Modelling Sea-Level rise in the Lisbon city coastal area, using Free and Open Source Technologies

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ABSTRACT

Sea-level rise is a consequence of global warming and is triggered by both, natural and man-made causes. The natural causes are mainly thermal expansion of water and melting of glaciers due to increasing temperatures. Man-made causes are related with the human-induced greenhouse gases, which are intensifying the process. Coastal regions are severely affected by the current tendency of sea-level rise, in the climate change context. These regions have also different land use and land cover, are densely populated, hence are considered particularly vulnerable. Researchers have been developing and working on scenarios regarding how much sea-level will rise and on its implications on coastal areas. This paper takes in consideration different scenarios, based on literature, on sea-level rise in the Portuguese coastal city of Lisbon, and measures the consequences of such impacts in terms of affected area. The modelling for this study is based on maximizing two scenarios regarding the following georeferenced data: i) 2D vector buildings outlines data; ii) Digital Surface Model and Digital Terrain Model, obtained from LiDAR data with a resolution of 1point/m^2. Then, the focus will be given on the social impacts requiring other sources such as population, from census data. The objective is modelling these scenarios based on a geoprocessing work-flow using the GRASS software environment. The outcomes concerning different scenarios will be made available in open data formats, through WFS (Web Feature Source) on a WebGIS platform.

Key words: *Sea-Level Rise, Coastal Areas, Hydrological Modelling. GIS, FOSS*

INTRODUCCIÓN

The institutional recognition between sea-level rise and climate change was initially assumed by the Intergovernmental Panel on Climate Change (IPCC) first report, in 1990 [1], being continued, and placed in greater evidence in the IPCC reports that followed, and by scientific community in general [2].

Sea level is changing over time, and its amplitude is of around 100 metres over the last hundreds of thousands of years. These changes are related to Glacial ages, commonly called Ice ages, corresponding to long-term cooler periods in which the Earth's atmosphere and surface temperatures are lower, resulting in the occurrence or increase of ice sheets, and of warmer long-term periods known as Interglacials.

Currently, sea level is in an ascendant situation; it rose more than 120 metres since the last glacial period [3], being in a more stable situation, with a rise of 21 centimetres since 1880, and in the second half of the last century, measurements on sea-level rise pointed out an acceleration, cutting through this stability period [4], associated to anthropogenic activities related to greenhouse gases effects [2].

The causes for the rise of sea level are driven by several processes, which can be separated considering different time-scales. In a longer scale, of over millions of years, processes can be: (a) continental collision; (b) dynamic topography fluctuations due to mantle convection; (c) sedimentation; (d) variations in the mean spreading rate of sea floor. The intermediate scale, considering hundreds of tens of thousands of years, the processes are due to glacial isostatic adjustments. The shorter time-scale can be divided in processes, which are, of more dynamic or static effects. The more dynamic effects are considered to be: (a) ocean-atmosphere interactions; (b) ocean circulation; (c) ocean tides; (d) salinity; (e) temperature variations. As more static effects are pointed (a) deformational; (b) gravitational; and (c) rotational signatures of mass flux from polar ice sheets and mountain glaciers [5].

Literature points out four main drivers to the current tendency of sea-level rise: thermal expansion of the oceans; the melting of Antarctic and Greenland ice sheets; glaciers and ice caps; and groundwater depletion and reservoirs. Because of the complexity of these drivers and its contributors, accuracy and consensus on predictions to sea-level rise are now hard to reach [2], and literature sets different scenarios according to several authors on how much sea will rise for a certain time period.

The contribution of thermal expansion of the oceans water is in the order of 30% in the last two decades [6], which in physical terms, is the response to the increasing water temperatures due to the global warming, resulting in higher water volume [2].

Antarctic and Greenland ice sheets are set to be a dominant contributor to sea-level rise in the next decades. In a recent study, through the setting of observational techniques, the concluding results were of an increase melting of its mass, three times faster than glaciers and ice caps [7].

Glaciers and ice caps share the same 30% rate of contribution to sea-level rise (from 1961 to 2003), as thermal expansion [8].

Studies on groundwater depletion and reservoirs are now increasing, and due to anthropogenic influence a larger contribution to sea-level rise is expected [9]. Groundwater depletion, between 2000 and 2008 contributed with 12% for sea-level rise [10] and [11], while reservoirs had a negative contribution of -0.55 millimetres per year, particularly because of the construction of artificial reservoirs, like dams, in the period from 1960 to 1980 [12].

All these factors are of a great complexity and it is impossible to reach an order of values that suits scientific community in a consensual sea-level rise considering different time-lines.

Further, sea-level scenarios are mentioned, followed by methodologies, ending on results and conclusive remarks.

SEA-LEVEL RISE SCENARIOS

Modelling sea-level rise is based, mainly, on two types of methodologies: physical or semi-empirical [13]. These models differ from each other on the used methodologies, and both have their strengths and weaknesses. Because of their differences, scenarios on sea-level rise have different values, and in general, considering referred literature, calculations are done until the end of the century.

Models based on physical principles consider the physical contribution like thermal expansion or land ice changes to the variations in temperature, as it is stated in the AR4 IPCC report [2]. It is expected that these models represent with accuracy, observed data from a certain period. This accuracy will mean a well calibrated model [8]. As it was mentioned before, there are still some gaps to fill in the IPCC model, because values have some discrepancies. For the period ranging from 1961 to 2003, it is of 0.7±0.7 millimetres per year, and between 1993 to 2003, of 0.3±1.0 millimetres per year [2].

The answer might be in the fact that ice sheet flow from Antarctica and Greenland was not modelled in the modelling available. Terrestrial storage was not accounted for, because there were no reliable assessments at that time [2] and [8].

The presented scenarios from the IPCC consider a variation in sea-level of more 0.18 to 0.59 metres for the period between 2090 and 2099. For 2100, the values change from 0.19 to 0.63 metres. The extremes cenario on ice-flow increases the sea-level to a rise of 0.80 metres. Because there were still some gaps on the understanding of ice-flow processes, the report recognizes the hypotheses of higher sea-level rise scenarios and the advantages other approaches can bring, namely, semi-empirical and other scaling approaches [2].

Semi-empirical models try to give the answers that physical models are not yet ready to give, concerning glaciers and ice caps, ice sheets and thermal expansion. Recent measurements point out a sea-level rises near the upper end of IPCC AR4, leading to conclude that during this century, sea-level can rise more than it was predicted, assuming there was an underestimation [14].

The sea-level semi-empirical model is based on the theory of a direct relationship between a global average near surface air temperature and sea-level rise observed in the past century. In a practical term, the model estimates sea-level variations according to variations in temperature [14] and [15]. Paleoclimate studies, reconstructing temperature and sea-level values, ensure this relation for at least the last millennium [16].

Scenarios based on semi-empirical models have higher projections values for 2100, when compared to physical models. They vary between 0.50 to 1.79 metres on the highest and worst case scenario [14] and [15]. However, scenarios go beyond 2100 and predictions on how sea level will rise are higher [13] and [17].Table 01 – Scenarios on sea-level rise

Authors	Scenario time-scale	Minimum value	Maximum value
Hansen and Sato, 2012 [18]	2095	-	5,00 m
IPCC, 2007	2099	0,18 m	0,59 m
IPCC, 2007	2100	0,19 m	0,63 m
Jevrejeva et al., 2010	2100	0,60 m	1,60 m
Pfeffer et al., 2008 [19]	2100	0,80 m	2,00 m
Rahmstorf, 2007	2100	0,50 m	1,40 m
Rohling et al., 2008 [29]	2100	0,60 m	2,50 m
Vermeer and Rahmstorf, 2009	2100	0,81 m	1,79 m
WOR, 2010	2300	2,50 m	5,10 m
Jevrejeva et al., 2012	2500	1,84 m	5,49 m

One of the advantages seen on these type of models are how practical they are, however it is also seen as a disadvantage due to the lack of physical basis to support the relationship between temperature and sea level [21], contested by the most recent study lead by Kemp, 2011 [16].On the other hand, there is the agreement that both models have huge uncertainties on ice-flows [6], [7] and [22].

Regional scale scenarios

Looking closer to sea-level rise issue, data from tide gauges and satellite tells us that there are considerable variations at a regional scale. These can vary positively or negatively in a rate of 10 millimetres per year, being called fingerprints [23].

These differences are caused by local effects, one related with ocean circulation and its temperature with a global influence of El Niño Southern Oscillation wind stress. It is mostly felt in the Indo-Pacific region but the thermal expansion of the ocean reaches the global scale [6]. The other effect concerns to regional gravity field of the Earth due to ice melting. The distribution of the melted ice will not be uniform, as sea-level is higher as distance increases from the melting source [24].

Other effects can also change sea level regionally, like vertical land movements as uplifting or subsidence. The first is likely to occur in icy areas. The ice melting will result in upper movement from the continental plates [6]. Subsidence occurs particularly on coastal areas, caused by drainage (groundwater or oil withdrawal), sediment trapping and floodplain engineering [25].

With a more recent and accurate knowledge of all sources of sea-level rise and the understanding of its effects on a regional scale, recent studies have better understanding of preciseness effects considering all kinds of projections locally [26] and [27].

In retation to Portugal, the whole country has a similar sea-level rise, and it is assumed of being in the neutral fingerprint region of global rising, with a trend of 3.2 millimetres per year in the last two decades, ensuring a direct relation with the global mean sea-level rise [6].

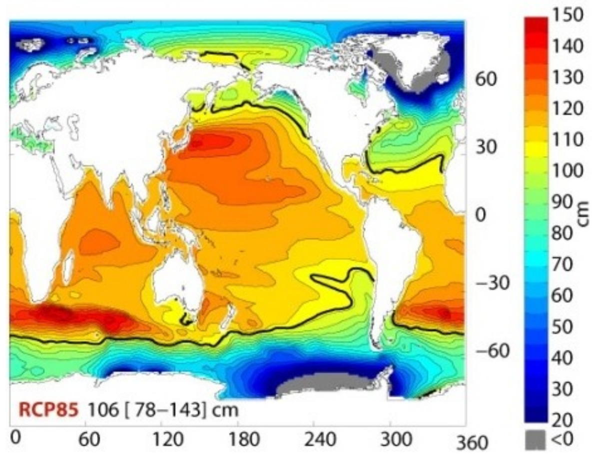

Figure 1: *Sea level fingerprints, their contribution and median (21st century projections). Projected total SLR for all components combined (contours every 5 cm). The thick black line corresponds to the global mean, and grey shading indicates areas of sea-level drop. Source: Perrette, M, 2012 (doi: 10.5194/esdd-3-357-2012)*

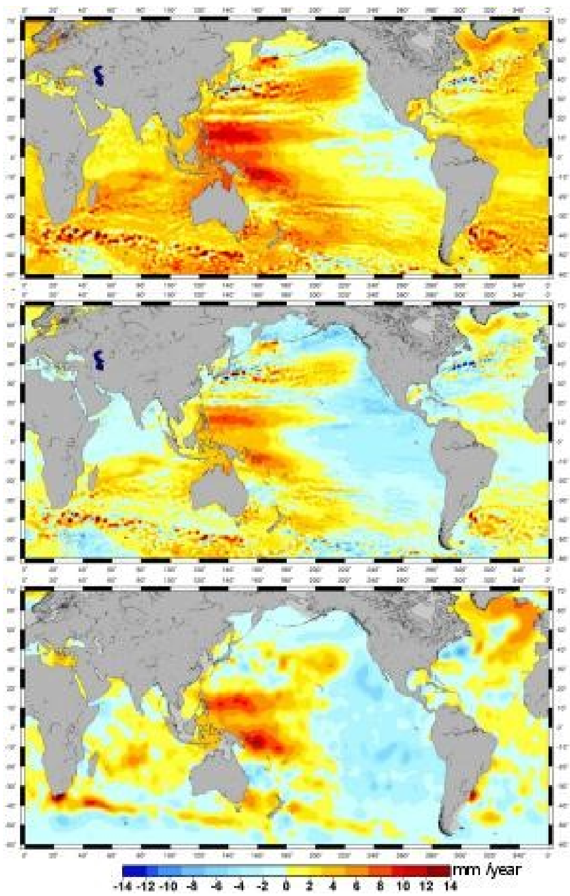

Figure 2. *Map of spatial trend patterns of observed sea level between January 1993 and 2010. Top: observed by satellite altimetry; Middle: same as the latest but a uniform global mean trend of 3.2 mm/year has been removed; Bottom: Spatial trend patterns in steric sea level over 1993-2010. Source: Meyssignac and Cazenave, J. Geodynamics, 2012*

METHODOLOGIES

The development of the present work is mainly done in GRASS GIS 6.4.3RC1, and after in Quantum GIS Desktop 1.8.0 for final analysis and layout display. The computer used to execute this project has a Windows 7 Home Premium, 64-bit Operating System instaled, Service Pack 1, with 8GB RAM in Intel(R) Core(TM) i5-2450M CPU @ 2.50GHz.

Using Free and Open Source Software (FOSS) [28] was seen as a key aspect, not only because of the character of the present event but also to test how FOSS would perform with such kind of analysis regarding Sea-level Rise (SLR) in the city/municipality of Lisbon, Portugal.

Starting to work in GRASS GIS requires setting some initial parameters as *GIS Data Directory*, *Project location* and *Mapset* before in becomes “operational”.

The first task was to import the raster file (*r.in.gdal*) to work in a GRASS GIS environment. This raster covers an area of 17012ha, with a pixel resolution of one square metre. It is the result of LiDAR data with a resolution of one point per square metre for the Lisbon area.

The core of the work is based on this information, from where new layers will result in the rising of sea level.

In order to obtain the affected areas by sea-level rise in the city of Lisbon, two scenarios were considered, one based on Rohling *et al.*, 2008 maximum scenario of 2,5 metres in 2100 and the other was based on Jevrejeva *et al.*, 2012 maximum scenario of 5,49 metres for 2500. The function for this analysis was the *r.lake* in the Hydrologic Modelling module.

With the new raster files obtained for SLR, the second task was to import vector data (*v.in.ogr*). The Lisbon city boundaries layer and Lisbon Parishes were imported and, from the last layer, was extracted (*v.extract*) the parish of São Nicolau for the case study area.

After, the vector layers of Lisbon city municipality and São Nicolau were converted in raster files (v.to.rast). The resulted file from hydrologic modelling was then reclassified (r.reclass) into one single value with the objective to be intersected with the Lisbon city area and selected parish with the Raster Map Calculator (r.mapcalc).

Lately, using GRASS GIS, all raster files resulting from SLR analysis were converted to vector files (r.to.vect), completing the main objective of the project, which was getting the exact areas affected by SLR.

The GRASS GIS project was then continued in Quantum GIS, being the first task the “cleaning” of residual information from SLR vector files.

The cleaning of these vector files resulted from the need of adding two accurate new fields, one with the area and the other with the perimeter. This task was performed using the *Geometry* functions from the *Field calculator* tool.

Concluded all analysis, Quantum GIS was then used as a cartographic tool to show the obtained results of analysis done so far.

All steps done to perform this project are systematized below (*figure 03*) and results are set and discussed in the next sections.

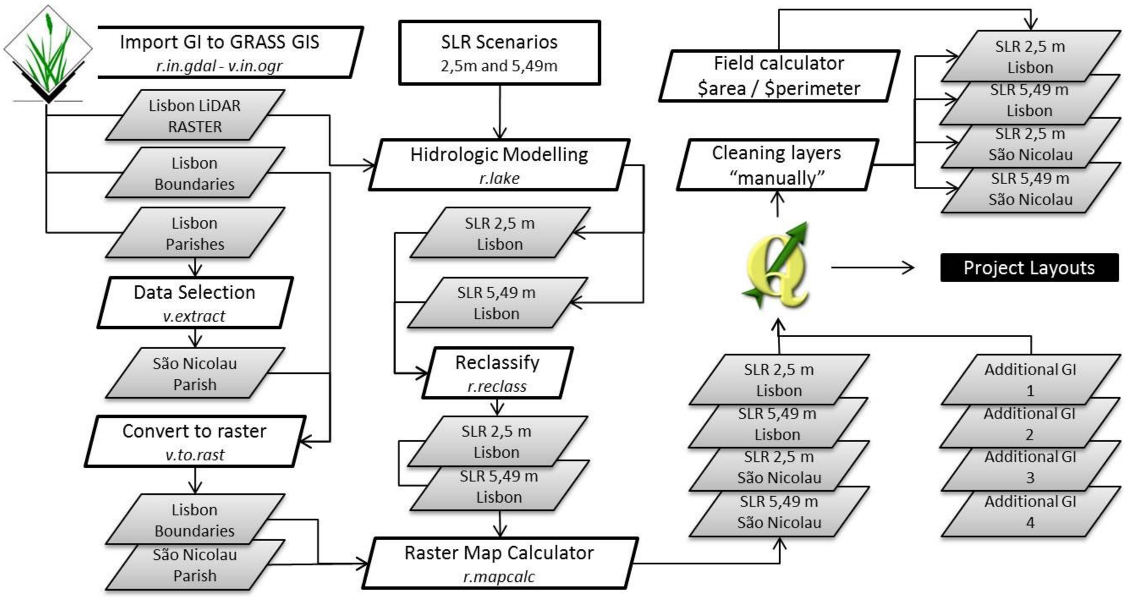

Figure 3. *Project workflow*

RESULTS

The Portuguese capital city of Lisbon (and municipality) was the selected case study area to develop this project (figure 04) and understand how selected FOSS would perform in such area.

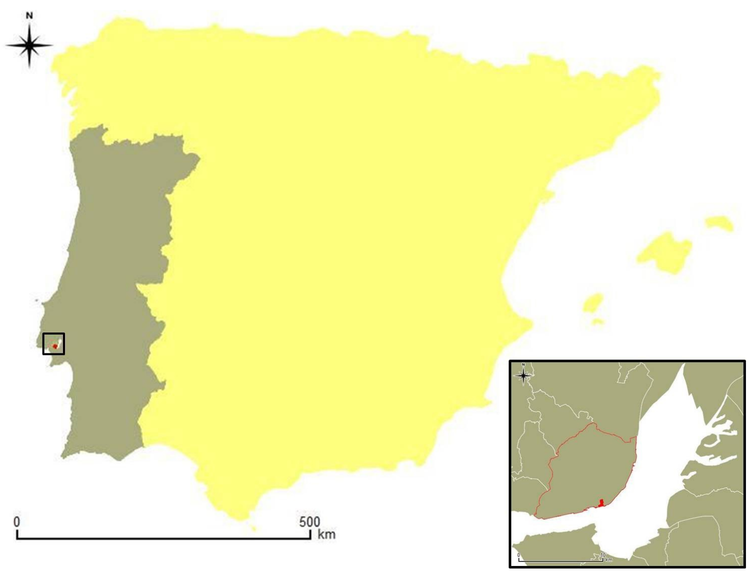

Figure 4. *Location (in red) of the case study area, in the Iberian Peninsula*

According to the selected scenarios regarding different time-lines, Lisbon, with a total area of 8550ha may see in 2100, 0,78% of its coastal areas affected if sea-level rises 2,5 metres, and 5,18% in 2500 with a sea-level rise of 5,49 metres.

In the specific case study of the Lisbon municipality, the São Nicolau parish, in Lisbon down town, with the same SLR for 2100 and 2500 will lose 1,02% and 36,69% of area, respectively (table 02).

Location	Scenario, year 2100 Rohling et al., 2008 SLR 2,5m		Scenario, year 2500 Jevrejeva et al., 2012 SLR 5,49m	
	N (ha)	%	N (ha)	%
Lisbon flooded area	66,91	0,78	442,95	5,18
Lisbon total area	8550,04	100	8550,04	100
São Nicolau flooded area	0,27	1,02	9,66	36,69
São Nicolau total area	26,33	100	26,33	100

Table 2. *Sea-level rise affected areas scenarios (Lisbon area)*

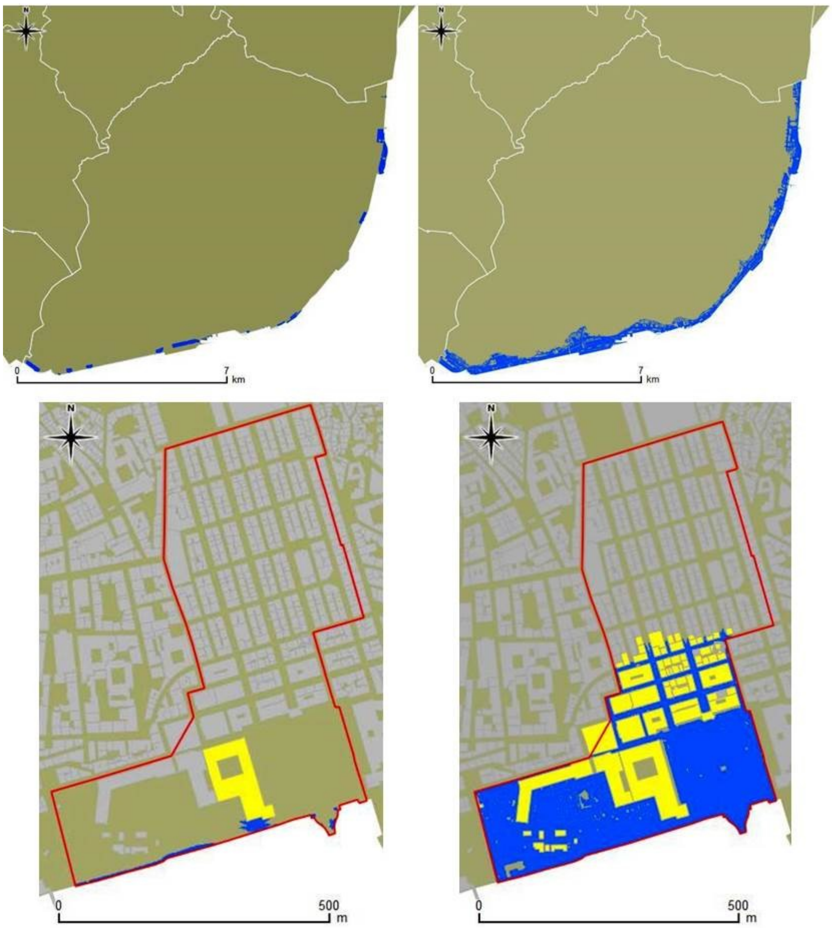

Figure 5. *Sea-level rise of 2,5m in Lisbon, 2100 (top left); sea-level rise of 5,49m in Lisbon, 2500 (top right); Sea-level rise of 2,5m in São Nicolau, 2100 (bottom left); Sea-level rise of 5,49 in São Nicolau, 2500 (bottom right)*

Regarding last population census (2011), the number of inhabitants living in Lisbon was of 547733, and in São Nicolau parish, it was of 1231 inhabitants. In order to estimate, hypothetically, the number of affected inhabitants affected by sea-level rise in 2100 and 2500, a direct relationship between the percentage of buildings in the SLR areas and the same percentage of population for those areas in Lisbon, and the parish of São Nicolau.

According with these calculations, and if the population in 2100 and 2500 for these areas remained constant, in Lisbon, with a sea-level rise of 2,5 metres, 219 people would be affected. Raising SLR to 5,49 metres above present values would affect 15775 inhabitants.

In the parish of São Nicolau, for 2100, the calculated amount of affected inhabitants is of 2, and in 2500 of 171 inhabitants (table 03).

Location	SLR 2,5m Scenario, 2100		SLR 5,49m Scenario, 2500		SLR 2,5m	SLR 5,49m
	Buildings		Buildings		Census 2011 Affected Inhabitants	
	N	%	N	%	N	N
Lisbon flooded area	26	0,04	1882	2,88	219	15775
Lisbon total area	65271	100	65271	100	54773	54773
São Nicolau flooded area	1	0,16	85	13,91	2	171
São Nicolau total area	611	100	611	100	1231	1231

Table 3. *Buildings and population affected by SLR*

DISCUSSION OF RESULTS AND FUTURE WORK

Despite uncertainties amongst the scientific community on sea-level rise, measurements, global or regional, are factual, and represent important tools for land planning and management, and even though its lower increase for the next couple of decades, it should be seen considering a longer time-line. Sea-level rise must be an instrument for planning, not only at an international scale, but also downscaling, at national, regional and local scales.

Portugal, having a great tide gauge dataset history from Cascais, should see it as an asset, together with satellite data, on land management.

We want to try other Hydrologic Modelling tools adding other layers, emphasising analysis on the quantification of affected infrastructures as roads, buildings and others, contemplating tides, waves influence and storm surges, for a more complete approach on this issue.

It is equally essential to go deeper on population scenarios for affected areas by sea-level rise considering the use of more feasible methodologies, rather than a direct relationship between the percentage of buildings and of population for a certain area in order to reach higher accuracy. We are certain that the use of population variation index with the 3D enabled by LiDAR data used to estimate the number of floors per building, and type of use of building, will improve the accuracy of estimated rates for affected population.

GRASS GIS performed well in tasks that were required for this project (taking no longer than a couple of minutes). Due to this performance, we see it as an asset, and alternative to Proprietary Software.

As mentioned, a step to be taken can be the modelling of larger areas, as the Tagus Estuary and the improvement of few steps concerning these kind of studies.

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