FLOOD MAPPING IN URBAN AREA USING HEC-RAS MODEL SUPPORTED BY GIS

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ABSTRACT: Floods are among the most damaging natural disasters in Brazil, not only financially, but also in human terms. Only in the Santa Catarina state, in the 1991-2010 period, about 5.7 million people were affected and 4,054 deaths were reported as results of these phenomena. This reality highlights the necessity for studies that can support flood control measures. Among these measures, flood maps have a non-structural character and can assist decision-making in relation to urban planning, increasing of public awareness regarding risk areas and evacuation routes. This study mapped the flood extent of Rio dos Cedros city urban area, Medium Itajaí River Valley – Santa Catarina, through the hydrodynamic mathematical model HEC-RAS, supported by a GIS. The following data were used: digital terrain model, hydrography map and orthorectified aerial image (1:10,000 scale), Cedros River discharge time series and field discharge measurements. Simulations were performed for events with return period of 2, 5, 10, 20, 50 and 100 years, and for a flood event occurred on 08/09/2011. The results indicated that the roads and buildings in the surroundings of the Cedros River bridge and the Ouro Creek and its tributary confluence region are more susceptible to flooding. In addition, show the absence of urban planning and the occupation of the watercourses natural flood areas. The model presented an underestimated result when compared to the flooded areas recorded in the 09/08/2011 event. This behavior may be due to the return of the Cedros River water by urban drainage system, and the possible backwater of the Cedros River in the Ouro Creek and its tributary. This study demonstrates the potential of use HEC-RAS model and GIS with high resolution spatial data for mapping highly susceptible flood areas.

Key Words: Flood Mapping, GIS, HEC-RAS, Cedros River.

1. INTRODUCTION

Floods are periodical events that occur primarily by water overflowing from the main drainage channel of natural or artificial systems to the adjacent areas, occupying riparian areas and floodplains. When a flood occurs in human occupied areas and interacts negatively with society, it is considered to be a natural disaster. This type of disaster can be amplified by human activities that interfere in hydrological cycle such as soil sealing, vegetation cover removal, flow channel modification, reservoir construction, along with susceptible flood areas occupation (TUCCI, 2011).

Only in the Santa Catarina state (SC), Southern Brazil, floods affected over 5.7 million people and caused 4,054 deaths during the 1991-2010 period. Among the geographical regions of Santa Catarina, the Itajaí River Valley is notoriously known by flood events and, according to CEPED UFSC (2012), this region has registered the second higher number of floods in Santa Catarina for the 1991-2010 period.

Preventive flood control measures can be divided in two main types: non-structural measures, which are related to land use management focusing on avoiding flood susceptible areas occupation and also include monitoring, warning and evacuation systems; and structural measures, which are linked to engineering structures to control and/or prevent water overflow. In either ways, flood maps are tools that can be used to support these actions.

The flood maps can help decision makers plan the urban land use development, increase public awareness regarding risk areas and evacuation routes, improve the understanding of the overflow water dynamics to riparian areas regarding rescue actions and defining safe areas to allocate affected people (EXIMAP, 2007; JAPAN, 2005).

In order to predict the extent of flood and create inundation maps, mathematical models are currently used. They simulate the actual event by means of mathematical equations that represent the physical phenomenon in a simplified manner. In this context, HEC-RAS model, developed by the US Army Corps of Hydraulic Engineers, has been used successfully in studies of forecasting and simulation of extreme flood events (e.g. GHANBARPOUR, 2011; TIMBADIYA, 2011; TATE, 2002).

HEC-RAS simulate one dimensional water profiles in steady and/or variable flow in single channel sections or dendritic systems of natural or artificial channels. Geometric aspects of channels sections are used as model input data in order to calculate standard geometric and hydraulic routines. In addition, it also allows insertion of hydraulic engineering elements to the channels, such as culverts, bridges, dams, retention basins, etc. The analysis component of steady flow calculates water profiles in sections considering the gradually varied flow permanent and is suitable for application in floodplain management and flood insurance studies (USACE, 2010).

The aim of this study was to generate maps of flood events with different frequencies of occurrence for urban area of the Rio dos Cedros city (SC) through simulations with the HEC-RAS model. These maps can be used by the Fire Brigade and Civil Defence in the planning and execution of emergency measures in flood damage mitigation and also by the local government on planning territorial land use.

2. MATERIALS AND METHODS

2.1 Study Area

The study area is the Rio dos Cedros urban area, located in medium Itajaí River Valley, Santa Catarina, Southern Brazil. Rio dos Cedros has a small urban area (only 2.5% of the total area), according to the 2010 census (IBGE, 2011), 10,284 people reside in the city, where more than half of residents live in the urban area. The Cedros River watershed has approximately 537 km² and two dams for power generation. The average annual precipitation is about 1554 mm (INMET, 2009). The Cedros River is 6th order watercourse, according to Strahler (1952) fluvial hierarchy classification, and has a total length of 60.7 km and an average slope of 0.075 m/m.

2.2 Materials

For this study, the following materials were used:

• HEC-RAS 4.1.0 Software for hydrodynamic modeling;

• SPRING 5.2.3 Software for mapping the land use and cover;

• ArcGIS 9.3 and the HEC-GeoRAS extension for extracting the geometric and Manning roughness data needed for the modelling, and post-processing results and maps elaboration;

• Historic flow discharge data and rating curve of Arrozeira fluviometric Station (ANA code 83675000), located in the urban area of Rio dos Cedros at latitude 26°44"27'S, longitude 49°16"14'O and altitude 80 m. These data were obtained from the National Water Agency (ANA – Agência Nacional de Águas);

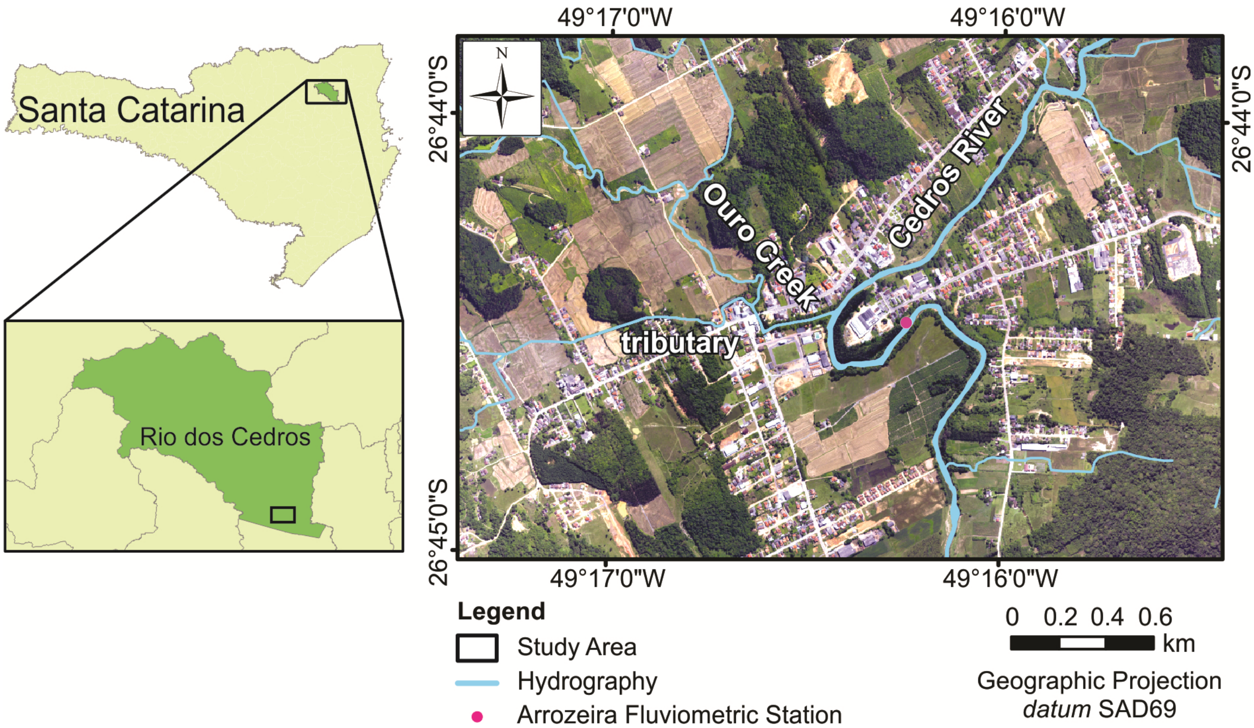

Figure 1: Rio dos Cedros urban area location.

• Digital Elevation Model (DEM) (1 m spatial resolution), hydrography features and aerial images (0.39 m spatial resolution - RGB) generated from a 1:10,000 scale aerial survey, obtained from Santa Catarina State Sustainable Development Department (Secretaria de Desenvolvimento Sustentável - SDS);

• Cedros River bathymetric cross sections, surveyed by Corrêa (2011); and

• Past floods Information in the Rio dos Cedros city Flood Emergency Plan (PMRC, 2011).

2.3 Methods

To apply the HEC-RAS model to the study area, the following datasets were necessary: preparation and extraction of geometric data and Manning's roughness coefficient at the streams cross sections and defining the flow discharge input data.

The cross sections geometric data were extracted from the TIN (Triangular Irregular Network), generated from the corrected DEM. The DEM correction was made by inserting the Cedros River bathymetric information. The Cedros River subsurface relief was represented by simplified trapezoidal channel cross section based on the cross sections surveyed by Correa (2011), which was assumed to be representative of the entire length of the Cedros River flow channel due to the similarity between its geometry and low channel width variability, observed on site and in the aerial images.

In order to define the Manning's roughness coefficient on the cross sections, a land use and cover map of the study area was created. For this, the aerial images of the area were processed in digital images processor Software SPRING, where segmentation was performed by growing areas method and supervised classification, grouping land use and cover into 5 categories: water course; forest; agriculture; Buildings and traffic routes; and grassland and scrub vegetation.

The values of Manning's roughness coefficient for each category of land use were defined based on Chow (1959). However, for the main channel of watercourses followed the methodology proposed by Cowan (1956), cited in Chow (1959), which is determined from the physical characteristics of the channel:

$$n=(n_0 + n_1 + n_2 + n_3 + n_4)\, m_5 \quad [1]$$

where n_0 is a basic n value for a straight, uniform, smooth channel in the natural materials involved; n_1 is a value added to n_0 to correct for the effect of surface irregularities; n_2 is a value for variations in shape and size of the channel cross section; n_3 is a value for obstructions; n_4 is a value for vegetation and flow conditions; and m_5 is a correction factor for meandering of channel.

In this way, the following Manning's roughness values were used: water course (n = 0.036); forest (n = 0.045); agriculture (n = 0.04); buildings and traffic routes (n = 0.06); and grassland and scrub vegetation (n = 0.02).

The flow discharge input data for the simulations were estimated by Gumbel distribution using the historic flow discharge data and Arrozeira fluviometric station rating curve, located in the Cedros River. According to Naghettini & Pinto (2007), this distribution is appropriate for estimation of extreme flood events studies. In this study flow discharge with return periods of 2, 5, 10, 20, 50 and 100 years were simulated.

In order to define the discharge flow at the non-gauged watercourses, an on-site discharge flow measurement was performed to establish a discharge proportion between the gauged stream, Cedros River, and the non-gauged ones, Ouro Creek and tributary. The simulated fluvial system composed by the Cedros River, the Ouro Creek and the tributary was divided in 5 reaches. Figure 2 illustrate the simulation area, reaches, and cross sections.

Finally, the extraction of geometric roughness coefficient data was performed in ArcGIS GIS, by HEC-GeoRAS extension tools.

After importing GIS processed data into HEC-RAS, steady flow state simulations were performed entering the discharge flow data at the upstream cross section of each reach, characterizing it as supercritical. The discharge flow defined to the reaches was entered as follow: Lower Cedros River (Reach 1) - Gumbel distribution; Upper Ouro Creek (Reach 2) - proportion of Reach 1 discharge (0.75%); tributary (Reach 3) - proportion proportion of Reach 1 discharge (0.25%); Lower Ouro Creek (Reach 4) - sum of Reach 2 and Reach 3 discharges; Upper Rio dos Cedros (Reach 5) - difference between Reach 1 and Reach 4 discharge.

Once the flow discharge data was entered for the reaches, the simulation was performed for each return period, where the water profiles in the cross sections were calculated by the Standard Step Method. The unknown water surface at a cross section is determined section by section throw the iterative solution of Equations 2 and 3, energy equation and energy head loss equation, respectively (USACE, 2010):

$$Z_1+Y_1+\frac{a_1V_1^2}{2g}=Z_2+Y_2+\frac{a_2V_2^2}{2g}+h_e \quad [2]$$

where Z_1 and Z_2 are the elevation of the main channel inverts [m]; Y_1 and Y_2 are the depth of water at cross sections [m]; V_1 and V_2 are the average velocities [$m.s^{-1}$] (total discharge/ total flow area); the a_1 and a_2 are the velocity weighting coefficients; g is gravitational acceleration [$m.s^{-2}$]; and h_e is the energy head loss [m].

$$h_e=L\bar{S}_f+C\left|\frac{a_2V_2^2}{2g}-\frac{a_1V_1^2}{2g}\right| \quad [3]$$

where h_e is the energy head loss between two cross sections [m]; L is the discharge reach length [m]; $\bar{S}_f$ is the representative friction slope between two sections [$m.m^{-1}$]; and C is the expansion and contraction loss coefficient.

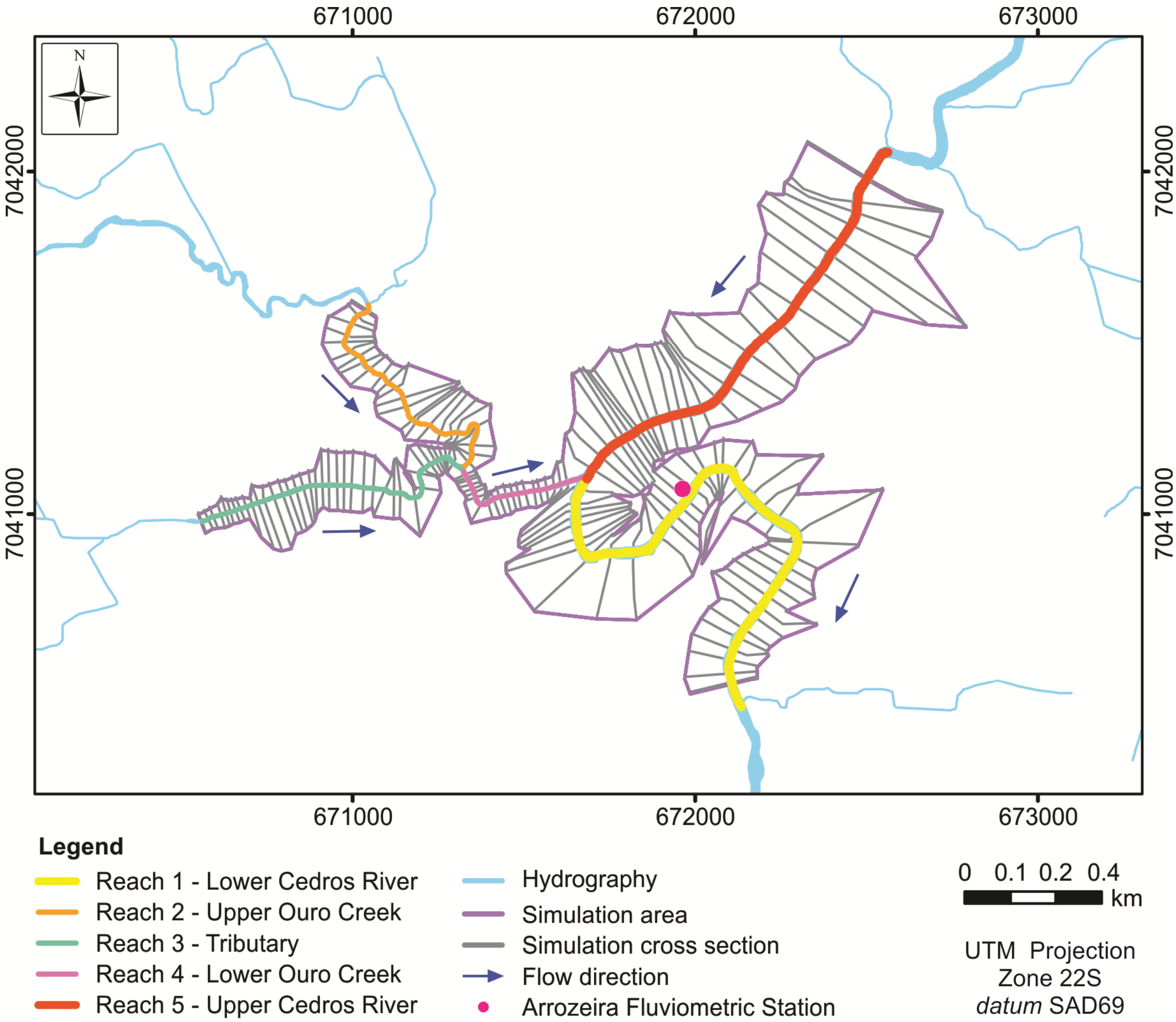

Figure 2: HEC-RAS simulated cross sections, hydrographic system and reach divisions.

The computational procedure is as follows:

1. Assume a water surface (WS) elevation at the upstream cross section (or downstream cross section if a supercritical profile is being calculated).

2. Based on the assumed water surface elevation, determine the corresponding total conveyance and velocity head.

3. With values from step 2, compute $\bar{S}_f$ and solve Equation 3 for h_e.

4. With values from steps 2 and 3, solve Equation 2 for WS_2.

5. Compare the computed value of WS_2 with the value assumed in step 1; repeat steps 1 through 5 until the values agree to within 0.01 feet (0.003 m), or the user-defined tolerance.

After the water surfaces in the cross sections have been calculated by the model, they were imported into ArcGIS 9.3 software, where the flood maps were created.

The model application assessment was done by comparing the simulation of a real event with flooded areas from a historical record, documented in the Rio dos Cedros city Flood Emergency Plan (PMRD, 2011). The real event took place in Rio dos Cedros on 09/08/2011, when it was recorded the depth of 7.73 m at the Arrozeira fluviometric station.

3. RESULTS

Figure 3 shows the flood extent for all return periods simulated. From this map, it is possible to understand the modeled flood dynamics study area.

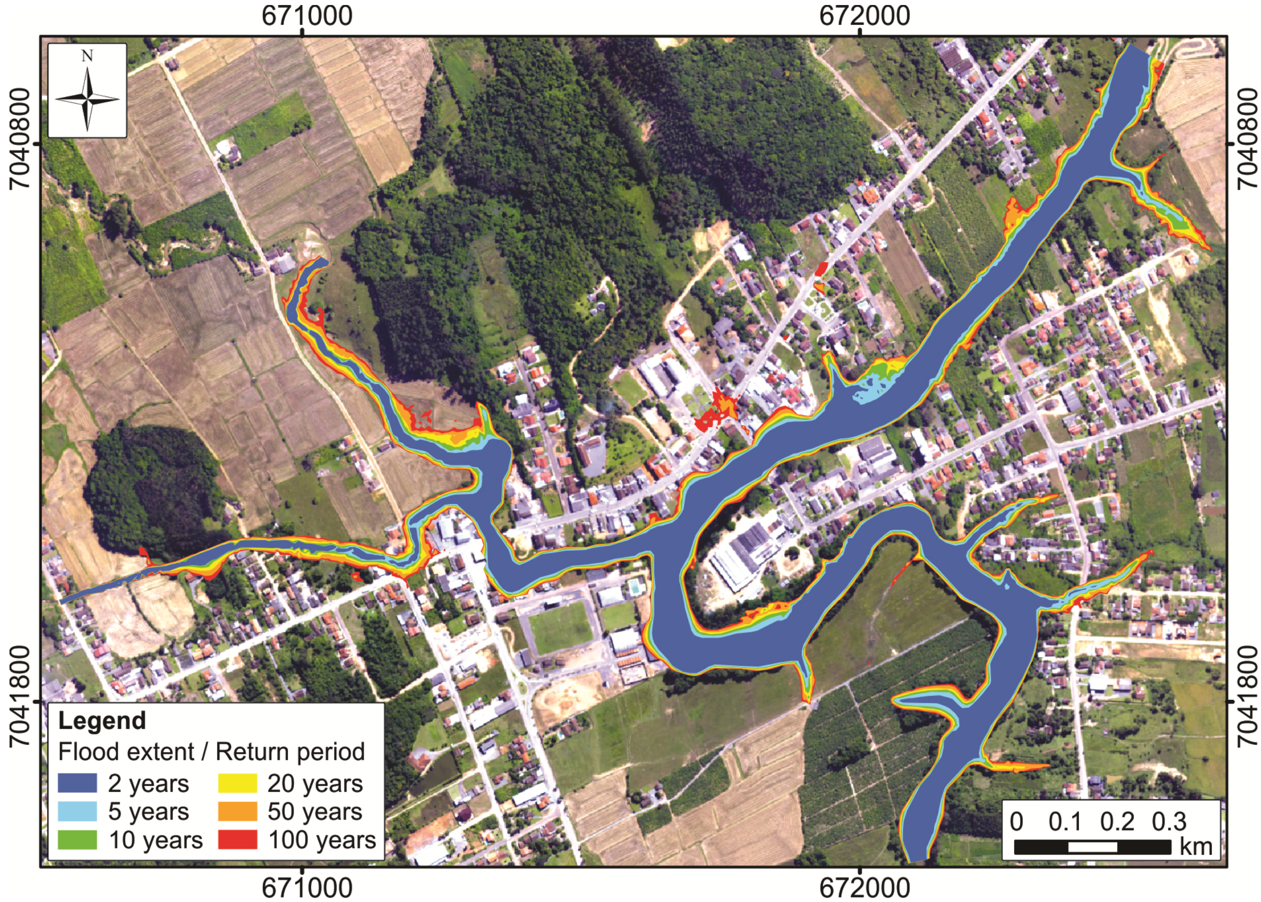

Figure 3: Simulated flood extent of 2, 5, 10, 20, 50 and 100 years return period.

Regarding the Cedros River, is notable a gradual advancement of water on natural drainage channels and built areas on the right bank of Upper Cedros River reach (near to the bridge). At the main road (center of the picture), an evident flood occur for the 100 years return period event. In the remaining flood occurrence the extent increasing is small.

The greatest variations occur in the Upper Ouro Creek and its tributary, however, these regions are mostly covered by crop and/or pasture. At the Lower Ouro Creek, the flood extent varies little in each event and the water reaches just a few houses near the river bank.

The results indicated that the areas near the Upper Ouro Creek and its tributary are those where the channel overflow is larger. Regarding the number of buildings affected, the 20 year recurrence period flood is the most significant as it reaches 21 of the 35 buildings affected by the 100 year event.

Furthermore, Ouro Creek and its tributary have the highest number of affected buildings, showing their greater importance in flooding events.

Between the 2 and 100 years simulations, an increase of 47% in the water levels (4.57 to 6.74 m) and 72% of the flooded area (0.183 to 0.314 km^2) is observed on the downstream reach of the Arrozeira station at the Lower Cedros River. This behavior can be explained by the flatness of the study area, as well as by the 1 meter DEM spatial resolution.

Figure 4 shows the flooded areas in 09/08/2011 event and simulated flood extent for the same event. In this figure is possible to see that there is limited overlap of the flood extents at two points (b), been the most pronounced one over the Ouro Creek bridge. Besides these points, proximity between borders of the real flood area and the simulated flood extent (c) correspond. The underestimation of the simulation is most apparent in the region (a), been the two extents areas approximately 100 m apart.

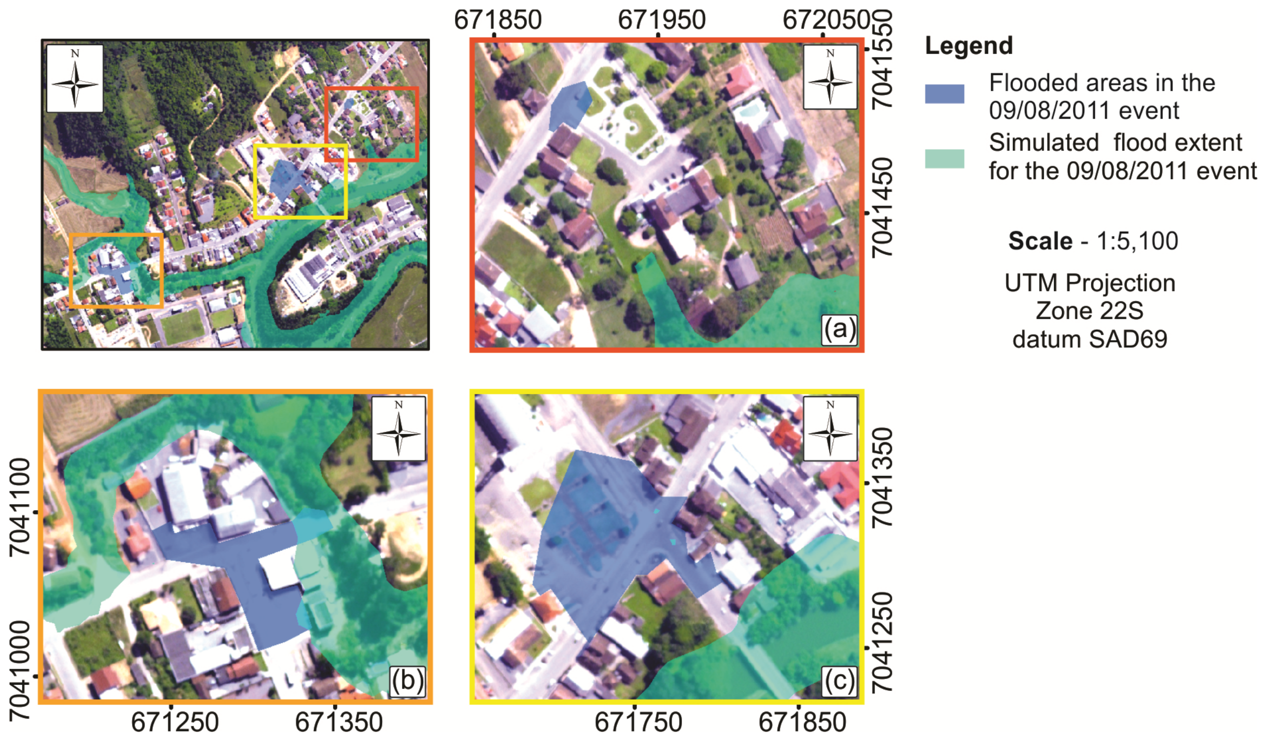

Figure 4: Simulated and real flood extent for the 09/08/2011 event.

Among the hypotheses that can explain these differences is, according to the Civil Defense, that the occurrence of flooding in the areas shown in Figure 4(a) and 4(c) is due to flood water entering stormwater drainage system, instead of draining lower regions, the system start conduct flood water to these areas before the Cedros River channel overflow. Another hypothesis is that the overflowing of Ouro Creek is caused by the Cedros River backwater, causing a superelevation of the water level in the channel and, consequently, generating a greater overflow (b), however, the stormwater drainage system flooding hypothesis can be happening simultaneously.

4. CONCLUSIONS

Analyzing the flood extent for different return periods is possible to understand overflow water dynamics on the contiguous areas. However, the model did not accurately simulate the flood extent when compared with the observed event. The main hypothesis for this behavior is related to phenomena that were not considered in the simulation, such as: flood water from Cedros River entering the stormwater drainage system and accumulating in low areas; and possible backwater of Cedros River invading Ouro Creek and tributary.

The flood mapping showed that, for low recurrence periods events, some areas are highly susceptible to flooding. Among them are: traffic roads and buildings surrounding the Cedros River Bridge and Ouro Creek and tributary confluence region. A sharp increase in areal flood extent in Upper Ouro Creek and tributary was noted, although the land use is predominantly agricultural/pasture and cannot inflict danger to population.

In relation to land use, it is possible to notice that the built-up areas are located very close to watercourses. This highlights an inadequate or even nonexistent urban planning which resulted in occupation of rivers and streams natural flooding areas.

For future studies it is recommended:

• Conduct a detailed bathymetric survey of the Cedros River, to improve DEM correction;

• Conduct adjustments to Manning's roughness coefficients, in order to adjust the model results;

• Check the possible occurrence of flooding due to the return of water by drainage of rainwater and the backwater caused by the Cedar River system;

• Perform a field survey of the a real event flooded area through community information using a GPS of topographical accuracy; and

• Conduct hydrologic rainfall-runoff modeling studies to analyze the influence of the dams on floods.

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