GEOTECHNOLOGIES AND INCREASED ACCURACY IN ORIGINAL AND ANTHROPOGENIC MORPHOLOGIES MAPPING APPLIED TO FLOOD RISK ASSESSMENT

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ABSTRACT

This paper presents new developments on cartographic methodologies to investigate the impact of urbanization on fluvial systems exploring new advances on geotechnologies. The analysis performed with high resolution data highlights the increase in surface connectivity due to urban structures, altering flood dynamics. Key findings include new possibilities for original fluvial plain restitution and mapping, identification of flood spread areas restriction due to the presence of buildings and the narrowing of floodplains. The results underscore the need for integrating geomorphological insights in urban planning to mitigate flood risks and preserve floodplain storage capacity.

Keywords: Urban floods; Urban geomorphology; Flood dynamics; Surface connectivity; Hydrological modeling.

RESUMO

GEOTECNOLOGIAS E MAIOR PRECISÃO NO MAPEAMENTO DE MORFOLOGIAS ORIGINAIS E ANTROPOGÊNICAS APLICADAS À AVALIAÇÃO DO RISCO DE INUNDAÇÕES. Este artigo apresenta novos avanços em metodologias cartográficas para investigar o impacto da urbanização nos sistemas fluviais, explorando os recentes avanços em geotecnologias. A análise realizada com dados de alta resolução destaca o aumento da conectividade superficial devido às estruturas urbanas, alterando a dinâmica das inundações. Os principais achados incluem novas possibilidades para a restituição e o mapeamento de planícies fluviais originais, a identificação de restrições nas áreas de dispersão de inundações devido à presença de edificações e o estreitamento das planícies de inundação. Os resultados ressaltam a necessidade de integrar *insights* geomorfológicos no planejamento urbano para mitigar os riscos de inundações e preservar a capacidade de armazenamento das planícies de inundação.

Palavras-chaves: Inundações urbanas; Geomorfologia urbana; Dinâmica de inundações; Conectividade superficial; Modelagem hidrológica.

RESUMEN

GEOTECNOLOGÍAS Y MAYOR PRECISIÓN EN EL MAPEO DE MORFOLOGÍAS ORIGINALES Y ANTROPOGÉNICAS APLICADAS A LA EVALUACIÓN DEL RIESGO DE INUNDACIONES. Este artículo presenta nuevos desarrollos en metodologías cartográficas para investigar el impacto de la urbanización en los sistemas fluviales, explorando avances recientes en geotecnologías. El análisis realizado con datos de alta resolución destaca el aumento en la conectividad superficial debido a las estructuras urbanas, alterando la dinámica de las inundaciones. Los hallazgos clave incluyen nuevas posibilidades para la restitución y el mapeo de planicies fluviales originales, la identificación de restricciones en las áreas de dispersión de inundaciones debido a la presencia de edificaciones y el estrechamiento de las planicies de inundación. Los resultados subrayan la necesidad de integrar conocimientos geomorfológicos en la planificación urbana para mitigar los riesgos de inundaciones y preservar la capacidad de almacenamiento de las planicies de inundación.

Palabras clave: Inundaciones urbanas; Geomorfología urbana; Dinámica de inundaciones; Conectividad superficial; Modelado hidrológico.

1 INTRODUCTION

The interaction between geomorphological processes and human activities has been widely recognized as a fundamental element in the configuration of urban environments and the intensified occurrence of flood events. Literature on the subject, notably DOUGLAS (1983), highlights this interdependence, emphasizing how social and economic agents actively shape natural systems through urbanization processes. Based on this premise, a detailed understanding of how anthropogenic actions influence the processes, materials, and forms of the Earth's surface becomes essential for a comprehensive and precise analysis of fluvial systems and their interactions with the urban environment (NIR 1987; RODRIGUES 1999, 2004, 2005, 2010).

The analysis of the impacts of urbanization on fluvial systems requires an integrated approach that considers both the original geomorphological aspects and the alterations resulting from human intervention over time (HOOKE 1995, GURNELL et al. 2003, LUZ & RODRIGUES 2015, RODRIGUES et al. 2019). In this context, high-resolution geotechnologies emerge as a powerful tool for characterizing and analyzing the geomorphological and hydrological processes associated with urban flooding. These technologies, when combined with a forensic approach to flood events, as proposed by OLIVER-SMITH et al. (2016) for "natural disasters," enable the precise identification of the causes and patterns associated with these events (SIMAS 2023).

To conduct this analysis, seeking causal factors of floods in highly urbanized basins, this study employs techniques and procedures from research in anthropogeomorphology, fluvial geomorphology, hydrological, and hydraulic modeling at a detailed scale, compatible with urban planning instruments at the lot or block level (NUNES et al. 1994). Additionally, it explores the fact that instrumentation for direct data collection (such as flow and rainfall data) has seen significant advancements in recent years, increasing precision, resolution (data with higher frequency of collection and transmission), and accessibility, with proportionally lower installation and maintenance costs, leading to denser telemetric networks. Simultaneously, in the last decade, public agencies related to the subject have played a role in disseminating open data through online portals integrated into GIS platforms, aggregating important material for geographic analyses.

The study is conducted based on a methodology developed by RODRIGUES (1999, 2004, 2005, 2010), which proposes an approach primarily for evaluating urban changes from a geomorphological perspective, focusing on fluvial systems. This enables metrics and dialogues with other analytical perspectives, including hydrology and hydraulics. This analytical perspective allows for the measurement of these changes, facilitating actions for recovery, preservation, among others. This methodology requires the development of retrospective geomorphological analyses of the studied hydrogeomorphological systems, starting from the pre-urban scenario. In this study, this retroanalysis was carried out through retrospective cartography of the original floodplain compartments. These analyses incorporated multiple tools and data types, such as aerial photographs, satellite images, land use and occupation maps, as well as various historical sources (GURNELL et al. 2003), alongside those used in hydraulic and hydrological modeling (BENITO & HUDSON 2010, VENEZIANI et al. 2019).

The reconstruction of the original floodplain system in a sample basin, currently with a high rate of urbanization, and the identification of flood events in the recent period were achieved, with the identification of precipitation, flow, and elevation patterns among them. In pursuit of identifying causal factors, these results revealed events that occurred exclusively due to process rates produced by anthropogenic action, such as impermeabilization and the increased surface connectivity through the introduction of macro and microdrainage structures. Additionally, it was possible to analyze these results comparatively, with studies developed internationally in environments distinct from the humid tropical environment, both in terms of the results obtained and the identification of the applicability of unprecedentedly adapted methodologies (HOOKE 2016, 2019; XIAORONG et al. 2021; MACDONALD et al. 2022). This instrumentation allowed for advancements on long-discussed issues within the scope of urban flood problems, such as the effect of the loss of storage capacity in floodplain morphology on the intensification of events and the hydraulic effects of the presence of buildings within these hydrogeomorphological systems (LUZ & RODRIGUES 2015, RODRIGUES et al. 2019).

2 OBJECTIVES

The research hypothesizes that recent floods in São Paulo's densely urbanized basins exhibit flash flood traits, and human interventions, like channel rectification, worsen flow extremes and storage loss, proposing a multidisciplinary approach to identify causal factors and flooding thresholds. Due to the study area's complexity, a representative urbanized watershed in São Paulo was selected for detailed analysis (Figure 1), featuring common lithological and hydrographic traits to most of the urban site and a main straightened watercourse originally meandering.

2.1 The need for high-resolution data

Within the scientific field of geomorphology, the specialty known as anthropogeomorphology focuses on analyzing the alterations resulting from human actions on forms, materials, and processes, among which urbanization stands out as the most intense (THOMAS 1956; BROWN 1970; NIR 1983; CRUTZEN 2002; RODRIGUES 1999, 2004, 2005, 2010; GOUDIE 2013; GOUDIE & VILES 2016; RODRIGUES & COLTRINARI 2004). This approach allows not only for an understanding of

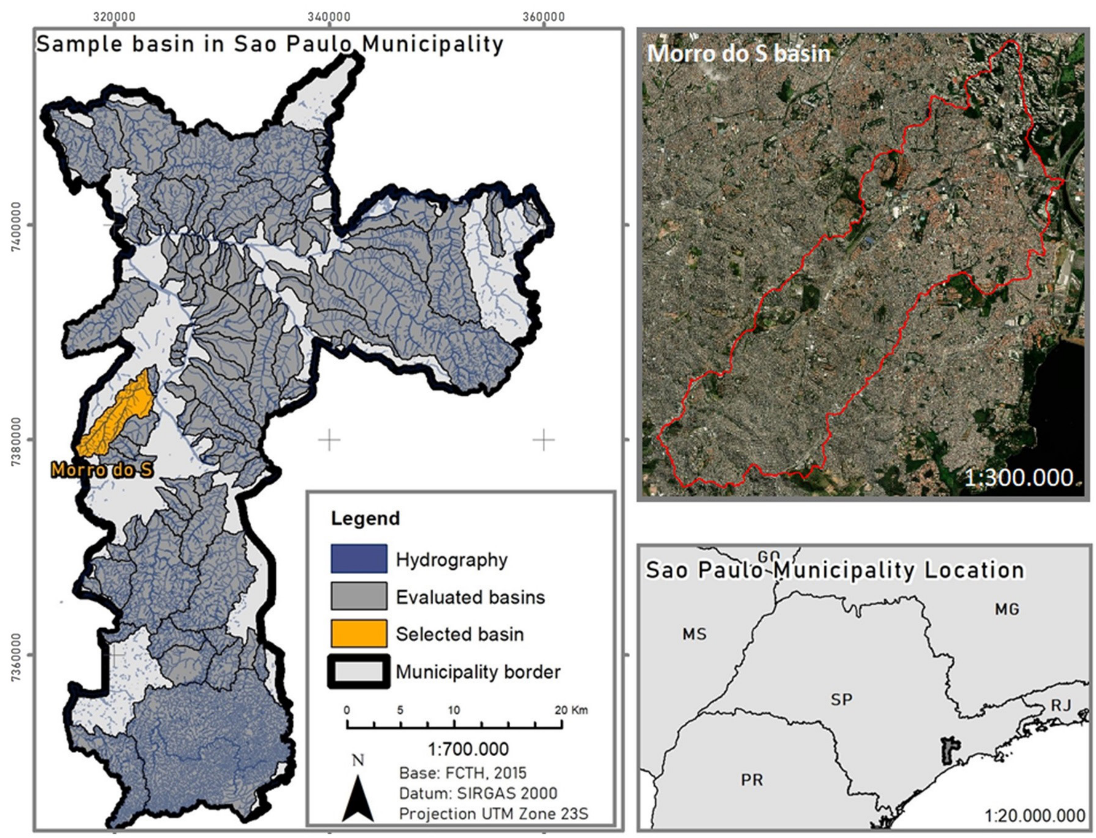


FIGURE 1 – The study area (sample basin) within the city of São Paulo.

long-term changes but also for the investigation of historical events and short-term fluctuations resulting from this environment's response to extreme climatic events (RODRIGUES 2010, RODRIGUES et al. 2019).

Similarly, within the scientific field of geographical climatology, the analytical perspective of urban climate, which examines the effects of intense or concentrated rainfall on urban areas, is crucial for understanding the modified physical systems (MONTEIRO 1976). This complex interaction between the atmosphere and the transformed urban environment not only influences the local climate but also generates a significant socio-environmental dimension (SANT'ANNA NETO 2011). Studies such as those by MONTEIRO (1976) and LOMBARDO (1985) demonstrate the impact of human interventions on the mechanisms governing precipitation, highlighting the importance of approaches that consider refined temporal details (MONTEIRO 1971, apud SANT'ANNA NETO 2001).

The assumption that comprehending climatic and geomorphological changes in urbanized environments is essential to mitigate risks, such as floods, has been disseminated across various fields of geographical knowledge for many decades. However, one of the significant challenges encountered in the practical application of these analyses in Brazil has long rested on the unavailability of systematized data and technological limitations for research. In this regard, authors such as CHRISTOFOLETTI (1981) foresaw that tools such as Geographic Information Systems (GIS) would play a crucial role in enabling the integration of topographic, hydrological, and environmental data for a detailed spatial analysis of watersheds. BROOK & MARKER (1988) also highlight that these tools would be essential for identifying areas susceptible to erosive and sedimentation processes along rivers, with direct implications for water resource management and territorial planning. Currently, this analysis can be instrumentalized through hydraulic modeling combined with GIS, widely employed in industries such as water utilities (treatment, distribution, and wastewater collection).

Another challenge for the use of geotechnologies in scientific research on anthropogenic changes in the environment has for many decades been defined by the inexistence or inaccessibility of high temporal and spatial resolution remote sensing data. This is particularly relevant for urban geomorphology since the introduction of urban structures (part of the anthropogenic morphology) adds new variables necessary for flood risk analysis while potentially suppressing others (such as lithology) on a non-proportional scale. For example, the study by MCDONALD et al. (2022) indicates that in a highly urbanized basin, peak flow becomes more sensitive to 10-minute rainfall intensity while antecedent soil moisture becomes less important. The complex forms of the built environment strongly influence local hydrological characteristics, with no direct relationship between runoff percentage and precipitation or antecedent soil moisture in a highly urbanized basin. Finally, recent studies indicate that greater accuracy is required in understanding how surface water drainage systems hydraulically connect to the urban surface (REDFERN 2017, XIAORONG et al. 2021, MCDONALD et al. 2022), which could not be observed without the tools or platforms capable of high-resolution analysis.

To locate, identify, collect, and catalog physical evidence of the determining factors in the occurrence of extreme flood events, remote sensing tools provide non-destructive and non-invasive means for information capture. High-resolution instruments and high-precision processing are required to achieve the proposed objective, allowing for the evaluation of small contrasts on the surface with a very high temporal frequency. In other words, this high-detail investigation should sample small and discrete temporal intervals of a location while obtaining high-quality data that has undergone validation procedures. According to DAVENPORT (2001), the factors that can limit the quality of the obtained data are resolution, signal-to-noise ratio, contrast, and size/depth ratio.

1. Resolution is defined as the ability to differentiate objects that are very close. The proximity of objects can relate to their physical closeness or the similarity of physical properties.

2. The intensity/strength of the signal must be higher than that of randomly generated background signals (noise). Field procedures, filters, and greater computational processing capabilities provide means to improve the signal-to-noise ratio, enhancing the quality and resolution of remote sensing data.

3. Contrast is measured by the ability to differentiate the properties of the target object from the adjacent material.

4. The larger the object, the more deeply it can be detected, and generally, lower frequency inputs (which are less affected by the terrain) are used to obtain better resolution than higher frequency signals.

Understanding anomalies in remote sensing data is based on knowledge of each method's capabilities and limitations and interpreting the data in correlation with other information, such as soils, geology, and climatic conditions. The challenge then is to properly leverage these technologies, using the highest quality and most current data possible, to encompass the complexity of modified hydrogeomorphological systems and provide more accurate information.

2.2 Usage of high-resolution data on urban flood risk assessment

It is recognized that the ability to provide interpreted and systematized information from a systemic perspective generates interest among stakeholders involved in the formulation and implementation of environmental and risk reduction policies, making them potential clients of geomorphological information (BROOK & MARKER 1988). According to BROOK & MARKER (1988), this information is traditionally conveyed in the form of:

A) Factual element mapping (distribution of rock types, presence of technogenic deposits, contaminated soils, etc.);

B) Interpretive maps (hydrography and water availability, susceptibility to floods and geodynamic events);

C) Databases of information regarding resources that enable and limit development (primary data such as terrain morphology necessary for prospecting and budgeting for works, for example).

For the use of this information in risk management (such as floods), JONES (2004) identifies gaps in communication exercised by cartographic documents, as most maps are not of actual floods but of imaginary floods. For example, consider the 100-year flood maps, whose name is misleading because they are based on statistical probabilities for a specific location and not for a region. This means there is always a chance that the "100-year flood" will occur somewhere in the region every year (JONES 2004).

More detailed forecasts are generally made for less specific points, and they do not indicate whether a house, business, or sewage treatment plant is in danger of being flooded. As JONES (2004) aptly summarizes, what the residents living in a floodplain need is a map showing where the flood is expected. If possible, this map should be in as simple and accessible a language as possible so that this information can be communicated effectively and quickly. To provide this product, it is necessary to acquire very accurate elevation data of the floodplain through LIDAR; a program that can simulate flood flows through a floodplain downstream of the prediction point; and spatial analysis software (GIS) that transforms the resulting models into maps and can provide an integrated view from the entire watershed to the specific point of interest.

Currently, systems based on artificial intelligence integrated with geographic (or locational) intelligence also allow for mass communication triggers for areas at risk in the situation of an extreme event being predicted. Likewise, these systems enable the translation of information present in complex mappings and geographic databases to make decision-making more effective, by converting cartographic information into natural language.

In consequence, without mastering detailed information about physical environment variables, built structures, and technologies that enable integrated analysis of these, permanent flood control cannot be conceived. By this is meant control as a permanent process, with attention to potential future violations of legislation in the expansion of land use in risk areas. Alongside the ideal of universalizing environmental sanitation, these form a pair of concepts in vogue in urban and environmental planning, but insufficiently articulated from a technical and methodological point of view.

3 METHODOLOGY

The following methodology was applied to a watershed located in the municipality of São Paulo, selected as a sample due to the size of the geographic databases necessary for conducting the proposed analyses. A total of 148 watersheds in the municipality were evaluated, and the sample watershed was considered representative for analyzing the effects of urbanization in the humid tropical environment based on the following variables: 1 - Average area of the municipality's watersheds; 2 - Total length of watercourses and drainage density of the watersheds; 3 - Altimetric gradient; 4 - Average slope; 5 - Presence of mapped risk areas and subnormal clusters; 6 - Population in the census sectors circumscribed within the watershed; 7 - Predominant land use; 8 - Concentration of Social Interest Zones; 9 - Availability of fluviometric and pluviometric stations within the watershed.

3.1 Orthophotos and topographic data

The hydrography was revised based on LIDAR topographic data and high-resolution orthophotos to correct vectors and correlated with information on sewage and stormwater collection structures to classify them as "courses in artificial channels," "channelized courses underground," and "courses in natural channels". Land use mapping and the delineation of subnormal occupations ("favelas") were also revised according to 2018 orthophotos, following the original class definitions as mapped by the São Paulo Municipal Government. These orthophotos are a product of aerial photography with a 12 cm GSD correction for perspective distortion using OrthoVista software and roughness correction using LIDAR topographic data, both made available by the São Paulo Municipal Government. The orthophotos covering the study area were composed into an orthomosaic using ArcGIS Pro software.

The processing of LIDAR data to generate digital terrain and surface models for the study area constituted a specific stage. The data were obtained through topographic surveying by laser profiling using an Optech GEMINI LIDAR sensor mounted on an aircraft at a constant height of 2870 m. The topographic data captured were calibrated by ground control points with GNSS in the field and then post-processed, resulting in a point cloud with valid sensor responses (noise excluded), identifying all surface objects. This product, separated into .las file sets, was organized into a Lidar Dataset, which was then used to generate a Digital Surface Model (DSM) with a resolution equal to the orthophotos generated by the same project, at 12 cm.

3.2 LIDAR data and connectivity

With the surface profiling data, an extensive reclassification of points was carried out by a production team into the following categories: buildings and structures, terrain (ground), vegetation, power transmission lines, water bodies, and other surface objects (vehicles, poles, etc.). Consequently, the points representing only the terrain could be separated, allowing the grouping of points stored in .las extension into a new Lidar Dataset, which was then used to generate a digital terrain model (DTM), also with a resolution of 12 cm.

It is emphasized that, as the objective of this research involves the application of an analysis methodology at a detailed scale aimed at providing viable results for urban planning, the data were processed to present results with a Cartographic Accuracy Standard A at a scale of 1:1000. This means that a maximum planimetric error of 0.5 m was assumed for all produced mappings, configuring a scale compatible with most urban infrastructure projects. To meet this same scale, aerial photos from the pre-urban period (1962) were used for georeferenced vector delineation, via stereoscopy (and subsequently from Lidar-derived spatial model), of compartments of the original Fluvial Plain (Floodplain, levels 1 and 2 of terraces, and backswamps).

Regarding the surface (land use) characteristics, based on what was carried out by REDFERN (2017), for a basin with a high rate of impermeabilization, which we identified across almost its entire surface, one of the indicators that would allow us to assess the discontinuities in the hydrological response of the altered system is the connectivity index. This can be defined as the surface distance from each impervious area unit to the nearest drainage, creating a heat map with metric units.

The surface connectivity mapping was performed for both the original and anthropogenic scenarios. In the first case, the distance to the available drainage network vectors was calculated, since there was no restitution of the original hydrography of the area and, even if there had been, the maximum difference found would be in the order of tens of meters. For the anthropogenic scenario, the vectors of the sewage collection network were included, as there is no availability of systematically georeferenced data of the stormwater drainage network. This data is considered adequate, given the recognized high incidence of interceptions between the sewage and stormwater networks, which satisfies the need to consider the artificially introduced gravitational water transport structures.

The resulting map for the anthropogenic scenario was subtracted from the map of the original scenario, thus representing the areas where the introduction of artificial drainage structures created the greatest increase in connectivity. The result, a map of connectivity increase, had its values normalized from the maximum found, so that it presented values up to 100%.

Finally, a simulation of flood spreads produced by the most intense rainfall events identified in the years 2017 and 2018 was performed, showing their progression (affected area and depth) every 10 minutes based on elevation data from three telemetric (pluvial/fluvial) stations positioned along the main course of the watershed. This was done by calculating the surface difference of the DTM of the watershed with the elevations recorded by the fluviometric stations (interpolated as TIN). Areas identified as "below" the projected water level were filtered according to their immediate connection with the main channel; areas not directly connected (intercepted by buildings, terrain cuts, vegetation, etc.) were removed.

4 RESULTS AND DISCUSSION

4.1 Original morphology mapping

The primary data production was carried out through the partial application of the methodology developed by RODRIGUES (1999, 2004, 2005, 2010) for evaluating changes in fluvial geomorphic systems resulting from human activities. This methodology requires, among other analyses (cartographic, historical, fluvial, geoindicators), the development of retrospective analyses of the hydrogeomorphological system studied through cartographic means, focusing on its pre-urban conditions. These analyses are performed using data obtained from aerial photographs, satellite images, land use and land cover maps, or other historical sources of information (GURNELL et al. 2003).

It should be noted that an entire flight strip was not located for the same date. The same location, from the middle to the downstream of the watershed, could not be found in a condition closer to the pre-urban stage in any other available aerial survey. Thus, it was not possible to perform stereoscopic restitution of the area using the method described above, which forced us to create ways to fill this gap.

Once this limitation imposed by the unavailability of source material was identified, recognized in other studies that applied the same methodology, a spatial analysis model was developed specifically for this complementation and mapping of the fluvial plain. This model seeks to leverage the contents and interpretative capabilities of classical techniques on current high-resolution databases, taking advantage of the spatial data processing capabilities of GIS environments. Its objective was to identify the spatial continuity of the fluvial plain boundary (and subsequently its compartments) for the area without photos from the pre-urban period based on altimetric patterns found in fluvial profiles of the segments restituted by stereoscopy with non-artificialized channels. The altimetric reference used for this processing was the DTM, generated from reclassified LIDAR data (without buildings, vegetation, etc.), considered the surface closest to the original capable of simulation.

Fluvial profiles were traced in segments with the mentioned characteristics with equidistance, measured along the thalweg line, resulting in a total of 30 profiles from the left boundary of the fluvial plain to the right boundary. The extension values of the profiles and altimetric gradient (difference from the plain boundary to the thalweg) found were analyzed through a geoprocessing routine that projected boundary elevations of the fluvial plain along the main channel and major tributaries, identifying surfaces below this topographic projection. The identification of terraces within the fluvial plain boundary, identified by this model, was carried out considering the altimetric limits between these and the floodplain, present in the fluvial profiles traced in segments with terraces identified in the stereoscopy restitution (SIMAS et al. 2021).

The validation of the spatial model was performed with reverse processing, that is: profiles were traced between the left boundary of the modeled fluvial plain and the right boundary, capturing the downstream progression profile and altimetric gradient existing between the plain edges and the thalweg. For the purposes of this validation, the fluvial plain boundaries delimited by stereoscopy were assumed as the real boundaries to be found by the model. It was also considered that it would not be possible to obtain a 100% accurate correspondence, since the profiles traced in the modeled area present the topography of the main channel artificialized in the reference DTM.

As result from the stereoscopic restitution on aerial photos from the pre-urban period, 1.358 km² of surface corresponding to the original fluvial plain of the studied area were identified. Of these, 0.985 km² correspond to floodplains and 0.373

km² to first-level terraces. These have an altimetric difference of 2 to 3 m with respect to the floodplain where they are located. Second-level terraces were not identified in the area, and morphologies corresponding to backswamps were not found.

With the restitution of the fluvial plain by photointerpretation, the spatial model was applied to identify the floodplain and terraces upstream on the digital surface model. The projection of the profiles surveyed in segments with non-artificialized channel courses led to the delimitation of an area of 1.646 km² where the projected altimetric elevations would produce the same altimetric gradient pattern within the plain, an area 33% larger than the total fluvial plain area restituted by stereoscopy.

The spatial model was then applied in reverse, for validation purposes, using fluvial profiles from the middle to downstream of the watershed on a stretch from the middle to upstream where non-artificialized channel courses are found. The sum of the areas correctly identified by the model corresponds to 86% of the total area delimited by stereoscopy. Only 6.97% of the restituted floodplain areas were not identified by the spatial model.

With this performance evaluation of the spatial model for delineating fluvial plains, we can assume its coherence and viability as a complementary method to procedures based entirely on geomorphological photointerpretations. This represents an important methodological result, since technical choices were made in this research, justified by the objectives outlined, which do not fully explore the indications of the original morphology for reading hydrological process trends, such as hydraulic gradient and other morphological indicators of the watershed.

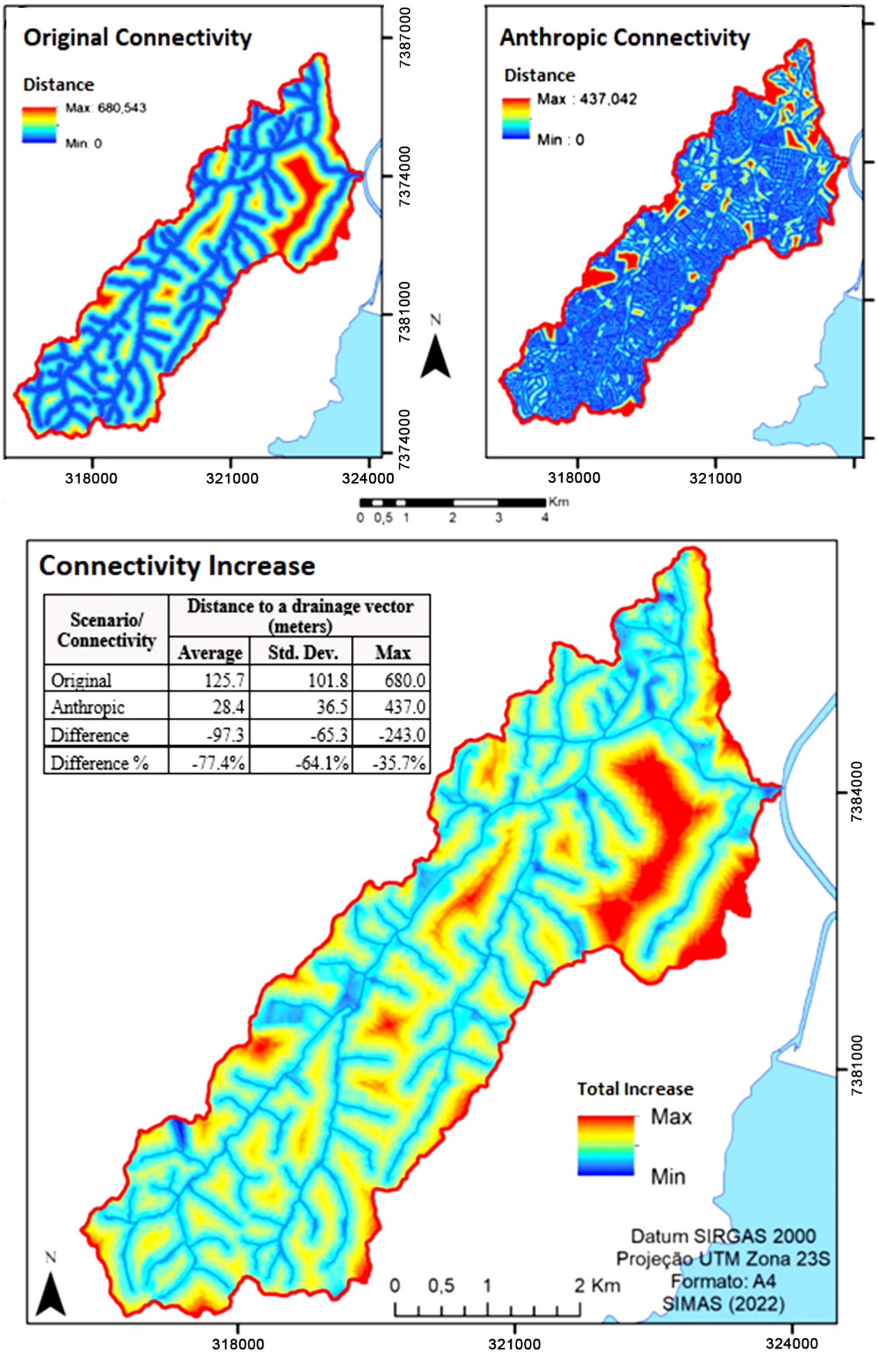
Among the results (Appendix - Map 1), the following stand out:

- The model's ability to identify alveolar floodplains in tributary courses further north in the watershed, provided they are supported by partial stereoscopy for interpolation or spatialization;
- The narrowing of the floodplain in the last kilometer of the main channel, where its extension decreases from 410 m to 130 m, indicating the high genetic potential of this subsystem sector to accommodate longer residence time overflow waters;
- Smaller dimensions of the terraces in the middle to downstream of the watershed and a considerably smaller proportion of these in relation to the total area of the floodplain. Their altimetric difference with respect to the underlying floodplain remains at the level of 2 m. This result corroborates the findings compiled in RODRIGUES et al. (2019), which point to discontinuities of this size as recurrent boundaries between fluvial plain compartments, serving as indicators of areas that should accommodate overflow flows more frequently (recurrence time of less than 2 years);
- Underground channeling placed many first-order courses outside the fluvial plain and concave sectors of the slope. This results in stormwater galleries and sewage collection networks designed with negative slopes, which, in turn, create conditions for return flow to properties and overflow through storm drains and inspection wells when operated at maximum capacity. Therefore, it is interesting to conduct (in future research) a search for records of these types of occurrences in these locations where first-order courses had their thalweg line displaced.

4.2 Connectivity increase and flooding scenarios

Regarding connectivity, among the results obtained, it is noteworthy that any point within the studied basin were, on average, 125.7 m away from the nearest drainage in the original scenario, while in the anthropogenic scenario, this average drops to 28.4 m. This means a 77.4% reduction in the distance between any area unit and drainage structures, highlighting a high proportion increase in connectivity throughout the basin. Spatially, this increase is concentrated on the Morro do S Creek and the São Luiz Creek main courses lowest sectors interfluvial tops, in the southeastern boundary of the basin (Figure 2). It is noteworthy that this highlighted area on the heat map is adjacent to the section of the basin's main channel that most frequently records overflow events.

With the use of ArcGIS Pro and QuickTerrain Modeler software, the Lidar data blocks covering the sample basin were consolidated into a single dataset, and subsequently, points classified as "ground" were filtered. This classification is an integral part of the original dataset, as elaborated by the consortium companies that provided the product to the São Paulo City Hall, having undergone quality control and assurance (QA/QC) routines. Therefore, the use of this data is possible for the entire extent of the municipality, not just for the sample basin. The filtered Lidar points were used to create a Digital Terrain Model (DTM) in raster format, originally with a resolution of 0.12 m, equal to the orthophotos of the reference year 2018. However, given the size of the resulting raster layer and the unavailability of computational power to employ this scale, the raster



Scenario/ Connectivity	Distance to a drainage vector (meters)		
	Average	Std. Dev.	Max
Original	125.7	101.8	680.0
Anthropic	28.4	36.5	437.0
Difference	-97.3	-65.3	-243.0
Difference %	-77.4%	-64.1%	-35.7%

FIGURE 2 – Surface distance heat maps to the nearest drainage and comparison.

was resampled to a resolution of 1m (X, Y). Given the abundance of points and their precision in the Z coordinate, which is not degraded by the procedure, it can be stated that the resulting DTM is suitable for the subsequently developed analyses.

The Lidar blocks covering only the delimited area of the original floodplain of the sample basin were filtered to represent only points classified as "Building." The exclusion of blocks that were entirely outside the floodplain was done to enable the processing of Lidar data, as the points are hyper-abundant at the level of detail at which they are available. Therefore, elements classified as "Bridges," "Transmission Lines," "Viaducts," and "Vegetation" were disregarded. Thus, only non-suspended constructions could be isolated to compose the three-dimensional scenes that would be used in simulations for volumetric estimates. It is noteworthy that these constructions are understood by the terrain model as solid and impermeable objects (the interior of the buildings is not considered).

Subsequently, the footprints of each filtered building from the previous DTM stage were obtained (Figure 3). This step was necessary for the segmentation of buildings that are only partially contained within the floodplain boundaries, as well as for assigning area and elevation values to a vector feature layer, which could be converted into a table. The delimitation of footprints was generated automatically by converting the raster (with a GSD of 12 cm) to polygons and manually reviewed with editing tools in ArcMap 10.5 software, using orthophotos with a resolution of 0.12 m. From this stage, it was possible to obtain the total volumetric value of the buildings present in the Floodplain of the studied basin.

The volumetric analysis tools of the QuickTerrain Modeler software were used to obtain two types of data: 1. The total volume of water that would be contained within the non-urbanized floodplain, considering a hypothetical flood that completely fills its shape at the same time (Figure

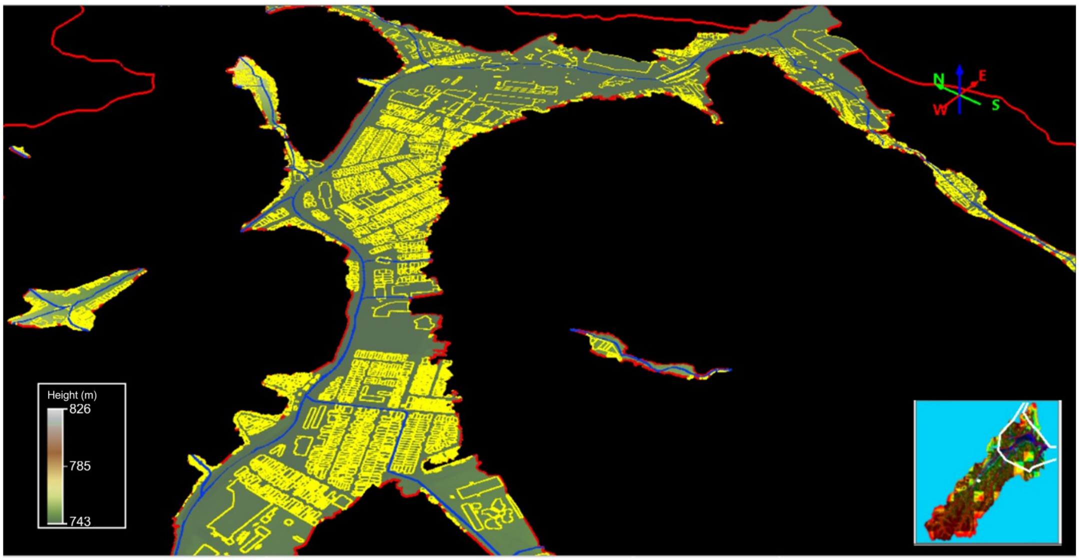


FIGURE 3 – Building footprints totally or partially within the fluvial plain.

FIGURE 4 – Example of reference surface for flooding projection used on volumetric calculation under the corresponding area of one Lidar block.

4). 2. The total volume of storage capacity lost due to the presence of buildings in the Floodplain, for hypothetical floods with water columns of equal height over the entire surface of the floodplain.

For the first estimation, a hypothetical inundation surface was created, with an area equal to each Lidar block, which had to be processed individually, and slope defined by the highest point at the upstream limit of the block and the lowest point at the downstream limit of the block. The height of this inundation surface was defined by the average altimetric elevation identified along the boundaries of the floodplain contained within the processed block. This surface was then used as a reference to obtain the total filling volume over the MDT (layer containing only terrain features) extracted by mask for the floodplain. This prevented volumes from being calculated for areas not belonging to the compartments of the floodplain. Through this procedure, it was also identified that the maximum level required for complete filling of the floodplain in any section of the basin would be 6.5 m above the full-channel margins level of the main channel.

For the second estimation, the process of obtaining the slope and area of the reference surface was identical. However, the height of the hypothetical flood surface reference was defined every half meter from the overflow elevation of the main channel present in the processed block. In other words, estimates of the total volume of buildings compared to the flood surface reference were obtained with heights ranging from 0.5 to 6.5 m (at intervals of 0.5 m) above the full-channel

FIGURE 5 – Water level still contained within the artificial channel.

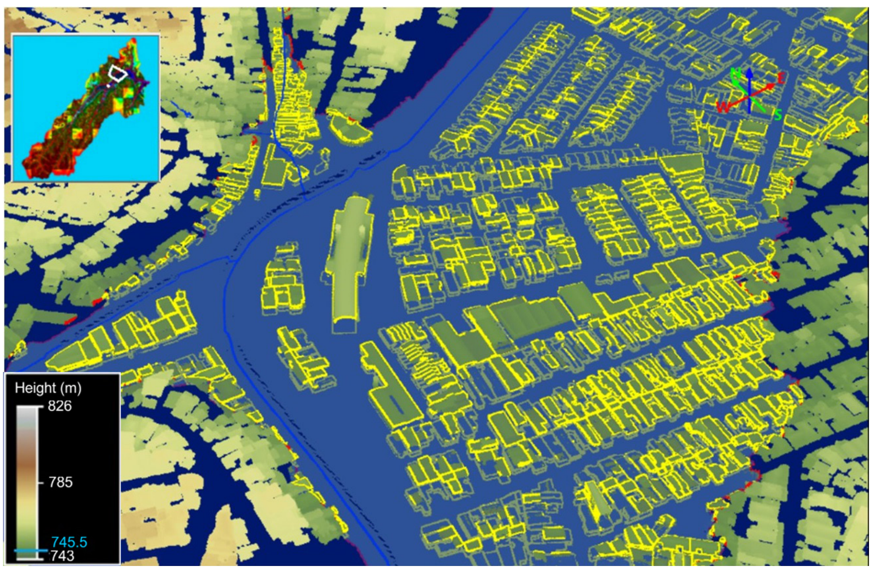


FIGURE 6 – Example of a 6.5 m overflow completely filling the floodplain.

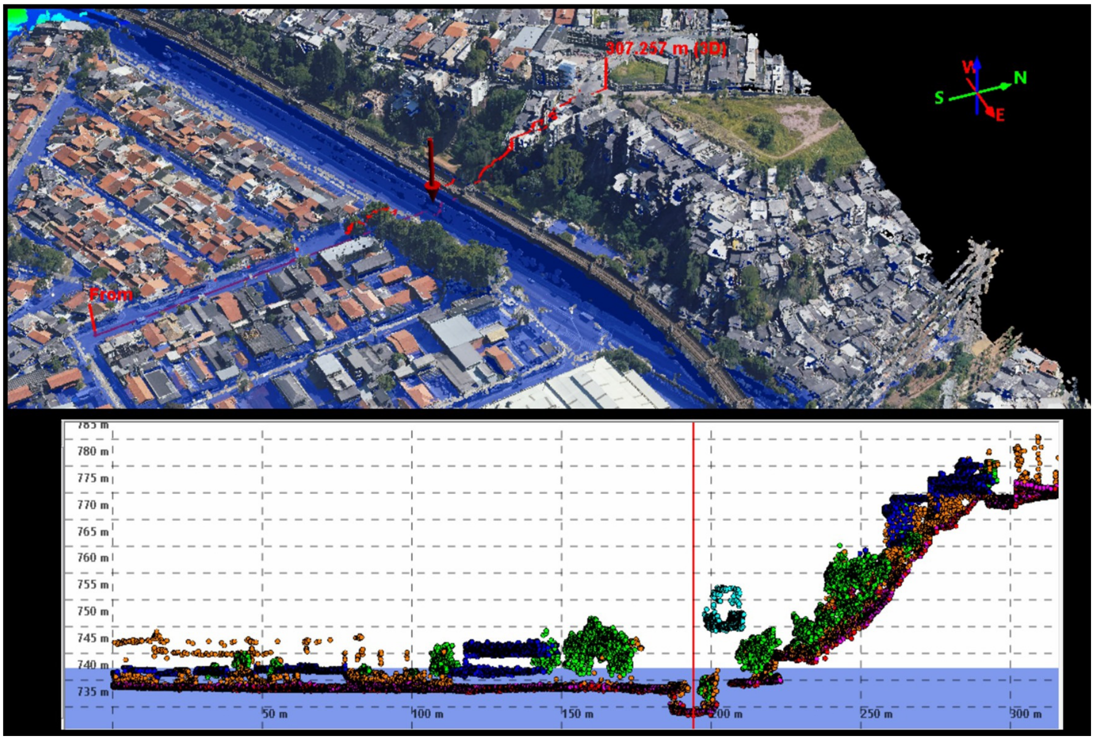


FIGURE 7 – Example of flood profile generated for estimation of water storage capacity loss in the fluvial plain.

margins level (Figures 5, 6 and 7). The limit of 6.5 m was adopted according to what was identified in the first volumetric estimation described (complete filling of the original floodplain).

With these results, it was possible to investigate the effects of the presence of buildings within the floodplain using the Caesar-Lisflood model. This is a dynamic model capable of calculating hydraulic variables with high-resolution temporal intervals and georeferenced output. Essentially, the objective with the application of this model was to obtain the following indicators for comparison between flood events when modeled on surfaces with and without buildings: 1. The maximum area of the flood spread generated. 2. The time elapsed for the flood spread to reach its maximum extent; 3. The maximum and average depths of the flood spreads; 4. The flow velocity generated during peak flow; 5. The volume of water present in the flood spread during the peak event.

The model was executed in "Reach" mode, meaning that the necessary inputs were the digital elevation models of the two scenarios and the estimated flow data for two entry points, one upstream and other downstream, corresponding to existing river gauge stations “Capão Redondo” and “P247”.

The DEM used for modeling the "without buildings" scenario was derived from Lidar data, excluding all elements corresponding to buildings and suspended structures. Meanwhile, the DEM used for modeling the "with buildings" scenario was generated with the exclusive inclusion of "building" objects on the previous DEM. It is worth noting that both modeled surfaces are urbanized surfaces, with the same rates of impermeability and connectivity of structures on the ground, allowing the proposed exercise in this stage to "isolate" the hydrodynamic effects of buildings during floods.

Modeling flood spread in scenarios with the presence of buildings within the floodplain and without them, using a dynamic hydraulic model, allowed us to observe:

The resulting maximum depths are consistent with the level data presented by the stations monitoring the main course of the basin. Values higher than those indicated by the stations are justified by the fact that the model extrapolates these measured data to the mouth at the Pinheiros River.

In all events, *the area of the flood spread is smaller in the scenario where buildings are present in the floodplain*. The first reason, and the most obvious one, is that the model considers that buildings are solid objects and the space occupied by them cannot be filled with water until their height is surpassed. The second factor concerns the vector of flood spread propagation. Its development over time allows us to observe how buildings impede the propagation of the flood spread, making it more restricted to the areas where it was able to expand during the onset of the peak flow wave.

The maximum depth is generally higher in scenarios with buildings due to their restriction on water spread. However, in three events, including the one with the highest recorded impacts (20/03/18, Appendix - Map 2), the maximum depth with buildings was 25% lower than without buildings. This is possibly because, in extreme events, the peak flow causes greater water accumulation in the tributary floodplains, blocking its outlet. In this scenario with buildings, the hydraulic barriers distribute the flood spread further upstream.

It is important to highlight that, among the modeling results in all events, the values of the *average depth of the flood spread are highly increased in the scenario with the presence of buildings* (a difference that reaches 78.3%). This reinforces what was previously considered, that buildings represent hydraulic obstacles that generate a more constricted flood spread with a more evenly distributed depth.

Consequently, it is also highlighted that the *volume of the flood spread is significantly larger in the scenario with buildings* (between 22.2% and 35.1%). This indicator effectively reflects the magnitude differences between events by accessing the event's spatial dimension and the morphology's overflow water storage efficiency. It is particularly useful for identifying the influence of buildings on the occurrence or worsening of flood impacts.

4.3 Further developments and additional comments

Geotechnologies play a fundamental role in supporting urban planning and flood risk mitigation in the urban environment. Among the field technologies for measurement, the Global Navigation Satellite System (GNSS) and Real-Time Kinematic (RTK) technology stand out. The use of these technologies allows for the acquisition of precise geolocation data in an agile manner, essential for detailed mapping of the urban environment and identification of risk areas, as well as validation of analyses performed in a controlled environment.

Furthermore, remote sensing technologies offer powerful resources for constant monitoring of urban areas. The use of Synthetic Aperture Radar (SAR) satellites, online maps, and satellite images with constant revisit (more than once a day) provide a comprehensive and up-to-date view of urban environmental conditions. Streaming of images and films captured by drones complements these technologies, allowing for more detailed and flexible coverage, especially in hard-to-reach areas, as the use of UAVs becomes increasingly common. Additionally, with the capability of obtaining surface profiling data by these platforms, there is the possibility of monitoring morphological changes on a very fine scale and with high recurrence. This enables measurement with high precision of mobilized material volumes and physical progress of surface changes, for example, for monitoring and inspection of construction works and geodynamic risk assessment.

The adoption of georeferenced mobile applications has become a common practice for field data collection in urban studies and risk management. These applications facilitate efficient and accurate data collection, including information about urban infrastructure, environmental conditions, and the behavior of natural phenomena, contributing to a more comprehensive understanding of urban risks and vulnerabilities through crowdsourcing. At the same time, the principle of the Internet of Things (IoT) has been consolidated, integrating not only telemetry stations and sensors but also all assets that make up a system. For example, in drainage systems, it is possible to integrate all physical characteristics and location of pipes and singularities as well as information about their construction and maintenance history, through increasingly accessible equipment (such as tags and beacons) that provide the necessary link between the physical asset and databases.

The presentation of the results of analyses made with these technologies is facilitated by online portals and web maps, which allow for the sharing and visualization of data in an accessible and interactive way. These portals provide a centralized platform for decision-makers, researchers, and the general public to access relevant information about the urban environment and associated risks.

Furthermore, the potential of artificial intelligence applied to data-driven decision-making is increasingly recognized. Advances in this area enable the development of algorithms and predictive models that can analyze large volumes of geographic data and identify complex patterns, providing valuable insights for urban risk management and the formulation of more effective public policies. When combining the analytical power of modern AIs with databases fed by sources that collect data directly from existing infrastructure (IoT) and models built with high detail and integrity (BIM), we have the possibility of envisioning operation from digital twins (originally conceived in GRIEVES 2002). At this level, the system itself would be capable, through its real-time digital representation, of making the necessary decisions for its optimal operation such as: opening or closing a valve, requesting mobilization of an inspection team, indicating when to perform preventive maintenance, etc.

In summary, geotechnologies today offer a range of tools and resources that are essential for planning and risk management in the urban environment. From field data collection to analysis and presentation of results, these technologies play a crucial role in promoting urban resilience and protecting communities against the impacts of adverse events.

5 CONCLUSIONS

It is important to note that one indirect result of this research was demonstrating replicability of its methodology to the case of floods in the city of São Paulo. All data comprising the database is publicly available. In other words, these data already exist and are accessible to public institutions responsible for urban planning, mitigation measures, and resilience enhancement. We emphasize that the replicability of these techniques, based on the optimized use of geotechnologies, gains special relevance in the context of discussions on climate change adaptations, which will inevitably require rethinking the classical models of human habitat construction that have characterized the Great Acceleration of the Anthropocene.

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