A Framework for the Generation of the Rainwater Flow Model in Streets

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Abstract. Urbanization in Brazilian cities often occurs without adequate planning. An example of this are urban drainage systems, that usually do not receive the proper attention from the public authorities. Therefore, drainage systems are often improvised or constructed in an emergency or provisional way, without adequate study. Furthermore, climate change has an impact in the dimensioning of such systems, and urban flooding tends to be more frequent. This work presents a framework that can be applied in any city to allow the user to identify, in their area of interest, critical regions that tend to receive greater water load during rainfall. The work is developed by associating two open software packages: QGIS and SWMM. The tool receives files with altimetric data (Digital Elevation Model) and shapefiles that represent the streets. The system generates a stormwater runoff model using the streets as the main drainage channels, allowing the identification of the segments that are likely to receive the highest volumes of stormwater. The tool can be used in support of public policies to prioritize urban drainage in specific and possibly critical areas. A case study in regions with known urban flooding problems in the city of Belo Horizonte in Minas Gerais is presented. Results are compared with reports of urban flooding in the city and prove to be consistent in identifying streets with a greater tendency to receive more water, with consequent impacts for the local population.

Keywords: geoprocessing, GIS, urbanization, runoff, public management, urban drainage.

1 Introduction

In recent years, the urbanization process has been accompanied by profound changes in land use and occupation. Often, this occupation may result in uncontrolled environmental impacts and landscape changes. Frequent patterns of land use and coverage, with more waterproof surfaces, make the analysis of the hydrological cycle complex and, consequently, make it difficult to produce information about the behavior of surface runoff, which is essential in the urban appropriation process. From this perspective, the growing urbanization process provides certain impacts on the intra-urban drainage network, associated with the change in the peak flow and the increase in surface runoff (Alves et al., 2011).

These impacts, according to Tucci (2005), have deteriorated the population's quality of life, due to the increase in the frequency and level of floods, the reduction in water quality and the increase of solid materials in rainwater runoff. Furthermore, fast transformations caused by urbanization generate changes in the quality of the landscape, environmental degradation, irregular occupation and reflect deficient planning in urban management (Ono et al., 2005).

According to Vieira (2006), conventional techniques, when applied to monitoring urban expansion and to the occupation of urban areas, have not been able to keep up with the speed with which these events happen. Therefore, it is necessary to emphasize the need to search for new methods, using more adequate technologies to detect, in near real time, urban expansion and the resulting environmental changes.

This work intends to help guide public policies aimed at the construction of drainage systems. Objectively, we propose a tool that is able to semi-automatically identify, in an area of interest, regions that are subject to a greater water load due to the local topography, in addition to showing the tendencies for water flow direction.

This study uses altimetric data, in the form of a Digital Elevation Model, which allows the identification of slopes, peaks and valleys which, associated with the street map, define a rainfall runoff model based on existing drainage pipes or on superficial flow on the streets of the study region. This model is analyzed in Storm Water Management Model (SWMM)[1] to simulate the flow of water in a scenario of intense rainfall, thus identifying the regions of attention.

2 Related Works

Urban drainage systems design requires understanding several related issues, and correlating them to the local terrain characteristics. Surface runoff potential in urban environments can be generated using the curve number model, developed by the Soil Conservation Service (SCS)[2]. A previous study (Alves et al., 2011) used this model in the city of Santa Maria (RS), combining information from land use and occupation to soil types found in the basin. Results indicate that surface runoff potential maps are a good instrument for identifying potential flooding areas according to rainfall conditions throughout a municipality, although the direction of runoff flow in the streets has not been considered.

Another approach is the construction of a flood risk graph to relate the volume and duration of the rainfall to the possibility of overflowing in a water body. A methodology for that purpose is introduced by Siqueira et al. (2019), along with a case study from the Cachoeirinha neighborhood in the city of Belo Horizonte (MG). Building the graph requires determining the land use types in the watershed, data on the drainage network and a local equation of intensity, duration and frequency of rainfall. The graph produced by for the case study presents results that are consistent with actual rainfall data. However, the implementation of the entire method in a semi-automatic way is not explored, and the study also does not analyze the volume of stormwater that flows in the city's streets.

[1] https://www.epa.gov/water-research/storm-water-management-model-swmm
[2] https://www.scs.nsw.gov.au/

Simulations can also be used to mitigate damage caused by urban flooding. Silva et al. (2013) compare several such methods applied to some regions of the city of Barreiras (BA). Geoprocessing techniques with street data and contour lines are required to prepare the data that is needed to feed the SWMM software. In that research, authors seek to test possible solutions to mitigate the consequences of flooding, but techniques for identifying risk areas are not developed. SWMM can also be used to run quantitative simulations of the surface stormwater runoff (Lima et al., 2017). Geographic information can be prepared in QGIS[3] to generate flood hydrographs, and SWMM is used to generate a concise hydrological model, including a rainfall-runoff curve that facilitates the analysis. Lima et al. (2017) present a study in the sub-basins delimited over the municipality of Sobral (CE), each covering areas ranging from 7.2 to 1080 hectares. However, that work does not develop the simulation of the flow through the streets, but through the natural features of the terrain.

The work presented here differs from the previous ones by designing and implementing Python code to integrate QGIS geoprocessing tools so that a SWMM input file can be automatically created. From this file, SWMM is used to create a runoff map, considering elevation and street geometry in the study area to determine the expected behavior of stormwater on the streets. The resulting analysis allows the identification of the areas that are more prone to flooding.

3 Methodology

3.1 Used Programs

For the development of this work, the free software packages QGIS and SWMM, were used. In addition, the plugins Open Street Map and Dzetsaka were used in QGIS.

QGIS is open-source software that consists of a geographic information system that allows the visualization, editing and analysis of georeferenced data, in addition to executing several useful algorithms in the field of geoprocessing.

The Storm Water Management Model – SWMM, from the United States Environmental Protection Agency (US EPA), is a software that uses a dynamic rainfall-runoff simulation model, which can be used for urban drainage management, simulating the quantity and quality of the water runoff, especially in urban areas. It can be used both for the simulation of a single rainy event and for a continuous long-term simulation. In this work, the translated version of the software was used. The current SWMM translation into Portuguese refers to the original English version 5.00.22 and was carried out by the Federal University of Paraíba (UFPB). This version can be downloaded from the page of the Laboratory of Energy and Hydraulic Efficiency in Sanitation at UFPB.

The Open Street Maps[4] (OSM) plugin can be installed on QGIS. This project offers maps for thousands of websites, mobile apps and hardware devices.

Dzetsaka is another plugin within QGIS that enables semi-automatic classification of satellite images. Thus, it is possible to identify the use and occupation of the soil and to determine its permeability.

[3] https://www.qgis.org/

[4] https://www.openstreetmap.org/

3.2 Elevation Data Sources

In order to know the dynamics of water runoff in a given location, it is essential to have knowledge of the topography/relief. For this, the Digital Elevation Model (DEM) can be used, which consists of a matrix in which each cell represents the height corresponding to that location. In this work, images from the Alos Palsar[5] satellite, whose spatial resolution is 12.5 meters, were used.

Optical satellite images were obtained using Google Earth, due to their excellent resolution. Once captured, the images are registered to their actual location using QGIS.

3.3 Work in QGIS

The geoprocessing part is carried out within QGIS. Five input parameters are used: the DEM, the shape of the polygon that delimits the study area (created by the user within QGIS), a street centerline layer (lines), obtained from OSM, a satellite image of the region and a layer of polygons defining samples of each type of land use and occupation.

From these parameters, a sequence of geoprocessing and data treatment methods are used to create four files: Points File, Excerpts File, Sub Basin Design File and Sub Basin Data File. They are all tables in CSV format.

The model considers the streets as conduits through which the water will flow. Thus, to generate a flow map, it is necessary to determine the nodes, which are responsible for connecting the conduits. These nodes are determined by the geographic coordinates of street crossings, or street endpoints. With the use of an area of interest polygon, it is possible to delimit where this process will occur, thus saving computational processing. The next step is to provide for each of these extreme points its respective elevation, through the DEM (which can also be limited to the area of interest, so that unnecessary data are not used). The entire procedure for generating the Points File is detailed in Figure 1.

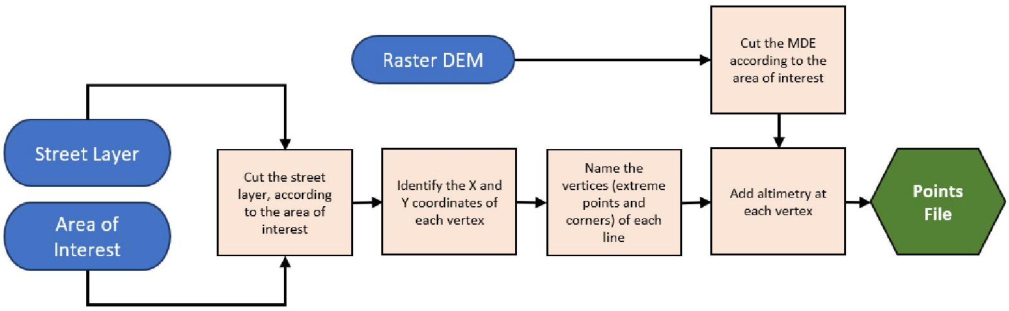

Figure 1 - Diagram of the process of generating the extreme points of the street centerlines

Figure 2 shows the procedure for obtaining the data from the street map to generate the excerpts that will make up the drainage network (arcs). First, the area of interest is used to obtain only the centerlines of the street layer to be studied. Then, each line receives an "id" (name) and its length is calculated. Finally, the coordinates of the extreme points (start and end) of each line are identified.

[5] https://search.asf.alaska.edu/

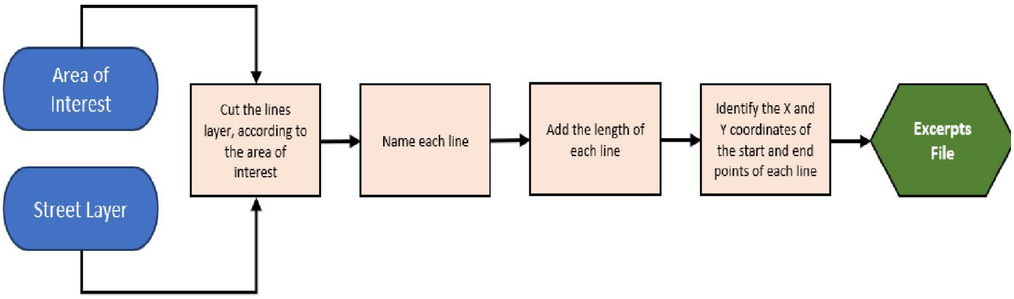

Figure 2- Diagram of the process to generate the Excerpts File

The next datafile to be produced contains the limits of the drainage area, i.e., sub-basins that are part of the watershed. In this work, sub-basins are represented by regions that are along the streets, including city blocks, parks, vacant areas, buildings, forests, squares and parking areas. First, it is necessary to identify and name each sub-basin that is encompassed by the area of interest and the corresponding streets. Once this is done, the next step is to obtain the coordinates of the points that delimit the margins of each sub-basin and connect them in the correct order. Figure 3 shows these steps schematically.

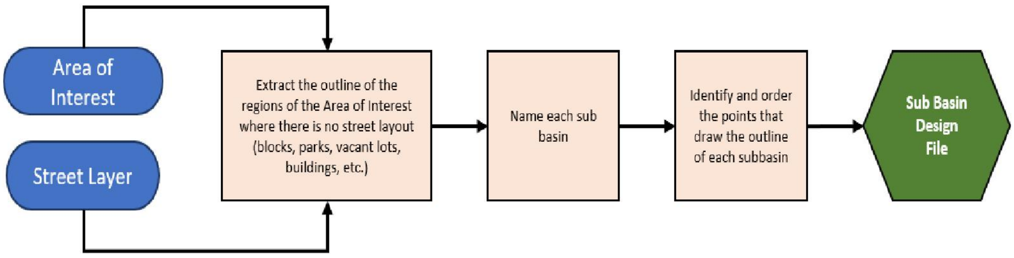

Figure 3 - Diagram of the sub-basin generation process

The sub-basin data can be generated from previously produced models. Using the MDE, we can determine the height at each edge point present in the sub-basin design file (Figure 3). After that, in each sub-basin, the border point(s) with the lowest height are selected; this/these point(s) is(are) called Guide Point(s). Therefore, the Guide Point represents the region of the sub-basin where the water captured by that sub-basin will be drained (runoff), since the water will be drained to the lowest location. However, the Guide Point belongs to the edge of the sub-basin and not to the street, which prevents to study the flow of water in the streets. Therefore, the next step is to choose the point on the street that serves as the actual outlet point for each sub-basin. This choice is made considering the street point (contained in the Points File, Figure 1) that is closest to the Guide Point. In this way, the outlet point of each sub-basin is determined, that is, the place on the street (and not on sub-basin's edge) where the water drained by each sub-basin will go.

Finally, a study of land use and occupation is carried out to determine the permeable area of each sub-basin. For this, it is necessary to provide a shapefile with the polygons with samples of permeable soil types and waterproof types, combined with the satellite image of the region of interest. Permeable area polygons involve green areas such as woods, parks, forests, pastures and crop fields. Polygons with impermeable samples are those that involve regions of black and gray colors such as tin roofs, asphalt, buildings, constructions in general. The Dzetsaka plugin performs the classification for the permeable area in each sub-basin and then calculates the proportion of each type in the sub-basin. The resulting estimated permeability rate is added to the sub-basin data file. Figure 4 presents an overview of this process.

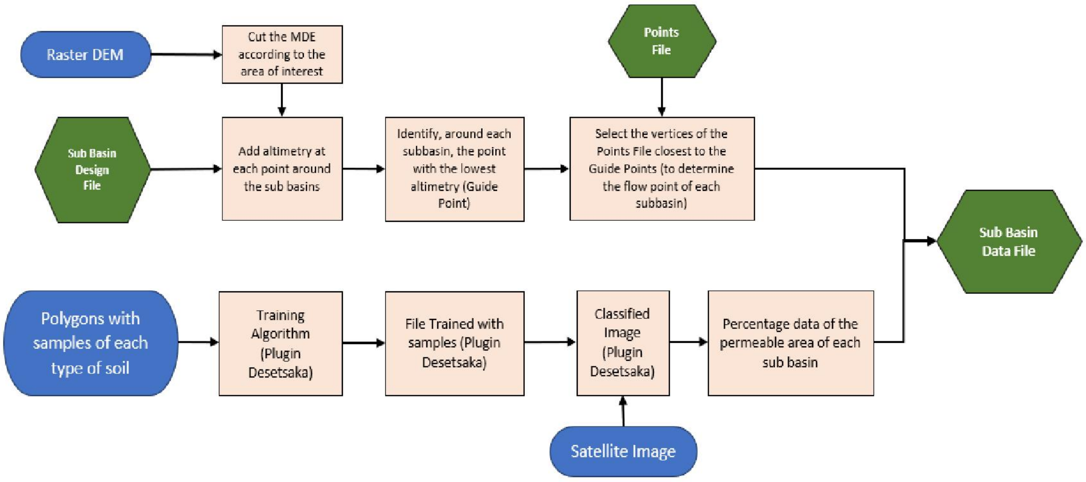

Figure 4 - Process diagram for generating the Sub-Basin Data File

Once the four files are generated, the last step is to produce a TXT file that is readable by SWMM. The processing of previously generated files is detailed in Figure 5. The TXT file contains the data necessary to produce the flow map of the study area in SWMM. The manipulation of the data in this software is detailed in the next section.

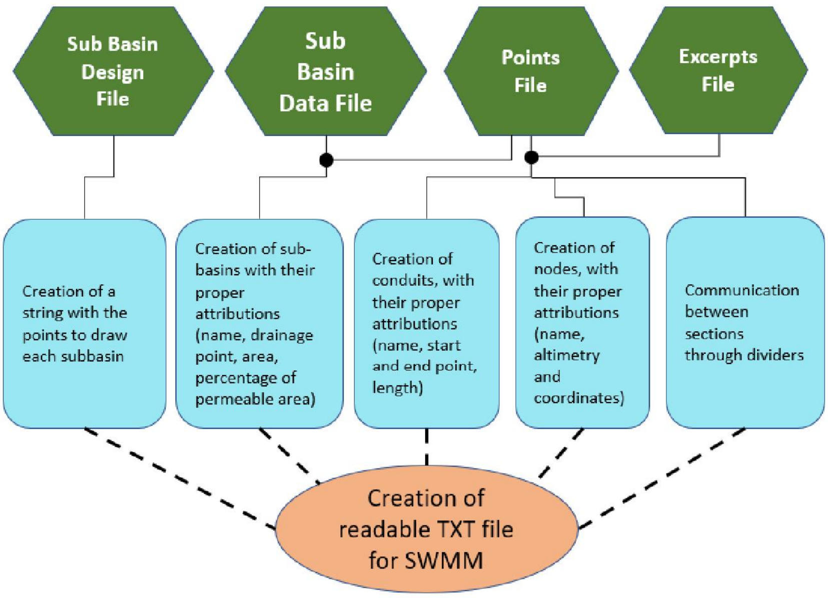

Figure 5 - Process diagram for generating the TXT file

3.5 Work in SWMM

The resulting TXT data file is input to SWMM. Thus, the street-based drainage network and the sub-basins are displayed. Next, the user must create a time series with pluviometric data - intensity (mm/h) and duration - of the study region and include them in the pluviometer parameter. A single pluviometer parameter in SWMM is enough to simulate the water flow, according to the incidence of rainfall as characterized in the pluviometric data. Once all sub-basins are connected to the pluviometer, the simulation can be started.

The visualization of the results can highlight the street segments that receive the largest water flow according to the simulation. It is also interesting to present segments classified according to slope, so the local topography can be better understood.

4 Experiment and Discussions

The algorithm was executed in some regions of the city of Belo Horizonte to test and validate the effectiveness of the generated model. The choice of these areas was based on streets that have a history of urban flooding. To obtain this information, the newspaper "*Hoje Em Dia*" was consulted, looking for lists areas prone to flooding in the capital of Minas Gerais. The algorithm was run in some of these regions.

Tocantins street's region:

Figure 6 – Tocantins Street area

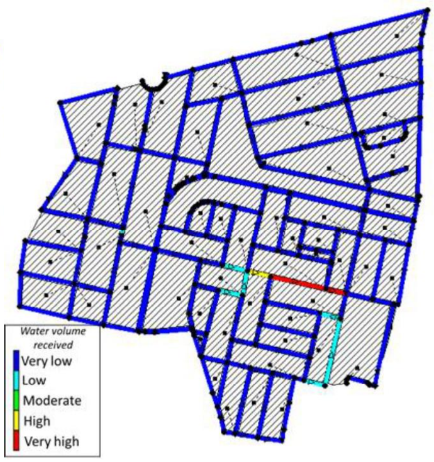

Figure 7 – Slope and altimetry map **Figure 8 – Water load map**

Osmar Costa street's region:

Figure 9 – Osmar Costa street area

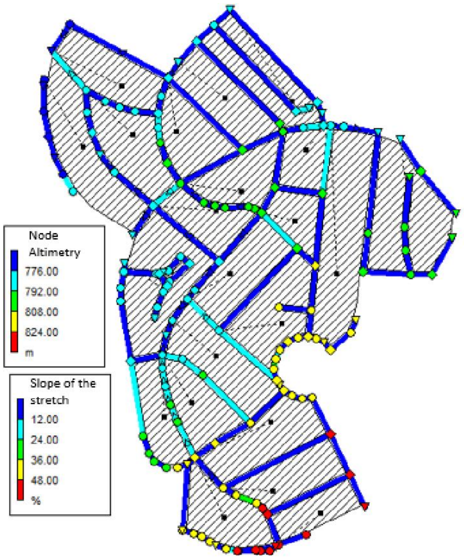

Figure 10 – Slope and altimetry map

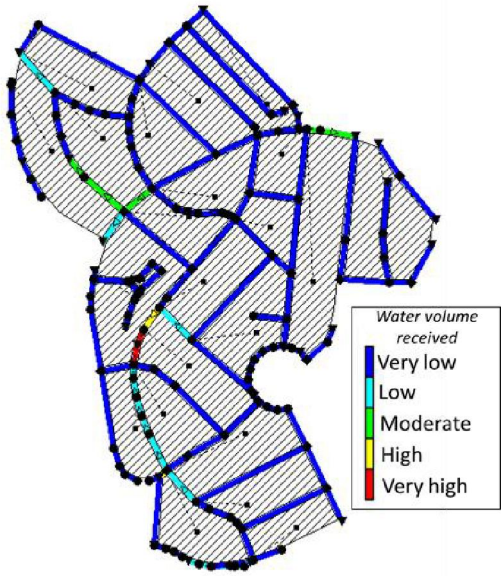

Figure 11 – Water load map

Maria José de Jesus street's region:

Figure 12 – Maria José de Jesus Street area

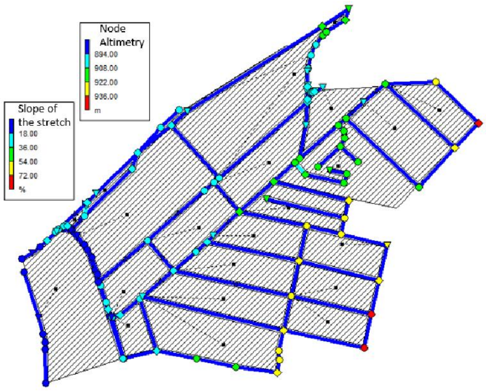

Figure 13 – Slope and altimetry map

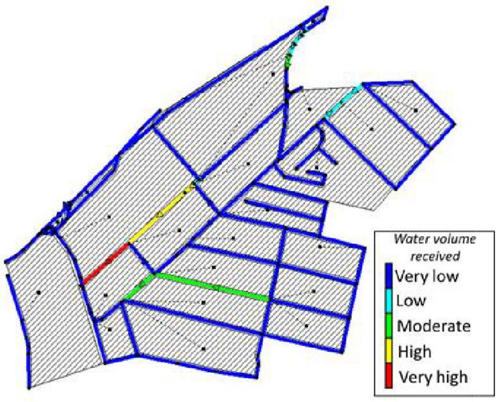

Figure 14 – Water load map

Flat streets (low slope) and located in regions where surroundings are higher than them, tend to receive more water and even present a risk area. Images 6, 9 and 12 show the regions around Tocantins, Osmar Costa and Maria José de Jesus streets, respectively. These streets are known to have a history of flooding, and for this reason it is to be expected that they, in their respective regions, have a greater tendency to receive higher volume of drained water in rain periods because they are flat and, located in a valley, in relation to their surroundings. The algorithm was run in the three study regions (Figures 6, 9 and 12) to confirm this expectation.

Results can be seen in Figures 8, 11 and 14. In these images, the streets with the warmest colors (yellow and red) tend to receive a greater volume of water, because of the relief on which they are located. Such topographic characteristics (altimetry and slope) can be observed in Figures 7, 10 and 13, where the hottest colored points are the highest and the coldest ones (blue and cyan) indicate the lowest altitudes. In addition, it is possible to analyze the slope of the streets: the steepest sections have the warmest colors and the flattest the coldest ones.

As can be seen in Figures 8, 11 and 14, the proposed algorithm generates results that satisfy the objectives of the work. Streets that were already known to be floodable, were identified by the method as being, in their respective region, segments that receive a greater load of water. In addition, the algorithm confirmed, in Figures 7, 10 and 13, the expected topographic characteristics for the three streets studied, such as low slope and low altitude in relation to the neighborhood. This is seen by the blue, cyan and green dots along the studied streets, which are surrounded by yellow and red dots in the neighborhood. In addition, the three streets are mostly shown in blue, and only a few parts in cyan, indicating their low slope.

5 Conclusion

This work presents a methodology capable of encapsulating the complexity of generating a map that indicates streets with a tendency to receive large amounts of water in rainy periods. This map can be used both to propose a better rainwater drainage model and to identify regions with potential for flooding. The technique works by receiving the satellite image of the region of interest and the terrain elevation model. The region is classified according to its level of permeability and slope, generating the sub-basins that receive rainwater. Regions with higher impermeability cause excess rainwater to flow to the neighborhood's streets. The runoff model is analyzed by SWMM, indicating the streets that are likely to receive the highest water loads.

From the results presented in SWMM, we show that the method explained in this work identifies the streets and segments that tend to receive greater volumes of water during the rainy season in a given region. The same streets were cited by the news site as subject to flooding.

Thus, this algorithm serves as an initial approximation, for institutions such as municipal administrations and civil defense organizations, for the development of projects to prevent urban flooding. However, the execution of the tool may not be trivial for people without some knowledge in the area, so training is necessary for its efficient application.

The code in Python and the tutorial that shows step-by-step the whole technique can be found at Git Hub[6].

Combining the flow and slope analysis with the study of land use and occupation, it is possible to improve the identification of areas susceptible to flooding. A connection to crowdsourced data on flooding problems (DEGROSSI, L. et al. 2014, HIRATA et al. 2015) can reinforce the indications generated by the produced method, and to establish priorities for the implementation of solutions.

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[6] https://github.com/tutakanamon/Modelo-de-Escoamento-de--gua

References

ALASKA SATELLITE FACILITY. Search, c2021. Home Page. Available in: <https://search.asf.alaska.edu/#/>. Accessed on: May 15, 2021.

ALVES, D. B. et al. Modelagem dinâmica do escoamento superficial na área urbana de Santa Maria – RS. Anais XV Simpósio Brasileiro de Sensoriamento Remoto. Maio, 2011. Available in: <https://www.researchgate.net/publication/281094964_Modelagem_dinamica_do_escoamento_superficial_na_area_urbana_de_Santa_Maria_-RS>. Accessed on: May 15, 2021.

DEGROSSI, L. et al. Flood Citizen Observatory: a crowdsourcing-based approach for flood risk management in Brazil. Proceedings of the International Conference on Software Engineering and Knowledge Engineering, SEKE. 2014.

HIRATA, E. et al. Flooding and inundation collaborative mapping – use of the Crowdmap/Ushahidi platform in the city of Sao Paulo, Brazil. Journal of Flood Risk Management, 2015. Available in: https://doi.org/10.1111/jfr3.12181.

HOJE EM DIA. BH tem mais de 60 áreas sujeitas a alagamento; veja quais são, 2020. Página inicial. Available in: <https://www.hojeemdia.com.br/horizontes/bh-tem-mais-de-60-%C3%A1reas-sujeitas-a-alagamento-veja-quais-s%C3%A3o-1.811489>. Accessed on: May 15, 2021.

LABORATÓRIO DE EFICIÊNCIA ENERGÉTICA E HIDRÁULICA EM SANEAMENTO DA UFPB. SWMM, 2020. Home Page. Available in: <http://ct.ufpb.br/lenhs/contents/menu/swmm>. Accessed on: May 15, 2021.

LIMA, J. W. S. et al. Uso do SWMM na modelagem hidrológica da área urbana de Sobral, Ceará, Brasil. Congresso ABES FENASAN. Outubro, 2017. Available in: <https://tratamentodeagua.com.br/wp-content/uploads/2019/06/22.pdf>. Accessed on: May 13, 2021.

OLIVEIRA, M. d. et al. Imagens do google earth para fins de planejamento ambiental: uma análise de exatidão para o município de são Leopoldo/RS. IV Simpósio Brasileiro de Sensoriamento Remoto-SBSR, 2009.

ONO, Sidnei; Barros, Mario Thadeu Leme de; Conrado, Guilherme Nunes. A Utilização de SIG no planejamento e Gestão de Bacias Urbanas. In: AbrhSIG. São Paulo/SP: 2005.

OPEN-SOURCE GEOSPATIAL FOUNDATION. Home Page. Available in: https://qgis.org/pt_BR/site/forusers/download.html. Accessed on: May 13, 2021.

SIQUEIRA, R. C. et al. Metodologia para construção de gráfico de risco de inundações urbanas. Revista Brasileira de Recursos Hídricos. March, 2019. Available in: <https://doi.org/10.1590/2318-0331.241920180125>. Accessed on: May 13, 2021.

SILVA, M. P. et al. Aplicação do modelo de gestão de drenagem urbana SWMM no controle de alagamentos em Barreiras-BA. Simpósio Brasileiro de Recursos Hídricos. Novembro, 2013. Available in: <https://www.abrhidro.org.br/SGCv3/publicacao.php?PUB=3&ID=155&SUMARIO=3998>. Accessed on: May 13, 2021.

TORLAY, R.; OSHIRO, O. T. Obtenção de imagem do google earth para classificação de uso e ocupação do solo. In: IN: CONGRESSO DE INTERINSTITUCIONAL DE

INICIAÇÃO CIENTÍFICA, 2010. Embrapa Territorial-Artigo em anais de congresso (ALICE). [S.l.], 2010.

TUCCI, C. E. M. Gestão de Águas Pluviais Urbanas, 2005. Available in: <https://files.cercomp.ufg.br/weby/up/285/o/Gest%C3%A3o_de_Aguas_Pluviais__.PDF?1370615799>

VIEIRA, P. B. H., Pinto, J. F., Galvão, M. L., Santos, L. K. S. Utilizando SIG na Análise Urbana da Microbacia do Rio Itacorubi, Florianópolis SC, In. COBRAC 2006 · Congresso Brasileiro de Cadastro Técnico Multifinalitário · UFSC Florianópolis · 15 a 19 de outubro, 2006, p. 1-9. (2006)