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# Dynamic scenarios and water management simulations: towards to an integrated spatial analysis in water urban planning

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## Abstract

By combining and integrating different areas of knowledge (Urban Planning, GIS, Remote Sensing, Cellular Automata, Climatology, etc.) with the cities traditional infrastructures using new digital technologies, it is possible to generate more efficient urban systems. Therefore, it can support new forms of water governance. This study aims to reproduce environmental and water management scenarios using Geographic Information Systems (GIS) and cellular automata as a methodological approach for spatial patterns simulations of urban growth (dynamic scenarios). Water consumption simulations plus floods modelling and environmental comfort simulations were integrated into the same SDSS (Spatial Decision Support Systems) environment as a GIS. To support the analysis, Dinamica EGO and Storm Water Management Model were chosen as modelling platforms. The simulations used the future land use trends (dynamic modelling) and legal aspects to evaluate the mitigation of floods with low impact development techniques (LID). Results indicated good runoff reductions with the integration of stormwater and dynamic modelling. This research expects to support interdisciplinary approach for urban planning teams making the water issues and urban planning issues closer and essential for the resilience of present and future cities.

**Keywords:** Dynamic modelling; Water management simulation; Urban Planning; Spatial Analysis

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# 1 Introduction

## 1.1 Water and Urban Issues

Many aspects of urban change in recent decades have been so rapid that they have overwhelmed government capacity to manage them. Disaster impacts show that a high proportion of the world's population most affected by extreme weather events is concentrated in urban centers (UNISDR, 2013). In Brazil, studies by the Intergovernmental Panel on Climate Change indicate that Climate changes impact a large part of the Brazilian population on its health, water resources, infrastructures, coastal zones, forests, and biodiversity, as well as the economic sectors. These changes impose great challenges and opportunities for better planning, especially for urban areas where most of the population lives (IPCC, 2014).

Urban Growing increases pressures for water (water supply problems). Brazilian semiarid region is facing the longest drought ever (over 6 years). In consequence, thousands of urban inhabitants are dealing with water scarcity. Brazilian Urban Master Plans usually not consider water resources issues in planning. So, the land-use and occupation planning usually does not take into account the pressure it imposes on water resources. Climate changes and urban growth in an ill-planned scenario also affects runoff patterns in cities. Impervious surfaces reduce the rainwater infiltration and increase the water runoff. Besides, a large occurrence of high buildings (urban density increasing) drives a water supply and water drainage pressure by reducing green and open spaces in urban areas.

Local government and utilities responsible for water supply and drainage management must confront these new climatic patterns and major uncertainties in availabilities and learn to respond to dynamic and evolving sets of constraints (Milly, et al., 2008). Urban planners and water resources managers should promote better strategies and practices of water conservation in urban environments.

This is the purpose of Water Sensitive Urban Design (WSUD). During the last years, many technologies in stormwater management have emerged. These are known as Low Impact Development (LID) in United States, Sustainable Urban Drainage Systems (SuDS) in United Kingdom and WSUD in Australia. These measures offer a more sustainable integration of stormwater management into urban design. These tools are designed to pond, infiltrate, and harvest water at the source, encouraging evaporation, evapotranspiration, groundwater recharge, and re-use of stormwater (Roy, Wenger, & Fletcher, 2008). It is important to understand the interactions at the city scale and to identify possible strategies for the development of a potential strategic planning tool, considering dynamic changes of the studied area.

## 1.2 Dynamic modelling in urban areas

Urban systems have an incredibly dynamic character and to model these systems this dynamic, i.e., models must incorporate the time variable (Batty, 2005). Also, the traditional aggregated models, much influenced by census data in urban areas, cannot efficiently characterize all the elements of this complex space. Aggregated models tend to "soften" the inherent dynamism of urban space. On the other hand, some "cell" modelling approaches (such as agent-based modelling) have become popular for phenomena such as disease propagation, crime and land use applications (Matthews, Gilbert, Roach, Polhill, & Gotts, 2007).

This type of modelling is also capable of simulating the dynamics of land use and human activities. Interactions between human activities and the land use are modelled and reached, providing a much more realistic urban pattern of scenario representation (Vliet, Jelle Hurkens, & Delden, 2012). Cellular automata are formal systems based on grids, in which change processes are represented cell by cell, as a simple mapping of the current state of a cell and its neighbors to the state of the next cell at the next time point (Batty, 2005).

## 1.3 Water management simulations

For water management, measures can be applied in urban areas through hydrologic modelling. The modelling allows to know which LID is suitable for a specific case. Researches have focused in adapting techniques in a way to increase the effectiveness by inserting the characteristics of the studied area (Norton, et al., 2015). The performance of these technologies is evaluated by the capacity of restoring pre-development runoff regime (condition before growth).

In dry and semi-dry weathers, climate challenges such as selecting plants that will grow under harsh conditions, potential of carbon and nitrate sequestration, assessing possible negative impacts on runoff water quality and optimizing stormwater retention are important (Lee & Fisher, 2016). Thus, there is a need for data from pre-development phase to a fully developed phase in the analyzed area. This paper proposes the use of dynamic modelling to estimate present and future consumption of water in a small area of a semiarid city of Brazil, and through hydrologic modelling, assess the effectiveness of WSUD as a water saving strategy and flood mitigation.

# 2 Study area peculiarities

Campina Grande county is located in the north-eastern region of Brazil and is the second largest city in the semiarid region which makes a significant pressure on natural resources. With a population of 407,754 inhabitants (IBGE, 2016) in the last three decades, the population increased approximately 20% as well the urban area such as the number of buildings, paved streets and impervious surfaces. From to 2013 and 2017, more than four hundred streets were covered by asphalt paving (Alves, 2017) without a previous study or drainage planning. It is often exposed to floods during the rainy periods, mainly due to concentrated rainy events (typical of semiarid regions).

In the other hand, last six years, the county has been facing the most severe water shortage in its human supply. All the water supply depends on the unique reservoir (named Epitácio Pessoa) located in another county. There is no river or groundwater available for water supply, which makes the city a good lab for resilience and adaptation studies and practices. This reservoir is about 8.9% of your maximum capacity (update on 10/13/2017 from the official website), and there are many water resources conflicts regarding its operation and management for Campina Grande and neighborhood (around 800 thousand people depends on that reservoir). In this study, there are two districts selected: Catolé and Sandra Cavalcante. Both are within the same drainage catchment and they are the most population density districts of the city. Also, the two selected regions show a faster urban development than other areas in the city, with a high number of buildings and urban services. So, the urban dynamic is a good research challenge.

# 3 Past, present and future scenarios

Past, present and future land use scenarios area acquired from RS data combined with data from Census and field data. In cities, land use changes too dynamically and fast. Field data is essential for a good quality of present scenarios and helps to explain better some land use transitions from past to present in the dynamic simulations (future). Figure 1a show some possibilities of urban dynamic analysis using cellular automata. In an urban expansion case it is possible a conversion of non-urban adjacent cells into urban cells. Another possibility are the common urban land use changes. It makes possible a conversion of a land use cell in another land use cell (adjacent patterns trends/influence).

Another scenarios methodology to an integrated analysis in an urban environment can consider the land use regulations limits. In this case, water resources issues must be simulated in a future scenario predicted/allowed by some law instrument as a Master Plan or an urban land use proper code. This option also considers all dynamics of a city but establishing a limit based on the current law permits. It comes up with bigger challenges that evolves legal and technical aspects of urban planning in a spatial analysis approach.

## 3.1 Water consumption estimate

Since the increased urban water demand is one of the main pressures of urban expansion on water resources, water consumption estimation is essential to help planning, managing, operating and modifying water supply systems (Tsutyia, 2006) . For past and present scenarios, the water consumption is calculated based on land use type (for each land use there are different consumption patterns); the number of floors and unities (sometimes estimated); based on the herein consulted literature used in Brazil (Creder, 2011). So, for future scenarios, there is a spatial analysis by pixel (land use consumption by pixel) establishing "a water consumption rate by pixel by LU" based on past and present scenarios (Soares-Filho, Rodrigues, O., & Follador, 2013). Additionally, it has been considered an increasing trend of high buildings in the area (population density in high buildings, water concentrated consumption). This trend is called in this study as a “verticalization trend” and it is one of the simulated variables in the dynamic modelling. Figure 1b shows results about using dynamic modelling to estimate future water consumptions scenarios. In this first result, the time interval used is 5 years. The transition from the scenario I to scenario II uses two types of variables: *dynamic* and *static*. A dynamic variable is updated throughout the simulation, whereas with a static variable this does not occur. For these areas, distances to high buildings and inbuilt lots are considered dynamic variables.

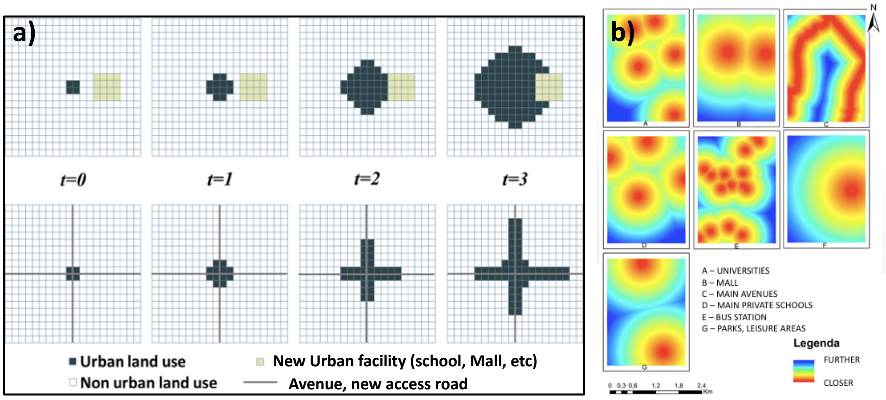
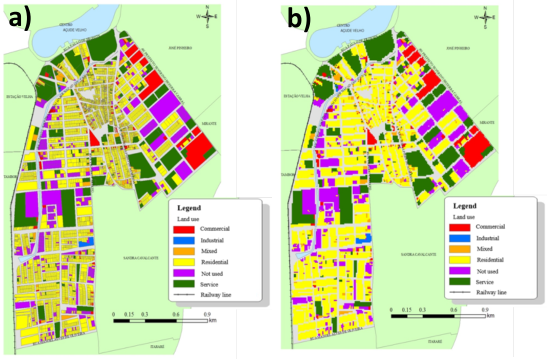


**Figure 1:** a) Urban growing patterns; b) Dynamic modelling (Source: adapted from (Rodrigue, 2017)).

In the other hand, distances to essential services (as big schools and public parks) are deemed as static variables (Figure 2). The computational platform used for simulations is the Dinamica-EGO software. It can offer modelling possibilities for the design from the very simple static spatial model to very complex dynamic ones, which can ultimately involve nested iterations, multi-transitions, dynamic feedbacks, multi-region and multi-scale approach and a series of complex spatial algorithms for the analysis and simulation of space-time phenomena. The future water consumptions considering a verticalization trend used the water consumption rate for pixel, the number of pixels of the scenarios and a high building factor (HBF) as it is presented in Figure 3. The HBF was established to estimate water consumption for different scenarios (1 floor and 2 or more floors), for long-term intervals as 2040, 2070 and 2100 for both Catolé and Sandra Cavalcante districts. The schematic diagram of the methodology used is shown on Figure 3.



| **Current situation** Current water consumption (l/day) | **Scenario I** Water consumption in 5 years (l/day) | **Scenario II** Water consumption in 10 years (l/day) |
|---|---|---|
| 5,160,960.20 | 5,899,659.97 | 6,194,302.11 |
| **the total increase of 20%** | | |

**Figure 2:** a) Land use scenario I (5 years) and (b) Land Use Scenario II (10 years); Both for Catolé District. Water consumption for Scenario I and II and the total increase

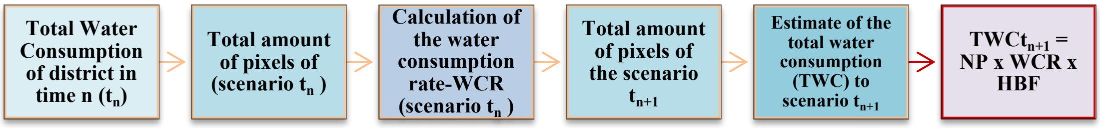


**Figure 3:** Methodology steps for water consumption estimate in a future scenarios

Figure 4 shows some simulations of “inbuilt” and “high buildings” scenarios for long-term intervals as 2040, 2070 and 2100 for both Catolé and Sandra Cavalcante districts.

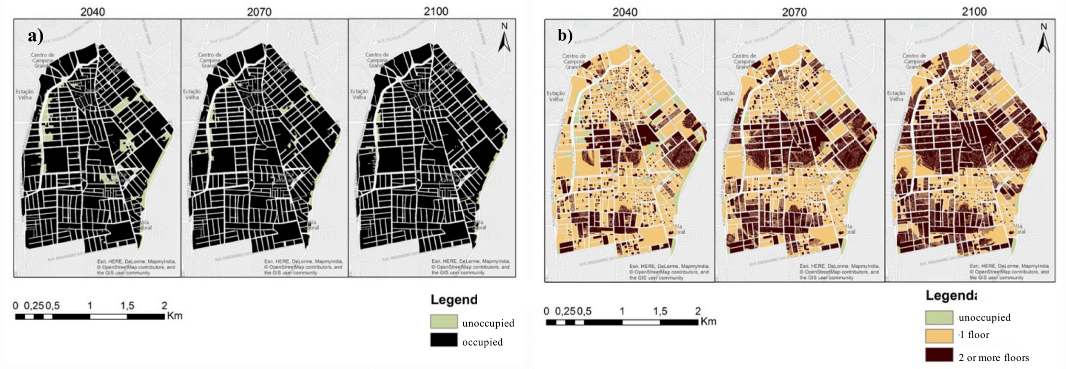


**Figure 4:** (a) Inbuilt lots scenario (b) High buildings density scenario

## 3.2 Stormwater and LID simulations

For stormwater, simulations use impervious surface derived from land use scenarios. The basic information for rainfall-flow hydrological simulation are the precipitation, the width and slope of the blocks, the Manning roughness coefficients, impermeable areas and the height of storage in depressions and infiltration parameters. These parameters came from local institutions, previous researches and some are parameters considered by the used software Storm Water Management Model (SWMM) (Rossman & Huber, 2015). So, for future scenarios, it keeps the same settings and changes the impervious surface area percent (predict by dynamic model), and precipitation data consider different events probabilities provided by climate models and Intense rainfall equation calibrated for the local area. The software ArcGIS 10.1 (ESRI™) is the environment to processing and generate both scenarios. Those scenarios are input for dynamic simulations on Dinamica EGO™ software which gives future scenarios outputs for the water consumption estimate and stormwater simulations. Figure 5 considered a scenario under the land use legal permission. The law allows a percentage of 80% of the total impervious area for a lot, so, LID simulation considered this prediction. In this case, the green roofs technique has been chosen to simulate how the sub catchments would react. The simulation considered a scenario without LID and with LID, respectively. Figure 5 shows first results for a precipitation event of 60 minutes with return time of 5 years. The criteria to choose which roofs to apply green roof technology, were the land use. Therefore, commercial and institutional uses with representative (big) areas have been chosen to apply some LID. Figure 5 shows the storm water immediately after the rainy event. It is possible to observe changes applying a LID in some lots (indicated by numbers 2 and 5, for instance).

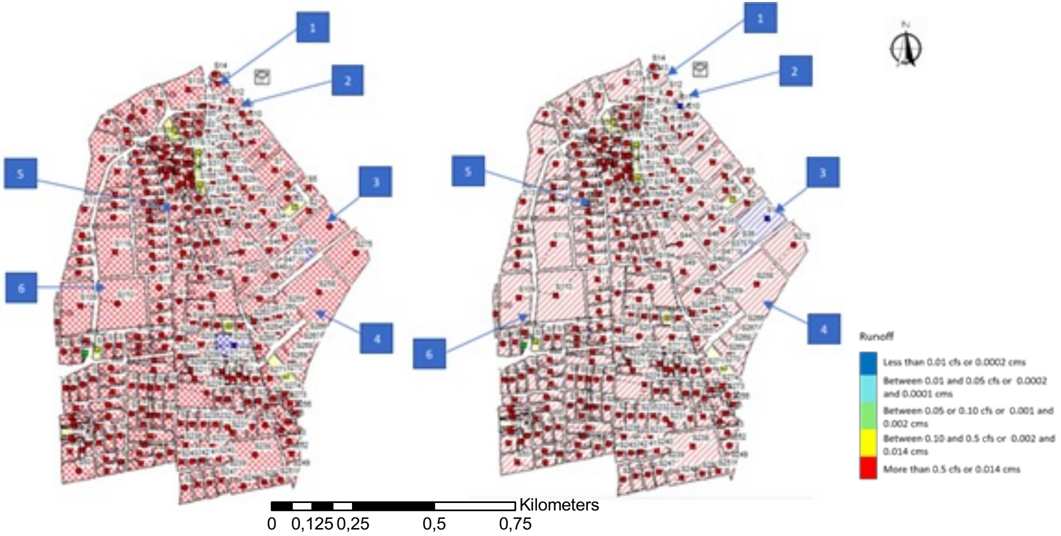


**Figure 5:** Stormwater simulation immediately after the rainy event (a) without LID; (b) with LID

Towards a better review of the implementation of LID on the legal scenario, another analysis was made and corroborates that, in some specific cases, LID techniques application can improve the present runoff scenarios. Then, Figure 6a shows the sub catchments 30 minutes after the rain ends, without LID implementation. In contrast, Figure 6b shows a scenario with LID implementation, with a better recovery of the sub catchments, 30 minutes after rain, where the compensatory measure was applied. The Table 1 shows the results of the application of LID for the specific roofs (lots), and a percent rate for the stormwater volume. All of the lots had the flow volume decreased after the implementation of compensatory measure. Some sub-catchments had more volume decreased right after rain ends than after 30 minutes of recovery, this fact is a good response to the application of LID as mitigation technique for natural hazard impacts immediately after the rain event.

Table 2 shows data used as input parameters for the simulations. In this simulation, the input is a real situation. Every sub-catchments with red colors indicates areas with high probability of flooding with 5 year return time rainfall. The colors are the model indication of areas with more necessity of actions. LID techniques implementation were tested to focus on elaboration of specific guidelines for land use policy makers. Climate change scenarios as precipitation changes also are used as input, in an integrated spatial and dynamic analysis of water resources. Different return time are being tested too in order to achieve short and long-term urban planning ranges and ensure greater longevity to drainage systems.

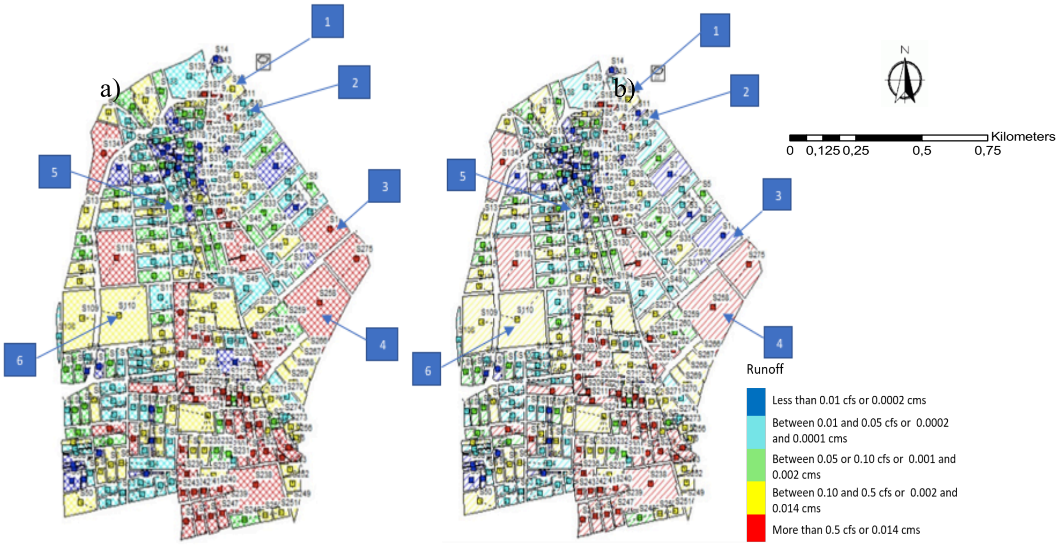


**Figure 6:** Stormwater simulation 30 minutes after the rainy event (a) without LID; (b)with LID.

| SUB-CATCHMENTS (lots) | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | Range (%) | 2 | Range (%) | 3 | Range (%) | 4 | Range (%) | 5 | Range (%) | 6 | Range (%) |
| Immediately after rain (cfs) | 5.80 | 30,5 | 2.61 | 100 | 16.79 | 100 | 12.10 | 16 | 11.07 | 8,6 | 2.47 | 50 |
| Immediately after rain with LID (cfs) | 4.03 | | 0.00 | | 0.00 | | 10.15 | | 10.12 | | 1.25 | |
| 30 minutes after rain (cfs) | 0.45 | 29 | 0.03 | 100 | 0.86 | 100 | 1.21 | 18 | 0.21 | 9,5 | 0.06 | 50 |
| 30 minutes after rain with LID (cfs) | 0.32 | | 0.00 | | 0.00 | | 0.99 | | 0.19 | | 0.03 | |

**Table 1:** Values of storm water volume for some lots (sub-catchments)

| PARAMETERS FOR LID IMPLEMENTATION – GREEN ROOF | | | | | | | |
|---|---|---|---|---|---|---|---|
| Surface | Height (mm)<br>15 | Vegetation Volume Fraction<br>0.11 | | Surface Roughness<br>0.15 | Surface Slope (%)<br>2.5 | | |
| Soil | Thickness (mm)<br>15 | Porosity<br>0.453 | Field Capacity<br>0.19 | Wilting Point<br>0.085 | Conductivity (mm/h)<br>0.43 | Conductivity Slope<br>10 | Suction Head (mm)<br>4.33 |
| Drainage | Thickness (mm)<br>3 | | | Void Fraction<br>0.6 | | Roughness<br>0.1 | |

**Table 2:** Input parameters

# 4 Further developments and acknowledgements

Ongoing simulations must show better trends and possible warnings for the study case. All results are tabulated to support guidelines for land use and occupation laws and regulations as Master Plans or other regulatory instruments, making possible a future adaptation upon possible changes. The methodology can be applied in other urban areas depending on available data. This work has been funded by CNPq (313323/2017-8), MCT/CNPq/UNIVERSAL (454350/2014-7), Coordination of Improvements of Higher Personal Level - CAPES (88881.129673/2016-01) support by INCT – Climate Change (National Institute of Technology and Science).

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