GENERATION OF A TOPOBATHYMETRIC DIGITAL ELEVATION MODEL OF URBAN STREAMS: A STUDY CASE IN THE SÃO PAULO METROPOLITAN REGION, BRAZIL

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ABSTRACT

Flooding represents a source of hazards for both developed and developing countries. Such events have been causing serious socioeconomic and environmental damage worldwide. Therefore, studies that characterize the features of rivers channels are essential for flood modeling. In this work, we performed topobathymetric surveys along stretches of three rivers in São Paulo Metropolitan Region, Brazil. Bathymetric sample points were collected every 50 m, and cross-sections surveys were performed every 200 m. In general, the topobathymetric digital elevation model (TBDEM) presents satisfactory results. Lastly, the product generated in this work will be merged into a digital terrain model (DTM) with a spatial resolution of 0.5 m, which in turn, will be made available for future urban flood modeling experiments in the study area.

***Key words*:** Flooding, urban management, GNSS-RTK.

1. INTRODUCTION

Hydrological disasters related to floods have increased considerably worldwide over the last decades, and hence, they have caused serious socioeconomic and environmental damage, including human losses [1]. In Brazil, only from 2013 to 2021, at least 205 people were killed by floods and more than 11.7 million people were affected by such events [2], most of them occurred in urban areas. Therefore, flood risk assessment and management are fundamental steps for identifying prone areas to such hazards and reducing them. In this context, a detailed description of the river channel is the primary task.

Bathymetry is the study of the beds or floors of water bodies, such as oceans, rivers, streams, and lakes [4]. In the same way that topographic maps represent the three-dimensional features (or relief) of overland terrain, bathymetric maps illustrate the underwater depth of water bodies as well as submerged relief [5]. Therefore, accurate bathymetry plays a key role in a variety of hydrologic and hydraulic applications including but not limited to flood modeling, sediment transport, aquatic habitat assessment, and river restoration.

Bathymetry can be executed by means of traditional techniques (e.g., field surveys) or even airborne and space-borne platforms. Point measurements of bathymetry through field surveys can be either land-based or vessel-mounted [6]. Land-based techniques include total station, terrestrial scanning, and a global navigation satellite system (GNSS). However, since this method involves manual measurements, the surveyor's abilities play a significant role on the observation accuracy [7]. According to [8], total stations and GNSS – real-time kinematical (RTK) provide the most accurate bathymetry data for shallow slow-moving water bodies. On the other hand, considering deep streams or reservoirs, GNSS-equipped vessel-mounted surveying techniques (e.g., echo sounders) are more convenient and provide higher precision and accuracy [7,9]. Lastly, field surveys are most suitable for small reaches and are not commonly recommended for an entire stream network due to the logistics, intense labor, high cost, and safety risks [10,11].

On the other hand, remote sensing-based methods have emerged as an attractive alternative compared to traditional field surveys once they are less costly and less time-consuming [12]. These approaches depend on electromagnetic sensors based on airborne or spaceborne platforms to map topography and with them it is possible to survey large areas in a relatively small time. However, topographic remote sensing often cannot penetrate water surface, hence the channel bathymetry (bed topography) is featured as a flat surface [13]. Aiming to solve such problem, researchers have extended the use of photogrammetry to water bodies by correcting for refractive effects [14]. They exploited the fact that light backscatter decreases exponentially with increasing depth of the water column and thus created equations relating measured backscatter and water depth [15]. However, this approach can only be applied to relatively clear water, once visible light needs to reach the channel bottom, and with depths up to 2 m [16]. Furthermore, the presence of vegetation or algal cover also produces uncertainties in the estimation [17].

Most Brazilian urban rivers are polluted since only 50.8% of the sewage are collected and treated [18]. So, uncollected, and untreated sewage goes to water bodies in the municipalities. In this context, remote sensing-based methods cannot be used to get bathymetry in most Brazilian urban rivers.

Given the foregoing, this work aims to carry out topobathymetric surveys of three streams surrounding the municipality of São Caetano do Sul, SP, Brazil. The study area was selected due to reported flooding events over the last few decades. Lastly, the product generated in this work, the topobathymetric digital elevation model (TBDEM) of the rivers under analysis with streambed elevation, will be extremely valuable for the execution of future flood modeling studies in the area.

2. MATERIAL AND METHODS

2.1 Study area

The three reaches studied in this work are located in: (i) Tamanduateí River (Rio Tamanduateí) and Meninos Brook (Ribeirão dos Meninos) that compose the territorial boundary of the municipality of São Caetano do Sul, SP, Brazil; and (ii) a small stretch of Couros Brook (Ribeirão dos Couros) that flows into Meninos Brook (Fig. 1).

São Caetano do Sul is located in the southern portion of São Paulo Metropolitan Region and belongs to an important industrial region in Brazil, named ABCD Region. The municipality is intensely conurbated with the municipalities of São Paulo, Santo André, and São Bernardo do Campo, with visually undefined boundaries between them. According to the Brazilian Institute of Geography and Statistics (IBGE), the current population of São Caetano do Sul is estimated at approximately 162,763 inhabitants in an area of 15.33 km^2 [19].

The study area is situated on a plateau adjacent to the (Mar Ridge) Serra do Mar. Its altitude ranges from 722 to 819 m above sea level (an average of 750 m). According to the Köppen climate classification [20], the study area presents a humid subtropical climate, with a mildly warm and rainy summer, and a moderate and dry winter. The average annual temperature is about 19.5° C, and the coldest and warmest months are respectively July (average of 16.2 °C) and February (average of 22.5 °C) [21]. The annual rainfall is nearly 1,496 mm. The 30-year-average-annual rainfall was generated from Station nº 2346051 of the Department of Water and Electricity (Departamento de Águas e Energia Elétrica – DAEE) of São Paulo State.

From 2000 to 2022, São Caetano do Sul was affected by at least 29 floods according to the local news agencies. The most severe event occurred in 2019, when it rained about 179 mm in 4 hours and caused an economic loss of over US$ 3 million [22].

2.2 Field survey

The GNSS-RTK method was employed in this work. The positioning method based on GNSS-RTK is based on a relative differential positioning approach, where the unknown position of a moving rover-station is determined in real-time with respect to at least one stationary base (reference) station of known coordinates. The base station transmits corrections to the roving receiver (or receivers using a radio link) [23].

The GNSS receiver was the GeoMax Zenith 35 Pro (GeoMax, Widnau, Switzerland) with a Samsung datalogger using XPAD Field software. The Zenith 35 Pro supports 555 channels (multi-constellation) and multi-frequency, and it can connect up to 10 rovers simultaneously. It tracks signals of Global Positioning System – GPS American satellite navigation system), GLONASS (Russian satellite navigation system), BeiDou (Chinese satellite navigation system) and Galileo (European satellite navigation system). Lastly, the Zenith 35 Pro can provide a precision of 1.5 cm for axes *x*

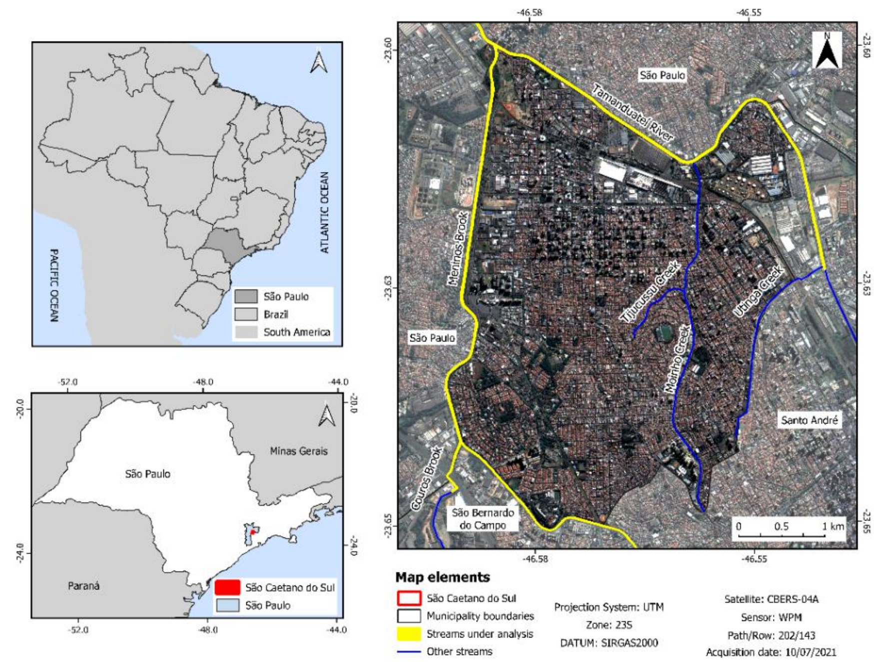

Figure 1: Location of the study area and stretches of the three analyzed streams (Tamanduateí River, Meninos Brook and Couros Brook) around the municipality of São Caetano do Sul, São Paulo, Brazil.

and *y*, and 2 cm for axis *z* (www.geomax-positioning.com).

The field campaign was performed from August 29 to September 19 of 2022. An extension of 15.41 km was surveyed along stretches of the three analyzed streams. The fieldwork for collecting ground points consisted in the following strategies: (i) the depth of the middle of the watercourse was surveyed every 50 m, and (ii) the cross-section of the watercourse (one point on each bank of the stream and one point in the middle of the watercourse) was surveyed every 200 m. However, due to the fact that some depths surpassed the surveyor's height, 15 center points could not be surveyed. In such cases, an average between the immediately preceding and succeeding points was estimated. Overall, 462 points were collected along the three reaches. Elevation data are referenced to mean sea level of Imbituba Brazilian Vertical Datum, located in Santa Catarina.

Lastly, it is important to highlight that control points were collected with the purpose to help drawing the bounding polygon of the study area. These points were collected in stretches with peculiar features, such as curves.

2.3 Data processing

Firstly, midpoints were created between the collected points aiming to improve data interpolation, i.e., to avoid calculation errors in the interpolation procedure. The average value of altitudes between the previous and posterior points was assumed for midpoints. Thus, the interval between points was reduced to 25 m.

Next, a polygon covering the entire area of interest (the three reaches of the water streams) was created from the points on the banks of the surveyed cross-sections and the control points. This polygon was used as a mask for creating the TBDEM of the study area. To do so, we used the tool 'point to path' in QGIS 3.22, a free geographic information system. Then, the TBDEM was created using the triangulated irregular network (TIN) interpolation in QGIS, and the linear method was adopted in this procedure. Lastly, the output cell size was set to 0.5 m.

3. RESULTS AND DISCUSSION

The TBDEM of the reaches of Tamanduateí River, Meninos Brook, and Couros Brook is shown in Figure 2. The confluences of Meninos Brook and Tamanduateí River is highlighted in Figures 2A-B. Figure 2B shows a 3D visualization of the TBDEM. The elevations ranged from 722.91 to 740.20 m. The lowest elevation value was observed in the lower Tamanduateí River (close to the confluence of Meninos Brook), located in São Paulo. On the other hand, the highest elevation value was found in the upper Meninos Brook (close to the confluence of Couros Brook), located in São Bernardo do Campo.

As well as almost all urban rivers in Brazil, the analyzed reaches have been subjected to a rectification process, i.e., the water streams lost the original form of their course. Since urban rivers have long straight distances and few curves, we believe that few details of the watercourse forms were lost (probably minor sections in the curved stretches). In this context, the methodology adopted in this work for the collection of bathymetric sample points seemed to be appropriate for its purpose. However, shorter distances (<50 m) should be used in curved stretches.

An important aspect to be highlighted is the presence of

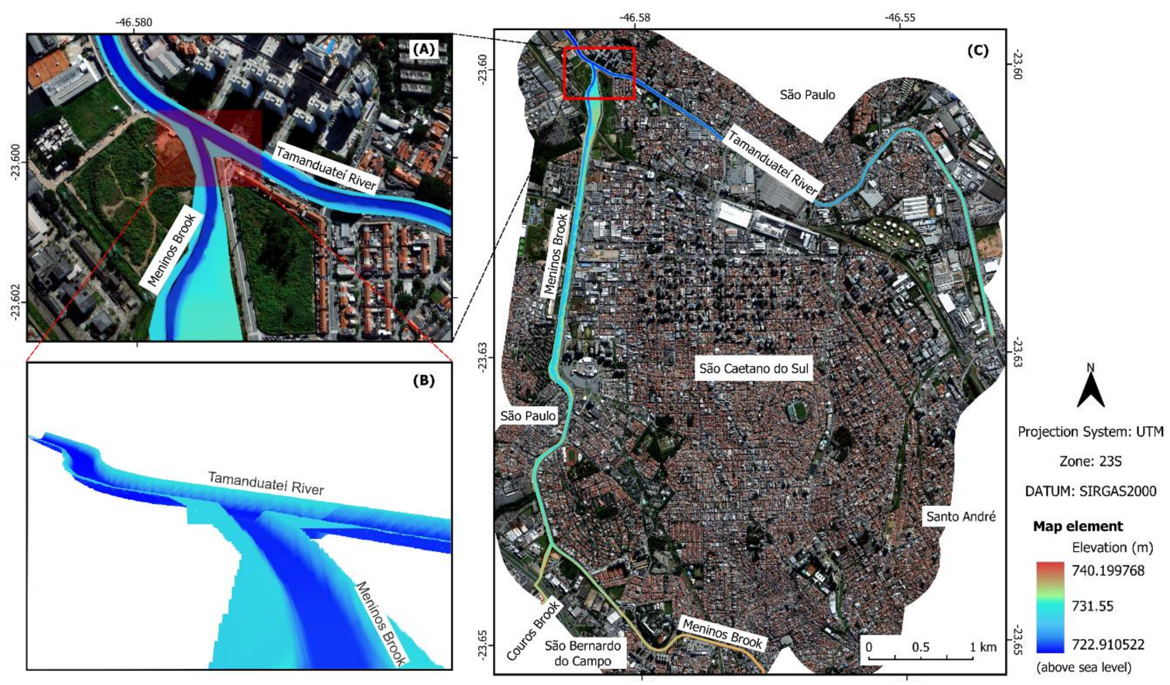

Figure 2: Topobathymetric elevation model (TBDEM) of the surveyed stretches of Tamanduateí River, Meninos Brook, and Couros Brook located around the municipality of São Caetano do Sul, São Paulo, Brazil. (A) Confluence of Meninos Brook and Tamanduateí River, (B) 3D zoom-in the confluence of Meninos Brook and Tamanduateí River.

several silted stretches in the three analyzed water courses. This silting is due to sediments as well as debris from construction and garbage. As a result, the watercourse channel is drastically reduced in these stretches. Thus, it is recommended that the collection interval of the cross-section sample points should be less than 200 m in such stretches. In fact, a maximum distance of 100 m is highly recommended.

4. CONCLUSIONS

In this work, we performed topobathymetric surveys of stretches along the Tamanduateí River, Meninos Brook, and Couros Brook, which are located around the municipality of São Caetano do Sul, São Paulo, Brazil. The traditional topobathymetric method was employed since remote sensing-based methods could not be alternatively used as the analyzed water streams are polluted. Although its higher precision and accuracy, this method relies on the surveyors' abilities to get satisfactory results. Thus, following a protocol previously defined for field data collection is essential to obtain reliable data.

In order to obtain a better detail of the form of the watercourse, it is recommended, whenever possible, to collect topobathymetric sample points at intervals less than 50 m in curved stretches, and cross-sections at intervals of 100 m or less. Lastly, the TBDEM generated in this work will be merged into a digital terrain model (DTM) with a spatial resolution of 0.5 m derived from a WorldView-2 images stereo-pair aiming to provide high-resolution input data for urban flood modeling studies.

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