APPLICATION OF HYDRAULIC, HYDROLOGIC AND DIGITAL TERRAIN MODELING IN FLOOD RISK AREA MAPPING

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ABSTRACT

Current patterns of land use in Brazilian cities have intensified the difficulties faced by the urban population during flood events. In this context, a thorough analysis of these extreme events are an important strategy for identifying areas most susceptible to the impacts caused by floods and the consequent development of local urban policies aiming at proper water resources management. The purpose is therefore to apply a set of measures for assessment and treatment of the hydrologic data available, as a way of mapping the flooding areas, through the application of mathematical simulation models, combined with digital terrain modeling tools and additional data collected in field. For the application of the methodology, specific critical events with disastrous consequences that took place between the months of December 2009 and February 2010, and again in January 2011, have been chosen, located near the Atibaia River, state of São Paulo, downstream regionally important reservoirs. The hydrological analysis implies that even low-recurrence interval floods may cause potential harm and the resulting inundation mapping process reveals a consistent response to field observations, despite the lack of gauging data.

Keywords: flood risk areas, hydraulics, hydrology

INTRODUCTION

Since the 1950s, the world urban population has been increasing and it is predicted that in 2020 this urban parcel will correspond to 56% (UNESCO, 2006). The challenge to be faced then is the suitable water resources management through supply and drainage sanitary systems and solid waste mechanisms. Urban development exacerbates the effects of extreme meteorological phenomena, leading to major social and economic impacts. In regard to flooding processes, urbanization contributes to the infiltration rate decline, increases surface runoff and accelerates the rise of hydrograph peak flows (Hirsch et al., 1990; McCuen, 1998; Rose and Peters, 2001; apud Burns et al., 2005). The situation described quite often occurs in countries with high growth rates of population concentrated in urban areas, such as Brazil.

The city of Atibaia, located on the banks of the Atibaia River, State of São Paulo, Brazil, has a population of 126,603 inhabitants, 91% of whom live in urban areas (IBGE, 2011b), which represents a population increase of 46.6 % since 1991 (IBGE, 2011a). Ascendant urbanization may be followed by the occupation of riparian areas. Such improper land use might also be related to a previous period featured by below-average rainfall, observed from 1997 to 2006 (LabSid, 2007), which could have caused areas that previously belonged to the river banks and were usually affected by the natural floods of the Atibaia River to be occupied, due to the non-occurrence of great significance events for a while. Therefore, owing to the fact that the areas were in use and the precipitation conditions achieved average and higher rates, the constructions began to be affected by these average or higher flow volumes from the Atibaia River. Flood events occurred between December 2009 and February 2010, again in January 2011, and displaced 450 families giving rise to great damage to the local society (Zanchetta, 2011).

The analysis of extreme events in order to identify the most susceptible areas to the impacts caused by floods is required in support of the development of local urban policies designed to properly manage the water resources. In this context, flood hazard area mapping is essential for formulating emergency plans and also for planning the regional development in the long term (Rabindra et al., 2008). According to the US Federal Emergency Management Agency (2009), river flood analysis is constituted of two steps: (1) hydrological analysis to determine the occurrence probability of events and (2) hydraulic analysis to identify the extent of the flooded area and the water levels associated with each event. The mapping process basically consists in defining the area covered by water, based on crossing data from the terrain surface and water level set for a particular event (Merwade et al., 2008).

A variety of methods and programs are available for the establishment and analysis of floodplains through computer modeling and the software set developed by the Hydrologic Engineering Center (HEC) of the U.S. Army Corps of Engineers is a case in point. The package, internationally recognized for its application in river floodplain assessment and protection against flooding (Azevedo, 2002), includes the Hydrologic

Modeling System (HEC-HMS), able to estimate the rainfall-runoff process, creating flow data to be used in the River Analysis System (HEC-RAS) (USACE, 2009) so as to determine water levels related to different return periods. Its set also includes a processing tool for geospatial information, entitled HEC-GeoRAS (USACE, 2008), which not only correlates the geometrical information applied to the River Analysis System, but also facilitates the results exploration and the mapping procedure through the software ESRI ArcGIS (ESRI, 2009). Examples of applications can be found in Colby and Dobson (2010), Paz et al. (2010) and Matkan et al. (2009).

Our aim is to apply hydraulic and hydrological models combined with spatial analysis techniques in order to determine the floodplains generated by critical water flows. This research attempts to obtain a methodology able to provide useful information to assist watershed land use planning and contingency measures during extreme events. The methodology will be conducted in the Atibaia River basin.

METHODS

Hydrologic Analysis

In order to carry out this study, information gathered from the National Waters Regulatory Agency (*Agência Nacional de Águas - ANA*) database was accessed, regarding three gauging stations. The daily flow series at the stations, situated by the Atibainha, Cachoeira and Atibaia Rivers, were recorded from 1952 to 1972, from 1935 to 2007 and from 1936 to 2007, respectively. A map showing their location is presented in Figure 1.

The treatment of the flow data was performed by running the software Computational System for Hydrologic Analysis (*Sistema Computacional para Análises Hidrológicas – SisCAH)* (Sousa et al., 2009), also employed by Oliveira et al. (2008) and Reis et al. (2008). After excluding the records from months with more than 5% of faulty data, the original daily flow data yielded annual maximum flow values for every station, which had the Gumbel, Pearson type III, Log-Pearson type III, Lognormal type II and Lognormal type III distributions fitted to them, considering different return periods and adopting October as the starting month of the hydrological year. For each annual maximum flow series, a probability distribution was chosen so as to produce minimum standard deviation of the samples. Furthermore, aiming at the statistical classification of the events that recently occurred in the region, and also for the analysis of the influence of the Cantareira System operation on those events, the statistical analysis for each gauging station time series also considered the periods before and after 1972 individually, time close to the creation of the reservoirs.

The available data relative to the floods that took place between December 2009 and February 2010, and again in January 2011, were obtained after the Telemetric Network of Hydrology database from the Department of Water and Energy of the State of São Paulo (*Departamento de Águas e Energia Elétrica do Estado de São Paulo - DAEE*), by the Flood Warning System of the State (*Sistema de Alerta a Inundações de São Paulo – SAISP*) (FCTH). The location of these stations is also represented in the figure as follows.

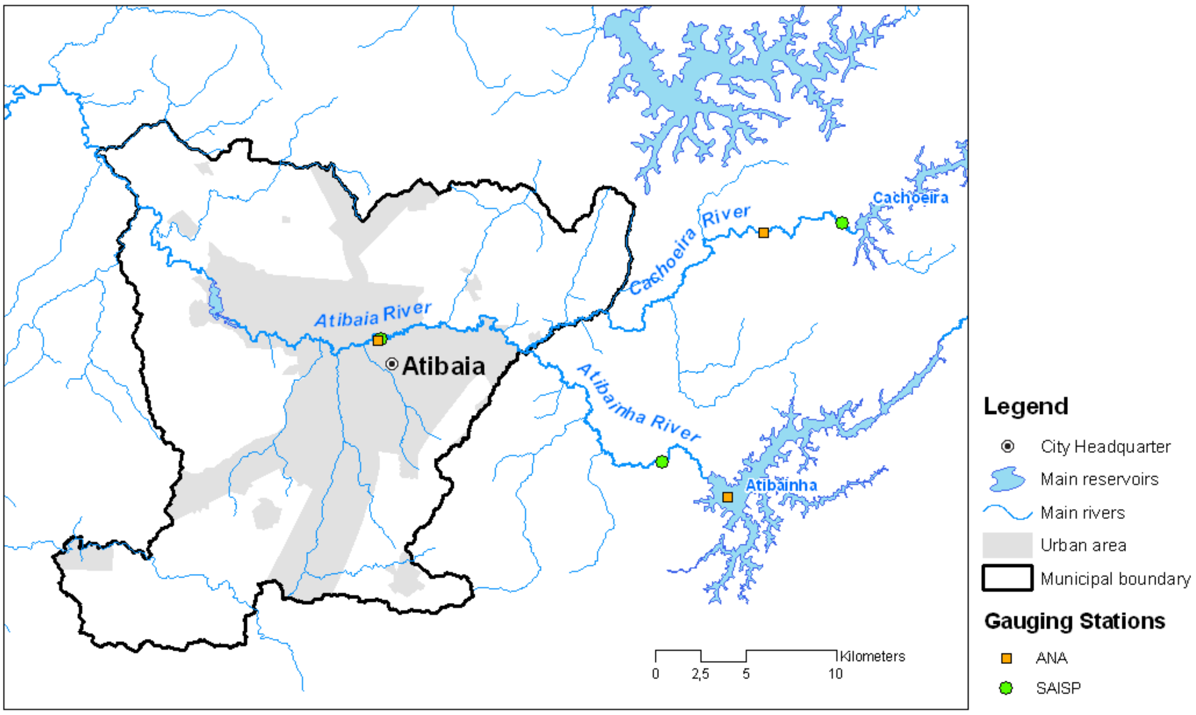

Figure 1. Location map of study site and gauging stations.

Flood Risk Area Mapping

Characterizing topography and terrain can be conducted through satellites or orbital systems capable of generating stereoscopic pairs of images. By means of digital conical or cylindrical stereoscopy techniques, due to the precision of images and their placement on the ground (geodesic), the terrain surface is restored via a DTM (Digital Terrain Model), which can be displayed in three dimensions. The use of a DTM not only enables the contour restoration, but also supports the watershed delineation, the drainage network mapping and the determination of the slope from a given area.

In 2005, the Embrapa Satellite Monitoring (Miranda, 2005) developed a methodology to contribute with a new product for the Brazilian society. Fundamentals include Brazil's terrain and topography numerical database, acquired by the American spacecraft during a mission known as SRTM (Shuttle Radar Topography Mission). Each area of 90 m by 90 m in the national territory is provided by an accurate altimeter measure. This massive database was recovered and mathematically treated by models that allow the country topography reconstruction, similarly to topographical maps except from homogeneousness and digital improvements. The SRTM images were employed to represent the three-dimensional surface of studied site.

The Atibaia River hydrography was defined through a manual digitalizing technique by means of Google Earth (Google Inc, 2011) images, using the drawing tools available in the software, followed by the conversion of the images into KML format.

So as to handle spatial information, the ESRI ArcGIS was utilized, including its spatial analysis and supplementary advanced features.

By way of taking precautionary measures beforehand, further requirements, which involve UTM projection data, the Google Earth data (Geographic Coordinates, WGS-84 [EPSG: 4326]) should be transformed into the local projection (UTM Zone 23S). It is very worth noting that an error-free and consistent process would only be accomplished through the conversion of all data into WGS_1984_UTM_Zone_23S. Errors would be committed due to the continuous projection displacement and hence information inconsistency would be interpreted as an error by the software itself. At this point, the aim is to define the so-called flood risk areas, which shall be filled with certain water volumes that overflow the natural river channel.

The Atibaia River hydraulic modeling was carried out by using HEC-RAS software, designed for one-dimensional hydraulic calculations of natural and artificial channel complete networks. This software includes tools for identifying stream lines (river channels), banks (limits of channel margins), flowpaths and cutlines (flow channel and cross sections), which constitute the premise for an XML file generation containing all HEC-RAS necessary input data in order to perform calculating procedures of the river free surface heights for different water flows.

HEC-RAS input data also comprehend Manning coefficient values, boundary slope conditions upstream and downstream and also the chosen flow rates acquired from historical series studies that relate values to each relevant return period. The water surface level is then applied to delimit the floodplain boundaries matching the digital terrain model contours. After this routine, the mass of data produced from HEC-RAS enters ArcGIS once more for the final procedure, generating a three-dimensional land surface that is then intercepted by the plane created in compliance with the water level heights estimated by HEC-RAS, so as to generate a surface control that represents the desired floodplain area.

Additionally, aiming at results assessment, a visit to the studied site was undertaken in order to collect, through accuracy GPS, points along the border of the area flooded at the acme of the events occurred in the city between December 2009 and February 2010 characterized by a peak flow of 64.48 $m^3.s^{-1}$. Besides these spots, some points measured throughout the full the period mentioned (DAEE, 2010) were also accessed. Regarding all this information, a reference grid was created and then plotted on Google Earth, providing an overview of the event and the flooded area boundaries at both left and right Atibaia River banks and delineating the region occupied by water.

By means of overlapping boundary lines and the patches resulting from the process, the results proved to be very inaccurate, causing areas that had not undergone floods to seem inundated and also leaving dry patches in areas that should be flooded.

As a consequence, to improve results satisfactoriness, an equivalent procedure was performed using ASTER images, also provided free of charge (ERSDAC, 2009), which has a 30 m by 30 m resolution. The results then started to more consistently agree with the real flooded areas, but still containing errors related to digital terrain model imperfections, yet due to lack of image accuracy and by not enabling corrections to flaws.

As argued by Pryde et al. (2007), the accuracy and good quality of the watershed delineation, as well as the river sections generation, is highly dependent on the DTM. The ASTER data have several advantages, such as low cost and high spatial resolution, but also have some disadvantages, mainly the potential masking by clouds and interference between tracks. The SRTM data, on the other hand, have a high elevation accuracy, although this accuracy directly dependents upon the terrain vegetation, because the radar cannot penetrate it. As an expected result, the DTM generated by the SRTM presented better results than the ASTER watershed methodology.

Floodplain area validation

Owing to the increasing use of GPS for positioning, especially regarding altitudes obtainment, combined with new geodesic information and newly available models, it is worth noting the technique limitations and the subsequent correction process application.

The altitudes obtained by the dual frequency GPS equipment gives the ellipsoidal height (h) shown in Figure 2. However, the water follows an orthometric height, because of its direct influence on gravity. Hence, in order to achieve greater accuracy of orthometric height, a few steps were required:

1. Positioning and capturing (30 minutes for each point) GPS readings were performed with special antennas that ensure accuracy;
2. Accomplishment of post-processing by means of the Trimble Geomatics Office (Trimble Navigation Limited, 2005) for satellite signal corrections through the ionosphere based on the Brazilian Network for GPS Continuous Monitoring (*Rede Brasileira de Monitoramento Contínuo do Sistema GPS - RBMC*);
3. Corrections concerning the benchmark and the geoid undulation, allowing geometric heights (referred to the ellipsoid) to be converted into orthometric ones (referred to mean sea level) with improved reliability.

The Brazilian Institute of Geography and Statistics (IBGE) through the Geodesy Coordination and the School of Engineering of the University of São Paulo developed the MAPGEO2010 (IBGE, 2010a), a computer model through which users can obtain the updated geoid undulation at one or at a set of points, referring to both SIRGAS2000 or SAD69, under a 5'-of-arc resolution.

The conversion between the heights can be undertaken by the equation as follows, since the angle among the perpendicular of the ellipsoid ( ) and the geoid ( ) is very small:

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Where is the orthometric height, measured along the plumb line; is the ellipsoidal height obtained via GPS and measured along the ellipsoidal normal; and is the geoid height (or undulation) provided by the program, indicating the separation between geoid and ellipsoid.

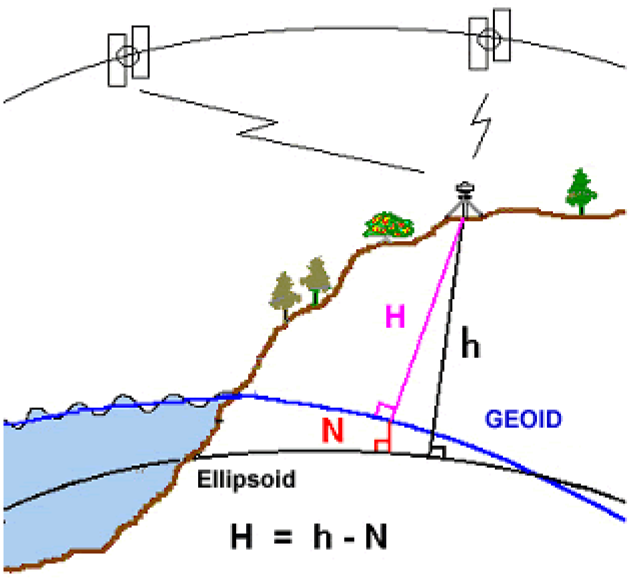

Figure 2. Relation between the different heights (IBGE, 2010b).

FINDINGS AND DISCUSSION

Hydrological Analysis

After a hydrological study based on the available data provided by ANA, the maximum annual flows were adjusted for various return times. The analysis of peak flows occurred in the Atibaia River resulted in the distributions shown in Table 1. Analyzing the complete time series and also the ones before and after 1972 independently, it is interesting to note a probable change in the hydrological regime, which might have possibly been influenced by the implementation of the dams of the Cantareira System. It is therefore likely that such a change may be understood as advantageous in matters of flood control, since it is reasonable to assume that the reservoirs cause a routing effect on the peak flow downstream.

Figures 3, 4, 5 and 6 illustrate the flood events that took place between December 2009 and February 2010 and again in January 2011, respectively.

Table 1. Maximum annual flow distribution at the Atibaia River.

Gauging Station ANA 62670000 – Atibaia River			
Return period (years)	**Peak flow ($m^3.s^{-1}$)**		
	Complete time series (from 1936 to 2007)	**From 1936 to 1972**	**From 1972 to 2007**
2	49.56	60.89	40.07
3	57.80	69.24	45.20
4	63.06	74.47	48.40
5	66.95	78.29	50.72
6	70.03	81.29	52.54
7	72.59	83.76	54.03
8	74.77	85.86	55.30
9	76.67	87.68	56.40
10	78.36	89.29	57.37
15	84.76	95.34	61.01
20	89.24	99.53	63.52
25	92.68	102.72	65.43
50	103.29	112.45	71.22
100	113.86	121.99	76.87
500	138.68	143.84	89.71
1000	149.60	153.24	95.19

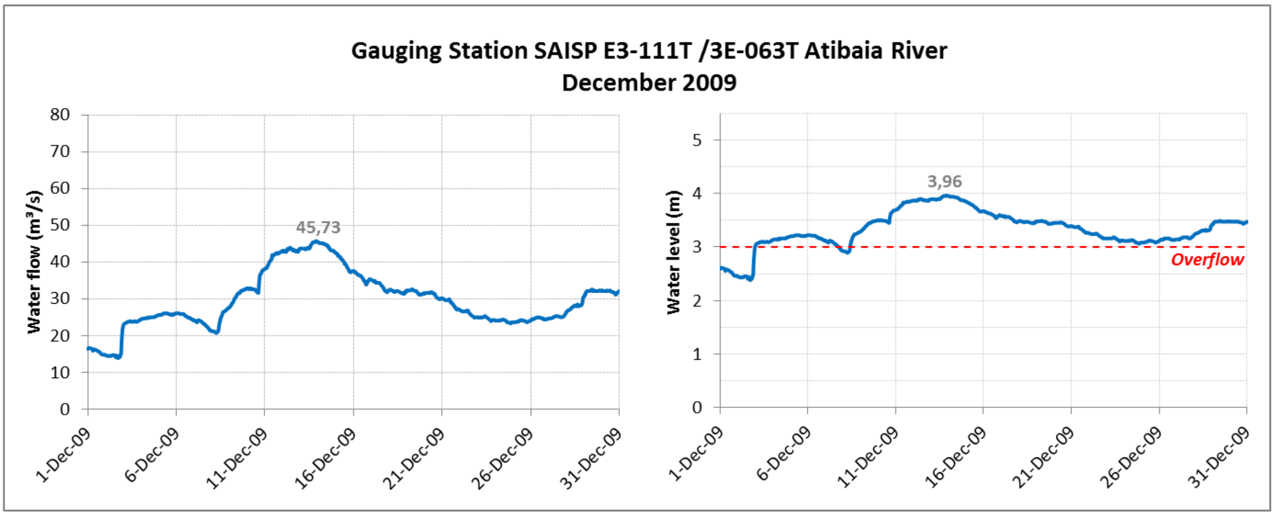

Figure 3. Water flows and water levels on the Atibaia River in December 2009.

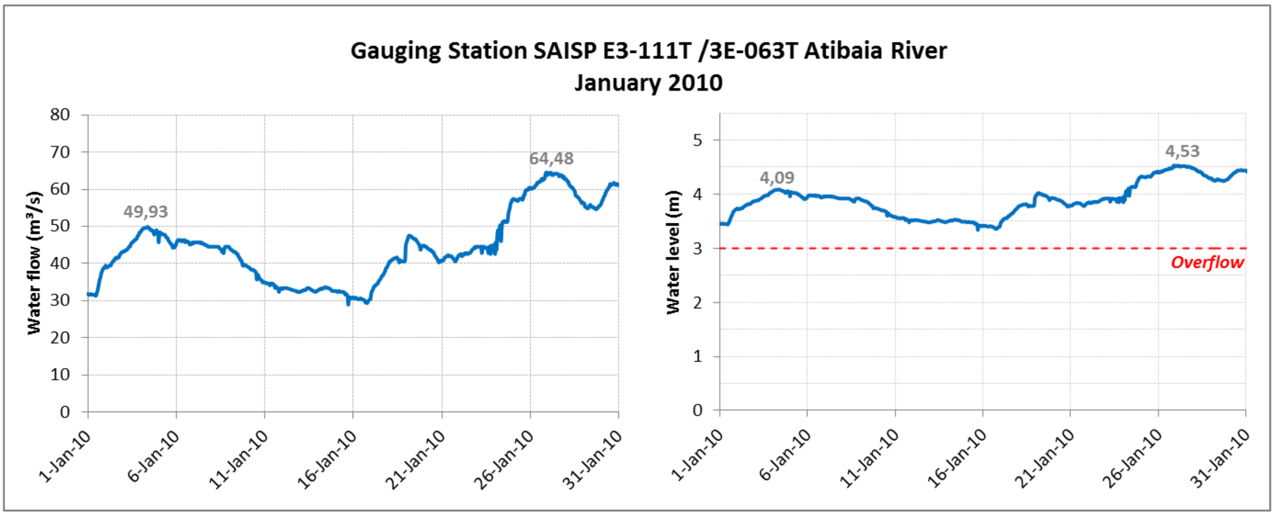

Figure 4. Water flows and water levels at on Atibaia River in January 2010.

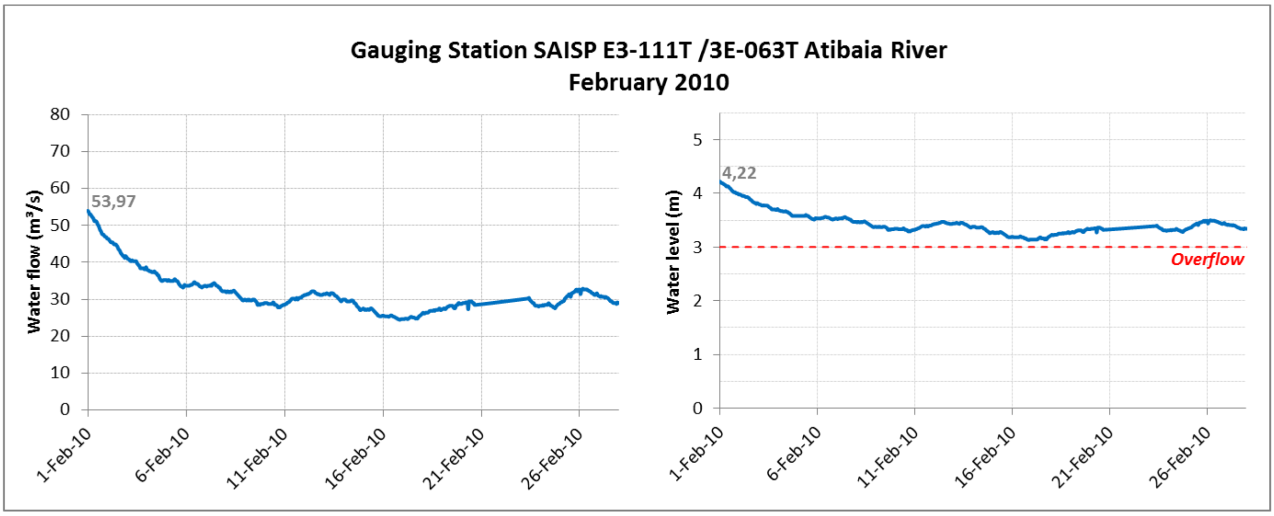

Figure 5. Water flows and water levels on the Atibaia River in February 2010.

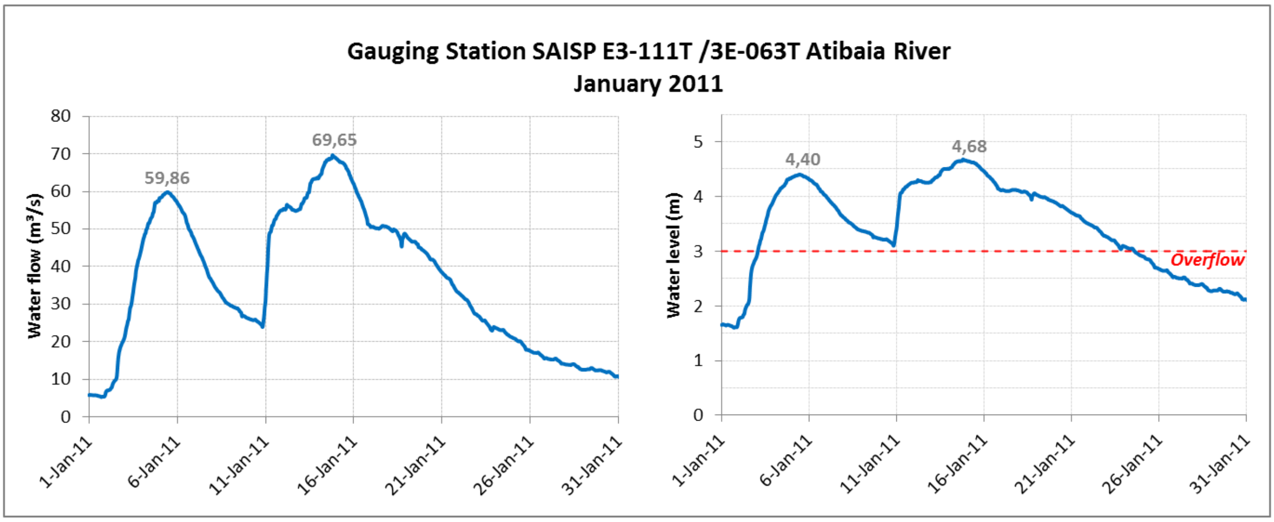

Figure 6. Water flows and water levels on the Atibaia River in January 2011.

The correlation between the peak water flow rates recorded at the SAISP gauging stations and displayed in the graphs above and the return periods calculated for the same section of the Atibaia River suggests that even quite low magnitude flows, i.e., rather high frequency flows, may cause serious harm related to flooding. In December 2009 (Figure 3), for instance, the maximum flow registered at the urban area of the city of Atibaia was 45.73 $m^3.s^{-1}$, corresponding to a return period of less than 4 years (Table 1). This rate has also caused the water level to increase by almost 1 m above the Atibaia river bank overflow limits in the city and launched the beginning of a period of severe impacts related to flooding. In that summer, the maximum water flow occurred in late January 2010 (Figure 4), when the stream in the Atibaia River section reached 64.48 $m^3.s^{-1}$, equivalent to an event with 22 years of probability of occurrence. Despite declining rainfall and flows behavior since then, it is worth mentioning the slow assimilation of these flood flows, which caused the water levels to retain critical conditions throughout the month of February 2010 (Figure 5). From December 2009 to February 2010, the river level in the gauging station SAISP E3-111T / 063T-3E at the Atibaia River remained above the critical level of overflow in 97% of the time.

The local population surmises that the state sanitation company Sabesp (*Companhia de Saneamento Básico do Estado de São Paulo*) would be rather responsible for the raise in the frequency and magnitude of floods, once the company operates the Cantareira System, which comprehends the Jaguari, Jacareí, Atibainha and Cachoeira reservoirs, aiming to partially supply the Metropolitan Region of São Paulo. The claim consists on the hypothesis that excessive outflows would be released from the dams to the downstream cities during the adverse situations mentioned. Conversely, the rapid urbanization has a negative effect on potential infiltration areas, by enhancing soil imperviousness. This trend not only increases the peak flow but also reduces the time of watersheds concentration, inflating the magnitude of problems related to floods that become more common. Thus the intense flooding of the studied area recurred after the start of a rainier season, caused by heavy floods between December 2009 and February 2010, and shall not be exclusively related to the dam outflow structures on the tributaries of the Atibaia River, seeing that standard operating water flows were obeyed during latest events, when there still were significant losses to the riparian population.

The belief that severe impacts related to flood events would result from even low return period flows was corroborated when, in January the following year (Figure 6), successive peak flows were recorded, being the uppermost flow yet greater than those in the previous year.

The findings on recent flood events in the city of Atibaia demonstrate the local vulnerability to low magnitude flows, despite the reservoir system operation, which weakens the impacts caused by the rains due to the routing effect as already seen. Figure 7 depicts the flows that occurred in December 2009 in a section of the Atibaia River, in the urban area of Atibaia, as contrasted to the flows downstream the Atibainha and Cachoeira reservoirs, according to the SAISP database. The differences between the total flows of the tributaries to the flow of the Atibaia River itself almost reach 40 $m^3.s^{-1}$. This remark reflects the fact that the water released from the dams is trifling when compared to the total flow in the Atibaia River, since the contribution from the basins located downstream the Cantareira System may be understood as the main source of the large volumes of water that ravaged the city at the time.

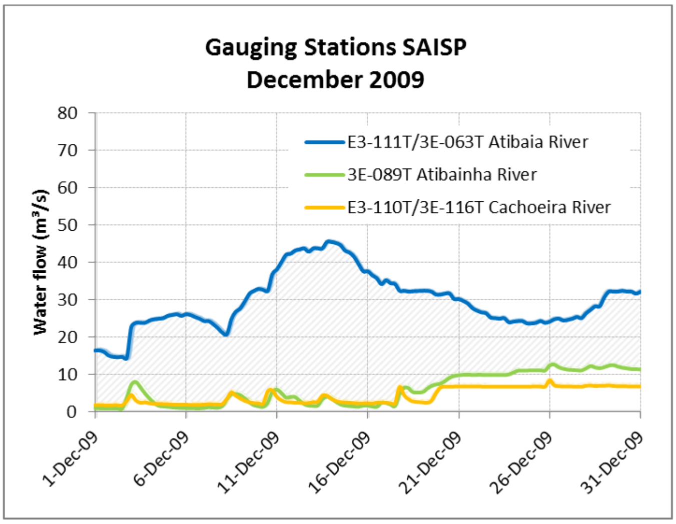

Figure 7. Hydrograph from the Atibaia River and its tributaries for December 2011.

Flood Risk Area Mapping

The area flooded due to the peak flow at the event in January 2010 is shown in Figure 8. The red dots represent measurements taken in the field for the same event and the green ones were obtained from DAEE (2010) for events occurring throughout the whole period from December 2009 to February 2010. The methodology applied produced a consistent result when comparing to field observed points for the same event of 64 $m^3.s^{-1}$ flow. The final outcome was considered satisfactory for the desired level of accuracy that can be used to plan the land use, future risk area delineation and also public policies and contingency plan formulation. If the municipality had already applied this methodology, disorders and damage caused by flooding could have been minimized.

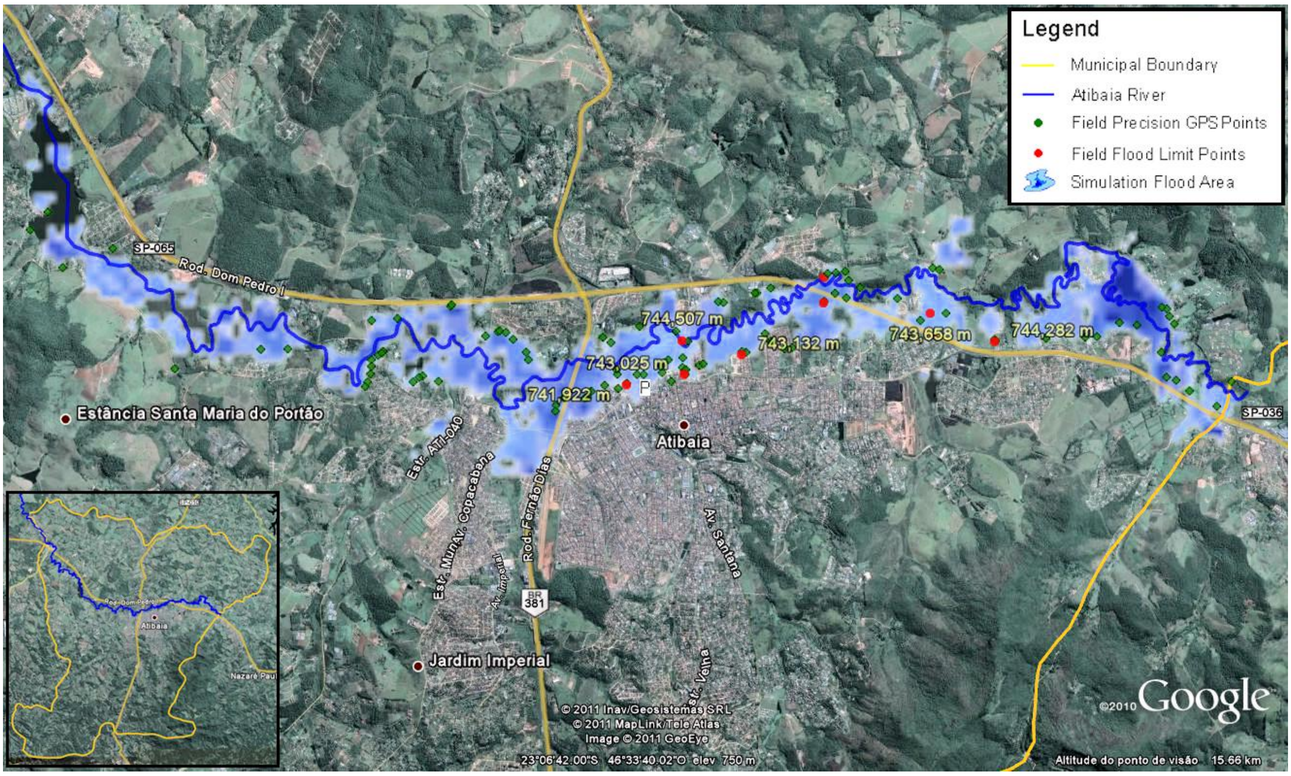

Figure 8. Flooded areas and gauged points in the city of Atibaia and during a 64 $m^3.s^{-1}$ flow event.

ArcGIS software posed problems in adapting to the coordinate projection and, despite a homogeneous referential, consistent results were not achieved. Besides, the processing often failed to fulfill any particular tool function since it interpreted the coordinates in WGS 84 projection as an incompatibility. Therefore, it was necessary to apply the WGS_1984_UTM_Zone_23S projection to all coordinates, so that the program would validate the input data.

Other sources for errors arose from the presentation tool of the HEC-GeoRAS results: once they were converted into KML files, the outcome layers entered in Google Earth led to imprecisions, again related to coordinates and positioning.

Both SRTM and ASTER images contain errors associated with inaccuracies in image sensor acquisition, related to the presence of clouds and atmospheric distortions, and also errors of considerable significance in image resolution. Since the digital terrain model is created, the heights captured by the sensor at interpolated spots are taken into account in order to generate a surface that represents an approximation of the natural terrain. However, when producing flooded patches, which encompass riverine areas that are usually occupied by riparian forest with tall vegetation, the images often depict spots with large disparities to the ground level, decreasing the model performance. Thus, these spots are represented as highlands and the drawn sections may give the idea of islands, exactly where the river bed depression should be placed. As a result, some patches generated in the study look as if they are not flooded, located above the stream bed itself, as shown in Figure 9.

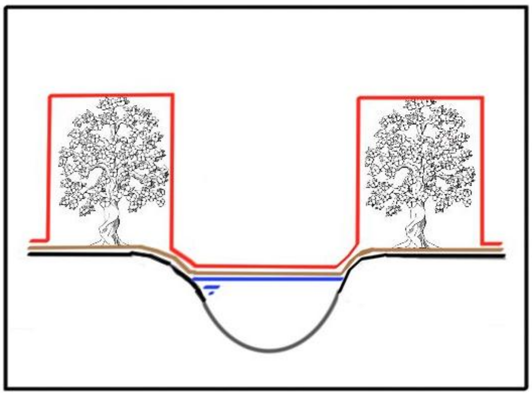

Figure 9. Surface superelevation induced by the vegetation heights in a river section.

The error caused by this imperfection in the digital terrain model was generally considered to be relevant, but nevertheless, it is conceivable that its influence on the final result tends to be reduced by the magnitude of the flooded areas, which would soften these areas without water. Such instance occurs because the flow is dissipated in a very large area and, therefore, the water enters the model with a slight difference with the actual observed level, only adding a few inches to the heights. The simulation of higher return period events, about hundreds of years, shall induce errors more randomly, since the flood water level increase can lead water to places protected by the topography, spots which might not actually be affected by floods.

CONCLUSION

The rain events occurred between December 2009 and February 2010 and in January 2011 caused extensive flooding along the Atibaia River banks. Flow rates of about 40 $m^3.s^{-1}$ are sufficient to overflow the river channel. These low return period flows are a sign of the basin great vulnerability to floods; furthermore, such events tend to become more frequent as the soil impervousness increases.

The methodology applied proved to be adequate for flood hazard area mapping. In the absence of bathymetric data from river sections, the terrain topography might as well be obtained from satellite images. SRTM images produced the best results in this study. Flaws regarding the ground surface superelevation induced by vegetation heights have not led to significant differences in the water level on an area flooded by a 64 $m^3.s^{-1}$ flow. High return periods flow, generally hundreds of years, may possibly result in errors when representing the flooded area due to inconsistent flow direction deriving from terrain superelevation.

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