and occupation impacted the immediate ecosystems, in view of the suppression of most of the natural vegetation cover, with consequent changes in the climate, in particular the variables of rainfall and temperature. The transformations imposed on the environment also changed the hydrological conditions of the hydrographic basins, due to the waterproofing of the surfaces, with a consequent decrease in the recharge of groundwater and increases in the surface runoff volumes, generating constant flooding. These phenomena, when associated with the segregation, have caused risks and losses of human lives, especially for the low-income population of cities (Quaresma *et al*., 2017).

In the economic sphere, the impacts of accelerated urbanization imply, among others, high public health spending, due to the problems caused by pollution. They also imply expenditures related to combating urban floods, which, according to recent studies, cause financial losses in the order of hundreds of millions of dollars to the government, industry, and commerce. Finally, accelerated urbanization also causes problems for the circulation of materials and people, in view of urban transport deficiencies and traffic jam, which affect the economic growth of cities (Quaresma *et al*., 2017).

Understanding and proposing solutions to the present urban problems may contribute to minimize their recurrence in the least developed areas of the planet, which, as explained in the previous item, should boost the process of planetary urbanization in the coming decades.

Zhu *et al*. (2019) highlight that the resources necessary for the construction and operation of tomorrow's cities will be enormous and that the world will need scientific knowledge that can assist in the creation of a future sustainable urban society.

Among the challenges imposed on this knowledge, the level of complexity of urban forms and processes stands out, as well as the development of technological instrumentation applied to research. With regard to technologies, Remote Sensing techniques stand out, since they have brought important advances and contributions to environmental and urban studies.

Remote sensing as an instrument applied to studies of complex urban systems

Cities are constituted in complex systems and, as such, their study, through the systemic approach, faces three difficulties (Batty; Torrens, 2005). The first is in the process of identifying its elements, attributes, and relationships, which falls on the outline of its extension. This difficulty is because most systems do not present themselves in isolation, but rather as constituents of a larger system, which is called the universe. The globalization process deepened this difficulty, especially because most of the processes and forms existing at the local scale find their origins and logic in agents of regional and global scale (Santos, 2000).

Within its universe, the system becomes an element and, therefore, coexists and depends on other subsystems, which constitute its larger set. Thus, a distinction can be made between two groups of systems, the controllers, or antecedents, and the controlled, or subsequent ones (Quaresma, 2008). The relationship between the controlled systems and controllers should not be considered in a linear manner, given the existence of feedback mechanisms, also known as feedback, by which the subsequent systems can again influence the antecedent systems, in an interaction between all their universe (Christofoletti, 1999).

From the decision on which system will be investigated, defining its elements and its relations, it becomes easier to delimit it in space, to identify its components interconnected by internal relations and to establish the external controlling environmental systems. In addition, for each element and relationship discerned in the system, numerous measurable variables can be listed, which express qualities or attributes, such as the number, size, shape, spatial arrangement, flows, intensities, transformation rates, among others (Quaresma, 2008).

In the case of the study of cities, the delineation of the extension of the system to be studied also encounters problems due to the lack of standardization of the concept that clearly establishes its limits. According to Batty and Torres (2005), the clear delineation of the physical limits of an urban area is not an easy task, given that there are at least three ways for its establishment in the literature.

The first path is the administrative limits, which refer to the territorial or political limits of a city. The second is about functional limits, which are delineated according to the connections and interactions between areas, like the interactions provided by economic activities. The third concerns morphological limits based on the form and structure of the landuse or the built environment. According to the authors, the choice among the three mentioned criteria depends on the research question and will substantially influence the results of the analysis.

The second difficulty found in the study of cities, through the systemic approach, is found in the researcher himself, since delimiting a certain system of the earth's surface, constituting a complex reality and which presents a multiplicity of phenomena, requires an ability to profound abstraction, which will depend on the scientist's intellectual training, as well as on his own worldview and environmental perception.

In this case, according to Christofoletti (1999), the reduction of subjectivity involved in the researcher's decision can be carried out based on four norms: (a) contiguity, or the physical proximity of its elements; (b) the same nature or similarity between its elements; (c) the common purpose of its elements; and d) the distinctive or recognizable standardization of its elements.

However, it must be remembered that any one of these rules can be disobeyed individually without harming the system's judgment. Such statement can be exemplified by means of the industrial system, whose constituent elements (raw material, factories and sales points), despite not being contiguously in space, are organized, interrelated and, interdependently, act for a given purpose, thus constituting a system (Quaresma, 2008).

Another obstacle to the study of systems is what Christofoletti (1999) calls the availability of technological instrumentation applied to research. Thanks to the possibilities guaranteed by technological development, the production of new equipment favors obtaining data, understanding, diagnosing, and managing complex organization systems.

In this context, geotechnologies, geographic information systems and remote sensing are inserted, which have been increasingly used in urban studies, contributing to a better understanding of their elements and relationships, as well as their forms and processes.

In view of the central theme of this article, it is worth presenting the concept of remote sensing. Thus, according to Novo (2010), remote sensing is a technology that makes it possible to acquire information about objects, without the need for direct physical contact with them.

Sabins (2007) also defines remote sensing as the science of acquiring, processing and interpreting images and data obtained through sensors on board aircraft and satellites, which capture the interaction between matter and electromagnetic radiation.

According to the aforementioned author, image acquisition refers to the type of sensor used, such as an electro-optical scanning system; processing is the procedure responsible for converting untreated data into images; and image interpretation allows the conversion of an image into information that is meaningful and valuable to a wide range of users.

Remote sensing is, therefore, closely linked to the measurement of electromagnetic radiation reflected or emitted from targets on the earth's surface, as well as to the treatment and availability of this information in a way that can be interpreted (Moreira, 2011).

The interaction between matter and radiation is determined by the physical properties of the matter and the electromagnetic wavelength detected remotely by the sensor. In this sense, the term remote sensing refers to methods that employ electromagnetic energy, such as light, heat and radio waves, to detect and measure the characteristics of objects, called targets (Sabins, 2007).

There has been a significant evolution in remote sensing in recent decades, both in relation to the way in which the sensors are transported, no longer being only airborne by means of aircraft (non-orbital sensors) and now being transported by artificial satellites (sensors orbitals), and in relation to improvements in their technical capacities for the acquisition and processing of the detected electromagnetic energy.

Before the 1960s, the view of the Earth and the Universe was restricted to direct observation and photographs that used visible light. Distant views were obtained only from aircraft and telescopes. Currently, remote sensing provides instruments that visualize targets by means of electromagnetic wavelengths much wider than the wavelengths corresponding to visible light (Sabins, 2007).

According to Zhu *et al*. (2019), there has been a consistent evolution of remote sensing applied to urban studies in the last fifty years. In the 1960s, urban remote sensing was based mainly on the interpretation of aerial photographs. In the same decade, new technologies began to be created, such as those aimed at the acquisition of images by means of wavelengths corresponding to the regions of the electromagnetic spectrum of the infrared and microwaves. This advance greatly expanded the scope and applications of remote sensing.

The launch, in the early 1970s, of the Earth Resources Technology Satellite 1 (ERTS-1), later called Landsat-1, allowed a revolution in remote sensing applied to urban studies, in view of the possibility of obtaining data from Earth's surface using sensors carried by satellites. Since then, the series of Landsat satellites has been widely adopted for remote sensing of urban areas with numerous application possibilities (Donnay; Barnsley; Longley, 2014). This is due to its moderate spatial resolution, which allows the differentiation of several urban elements, as well as the continuity of obtaining images in the long term (z0078 *et al*., 2019).

The Landsat series started from a project developed by the National Aeronautics and Space Administration (NASA), being exclusively dedicated to obtaining data related to terrestrial natural resources. Landsat-1 was the first remote sensing satellite in the world and was also the first to be developed to act directly in research on natural resources (Jirout, 2017).

At the beginning of the 80s, a thermal band was included in Landsats 4 to 8, which allowed to provide consistent measurements of the Earth's surface temperature, being of great value to studies of urban heat islands (Voogt; Oke, 2003).

At the end of the 1990s, the launch of commercial satellites of high spatial resolution, such as IKONOS and QuickBird, further stimulated urban studies that use remote sensing techniques (Bhaskaran; Paramananda; Ramnarayan, 2010), with a view to that such commercial satellites can provide images of spatial resolution similar to that of aerial photographs, but with the advantage of providing this data routinely.

According to Zhu *et al*. (2019), the global mapping of all existing urban areas was not possible before the launch of the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor in 1999. This year, the launch of the Terra satellite took place, and in 2002, from the Aqua satellite, both carrying the aforementioned sensor and which was designed to serve studies of atmospheric, oceanic and terrestrial phenomena.

Although most urban studies that use remote sensing are based on optical and daytime thermal sensors, there are other sensors that also allow unique observations of other urban attributes, such as night light sensors, LiDAR and RADAR (Zhu *et al*., 2019).

Night light sensors can measure artificial night light from specific anthropic activities or in urban areas (Elvidge *et al*., 1997). According to Zhu *et al*. (2019), some of these sensors can provide daily information related to night lights in cities, with an accuracy capable of even detecting small and less developed settlements.

The LiDAR (Light Detection and Ranging) is an active remote sensor (it has its own energy source), which emits laser beams in the band corresponding to the near infrared and allows the generation of three-dimensional models of the surface like the Model Digital Terrain and the Digital Surface Model (Dong; Chen, 2017). Such a sensor has been used more in studies of local scale and has applications in topographic surveys and in studies of characterization of the structure of vegetation and measurements of three-dimensional characteristics of urban infrastructure, such as the volumetric calculation of buildings.

Since the launch of the ERS-1 Satellite (European Remote Sensing Satellite 1), in the early 1990s, RADAR data has been used to map urban growth, with most of the existing small-scale studies. However, given the launch of a larger number of RADAR satellites in recent decades, such as TerraSAR-X, TanDEM-X and Sentinel-1, studies on a continental and global scale are beginning to emerge (Zhu *et al*., 2019). In addition, according to Zhu *et al*. (2012), recent studies have suggested that RADAR and optical data are complementary, and their combined use can increase the accuracy in urban mapping.

In view of the evolution in tools and techniques of remote sensing, as presented in the previous paragraphs, it is worth pointing out examples of their applications in urban studies. In this sense, the topics Heat Island and Monitoring and Water Quality were chosen for this article. However, it is important to highlight that the themes selected here are just as important as all the other existing ones, which will be similarly addressed in future publications.

Remote Sensing and Urban Heat Island studies

Among the changes in terrestrial environments caused by anthropic action, the phenomenon of the Heat Island stands out, which has been observed in the most varied cities in the world and which consists in the fact that temperatures are higher in urban areas than in other areas that surround them (Gartland, 2010).

The main causes of this phenomenon are attributed to changes in the exchange of energy between the Earth's surface and the atmosphere, with a view to waterproofing the surface, caused by changes in land use and occupation (Zhou, 2019). Thus, in urban and suburban areas, many building materials absorb and retain more heat from the sun than natural materials that cover the surface in rural areas (Gartland, 2010).

The Heat Island, as it causes changes in the conditions of the built environment, contributes to the modification of local and regional climatic conditions, as well as impacts the growth of vegetation and the quality of water and air. Such changes, in turn, impact the health and well-being of the inhabitants of urban areas (Zhou *et al*., 2019).

In view of these impacts and many others caused by this phenomenon, as well as the likely intensification of its effects over the next few years, given the expected accelerated urbanization, especially in less developed areas of the planet, the study of the Heat Islands has stood out in academic literature over the past few decades.

According to Zhou *et al*. (2019), existing studies on Heat Islands can be classified into two categories. The first deals with the effects of the phenomenon on the air, which requires the installation of fixed weather stations, or radiosondes on special platforms, in order to carry out their monitoring. However, such equipment is expensive and may take time to install. Thus, they are available in only a few major cities in the world, a fact that does not allow the availability of sufficient data for planning landuse. The second category deals with the differences in electromagnetic radiation between urban and non-urban surfaces, which can be measured by data from thermal remote sensing by satellites. In this sense, remote sensing can provide consistent and periodic data on the Earth's surface, enabling the study of the urban thermal environment at multiple spatial and temporal scales (Weng, 2009).

Zhou *et al*. (2019) bring an important contribution to the theme of remote sensing applied to studies of Heat Islands from the surface, by carrying out a systematic review of existing academic works, from the beginning of the 70s to 2019, the year of publication of their work. In this sense, the aforementioned authors identified an exponentially growing research trend regarding urban surface Heat Islands as of 2005, with trends related to geographic areas, time of day, seasons, research focuses, as well as platforms and the sensors used.

The analysis of the authors allowed to verify that the Asian continent presented 62% of the existing literature on the subject, followed by North America and Europe, with 24% and 15%, respectively. Few publications were found for Oceania, South and Central America, as well as for the African continent, and even for the studies existing in these regions, most of the cities involved were included in global studies and not in studies focused on them. Among the countries that presented publications, China stood out, with 213 works, followed by the United States, with 106, and India, with 38.

Regarding the time of day and season, Zhou *et al*. (2019) pointed out that 69% of surveys focused on a specific time, especially in the morning. The authors also pointed out that the data obtained by the satellites do not normally coincide with the periods of the day when the temperature of the earth's surface is at its maximum or at its minimum.

Regarding the season, the authors cited also observed that more than half of the existing studies focused on a single season, especially in the summer, with only 23% of the existing studies covering all seasons. The authors also pointed out that several studies have confirmed that the intensity of heat islands and their mechanisms vary greatly over time, which highlights the importance of future studies based on data obtained at different times of the day and in different seasons.

With regard to the research focuses, the authors observed that the existing works on urban heat islands are able to address a wide variety of topics, with a predominance of variations in surface temperatures on the local scale, corresponding to 64% of the surveys, followed by impacts of urban expansion, which corresponded to 18%.

Also according to Zhou *et al*. (2019), among the existing remote sensors for the purpose of studying the phenomenon of Heat Islands of urban surface, the following sensors were highlighted: Thematic Mapper (TM), Enhanced Thematic Mapper Plus (ETM+) and Thermal Infrared Sensor (TIRS). All of which belong to the Landsat series. Another sensor that also stands out is the Moderate Resolution Imaging Spectroradiometer (MODIS), carried by the Terra and Aqua satellites. The four sensors mentioned contributed, according to the authors, to 78% of the total of existing publications.

The images obtained by ASTER deserve to be highlighted, since this satellite appeared as the third largest source of data present in the analyzed studies. According to Zhou *et al*. (2019), the lower participation of the use of images from this satellite in the evaluated studies is explained by the high cost to obtain its images, in view of the demand for charging for access to them between 1999 and April 2016. The Since then, the images have become available at no cost to all users, a fact that, according to the authors, should favor the growth in the use of this technology in future studies.

Remote Sensing and monitoring and water quality studies

The physical, biological, and chemical characteristics that water must have to meet the needs of various types of use, including human consumption, irrigation, and recreation, define its quality (Sagan *et al*., 2020). This quality is related to the health of society and ecosystems, so its deterioration represents a risk to human health, food productivity and biodiversity (Ramadas; Samantaray, 2018). However, access to clean water has become an increasingly critical issue worldwide, in view of population growth, changes in land use and occupation and the increase in the load of pollutants, both in rural and urban areas (Sagan *et al*., 2020).

Thus, most of the existing water bodies are currently contaminated with arsenic, cadmium, chloramine, chromium, fluoride, bacteria and viruses, lead, nitrates, nitrites, mercury, perchlorate, radio, selenium, silver, and uranium. In addition to these, there are also contaminants from pharmaceutical products, personal care products and endocrine disrupting compounds, called emerging pollutants (Reis Filho; Luvizotto-Santos; Vieira, 2007), whose effect is not yet fully understood (Petrovic; Xydeas, 2004).

The study of the quality of the water depends on the distinction between point sources and non-point sources of pollution. As examples of the former, factories and other industrial and commercial installations that release toxic substances into the water can be mentioned. Non-point sources, on the other hand, are a more complex problem, including emissions from transport vehicles, agricultural runoff, which can carry excess nutrients, pesticides and sludge into rivers and aquifers, as well as urban runoff, which can carry toxic and organic metals from manholes to sewage treatment plants or directly to rivers and lakes (Spiro; Purvis-Roberts; Stigliani, 2012).

In this sense, water quality is affected by the load of nutrients, chemicals, and sediments from runoff in rural and urban areas. The excess of nitrogen and phosphorus can create conditions for the growth of algae and of aquatic plants, leading to eutrophication (a drop in dissolved oxygen) and the death of fish. Climate changes, characterized by rising temperatures and anomalies in rainfall, are also associated with increased nutrients in the waters, as they contribute to the algae growth. Some of these algae can cause damage to human life, from limiting the recreational use of lakes and coastal waters, due to changes in taste and smell, to some types of cancers and tumors. Water pollution and eutrophication are estimated to cause an economic loss of 6 to 16 billion dollars, in addition to causing more than 3 million deaths per year worldwide (Sagan *et al*., 2020).

Among the main parameters used in studies related to water quality, it is possible to mention the concentration of chlorophyll-a, salinity, temperature, pH, total dissolved solids, total suspended solids, algae proliferation, turbidity, total organic carbon, total hardness and concentration of potassium, phosphorus and nitrogen. The concentration patterns of the contaminants vary depending on the type of use needed (Gholizadeh; Melesse; Reddi, 2016).

According to Ramadas and Samantaray (2018), the collection in the field of water samples from water bodies and at regular intervals of time has been the first source of information regarding water quality for monitoring purposes. However, this practice becomes worrying in relation to costs and time, especially when applied to large-scale spatial studies.

Thus, advances in the field of Remote Sensing, reflected in the improvement of the spectral and spatial resolutions of the sensor systems used, as well as in the improvement of spatial modeling techniques, have allowed the monitoring of water quality parameters in a satisfactory manner, at low costs and with greater precision (Ramadas; Samantaray, 2018).

It is important, however, to highlight that remote sensing techniques do not imply the elimination of field monitoring activities, but are added to these, allowing the identification of zones and types of contamination, as well as the development of strategies for the remediation of contamination.

At the beginning of space environmental monitoring, marked by the launch of the ERTS-1 Satellite (Earth Resources Technology Satellite) in August 1972, oceanographers were aware that chlorophyll and temperature could be monitored remotely. They also had ideas about procedures needed to extract information obtained by satellites about chlorophyll concentrations through the color of the water in the middle of the ocean. Limnologists, however, had almost zero knowledge on how to perform spatial monitoring of inland water quality parameters or how to extract such parameters if they could be monitored (Bukata, 2013).

However, after the early 1970s, physical limnologists conducted exceptional research in the field of lake optics and biogeo-optical modeling for inland waters and coastal water bodies. In such a way that important advances can be pointed out, such as: (a) Monte Carlo simulations of the energy transfer that occurs in waters of optically complex lakes (Gordon *et al*., 1975); (b) field and laboratory methods for determining the optical spectra of cross-section of color producing agents, organic and inorganic, in suspension and/or dissolved in lake waters; (c) non-linear multivariate optimization methodology; and (d) inverse biogeo-optical models that extract co-existing concentrations of these color-producing agents from color spectra of inland waters obtained from satellites (Bukata, 2013).

The contributions of remote sensing lie in the fact that the different existing sensors have the ability to acquire information about objects on the planet's surface by reading their spectral signatures. In this way, such sensors provide information about contaminants present in water bodies and their concentration and can be translated into different water quality indicators.

Thus, the spectral reflection of clean water is low in all bands of the electromagnetic spectrum. However, the reflection increases in the visible part due to different materials suspended in the water helping the distinction between clean water and water loaded with sediments (Lillesand; Kiefer, 1994).

The water absorbs radiation in the red and infrared regions close to the electromagnetic spectrum and no reflectance is detectable from a body of clean water above 750Nm of wavelength, however, the algae reflectance is detectable due to the presence of chlorophyll-a and phycocyanin. Sagan *et al*. (2020) mentions several studies and models that have been developed from the Landsat, MODIS and MERIS sensors, with ways to estimate the levels of chlorophyll-a and suspended sediments in large rivers, in reservoirs and in lakes.

However, in addition to the water quality variables mentioned in the previous paragraph, there are others that, because they are not optically active or because there is a lack of hyperspectral data in good spatial resolution, cannot be measured directly using current satellites, such as concentrations of nitrogen and phosphorus, dissolved oxygen levels and microorganisms/pathogens. Some studies, based on hyperspectral images, have made it possible to improve estimates of total nitrogen and phosphorus, based on scattering peaks and reflectance values caused by chlorophyll absorption. However, the models generated from these studies cannot yet be generalized (Sagan, 2020).

Despite the advances in the development of algorithms, which contribute to the improvement of the generated models, one of the still existing limitations is the relative unavailability of sensors that contemplate, at the same time, good spatial and spectral resolutions. This highlights the importance of sensors such as AVIRIS, HyMap, HyspIRI (Hyperspectral Infrared Imager) and future satellite missions, including NASA's Surface Biology and Geology mission, PRISMA (Italy), HISUI (Japan) and EnMAP (Germany), which can contribute to the solution of this problem (Sagan, 2020).

Regarding the potentials of modern technological instruments that allow evolution of studies related to monitoring water quality, Ramadas and Samantaray (2018) also highlight that monitoring and remediation of water quality were benefited by the most recent images from Sentinel-2 and Landsat 8. Sentinel-2 is part of Global Monitoring for Environment and Security (GMES), which is an initiative of the European Commission and the European Space Agency.

According to Drusch *et al*. (2012), Sentinel-2 has a high temporal resolution, considering that the presence of two identical satellites operating simultaneously allows a revisit frequency of five days. In addition, it also has an excellent spectral resolution with thirteen spectral bands that cover the visible, near infrared and infrared. Finally, its spatial resolution also becomes a major differential, ranging from 10m to 60m, depending on the spectral band used. These characteristics, added to the wide field of view of 290km, make Sentinel-2 a great advance in comparison to other existing multispectral missions.

The main objectives of Sentinel-2, according to Drusch *et al*. (2012), are: Provide global and systematic acquisition of high resolution multispectral images with a high frequency of return visits; Provide enhanced continuity to multispectral images provided by the SPOT satellite; And provide information for the next generation of operational products such as land cover maps, maps for detecting changes in use and occupation and geophysical variables (Drusch *et al*., 2012).

The data obtained by Sentinel-2 bring important contributions to studies inherent to risk management (floods and forest fires, subsidence and landslides), changes in land use, forest monitoring, food security, management of water and soil protection, urban mapping, and humanitarian aid and development mapping (Drusch *et al*., 2012).

Sentinel-2 also provides data with the proper quality for monitoring agricultural practices and for monitoring coastal and inland waters (Ramadas; Samantaray, 2018).

Also noteworthy are the advances in the use of Unmanned Aerial Vehicles (UAV), which have allowed regional and innovative monitoring of inland surface waters, especially regarding the presence of algae and suspended sediments (Vogt; Vogt, 2016).

Ramadas and Samantaray (2018) published a review on the state of the art of Remote Sensing applications in monitoring and remediation of water quality and highlighted the contributions of Geographic Information Systems in this field. According to the authors, several remote sensing techniques have been adopted in studies with ways to assist in monitoring and managing water quality, however, it is the Geographic Information Systems that make it possible to link water quality monitoring in space and time perfectly with reduced cost remediation strategies. According to the authors, such systems have also contributed to data collection and communication of risks related to water quality in real time through the display of maps.

References

Batty, M.; Torrens, P. M. Modelling and prediction in a complex world. *Futures*, v. 37, n. 7, p. 745-766, 2005. https://doi.org/10.1016/j.futures.2004.11.003.

Bhaskaran, S.; Paramananda, S.; Ramnarayan, M. Per-pixel and object-oriented classification methods for mapping urban features using Ikonos satellite data. *Applied Geography*, v. 30, n. 4, p. 650-665, 2010. https://doi.org/10.1016/j.apgeog.2010.01.009.

Bukata, R. P. Retrospection and introspection on remote sensing of inland water quality: "Like Déjà Vu all over again". *Journal of Great Lakes Research*, v. 39, p. 2-5, 2013. https://doi.org/10.1016/j.jglr.2013.04.001.

Christofoletti, A. *Modelagem de sistemas ambientais*. São Paulo: Editora Blucher, 1999.

Cordeiro, A. M. *et al*. Systematic review: a narrative review. *Revista do Colégio Brasileiro de Cirurgiões*, v. 34, n. 6, p. 428-431, 2007. https://doi.org/10.1590/S0100-69912007000600012.

Dong, Pinliang; CHEN, Qi. LiDAR remote sensing and applications. CRC Press, 2017.

Donnay, J-P.; Barnsley, M. J.; Longley, P. A. (ed.). *Remote sensing and urban analysis*: GISDATA 9. Boca Raton: CRC Press, 2014.

Drusch, M. *et al*. Sentinel-2: ESA's optical high-resolution mission for GMES operational services. *Remote Sensing of Environment*, v. 120, p. 25-36, 2012. https://doi.org/10.1016/j.rse.2011.11.026.

Elvidge, C. D. *et al*. Mapping city lights with nighttime data from the DMSP Operational Linescan System. *Photogrammetric Engineering and Remote Sensing*, v. 63, n. 6, p. 727-734, 1997.

Gartland, L. *Ilhas de calor*. São Paulo: Oficina de Textos, 2010. p. 9-10.

Gordon, Howard R.; Brown, Otis B.; Jacobs, Michael M. Computed relationships between the inherent and apparent optical properties of a flat homogeneous ocean. *Applied Optics,* v. 14, n. 2, p. 417-427, 1975.

Gholizadeh, M. H.; Melesse, A. M.; Reddi, L. A comprehensive review on water quality parameters estimation using remote sensing techniques. *Sensors*, v. 16, n. 8, p. 1298, 2016. https://doi.org/10.3390/s16081298.

Hoornweg, D.; Bhada-Tata, P. *What a waste*: a global review of solid waste management. Washington: World Bank, 2012. (Urban development series. Knowledge papers n. 15). Available from: https://openknowledge.worldbank.org/handle/10986/17388. Cited: Oct. 27 2020.

Jirout, Brian. *One satellite for the world: The American Landsat earth observation satellite in use, 1953-2008.* 2017. Tese de Doutorado. Georgia Institute of Technology.

Kadhim, N.; Mourshed, M.; Bray, M. Advances in remote sensing applications for urban sustainability. *Euro-Mediterranean Journal for Environmental Integration*, v. 1, n. 1, p. 7, 2016. https://doi.org/10.1007/s41207-016-0007-4.

Lillesand, Thomas M.; Kiefer, Ralph W. Remote sensing and image interpretation. 3rd ed. New York: John Wiley, 1994.

Moreira, M. A. *Fundamentos do sensoriamento remoto e metodologias de aplicação*. 4. ed. Viçosa: Editora UFV, 2011.

Novo, E. M. L. *Sensoriamento remoto*: princípios e aplicações. São Paulo: Editora Blucher, 2010.

Oke, T. R. The energetic basis of the urban heat island. *Quarterly Journal of the Royal Meteorological Society*, v. 108, n. 455, p. 1-24, 1982. Available from: http://www.patarnott.com/pdf/Oake1982_UHI.pdf. Cited: Oct. 27 2020.

Petrovic, V. S.; Xydeas, C. S. Gradient-based multiresolution image fusion. *IEEE Transactions on Image Processing*, v. 13, n. 2, p. 228-237, 2004. https://doi.org/10.1109/TIP.2004.82382.

Quaresma, C. C. *et al*. A crise de mobilidade urbana brasileira e seus antecedentes socioespaciais. TTP na qualidade de vida de idosos. *Ciência & Saúde Coletiva*, v. 13, n. 4, 2017. Disponível em: http://esppiral.hom.capes.gov.br/handle/esppiral/395802. Acesso em: 27 out. 2020.

Quaresma, C. C. *Organizações espaciais físico/naturais e fragilidades de terras sob Cerrado*: abordagem sistêmica aplicada à escala local. 2008. 138 p. Dissertação (Mestrado em Geografia – Instituto de Geociencias, Universidade Estadual de Campinas, Campinas, 2008. Disponível em: http://www.repositorio.unicamp.br/handle/REPOSIP/287380. Acesso em: 27 out. 2020.

Ramadas, M.; Samantaray, A. K. Applications of remote sensing and GIS in water quality monitoring and remediation: a State-of-the-Art Review. *In*: Bhattacharya, S. *et al*. (eds). Water remediation. *Energy, Environment, and Sustainability*. Singapore: Springer, 2018. https://doi.org/10.1007/978-981-10-7551-3_13.

Reis Filho, R. W.; Luvizotto-Santos, R.; Vieira, E. M. Poluentes emergentes como desreguladores endócrinos. *Journal of the Brazilian Society of Ecotoxicology*, v. 2, n. 3, p. 283-288, 2007. https://doi.org/10.5132/jbse.2007.03.012.

Sabins, F. F. *Remote sensing*: principles and applications. Illinois: Waveland Press, 2007.

Sagan, V. *et al*. Monitoring inland water quality using remote sensing: potential and limitations of spectral indices, bio-optical simulations, machine learning, and cloud computing. *Earth-Science Reviews*, v. 205, p. 103187, 2020. https://doi.org/10.1016/j.earscirev.2020.103187.

Santos, M. *Por uma outra globalização*: do pensamento único à consciência universal. São Paulo: Record, 2000.

Scarlato, F. C. População e urbanização brasileira. *In*: *Geografia do Brasil*. 5. ed. São Paulo: Edusp, 2005.

Seto K. C. *et al*. Human settlements, infrastructure and spatial planning. *In*: Edenhofer, O. (ed.). *Climate change 2014*: mitigation of climate change. Contribution of working group III to the fifth assessment report of the intergovernmental panel on climate change. Cambridge: Cambridge University Press, 2014.

Spiro, T.G.; Purvis-Roberts and Stigliani, W.M. Chemistry of the Environment London: Prentice-Hall, 2012.

United Nations. *2018 revision of world urbanization prospects*. 2018. Available from: https://population.un.org/wup/Publications/Files/WUP2018-Report.pd. Cited: Aug. 7, 2020.

Villela, A. V.; Suzigan, W. *Política econômica e crescimento da economia brasileira*: 1889-1945. Brasília: Instituto de Pesquisa Econômica Aplicada, 1973.

Vogt, M. C.; Vogt, M. E. Near-remote sensing of water turbidity using small unmanned aircraft systems. *Environmental Practice*, v. 18, n. 1, p. 18-31, 2016. https://doi.org/10.1017/S1466046615000459.

Voogt, J. A.; Oke, T. R. Thermal remote sensing of urban climates. *Remote Sensing of Environment*, v. 86, n. 3, p. 370-384, 2003. https://doi.org/10.1016/S0034-4257(03)00079-8.

Weng, Q. Thermal infrared remote sensing for urban climate and environmental studies: methods, applications, and trends. *Journal of Photogrammetry and Remote Sensing*, v. 64, n. 4, p. 335-344, 2009. https://doi.org/10.1016/j.isprsjprs.2009.03.007.

Zhou, D. *et al*. Satellite remote sensing of surface urban heat islands: progress, challenges, and perspectives. *Remote Sensing*, v. 11, n. 1, p. 48, 2019. https://doi.org/10.3390/rs11010048.

Zhu, Z. *et al*. Understanding an urbanizing planet: Strategic directions for remote sensing. *Remote Sensing of Environment*, v. 228, p. 164-182, 2019. https://doi.org/10.1016/j.rse.2019.04.020.

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