ACTION MODULERS

Urban Floods

Final report on numerical modeling of urban floods in 4 Portuguese cities

Prepared for

CCIAM

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Data	October, 2013
Pages	32
Version	1.0
Observations	---

Índice

1 Context

Being risk defined as product of probability of occurrence by caused damage, urban floods have particularly high risk due to the damage they cause. Taking into considerations climate change scenarios, the risk can even be higher, since the probability of occurrence of heavy rainfall events is expected to increase.

Being aware about this the Portuguese Assurance Association (Associação Portuguesa de Seguros – APS) requested the Center for Climate Change Impacts Adaption & Modeling (CCIAM) to perform a study to access urban flood risk in context of climate change scenarios, called CIRAC (Floods and Flood Risk Maps in Climate Change Scenarios). In context of this project several tasks have been performed, including: (i) setup of several climate change scenarios, (ii) evaluation of mean sea level rise, (iii) elaboration of future design rainfall events for different return periods, (iv) modelling of urban floods, (v) inundation maps, (vi) risk maps, (vii) uncertainty analysis and (viii) result communication.

With its experience in numerical modeling Action Modulers collaborated in this work by setting up integrated numerical urban flood models for several Portuguese cities.

2 Introduction

Urban floods have major impact over people and goods, since they always occur in areas with high population density. A good understanding of all processes which lead to urban floods can help identifying areas where risk is high and preform an evaluation of the mitigation measures (Jha et al., 2011). Numerical models can be used to simulate processes which are involved during urban floods and are therefore valuable tools to support decision makers.

So far models have been used to simulate: (i) behaviour of the storm water system during events, (ii) overland flow at the flooded urban areas, (iii) contributions from watersheds located upstream. In the major part of studies performed in the recent years, these processes have been studied individually. More recently available technology allowed using numerical models in an integrated approach. For example the widely used SWMM model is very well suited to study flow in the storm water drainage system, but has a very simplified approach for simulating ponded water on the surface. Other models, like MOHID Land, are designed to simulate 2D surface flow, but do not simulate explicitly the storm water drainage system. Recently some approaches have been made to integrate urban flood models (Russo et al., 2011).

The objective of this work was to apply an integrated approach four Portuguese urban areas (Algés, Lisbon, Coimbra and Oporto) and use results from different return periods to establish damage curves.

This report describes the methodology and presents results which have been obtained during the project. Initially a description of the methodology and strategies which have been used in order to implement the numerical models in the different study site is given. Afterwards site specific considerations, model implementation and achieved results are presented.

All numerical modelling was performed with this work is based on state of the processed based numerical models. Data used to feed the models has been obtained from local authorities.

3 Methodology

3.1 Introduction

Numerical modeling of urban floods is a challenging issue, since many processes are involved during urban floods. Figure 1 shows the relevant processes of the natural water cycle and of the artificial water cycle. Urban floods may occur when: (i) a river which pass through urban areas exceed the transport capacity of the channel and consequently urban areas are inundated by riverine water, (ii) local storm events occur directly over highly imperviousness area and the rain intensity exceeds infiltration capacity of the storm water drainage system or (iii) a combination of the previous situations.

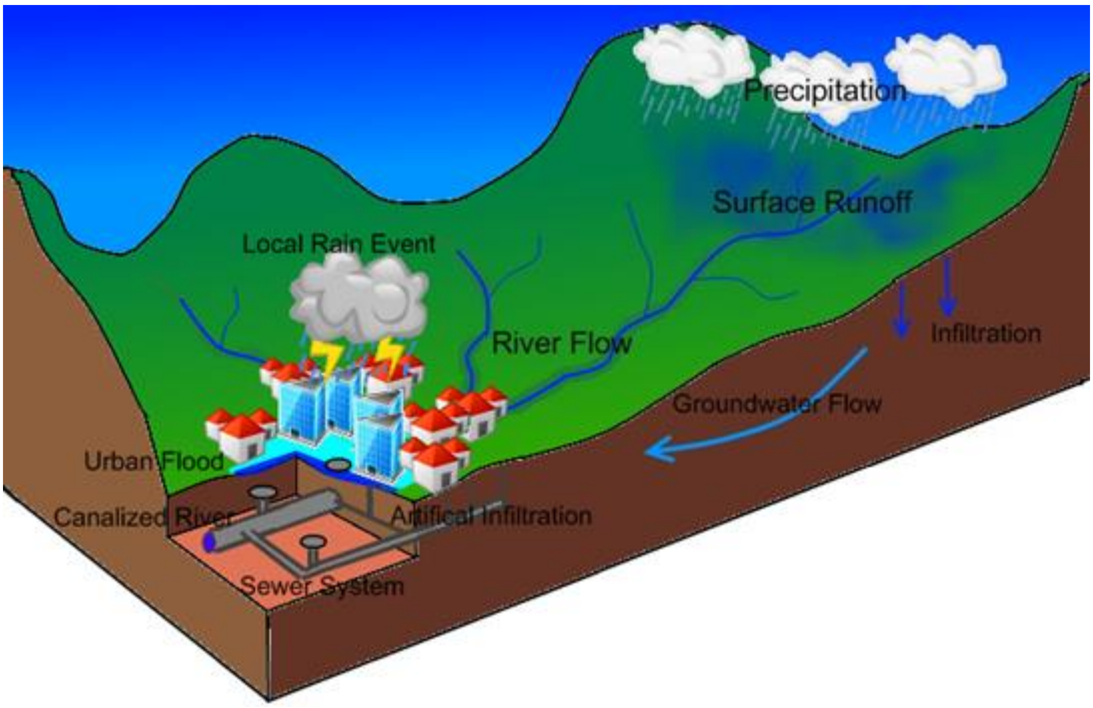

Figure 1: Processes involved during local urban floods

Several numerical models are available to simulate the processes shown in Figure 1. In the context of the current project, models from the MOHID Water Modelling System and the SWMM model has been used.

3.2 Model Descriptions

MOHID Water Modelling System is a state of the art numerical modeling system, developed and maintained by the Technical University of Lisbon and Action Modulers, which is composed by three main models: (i) MOHID Water for surface water bodies and (ii) MOHID Land for watersheds and (iii) MOHID River for river systems. MOHID Water Modelling System is used by hundreds of users worldwide.

SWMM is developed and maintained by the Environmental Protection Agency of the United States. This model is one of the most used models for simulating water flow in urban drainage systems.

In the context of the current project it was proposed to use always the most suitable model, integrating them whenever necessary. In three areas (Algés, Lisbon and Coimbra), MOHID Land was coupled with SWMM model in order to simulate processes represented in Figure 1 in an integrated way. In the case of Oporto, due to the estuarine characteristics of the Douro River near the urban area, MOHID Water has been used to perform the numerical simulations.

3.2.1 MOHID Land Description

MOHID Land is a spatially distributed, physically based, numerical model. It accounts for various hydrologic processes that produce flow in watersheds. These include:

- Time and space varying rainfall;
- Evaporation and Transpiration from soil, plants and standing water;
- 3D water flow in saturated and non-saturated porous media;
- 2D overland flow in function of land use with different routing approaches (cinematic wave, dynamic wave and diffusion wave);
- Infiltration in function of soil sealing, soil physical properties and soil moisture;
- 1D channel network with different routing approaches (cinematic wave, dynamic wave and diffusion wave).

- Rain interception by plants;
- Dynamic water exchange between overland flow, channel flow and groundwater flow based on hydraulic gradients.

Figure 2 shows schematically the hydrological processes solved by MOHID Land.

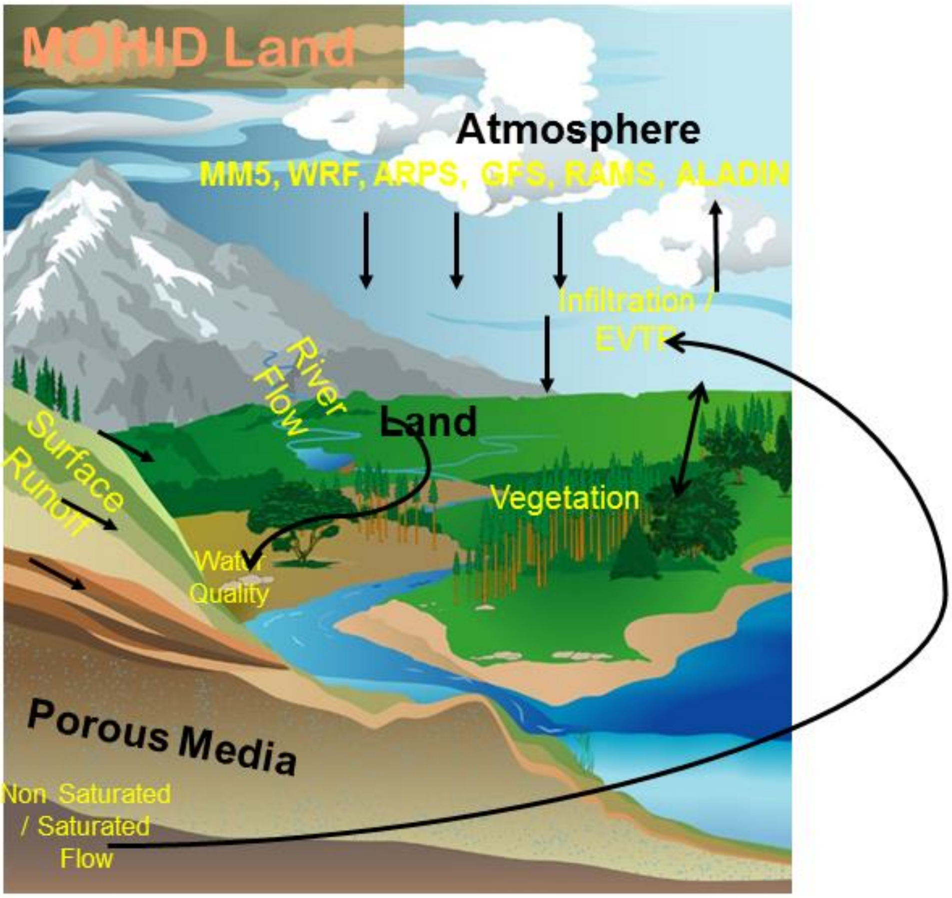

Figure 2: Processes included in MOHID Land

3.2.2 MOHID Water Description

MOHID Water is a fully 3D spatially distributed, physically based, numerical model for surface water bodies (oceans, coastal areas, reservoirs and large rivers). It accounts for various hydrodynamic processes and boundary conditions. These include:

- 3D finite volumes hydrodynamic and transport model
- Hydrostatic and Boussinesq approximations
- Baroclinic

- Wide range of boundary conditions for wind, tide, river discharges, surface heat exchange, lateral friction, bottom layer, wave interaction, etc.
- Generic vertical coordinate system and orthogonal horizontal coordinates
- High order advection schemes library
- Sub-model nesting

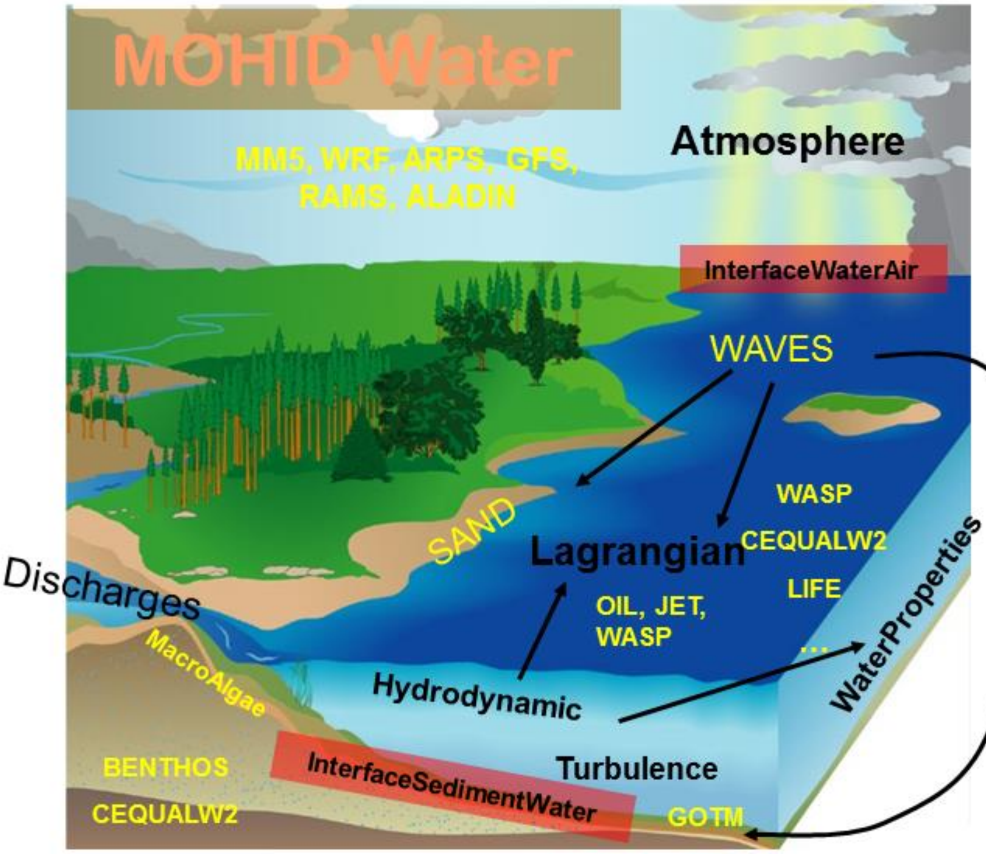

Figure 3: Processes included in MOHID Water

3.2.3 SWMM model

The Storm Water Management Model (SWMM) is a dynamic rainfall-runoff-subsurface runoff simulation model used for single-event to long-term (continuous) simulation of the surface/subsurface hydrology quantity and quality from primarily urban/suburban areas. SWMM 5 accounts for various hydrologic processes that produce surface and subsurface runoff from urban areas. Processes handled by SWMM include:

- Time-varying rainfall for an unlimited number of rain gages

- flexible set of hydraulic modeling capabilities used to route runoff and external inflows through the drainage system network of pipes, channels, storage/treatment units and diversion structures
- subdivision of areas in subbasins to simulate infiltration, return flow and ponding process
- variety of standard closed and open conduit shapes as well as natural or irregular channels model special elements such as storage/treatment units, outlets, flow dividers, pumps, weirs and orifices
- steady, kinematic wave or full dynamic wave flow routing methods
- model various flow regimes, such as backwater, surcharging, pressure, reverse flow and surface ponding
- apply user-defined dynamic control rules to simulate the operation of pumps, orifice openings and weir crest levels
- washoff and transport of pollutants

Figure 4 shows a schematic representation of the elements which can be modeled with the SWMM model.

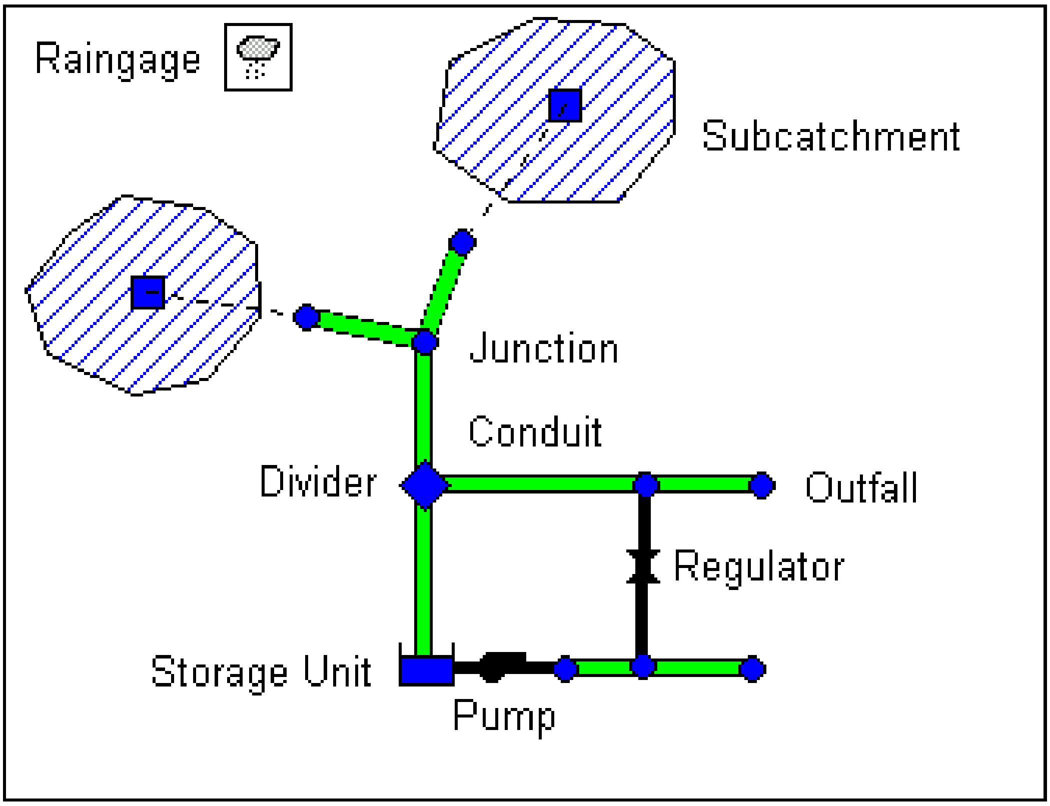

Figure 4: Schematic representation of the SWMM model

3.2.4 Integrated Models

As mentioned previously, in context of the CIRAC project, MOHID Land was integrated with the SWMM model in order to simulate urban floods in an integrated way. Conceptually, the two models have been linked in the two levels:

- Street inlets and manholes:
    - MOHID Land calculates "potential" flow through street inlets based on ponded water on the surface;
    - This flow, together with the surface water level, is provided as input to SWMM
    - SWMM receives the "potential" flow as lateral discharge and the surface water level as hydraulic gradient. Depending on these two variables and the state of the system, SWMM calculates the actual inflow. In the case of storm water system overflow water returns, through manholes, to the street.
- Canalized Rivers
    - SWMM can accept flow from MOHID Land's 1D river network as lateral discharge in the case where a reach of the natural channel network simulated by MOHID Land ends in the storm water system.

From a technical point of view, coupling these two modes was a challenging issue. SWMM and MOHID Land are programed in different languages (C and FORTRAN), use different topologies (network and structured grid) and run on different time steps. The Open Modelling Interface (OpenMI) has been designed to couple models which have these kinds of differences and has been used in the scope of this work.

After model coupling, an extensive number of schematic tests have been performed to check the integrated version, including a global mass balance analysis.

3.3 Model Implementation, Calibration and Validation

Model implementation, calibration and validation are three common steps which have to be performed when using numerical models.

Model implementation consists in preparing all data in way the model understands it. This often requires conversion and interpolation of existing data to the computational grid/network used by the model. With the aid of graphical user interfaces, which exists for MOHID and for SWMM, this step was performed for all study sites, using data collected from several data sources (local authorities, national authorities and global data sets). Detailed information about model implementation is described later.

Model calibration consists in fine tuning of model parameters in a way that the implemented model reproduces well observed records. For example, for a rainfall runoff model this means that a calibrated model should reproduce well observed levels at hydrometric stations, when feed with observed data from rain gauges.

Model validation consists in running the calibrated model for periods, different from the periods used during calibration, and check if the calibrated model also gives satisfactory results in the validation period. Otherwise the model has to be recalibrated.

Model validation and calibration can easily be done for normal events, but it's much more difficult for flood events with high return periods:

- By definition, flood events with high return periods occur seldom;
- Level discharge curves of hydrometric stations are many time invalid for very high discharge levels;

This makes a classical calibration and validation for storm events more difficult. In the case of the current project model validation and calibration has been done for existing data. Base model parameters have also been used from previous projects where more detailed calibration was possible.

4 Specific model implementation and results

4.1 Introduction

In this chapter the implementation and results of the models in the specific places are presented. The first three cases, Riberia de Algés, Lisbon and Coimbra, an integrated version of the MOHID Land and SWMM model has been used. In these cases different boundary conditions for rainfall, initial soil moisture and water level at the outlet has been considered.

For rainfall schematic patterns for different return periods (2, 5, 10, 20, 50, 100 and 500 years) have been established, following the Intensity-Duration-Frequency (IDF) methodology. Historical rainfall records were obtained from nearby meteorological stations.

Three different initial soil conditions have been considered: (i) dry, (ii) normal and (iii) wet, but for the final damage curves, only the worst case (initially wet) have been considered.

Water level at the outlet has been imposed as varying tidal curve. In some cases extra elevation due to mean sea level rise or low atmospheric pressure has been considered. Obtain model results (expected maximum inundation) has been integrated into damage curves.

In the case of the Rio Douro the model MOHID Water has been used. In this case, boundary conditions were the river discharge and the mean sea level. Like in the other cases, results have been integrated in damage curves.

In this chapter most relevant aspects related with model implementation and main results are presented.

4.2 Case 1 – Ribeira de Algés

4.2.1 General Characterization

A Ribeira de Algés is a small watershed located west of Lisbon. The watershed has an approximate size of 12km^2 and the main water course a length of about 5km. The watershed intersects three municipalities: (i) Lisbon (East), (ii) Oeiras (West) and (iii) Amadora (North). Figure 5 shows the limits of the watershed and boundaries of the municipalities.

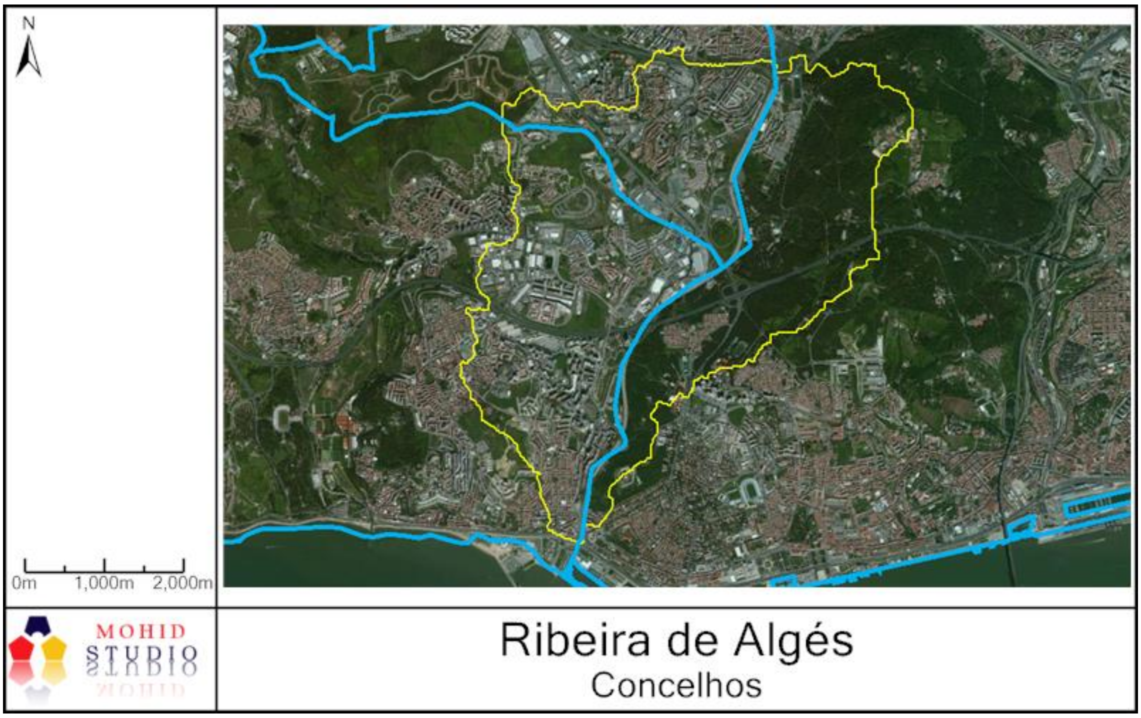

Figure 5: Boundaries of the watershed (yellow) and the intersecting municipalities (blue)

Due to construction areas, in Oeiras and Amadora, the watershed is highly impermeable. The area which belongs to Lisbon is mainly occupied by forest (Monsanto Municipal Park).

Main water course runs in an open channel until it “disappears” in a subterranean conduit, which passes below the downtown of Algés.

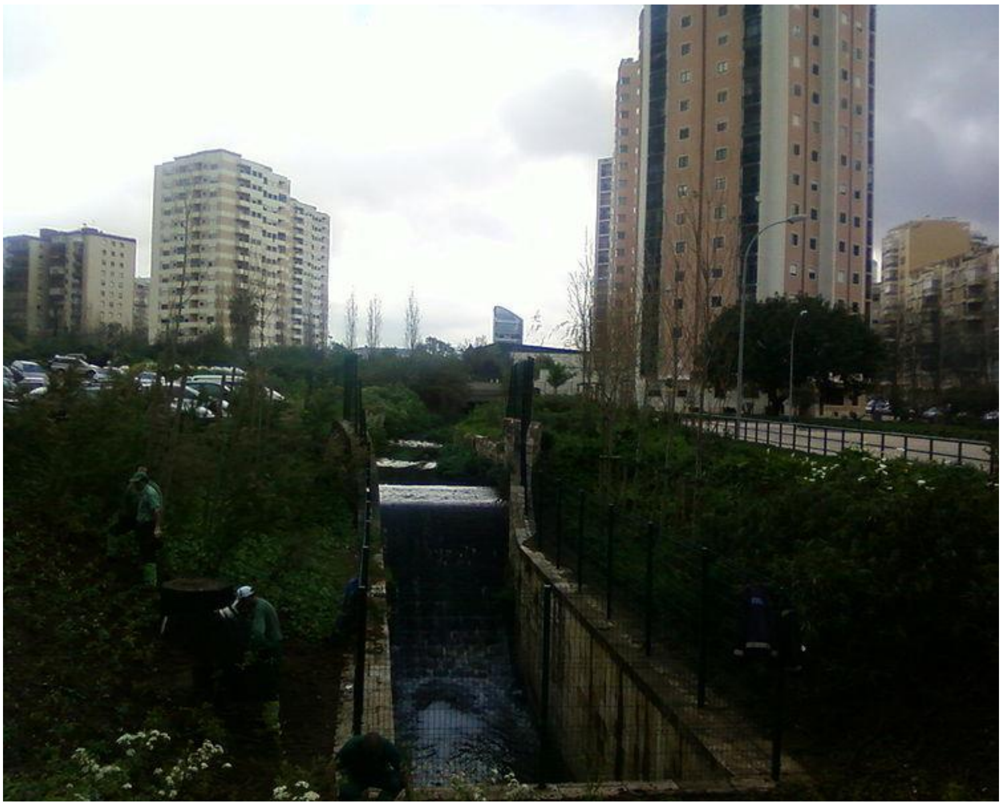

Figure 6: Ribeira de Algés in the place where it enters subterranean conduit

The outlet of the Ribeira de Algés ends in the Tagus Estuary in a place where tidal influence is significant. Historic flood events in Algés are mostly associated to high tides. Figure 7 shows the outlet of the Ribeira de Algés.

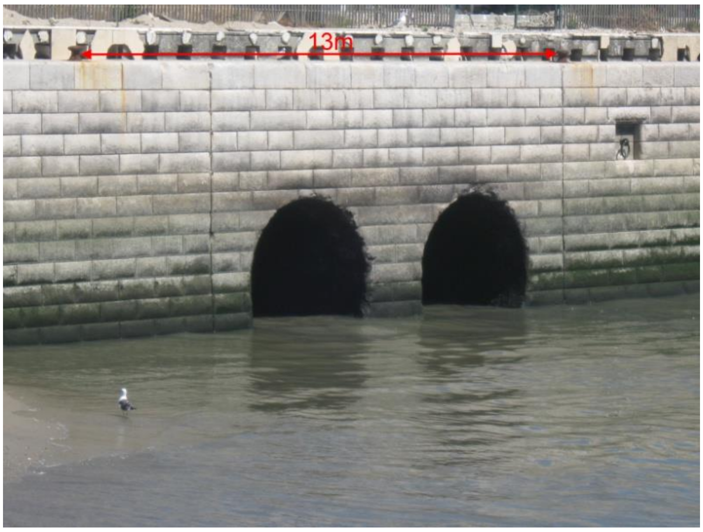

Figure 7: Outlet of the Ribeira de Algés

4.2.2 Model Implementation

In the Algés watershed an integrated version of MOHID Land and SWMM was implemented. For MOHID Land a computational grid with 356x330 points, corresponding to a spatial resolution of 15m, was used (Figure 8). MOHID Land model covers the entire catchment. SWMM model was implemented only in the downtown Algés, with a total of 1054 nodes (Figure 9). The two models were linked through street inlets, manholes and at the point where the Ribeira de Algés enters the subterranean conduit.

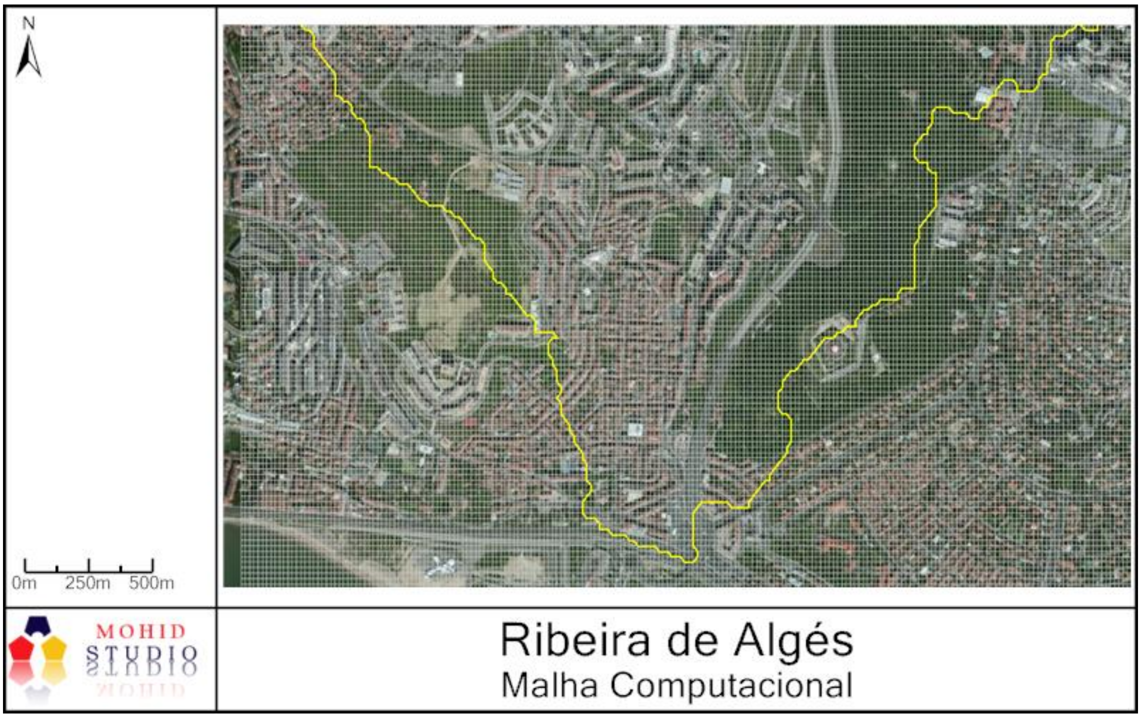

Figure 8: Zoom of the computational grid used for MOHID Land near the outlet

Figure 9: Storm water drainage system simulated by the SWMM model

All data for model implementation was collected from local authorities and interpolated to the model grid. As example, next figures show the digital terrain model (Figure 10) and the soil impermeability (Figure 11) which has been used to feed MOHID Land.

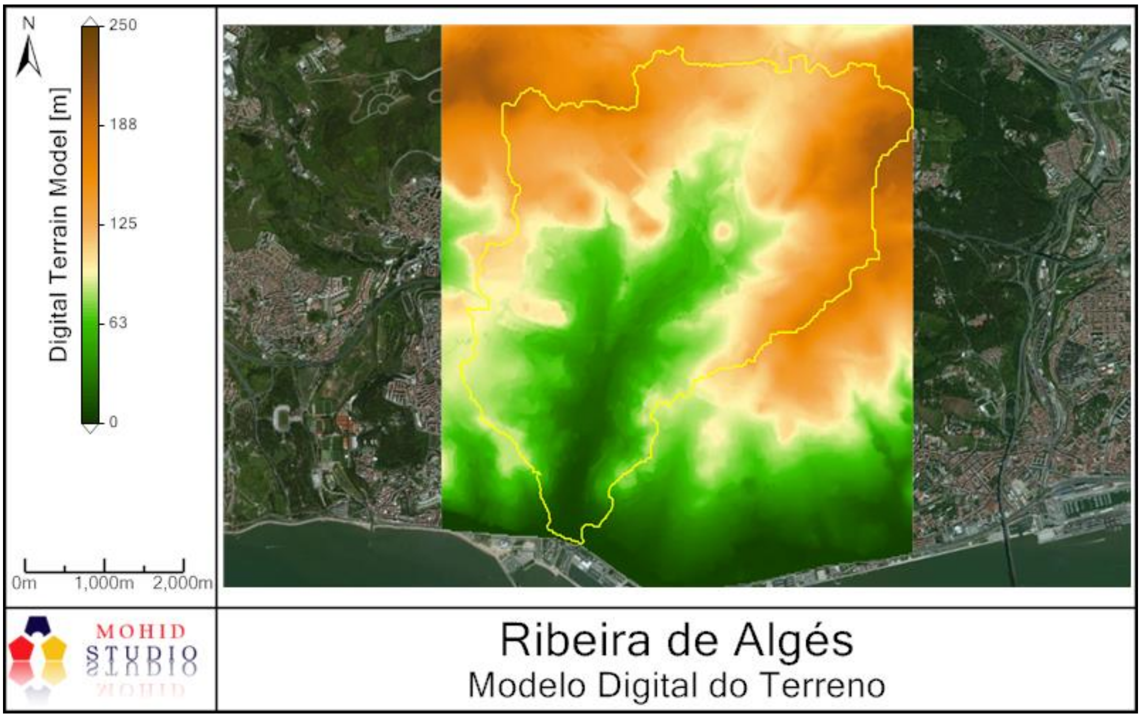

Figure 10: Digital terrain model used for MOHID Land model

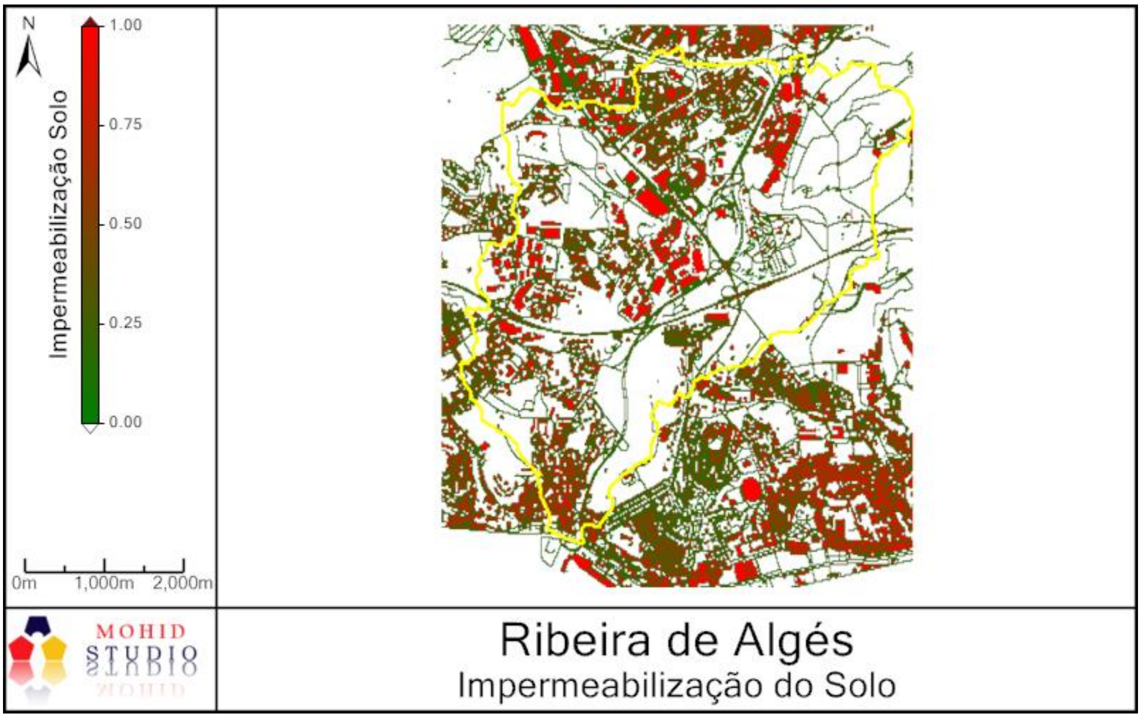

Figure 11: Estimated soil impermeability (obtained from buildings and streets)

4.2.3 Boundary Conditions

Different boundary conditions for rainfall, initial soil moisture and water level at the outlet has been considered, as described in the introduction of the chapter.

The theoretical design events have been obtained by using a common approach. First the total amount of rainfall which occurs during an event with duration equal to the concentration time of the watershed is calculated. Afterwards this amount is distributed in blocks of 5 min in an alternate way, with the highest precipitation intensity in the middle. Figure 12 shows the resulting hyetograph for a 100 year event.

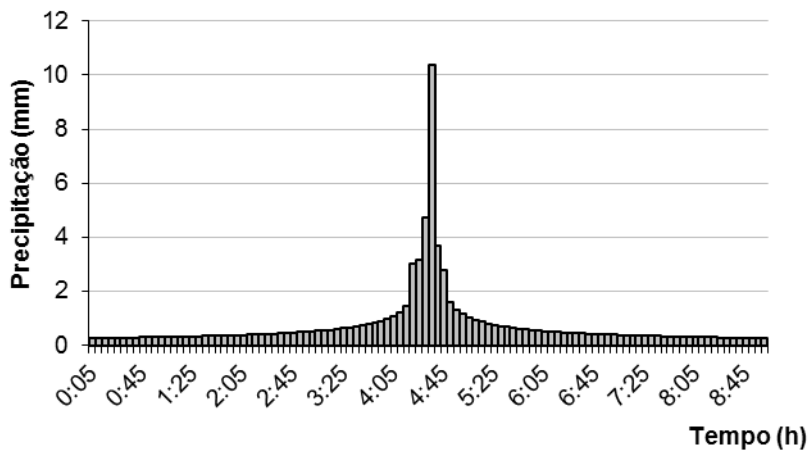

Figure 12: Design event of a 100 years flood

4.2.4 Main Results

The quantity of model results is very large, so here only a few key results are presented.

Next figures show the maximum inundation depth for the periods of 2, 50 and 100 years.

Figure 13: Maximum expected inundation depth (T=2 years)

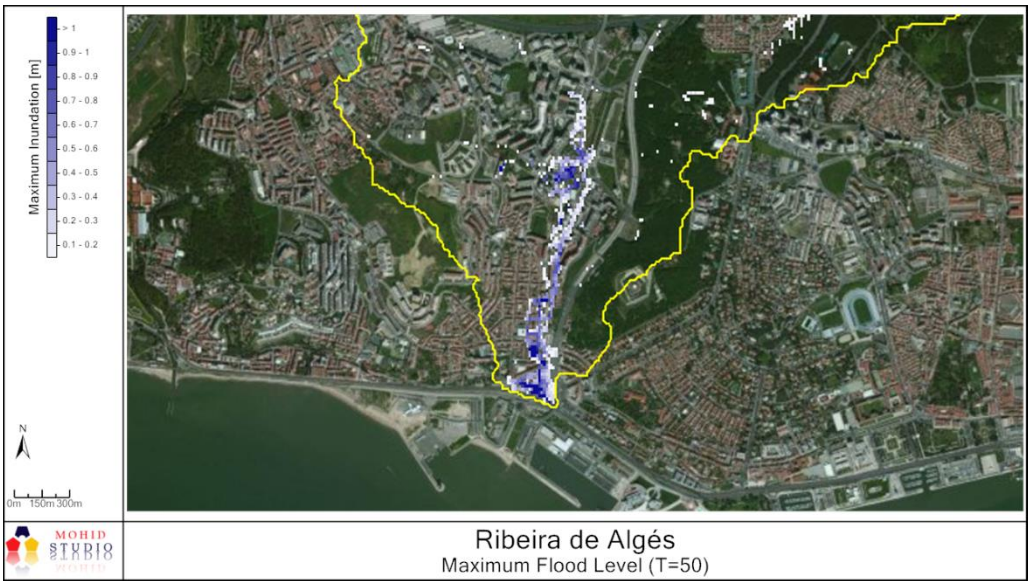

Figure 14: Maximum expected inundation depth (T=50 years)

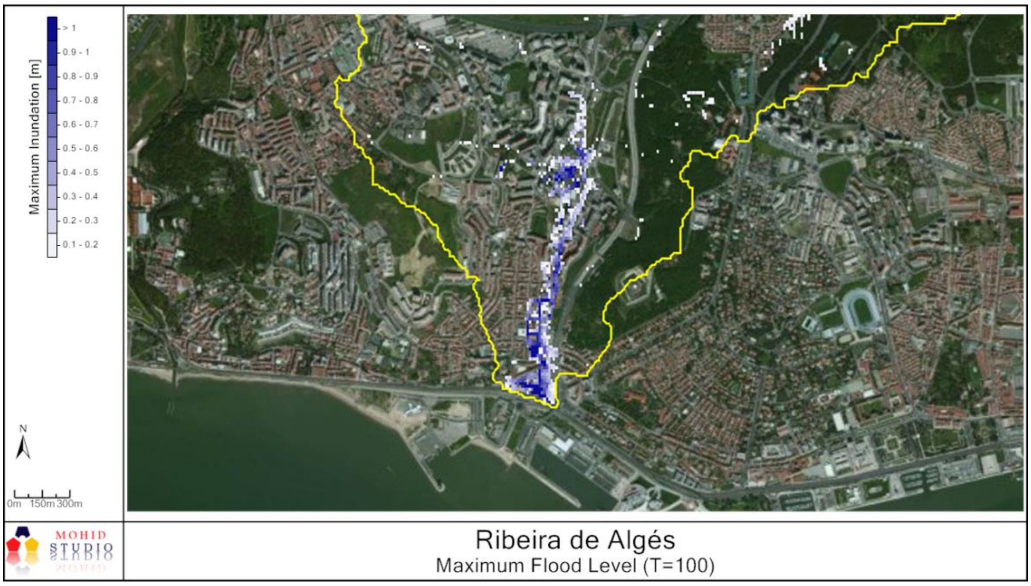

Figure 15: Maximum expected inundation depth (T=100 years)

These model results show that the downtown of Algés is affected even during rain events with small return periods. For events with higher return periods, a significant area of the downtown of Algés is inundated. For the presented results, it's necessary to take into considerations that the other boundary conditions (initial soil moisture, water level in the estuary) were set in way that they favor flooding (worst case).

4.3 Case 2 – Baixa de Lisboa

4.3.1 General Characterization

The Baixa de Lisboa is located at the confluence of two small rivers, one located below the Avenida Almirante Reis e another located below the Avenida da Liberdade. The watershed defined by these two small rivers has an approximate size of 3 km^2. It's located entirely in the municipality of Lisbon and almost completely urbanized. Figure 16 shows the limits of the watershed.

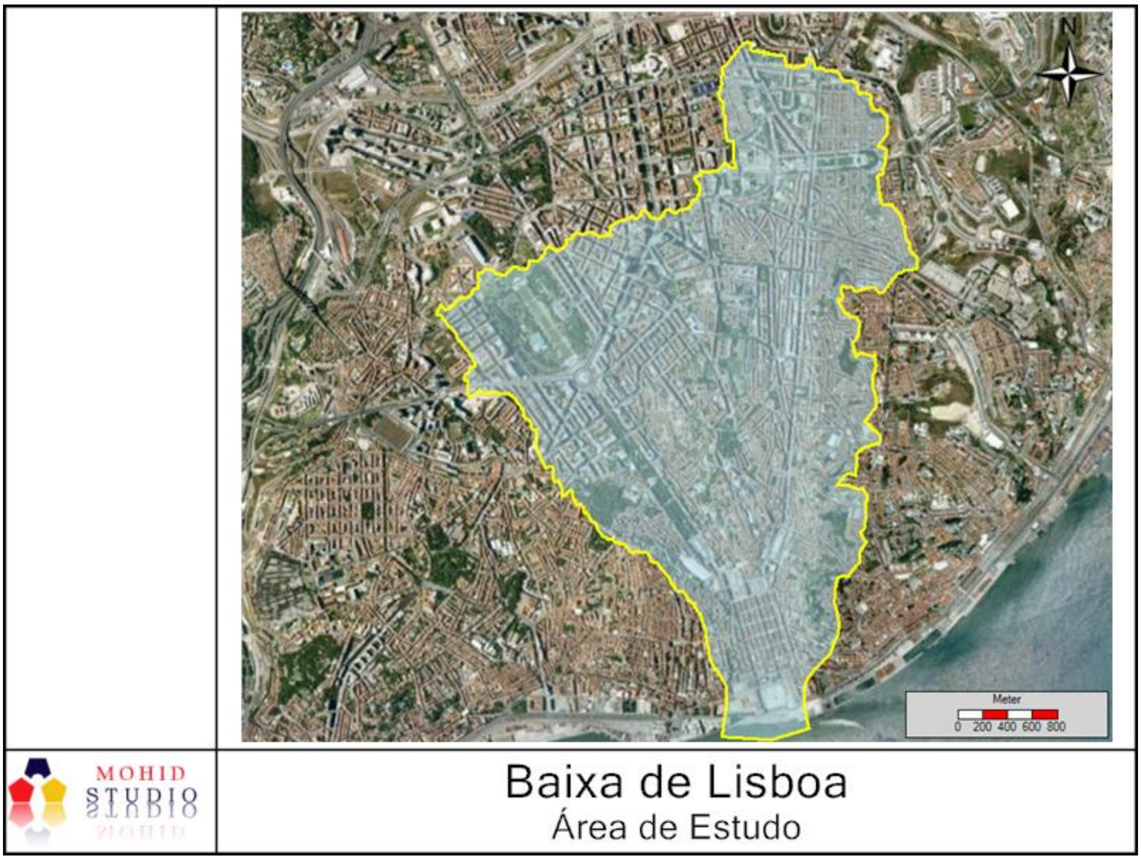

Figure 16: Boundaries of the watershed (yellow)

In the entire watershed the rain water is drained through the urban storm water system. The water is collected in a subterranean storage near the Terreiro de Paço and pumped from there into the Tagus Estuary.

4.3.2 Model Implementation

In the Lisbon watershed an integrated version of MOHID Land and SWMM was implemented. For MOHID Land a computational grid with ~500.000 grid points, corresponding to a spatial resolution of 4m, was used (Figure 17). SWMM model was implemented for the entire primary network (Figure 18). The two models were linked through street inlets and manholes.

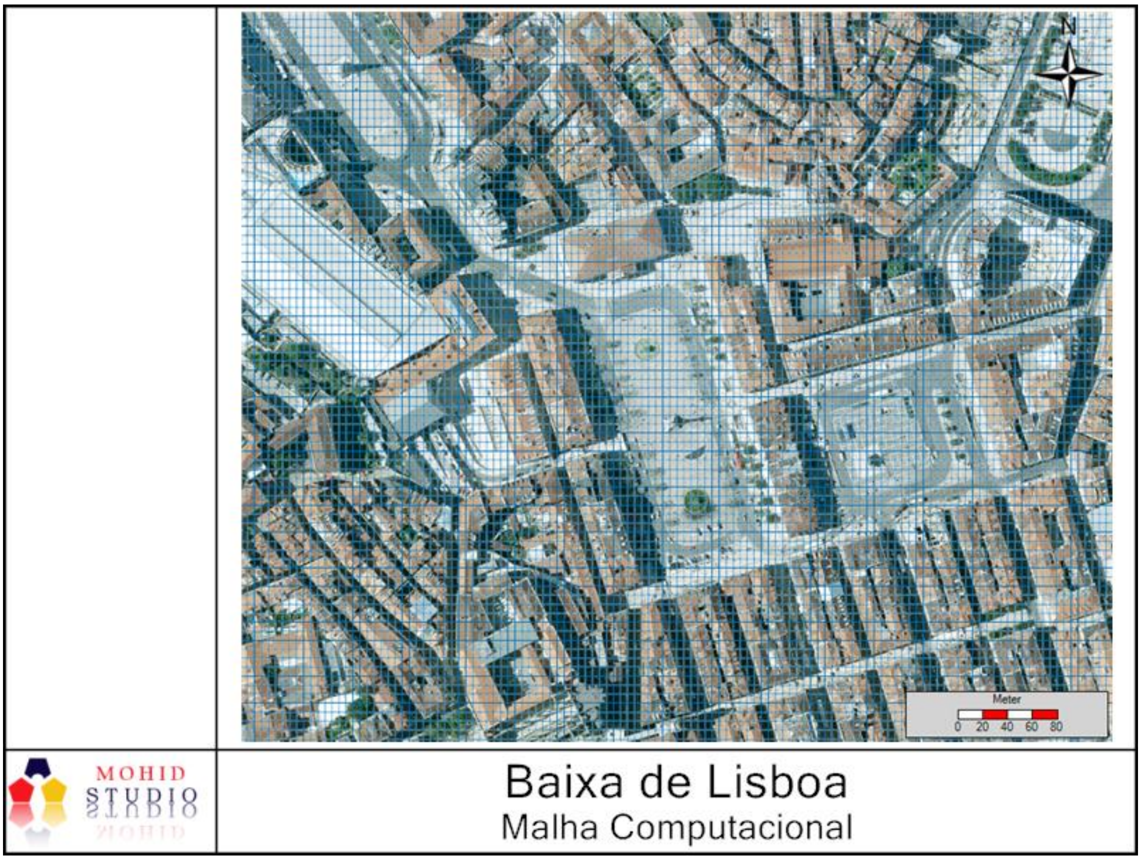

Figure 17: Zoom of the computational grid used for MOHID Land (Praça de Rossio)

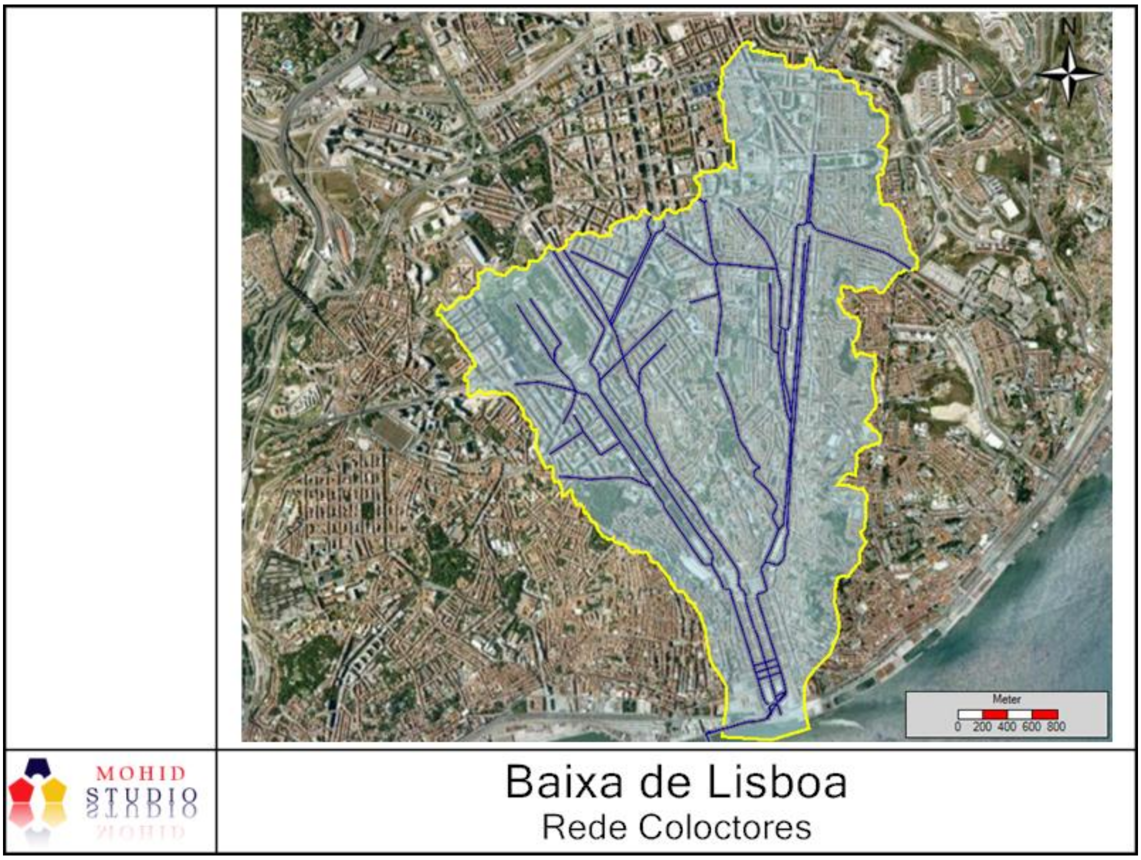

Figure 18: Storm water drainage system simulated by the SWMM model

All data for model implementation was collected from local authorities and interpolated to the model grid. As example, next figures show the digital terrain model (Figure 19) and the soil impermeability (Figure 20) which has been used to feed MOHID Land.

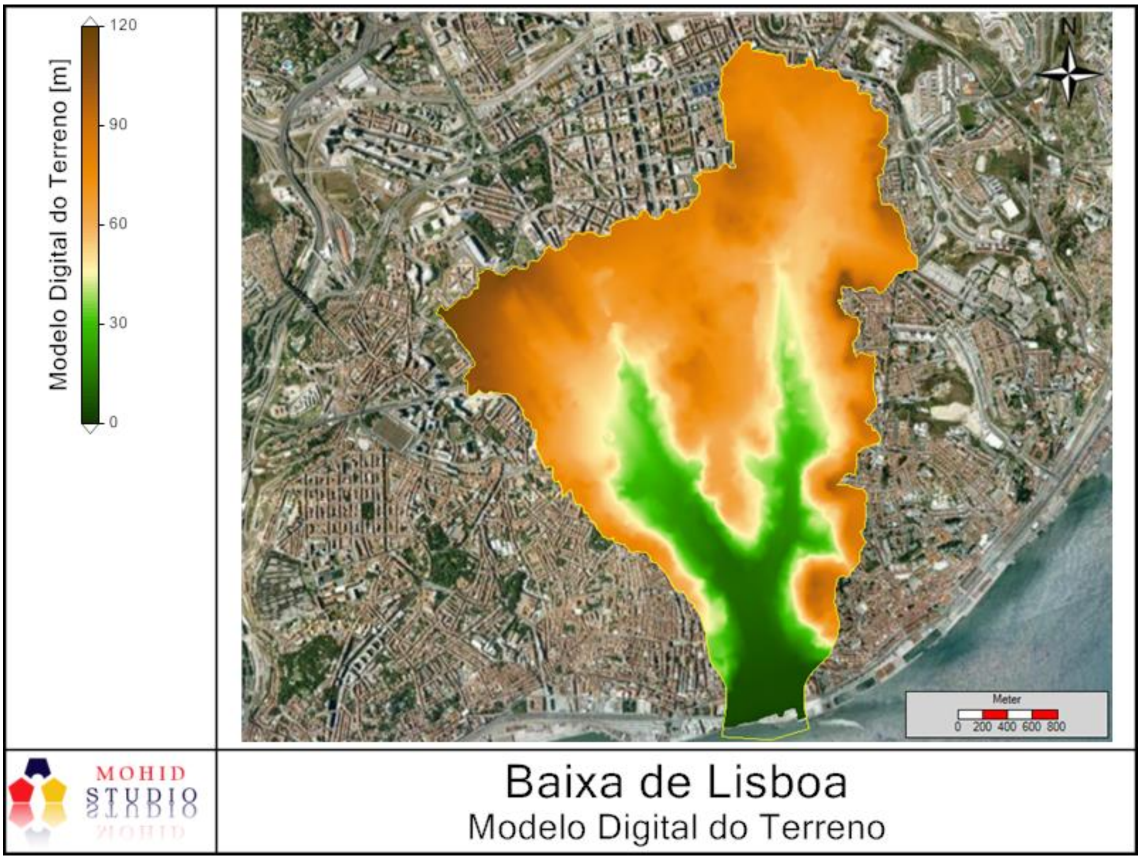

Figure 19: Digital terrain model used for MOHID Land model

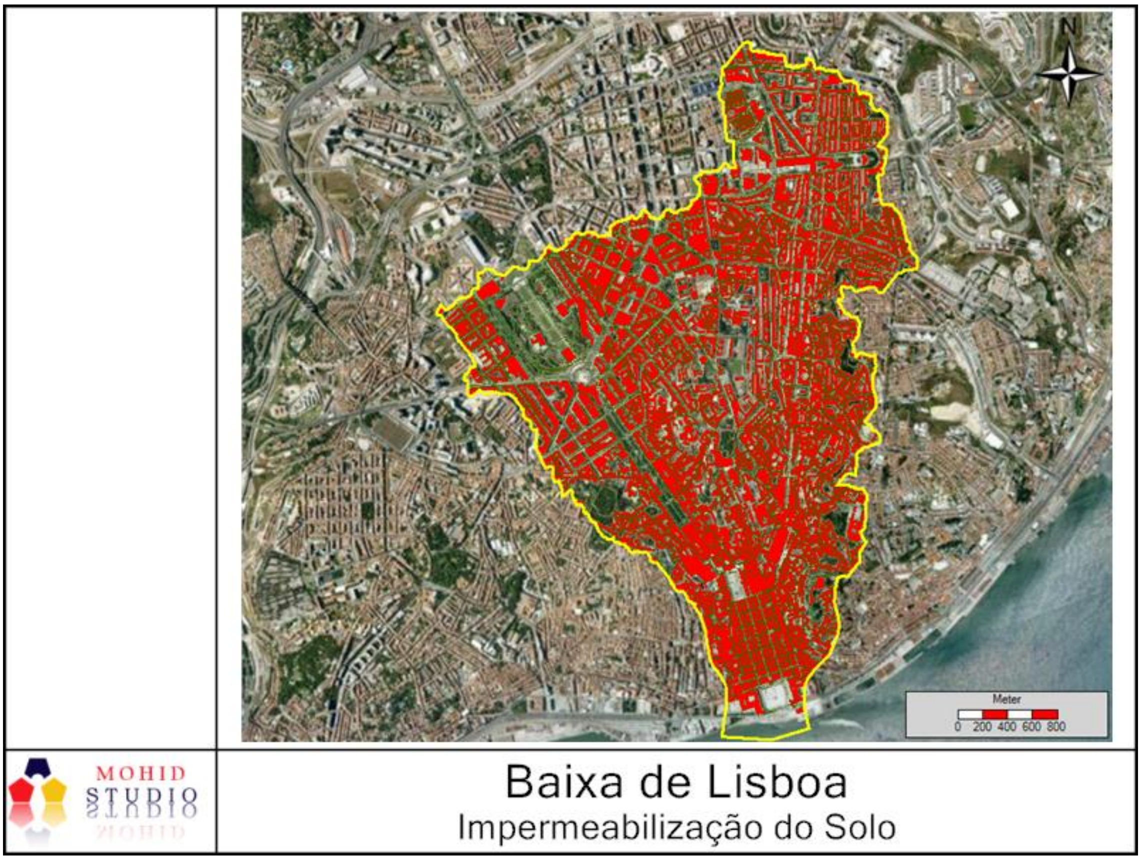

Figure 20: Estimated soil impermeability (obtained from buildings and streets)

4.3.3 Boundary Conditions

Different boundary conditions for rainfall, initial soil moisture and water level at the outlet has been considered, as described in the introduction of the chapter.

4.3.4 Main Results

Model was run for several return periods and a recent event (2008). Results from the different return periods have been integrated into the damage curve. Here, only some key results are presented. The next set of figures show the flood propagation during a 100 year event in the downtown of Lisbon. The inundation level at the surface is colored in a blue scale and the %of occupation in the drainage system in colors varying from green (empty) to red (full).

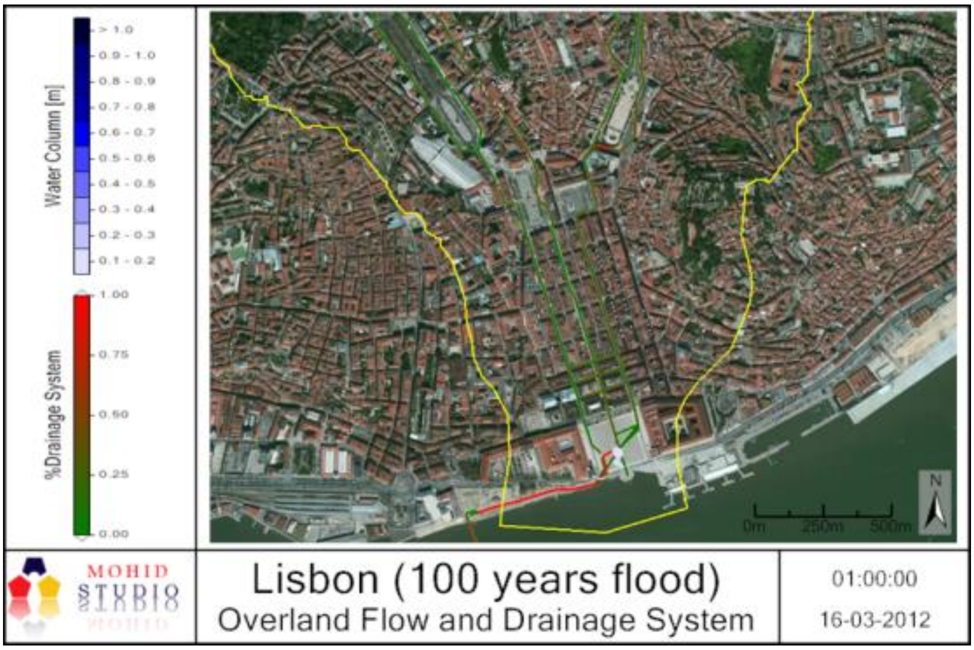

Figure 21: Propagation of a 100 year flood in Lisbon downtown (after 1h)

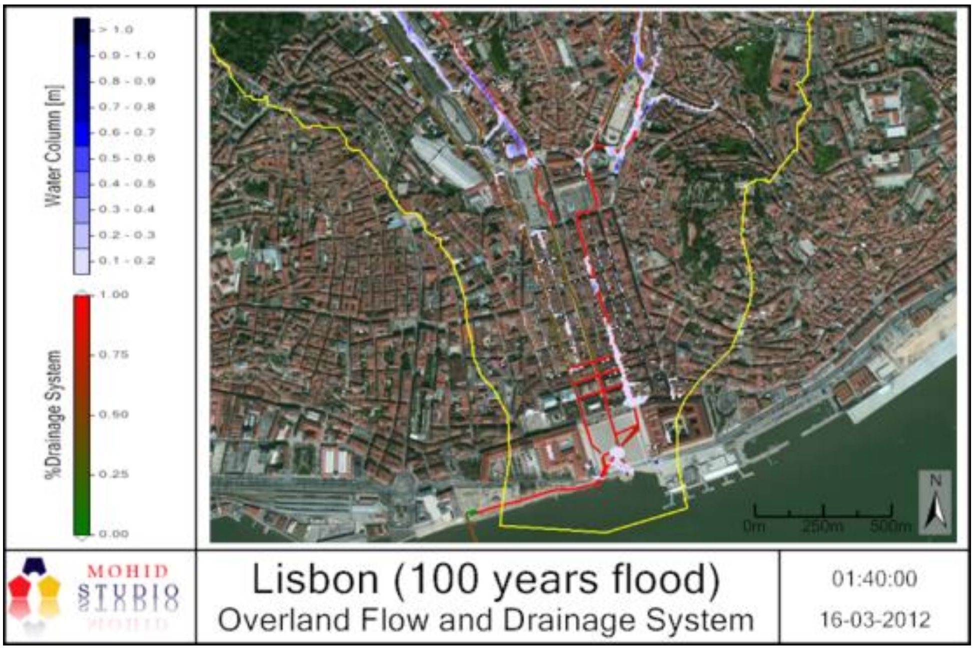

Figure 22: Propagation of a 100 year flood in Lisbon downtown (after 1h 40min)

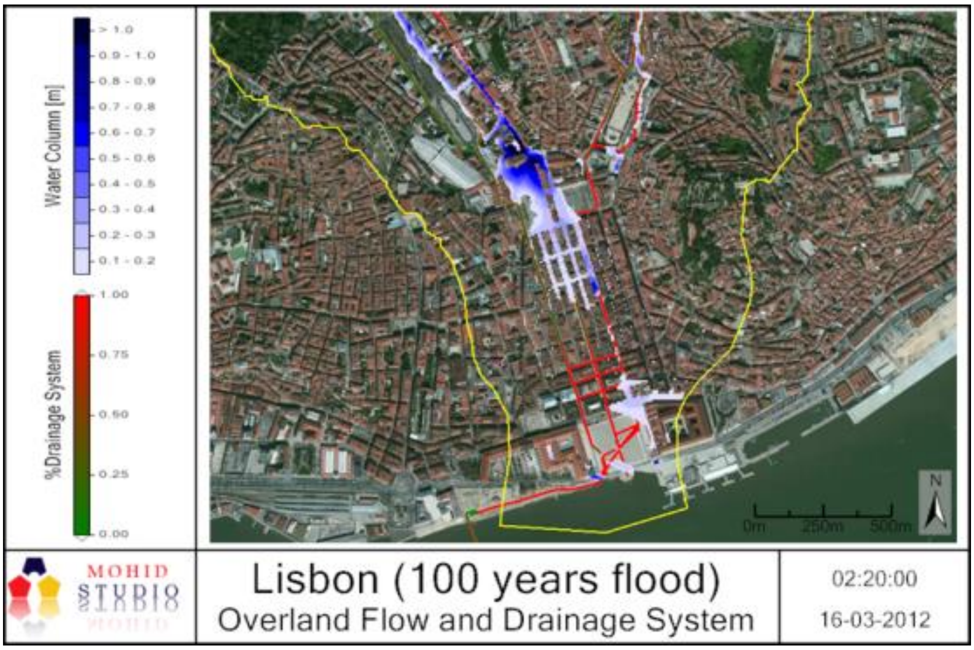

Figure 23: Propagation of a 100 year flood in Lisbon downtown (after 2h 20min)

Previous pictures show the severity of a 100 year event in Lisbon downtown. Not only places which used to get inundated are affected, but almost all roads in the Baixa.

In 2008 occurred an event which caused flooding in Lisbon downtown. This event has been recreated for validation purposes. Figure 24 shows the maximum expected inundation levels for an event occurred in 2008[1].

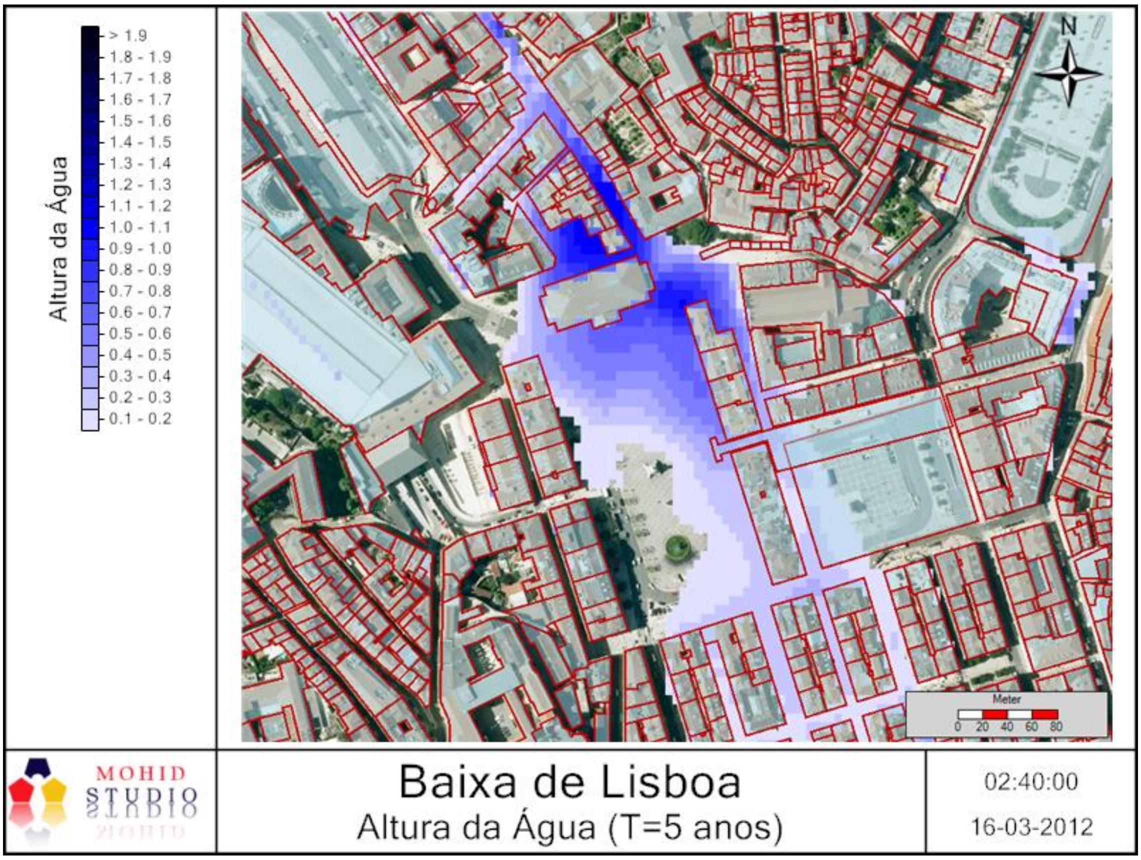

Figure 24: Maximum inundation level for an historic event occurred in 2008

Next three pictures show photographs taken near the *Teatro Dona Maria*. The first picture (Figure 25) shows the inundation in the street of the Coliseum, where cars are "swimming". Model results show in this street water depth of ~1m. The second picture (Figure 26) shows the inundation in front of the theater where water depth seems to be lower, corresponding to the model results (~0.3m). The last picture (Figure 27) shows that the Praça de Rossio is only partially submersed, which can also be observed be the model results.

[1] The legend of the figure says 2012, but it was used the rain of 2008

Figure 25: Inundation during the 2008 event (Street of the Coliseum)

Figure 26: Inundation during the 2008 event (Front of the Theater)

Figure 27: Inundation during the 2008 event (Praça do Rossio)

The previously presented pictures show that the model is able to reproduce this specific real case in an accurate way. This strengthens the idea that the model was correctly implemented and calibrated.

4.4 Case 3 – City of Coimbra

4.4.1 General Characterization

In the city of Coimbra areas have been studied. A first one which drains to the old town and a second one which covers areas a little bit more in the south. Both areas are located entirely in the municipality of Coimbra and drain directly to the Mondego River. Due to its characteristics, these are have not been simulated as individual catchments, but as a continuous area.

4.4.2 Model Implementation

In Coimbra an integrated version of MOHID Land and SWMM was implemented for the first area. For the second area only MOHID Land was implemented, once it was impossible to obtain consistent information about the storm drainage system. Figure 28 shows the digital terrain model used in the downtown of Coimbra. The model grid has a spatial resolution of 5m, composed by 600x280 grid points. Figure 29 shows the digital terrain model used in the second area of Coimbra. Here the model has also a spatial resolution of 5m, composed of 600x724 grid points.

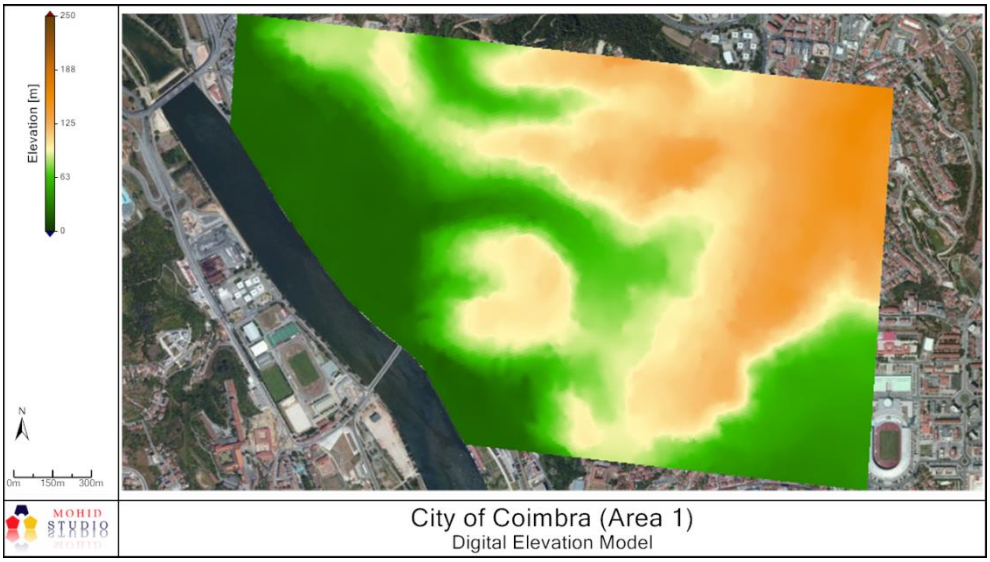

Figure 28: Digital terrain model of the downtown of Coimbra

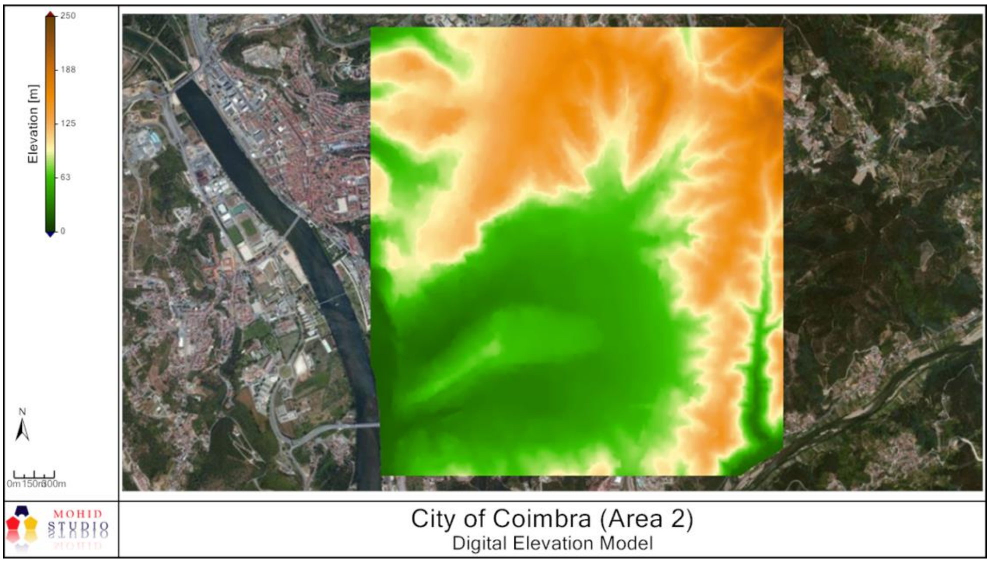

Figure 29: Digital terrain model of the second area in Coimbra

4.4.3 Boundary Conditions

Different boundary conditions for rainfall, initial soil moisture and water level at the outlet has been considered, as described in the introduction of the chapter.

4.4.4 Main Results

Model was run for several return periods. Here only results for maximum expected inundation levels for the 100 year return period are presented (Figure 30 and Figure 31).

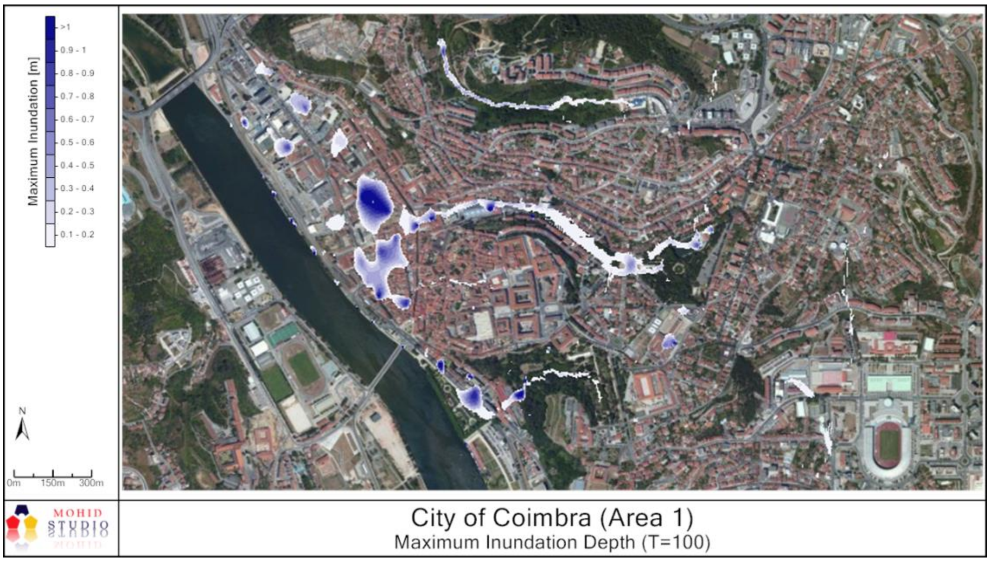

Figure 30: Maximum Inundation Level – Coimbra Area 1 (T=100)

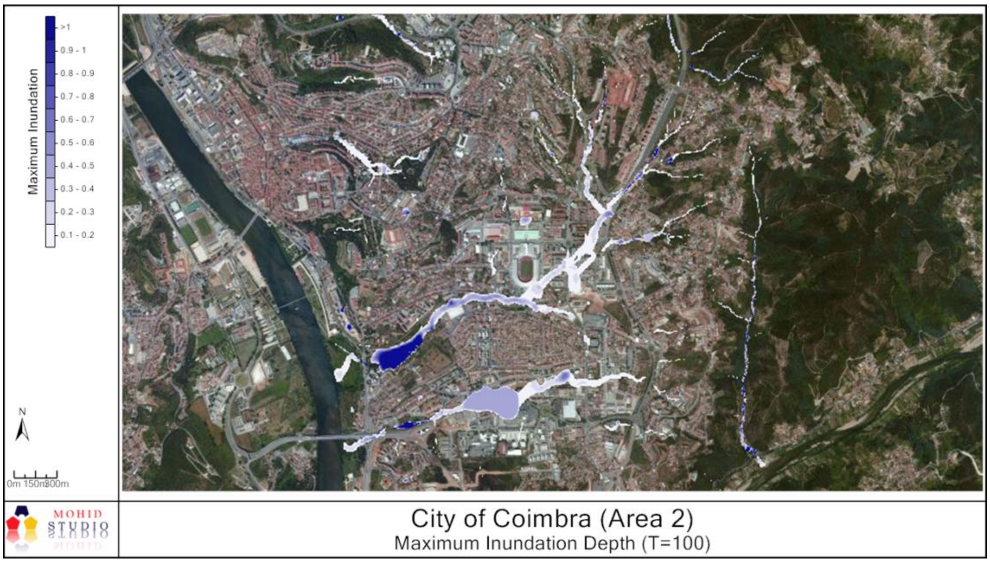

Figure 31: Maximum Inundation Level – Coimbra Area 2 (T=100)

Results presented here must be analyzed with care, since:

- Digital terrain model showed some inconsistency, resulting of spatial interpolation. This can be observed by the "lakes" which are getting created.

- Area 2 was run completely with storm water drainage system, consequently the model routes all water over the ground. This creates higher inundation levels then should be expected in the reality.

Nevertheless, the results shows indications where main problems are expected to occur.

4.5 Case 4 – Rio Douro and Oporto

4.5.1 General Characterization

The Douro is one of the major rivers of the Iberian Peninsula, flowing from its source near Duruelo de la Sierra in Soria Province across northern-central Spain and Portugal to its outlet at Oporto. Figure 32 shows the Douro River near the outlet.

Figure 32: Douro River near the outlet. Oporto is located on the right margin, Gaia on the left margin

The Douro is controlled by a set of reservoirs with a limited storage volume. During wet seasons, when the river discharge is continuously high, flooding may occur at the margins of the river.

4.5.2 Model Implementation

In the Douro case, a different approach has been used. Instead of implementing a model for a watershed, the coastal model MOHID Water has been implemented in the Douro estuary. Depth data has been obtained from the Portuguese hydrographic institute and complemented at the margins by elevation data from the local authorities. With this implementation, it's possible to simulate the lateral inundations of the river. Figure 33 show the final computational grid used by the model.

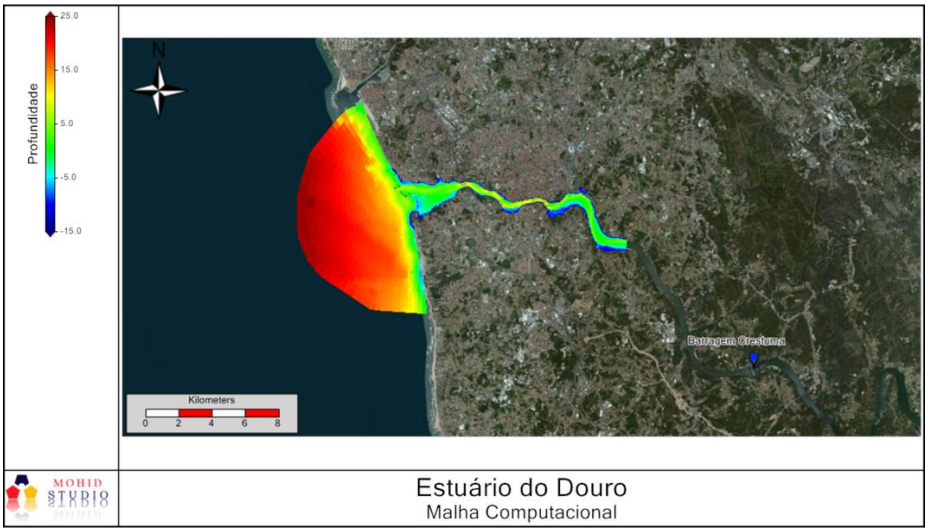

Figure 33: Computational grid used in Oporto

4.5.3 Boundary Conditions

The model was forced at the open boundary by tide (obtained from a global data set) and at the river boundary by discharges.

4.5.4 Main Results

Initially the model was run for an historical event in 2010. Results from this validation period are shown in Figure 34.

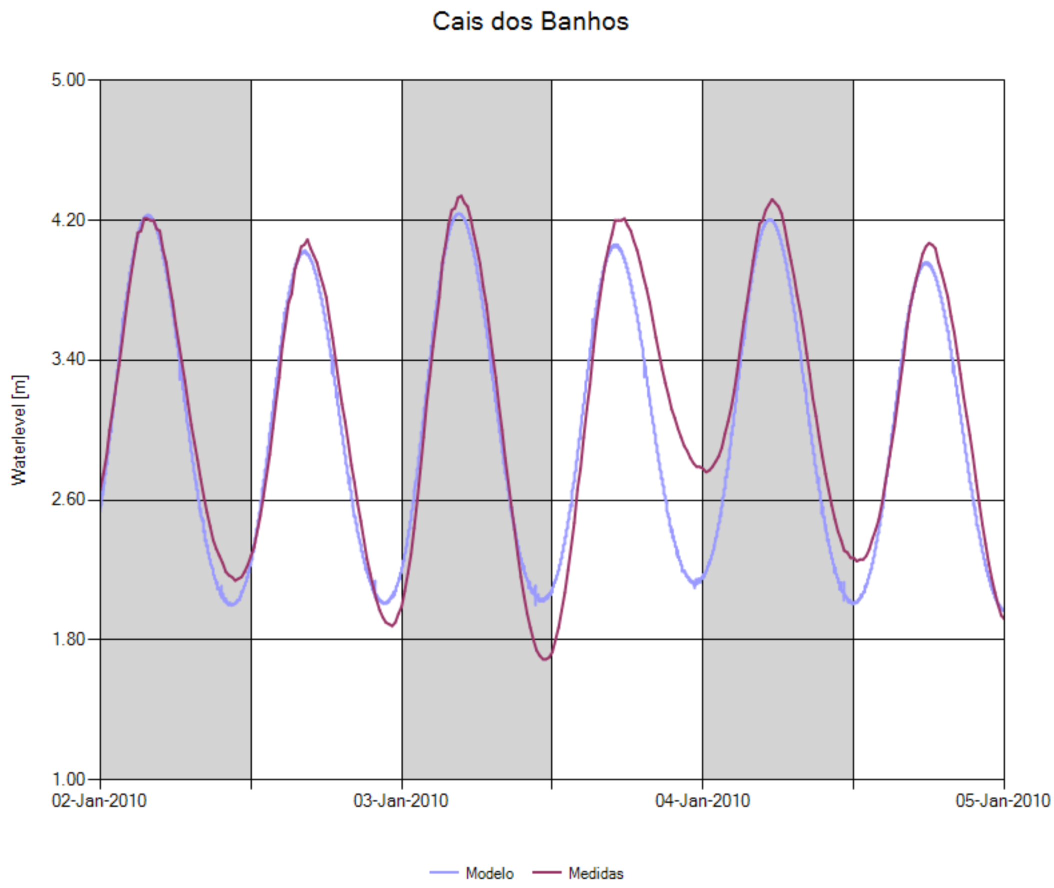

Figure 34: Comparison of modeled and observed water levels (Cais dos Banhos)

Afterwards the model has been run for different return periods, corresponding to different river discharges. Next figures show the evolution of the water depth during a 100 year flood event. The small graph on the right show: (i) the imposed water level at the open sea boundary, (ii) the river discharge (reaching 16.000m^3/s) and (iii) the water level in the river near *Cais dos Banhos*.

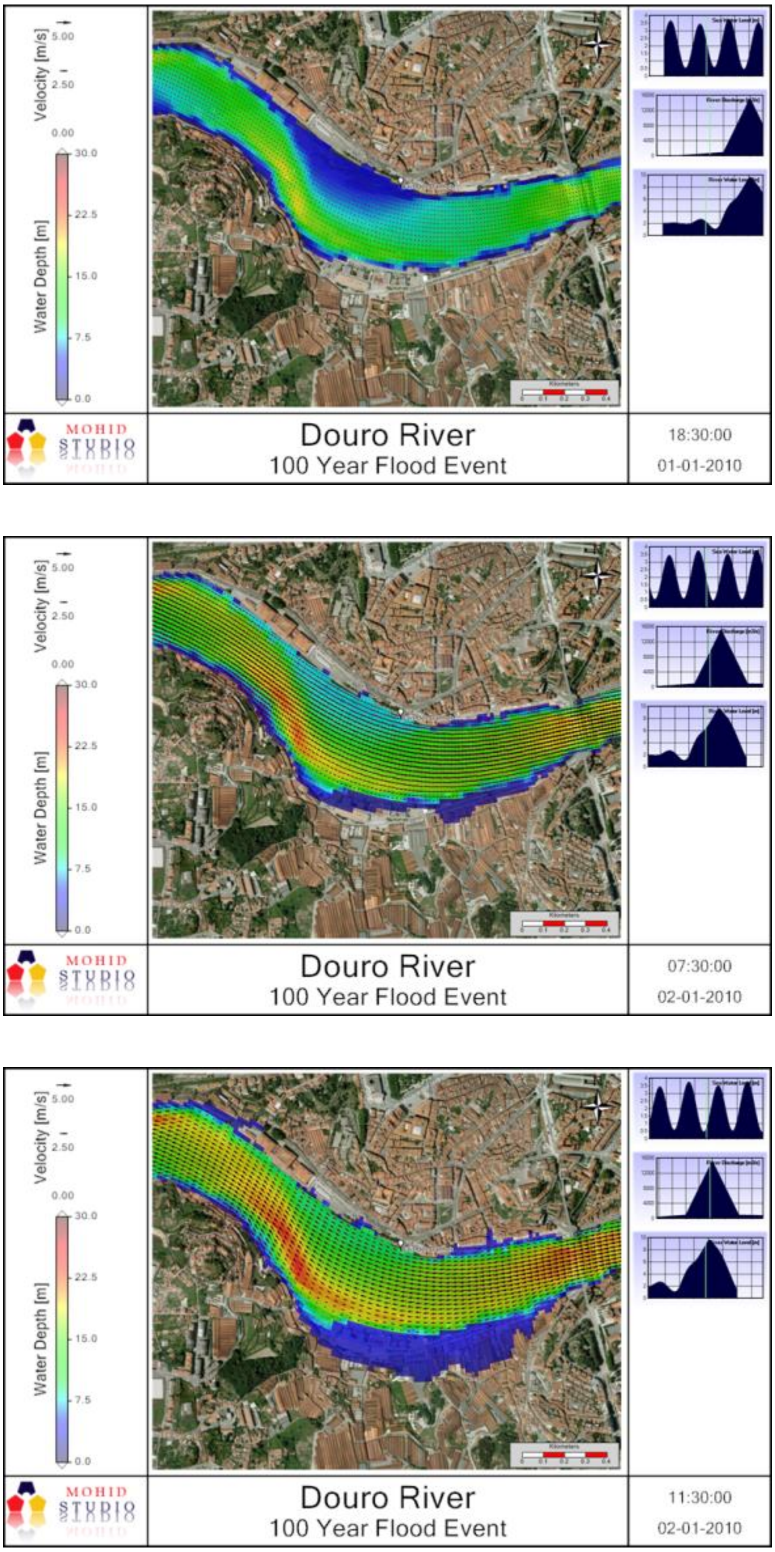

Figure 35: Different instants during a 100 year event (Douro River)