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MATHEMATICAL MODELLING SUPPORT TO THE PDMAT-3 STUDY FOR SÃO PAULO

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ABSTRACT: São Paulo is a typical example of a fast growing city where the development of the primary drainage system has not kept pace with the increased runoff from the newly urbanized areas. Recently, the third Drainage Master Plan (PDMAT-3) for the Upper Tietê Basin has been completed. Although during the past few years many detention basins have been built and drainage channel capacities have been increased, persistent flooding occurs, primarily on the roads and highways along the main drainage routes. This leads to significant economic losses, primarily due to the interruption of transport. For the first time in the sequence of studies a fully integrated numerical simulation model was developed and applied, based upon Deltares' modelling system SOBEK. The model consists of the following components: (1) rainfall runoff models for 100 up to 420 subcatchments (depending on the discretization level applied), using the SOBEK linear urban runoff and SCS concepts; (2) 1D models for the principal rivers and drainage channels; (3) Real time control (RTC) module for the control of weirs, gates and reservoirs; and (4) overland flow (2D), implicitly connected to the 1D schematization. The SOBEK model covers a catchment area of 5.868 km^2 with an urbanized area of 2.300 km^2 and a population of approximately 19 million. The model has been developed in three discretization levels, where more refinements were progressively introduced, based upon additional data collection. The paper addresses a state-of-the-art method with which rainfall data were generated for the calibration and validation events. Rainfall measured at 111 ground stations were used to calibrate the spatial distribution provided by instantaneous radar images. Processing of the rainfall data was based upon the Delft-FEWS system of Deltares, where the rainfall on each individual catchment could be estimated more precisely than on the basis of the ground stations alone. The paper also addresses the calibration and validation procedure, various application issues, as well as some practical problems that were encountered during the development of the model and the way in which these were overcome.

Key Words: Flood management, flood control, flood forecasting, numerical simulation, SOBEK model.

1. INTRODUCTION

One of the problems of the São Paulo Metropolitan Region is the flooding. Floods in São Paulo are often associated with the urbanization process of the city and, more recently, climate and environmental issues.

Floods reduce the city's growth and well-being of the population. Floods increase costs for enterprises located in São Paulo and undermine their competitiveness in domestic and international markets.

According to Haddad and Teixeira, 2013, after a heavy rain each flooding point in São Paulo City, causes a daily loss of more than R$ 1 million to the country. Considering an approximate number of 749 flooding points identified in the city, the annual losses to the city can potentially reach R$ 336 million and, with the spread of the effects by long chains of production and income, the injury will more than R$ 762 million to national scale.

To combat this problem the State Government initiated the Third Macro-drainage Master Plan for the Upper Tietê Basin (in Portuguese: "Terceiro Plano Diretor de Macrodrenagem da Bacia do Alto Tietê" - PDMAT-3) aiming at diagnosing and analyzing the current macro-drainage system of the region and propose a set of solutions that can reduce the effects of floods. This plan combines structural solutions, such as macro-drainage works and non-structural solutions, such as the creation of an integrated management of the macro-drainage system.

The methodology applied for diagnosis and new propositions used a very complex set of procedures. It included a vast data survey, use of high resolution rain observations and a hydrologic-hydraulic 1D-2D numerical modelling study using SOBEK, an integrated software package for management of open channel flow in rural and urban areas (http://www.deltaressystems.com/hydro/product/108282/sobek-suite). The model is composed of seven different modules applicable to the hydrology and hydrodynamics of canals and rivers, including hydraulic structures, sewers, runoff control, water quality, wetlands and forecasting. Tietê River Basin has been studied since the beginning of the 20th century in order to minimize flooding areas along the reaches that cross São Paulo City. These studies reflected the technology and knowledge available at the time and resulted in several propositions including the canalization and the enlargement of Tietê Channel. In those previous studies, each sub-basin was modeled separately, without considering their interrelations in terms of downstream impacts and their response to different events, in terms of temporal and spatial distribution.

The new approach, using an integrated model allowed the simulation of the interaction between the various sub-basins, different storm patterns as well as different alternatives of structural interventions and operational rules. Another important contribution of integrated 1D-2D modelling was the delineation of impacted areas, which allowed the development of propositions minimizing risks and costs of remediation.

With the help of the model, plans like PDMAT can be reviewed and updated periodically. Updates are necessary because changes occurring in the basin over time, such as, for instance, the advancement of urban occupation or the deployment of new hydraulic structures. These changes are simulated and the results provide information for planning of the actions.

The model was calibrated and validated from observed data of precipitation, discharge and water levels, available in the DAEE (Departamento de Águas e Energia Elétrica) databases, weather radar and the telemetric network of the Upper Tietê Basin (UTB).

2. MODEL SCHEMATIZATION

The objective of this modeling study is the numerical simulation of the present macro-drainage system of the region and to make scenario tests with possible solutions to reduce the effects of floods. The modeled domain covers an area of 5,868 km² of the UTB from the headwaters to Rasgão Hydroelectric Plant at the downstream side. It covers the largest tributary basins Tamanduateí (332.5 km²), Pinheiros (1,448 km²) and Juqueri (854.3 km²) and 39 municipalities. The model represents 58 rivers, 420 sub-basins, 14 hydraulic structures (dams and pumping stations), 53 smaller existing retention lakes called "piscinões" and 156 additionally proposed "piscinões".

To arrive at full implemention, the model was built in successive layers composed as follows:

Layer 1: Tietê River, from the Ponte Nova dam to Rasgão Hydroelectric Plant; Tamanduateí River from Maua to the mouth; Pinheiros River from Billings dam to the mouth; and Juqueri River, from Castro Paiva dam to the mouth;

Layer2: describing in more detail the main tributaries of layer 1:

> i) Tributaries of Tietê (Paraitinga, Biritiba-Mirim, Jundiaí, Taiaçupeba, Baquirivu, Cabuçu de Cima, Mandaqui, Cabuçu de Baixo, Aricanduva, Vermelho, Cotia and São João do Barueri);

ii) Tributaries of Tamanduateí (Meninos and Oratório);

iii) Tributaries of Pinheiros (Jurubatuba, Pirajuçara, Embu-Guaçu and Guarapiranga dam);

Layer3: other tributaries identified as relevant to the study and with flooding problems.

The operations of hydraulic structures such as pumping stations, dams and small and midsize reservoirs, known as "piscinões", were simulated using the SOBEK-RTC (Real Time Control) module and Matlab, to reproduce numerically the operation that was adopted during a given precipitation event. The RTC module also enables the realization of operation tests that prevent or reduce the effects of floods.

For calibration, 420 sub-basins were adopted. 67 of them are considered rural catchment and modeled using the SCS (Soil Conservation Service) rainfall-runoff concept (United States Department of Agriculture, 1986). The other 353 basins are modeled using the SOBEK Urban rainfall-runoff model concept. Figure 1 shows the various layers defined in the development of the model.

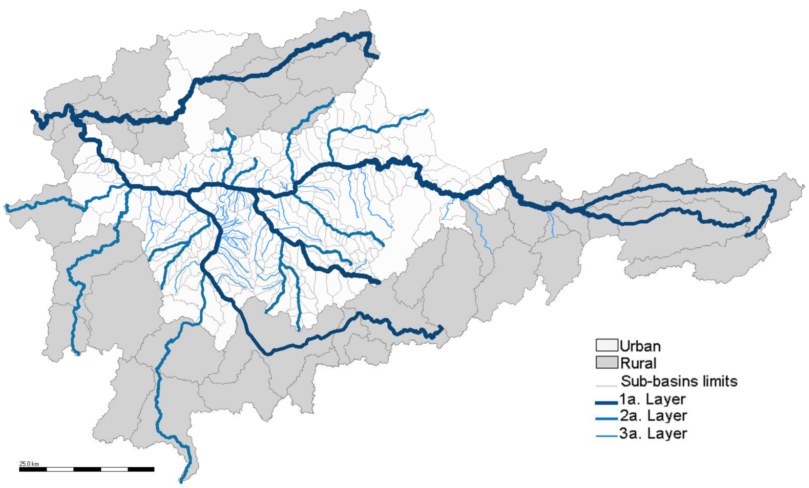

Figure 1: Layer approach adopted in the model development

Figure 2 shows the complete schematization of UTB in the SOBEK model.

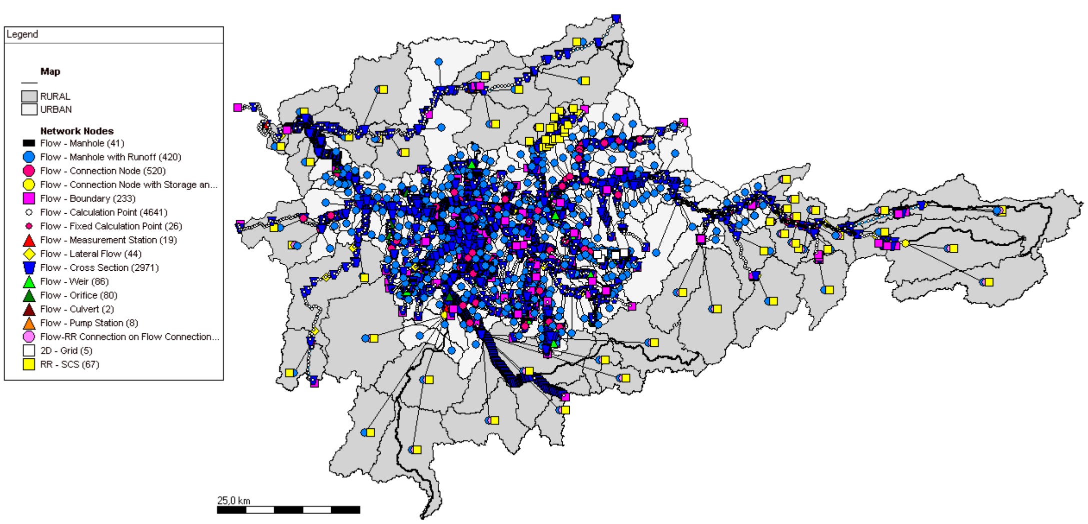

Figure 2: Complete schematization of UTB in SOBEK

The transformation of rainfall into runoff is a complex, non-linear, time and spatial varying process (Singh, 1988). It is among one of the most complex hydrological phenomena to comprehend as it usually involves a number of interconnected process components, such as evapotranspiration, infiltration, surface and subsurface runoff generation and routing, etc. The understanding of these hydrological processes is further complicated with the consideration of heterogeneity of the watershed geo-morphological characteristics (such as soil type, land use pattern, etc.) and the spatial and temporal variations of model inputs (such as rainfall patterns). For many years, hydrologists have endeavored to better understand the rainfall-runoff transformation process through efforts to improve conceptual models by incorporating more accurate descriptions of the hydrological processes and patterns.

Storm water arriving at the main channels of the model schematization partly follows a path via the catchment surface and partly via (small) open channel or pipe drains. The first process is often represented as a linear process (laminar flow), while the second part is better described by a non-linear flow process (turbulent flow). Following Verwey *et al*., 2008, the first linear flow part is described on the basis of the linear SOBEK-Urban runoff description, delivering runoff to the centre of the sub-catchment. The second non-linear part is described by an artificial manhole, acting as a collection point at the centre of the sub-catchment, which is connected via an artificial pipe to the nearest channel forming part of the hydrodynamic schematization of the SOBEK model. This last description allows for a realistic representation of routing and dampening of the sub-catchment runoff wave. The conceptualization is shown in Figure 3.

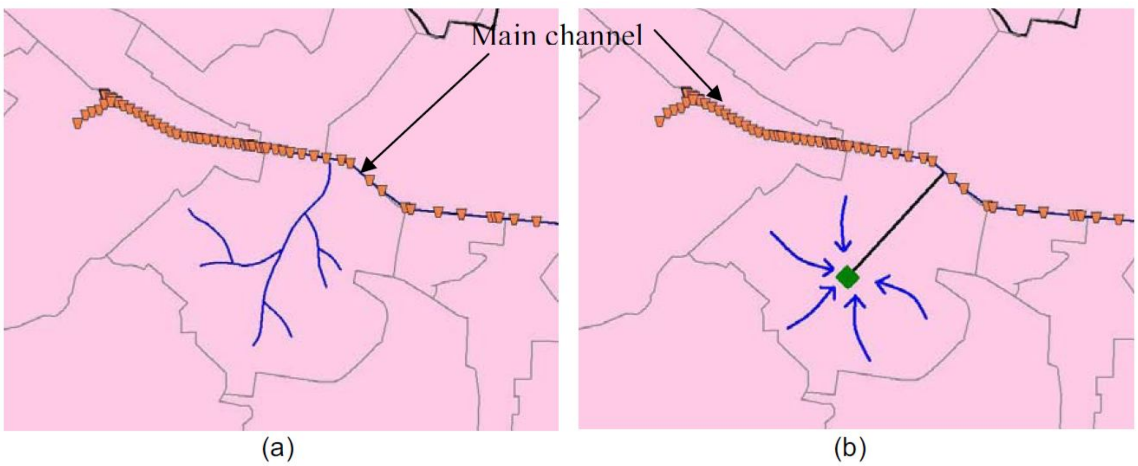

Figure 3: Drainage network in a sub-catchment conceptualized by a Manhole – Pipe system, extracted from Verwey *et al.* (2008)

Manhole and pipe dimensions were related to the size of the sub-catchment via proportionality factors which were adjusted in the calibration. Although the method had proven its validity under Singapore conditions, a correction was required for application in the São Paulo model. Due to the steepness of the terrains, various sub-catchments generated pressurized flow in the artificial closed conduits. As a result, the peak flow was limited by the relation between full pipe capacity and the steepness of the terrain. In particular in the Tamanduatei Basin, various peaks of modeled runoff waves were shaved off and measured peaks could not be reproduced. For this reason, the concept applied was modified by introducing artificial open channel flow connections between the artificial manholes and the channels of the hydrodynamic model.

3. CALIBRATION OF THE RAINFALL RUNOFF MODEL

Seven significant rainfall events were chosen as critical events. For each sub-basin hyethographs were generated for use in the calibration and validation of the model. These events were registered by a weather radar and a network of automatic ground-stations, both operated by the Flood Alert System of São Paulo (FCTH, 1985). These events were referenced by their periods as: January 2005, February and December 2007, September and December 2009, January 2010 and January 2011.

As weather radar can capture rainfall spatially and temporally but not so well quantitatively (Calvetti *et al*., 2003; Rocha Filho, 2010; Silva, 2006), original data from São Paulo radar were calibrated with ground-station data to reduce the various sources of errors (Pereira Filho *et al.,* 1999). Several methodologies have been developed over the past 3 decades. Some methodologies are classified as "simplified" methods such as G/R (Gauge - Radar). Others are classified as "sophisticated" methods like conditional merging, application of the Kalman filter, among others. In this study the method of conditional merging was used, as described in detail in the work of Sinclair and Pegram (2002), Pegram (2002).

The process of merging was applied to the accumulated values of 10 minutes from weather radar, using a moving average filter with a window of 30 min and a spatial filter considering 9 squares around the pixel, combined with 54 primary telemetry stations for better spatial representation of the surface.

Finally, rainfall data were spatially interpolated on a regular grid with a resolution of 2 x 2 km and interpolated in time interval of 10 minutes. The rainfall data grids were converted to subcatchment average rainfall for all three layers of the model using the Delft-FEWS system (Werner *et al*., 2013), and transferred as input to the SOBEK model. Figure 4 shows an example of Delft-FEWS application.

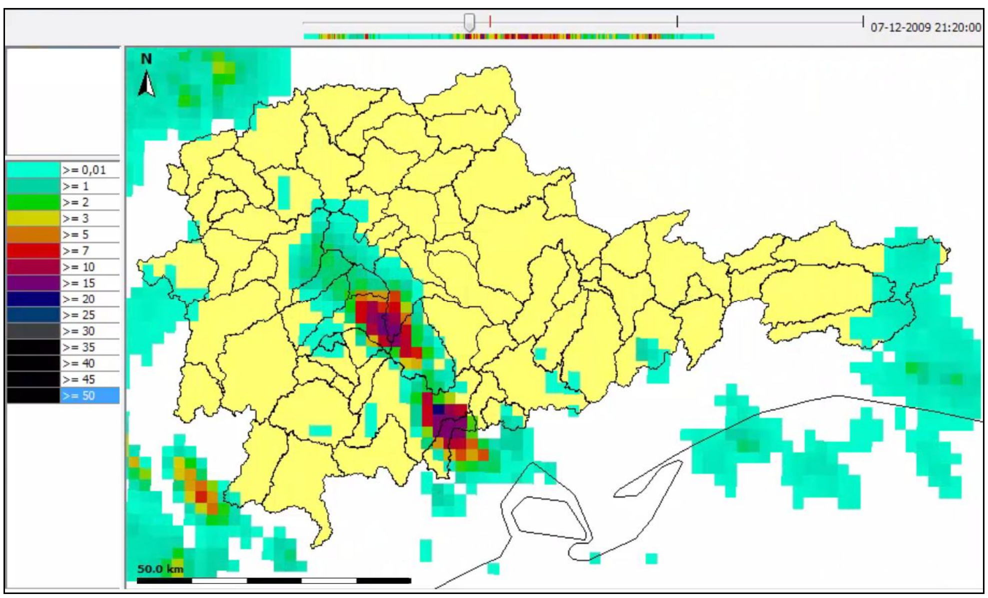

Figure 4: Example of the application of Delft-FEWS for the event of December 2009

Calibration parameters of the hydrological model are described below.

Regarding the permeability of urban sub-basins, a study was conducted to determine the permeable and impermeable areas of each sub-basin from land-use maps. The parameters in the hydrologic model for urban basins have different values for each type of area. The following parameters can be adjusted for calibration in the SOBEK-Urban model:

i) Runoff Coefficient: linear factor applied on the rain storage depth on the terrain, producing runoff that varies depending on the length, roughness and slope of the basin;

ii) Storage: storage depth of precipitation on each sub-catchment;

iii) Infiltration: the infiltration capacity is a function of time for different types of areas in each sub-basin, based upon the Horton formulation, including recovery of infiltration capacity after a dry period.

For rural sub-basins the SCS method was used (Soil Conservation Service) method. Basically, SCS estimated precipitation excess as a function of cumulative precipitation, initial loss, soil cover, land use and antecedent moisture.

For the SCS method the parameters that can be adjusted for calibration are:

i) Average length of water courses until the main channel of the basin;

ii) Average slope of the land;

iii) Time lag: representing the time between the start of runoff generated by a rain event and the moment when the flow reaches its maximum value.

For the various rural sub-catchments the calibration led to curve numbers (CN) varying from 50 to 82. The adoption of the CN value was also guided by the standards specified for UTB in Kutner, *et al.* (2001).

4. CALIBRATION OF THE HYDRODYNAMIC MODEL

Calibration of the hydrodynamic module was carried out through the values of Manning coefficients (n) suitable for each channel reach. The following values of the Manning coefficient were adopted:

i) River channels: n around 0.03;

ii) For parts of the channel with dense vegetation, irregular sections and many meanders n-values ranging from 0.04 to 0.08 were adopted;

iii) For the banks, the value of the Manning coefficient varies with the water level and the values are consistent with the characteristics of each section.

Also the parameters of the urban subcatchment concept with artificial pipe and manhole as described in section 2 were calibrated. After hydrological and hydraulic calibration, tests were carried out to verify the performance of the model, considering both water level and discharge at selected stations during the events of December 2009, January 2010 and January 2011. Some comparisons are shown below, as example. It is important to consider both water level and discharge in the calibration and verification, to make sure that both the total flood runoff volume and the distribution in time are correct.

Figures 5 and 6 below show the comparisons between the model output and the observed values of discharge and water level for the December 2009 event at station Ponte do Limão located along River Tietê.

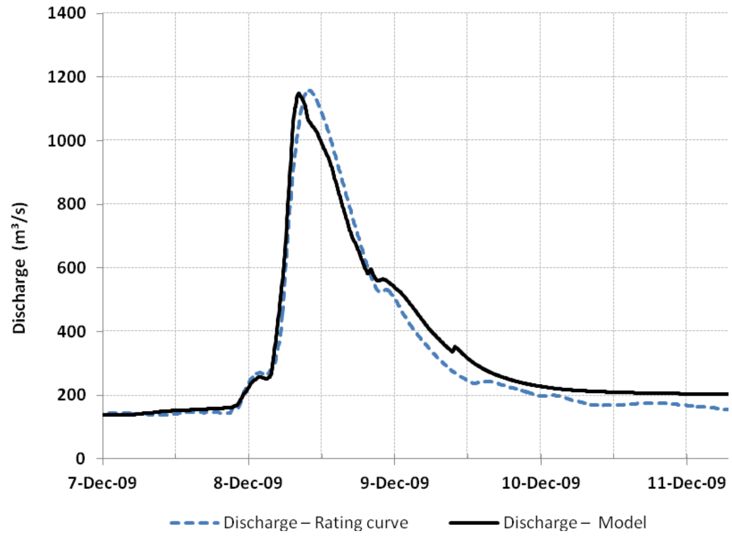

Figure 5: Comparison between discharge calculated by the model and observed (rating curve) for the event of December 2009 - Ponte do Limão Station - Tietê River

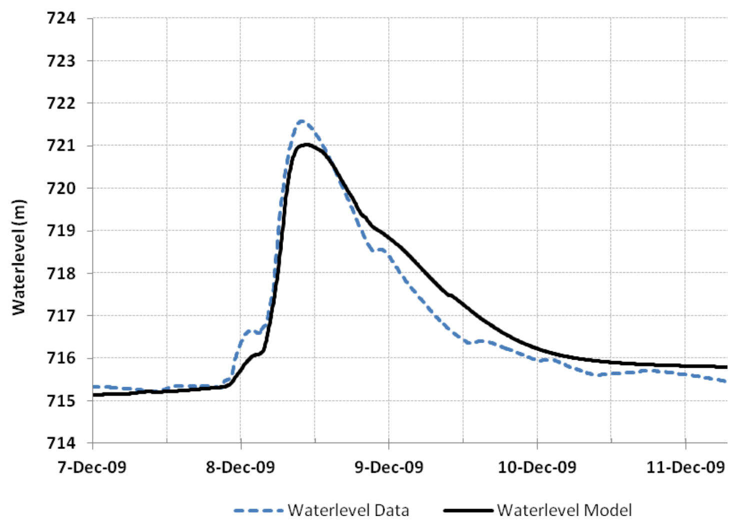

Figure 6: Comparison between water level calculated by the model and observed for the event of December 2009 - Ponte do Limão Station - Tietê River

Figures 7 and 8 show the comparisons between the model output and the observed values of discharge and water level for the event of December 2009 at station Pacheco Chaves located along Tamanduateí River.

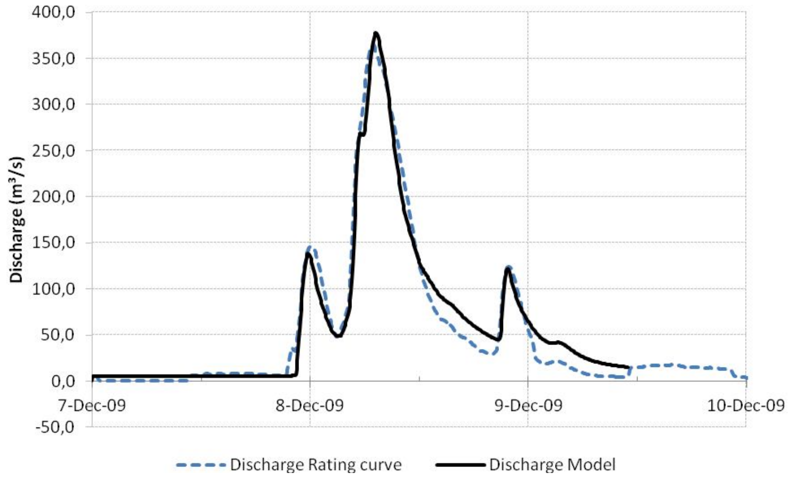

Figure 7: Comparison between discharge calculated by the model and observed (rating curve) for the event of December 2009 - Pacheco Chaves Station - Tamanduateí River

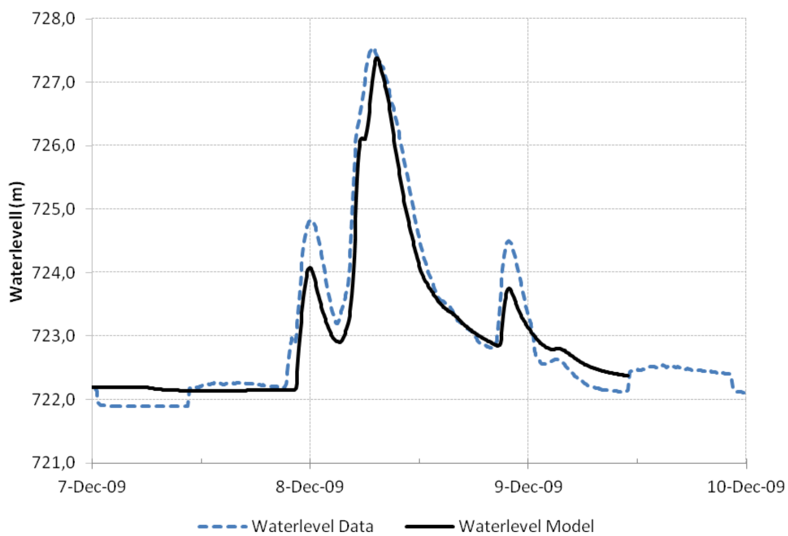

Figure 8: Comparison between waterlevel calculated by the model and observed for the event of December 2009 - Pacheco Chaves Station - Tamanduateí River

5. MODEL VERIFICATION

To verify the model accuracy, the events of 2005, 2007 and September 2009 were used. Figures 9 and 10, below, show the comparisons between the model output and the observed values for the December 2007 event at Ponte do Limão Station - Tietê River.

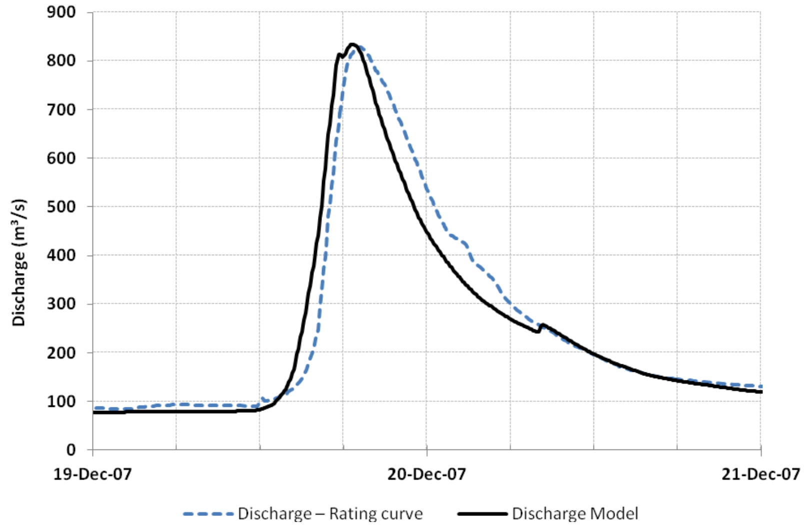

Figure 9: Comparison between discharge calculated by the model and observed (rating curve) for the event of December 2007 - Ponte do Limão Station - Tietê River

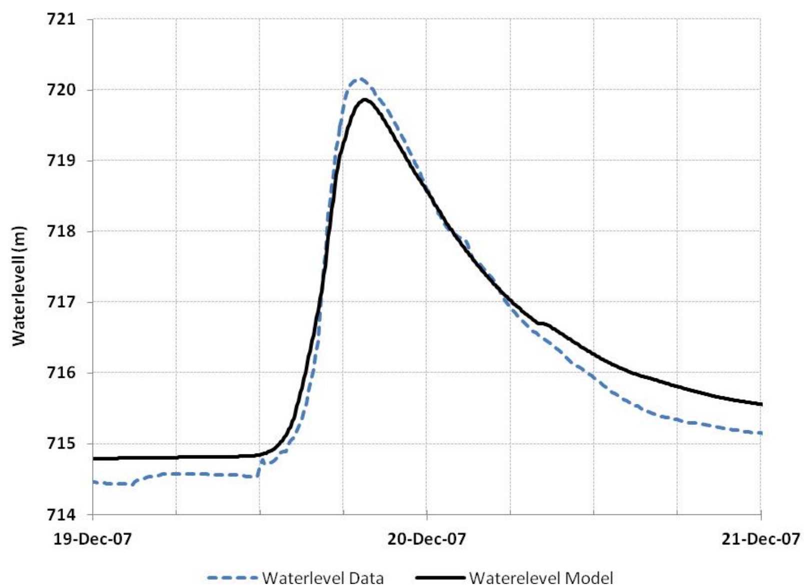

Figure 10: Comparison between waterlevel calculated by the model and observed for the event of December 2007 - Ponte do Limão Station - Tietê River

Figures 11 and 12 show the comparisons between the model output and the observed values of discharge and water level for the September 2009 event at station Pacheco Chaves located along Tamanduateí River.

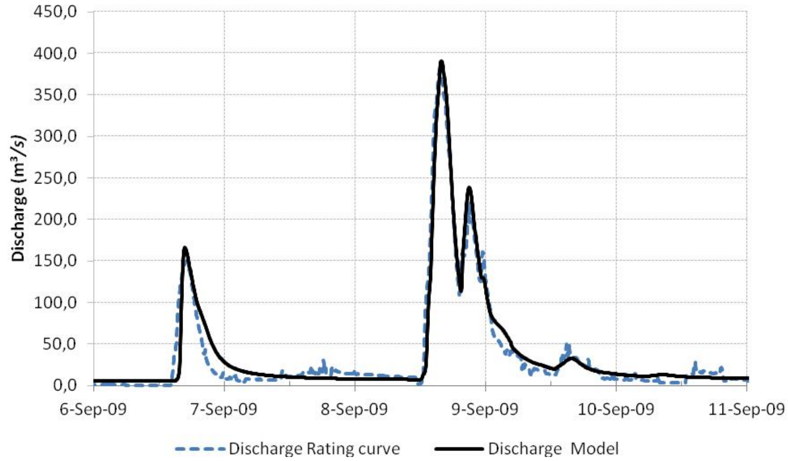

Figure 11: Comparison between discharge calculated by the model and observed (rating curve) for the event of September 2009 - Pacheco Chaves Station - Tamanduateí River

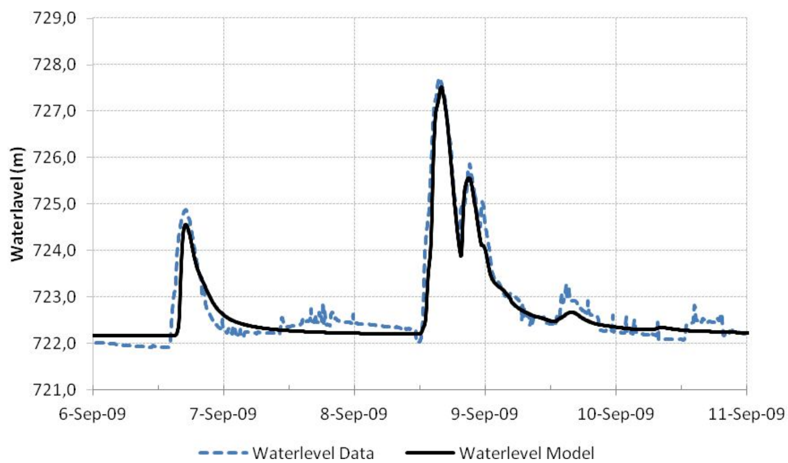

Figure 12: Comparison between waterlevel calculated by the model and observed for the event of September 2009 - Pacheco Chaves Station - Tamanduateí River

6. ANALYSIS OF MEASURES

The calibrated and validated model can be used to perform tests and analyze proposed structural and non-structural measures to combat floods. Structural measures can be categorized as follows:

Type 1) works to reduce the volume of influent water to the rivers during critical events;

Type 2) works that increase the transport capacity of the volume of influent water;

Type 3) changes in the operation of dams and pumping stations.

Type 1 interventions are primarily "piscinões", reservoirs for flood control or detention basins. The model allows to investigate the efficiency of these reservoirs in storing a part of the flood volume and reducing the peak of runoff.

Type 2 interventions include changes in the geometry and roughness of the channels, for example, by increasing the cross-section width of the channels, introducing higher vertical side walls and/or deepening of the channels, changing cross-section side slopes and the placement of a coating on the channel walls to reduce friction. Other interventions investigated for São Paulo include the construction of bypass channels or tunnels or the diversion of flood water to neighboring catchment reservoirs.

For type 3, the model can be used to analyze the effect of changes in operation rules of gates and pumping stations during flood conditions and analyze the impact of increasing the capacity of pumping stations.

7. CONCLUDING REMARKS

Very complex urban drainage systems, like the macro-drainage system of the metropolitan area of São Paulo, require an integrated approach to consider factors such as spatial and temporal patterns of storms, an adequate watershed area rainfall-runoff description, a realistic representation of channels, hydraulic structures and storage devices and the effect of structure operation rules in order to arrive at a realistic delineation of flooded areas and minimizing the extent and flood depths of these.

For the Upper Tietê Basin, so far, only models of sub-basins had been developed and used. The newly constructed model allows for the development of a much better understanding of the interactions between these sub-basins and its construction under the PDMAT-3 program is a great step forward in guiding the choice of a package of interventions that improve the flood situation of the metropolitan area of São Paulo.

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