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# Implication of Urban Occupation Patterns in the Natural Infiltration

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# Implication of Urban Occupation Patterns in the Natural Infiltration

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## Abstract

The article aims to contribute to the study of urban form and hydrological impacts relations, especially with regard to a recharge of the aquifers. The focus on the natural water infiltration and recharge of aquifers is due to the similarities between the characteristics of the physical environment conducive to aquifer recharge and urbanization, which lead to urban occupation of recharge areas. To address the proposed objective, the study developed a methodological framework that relates elements of the urban form, intervening factors of urban infiltration and water sensitive urban design guidelines. To accomplish this, recent literature were reviewed in urban drainage, water-sensitive urbanism and urban morphology, seeking to organize and identify the links between them. The intervening factors of natural infiltration found in the literature were: (i) Sealing of the soil; (ii) soil compaction; and (iii) reduction of tree cover. The urban morphological elements related to these factors were: (i) streets; (ii) public spaces; and (iii) lots. The analysis characteristics of each of these morphological elements were identified from the revised intervening factors and urban design guidelines. The use of the framework for the analysis of the Lago Paranoá Basin in the DF – Distrito Federal, Brazil, demonstrated the validity of the identified analysis criteria for the study of the urban form hydrological impact. In addition, it confirmed the premise of the study that more details about the urban occupation form are needed, besides the percentage of impervious surfaces, for the evaluation and planning of water sensitive cities.

Keywords: intervening factors of natural infiltration, water sensitive urban design, aquifer recharge areas and urban morphology

## Introduction

It is established in the scientific knowledge that conventional urbanization interferes with the hydrological regime, leading to a reduction in the quantity and quality of water in urban environments. The challenge of dealing with these impacts is mainly due to the similarities between the characteristics of the physical environment conducive to aquifer recharge and urbanization (SERAPHIM, 2018). These similarities make it difficult to avoid urban occupation in recharge areas, increasing the proportion of the impact on this ecosystem (SERAPHIM, 2018). This makes the implementation of urban occupation strategies of low impact to aquifer recharge necessary in urban areas. However, this task poses a great challenge due to the complexity and heterogeneity of urban patterns and hydrological form-impact linkage.

Historically, urban hydrological modeling has been done with a focus on designing drainage measures. For this, several models use the percentage of impermeable areas as the main urban characteristic considered to estimate surface runoff, for instance SWAT – Soil and Water Analysis Tool and SWMM – Storm Water Management Model. Although this measure may be sufficient for the management of urban drainage, in order to build water sensitive cities, we need instruments that relate the hydrological impacts of urban occupation with urban parameters and urban management instruments.

Since the mid 1980s, new approaches have sought to integrate urban land use and occupation with water management, providing a range of solutions to mitigate the negative impacts of urbanization on the hydrological regime, such as LID - Low Impact Development LID and WSUD - Water Sustainable Urban Design. The guidelines proposed by these approaches represent an important advance in the construction of water sensitive cities. However, its implementation still occurs punctually and incompletely, due to its complexity and uncertainties, demanding the development of techniques that reduce uncertainties and assist in decision making.

The study aims to contribute to this aspect by constructing a methodological framework that highlights the associations between: (i) the main factors leading to the loss of natural infiltration in cities; (ii) urbanization strategies that may mitigate the occurrence of these factors; and (iii) the configurational elements of the urban form that cover these strategies and can be used in the management of urban occupation. This framework and its causal links can help deepen the understanding of the link between urban form and hydrological impact and the greater involvement of urban planning in the quest for water sensitive cities.

For this, the study starts with a bibliographical review and systematization of factors and guidelines that influence urban natural infiltration. From this systematization we construct a methodological framework capable of assisting in a deeper evaluation and understanding of the relationship between the urban form and the hydrological impact. In a second moment, to verify it consistency, the methodological framework is implemented in the analysis of the urban occupation of the Lago Paranoá River Basin - Federal District, Brazil.

Urban soil manipulation factors with implications for natural infiltration

Natural infiltration is significantly reduced in urban areas due to factors affecting the maximum rate of water entering into the soil. From the recent literature review on the subject, three main factors of traditional urbanization have been identified: (i) sealing by impervious surfaces (SHUSTER et al., 2005; JACOBSON, 2011); (ii) soil compaction (PITT et al., 2003, 2009); and (iii) deforestation (AMARAL, 2015; HAMILTON; WADDINGTON, 1999; KAYS, 1980).

**Soil sealing by impervious surfaces** is perhaps the most visible impact of urbanization on soil permeability, consisting of buildings and areas paved with impermeable materials. When analyzing it impact, it is necessary to consider, besides its extension, other characteristics acquired in the urban structure and that affect the hydrological regime, as its intra-connection and its connection with near permeable areas. In this regard, Jacobson (2011) and Shuster et al. (2005) point out that areas directly connected to the drainage network must be separated of indirectly connected areas, such as roofs and sidewalks. Water that falls on directly connected impervious surfaces is quickly drained out of urban boundaries, diminishing the opportunity for infiltration, while water that falls on indirectly connected areas can run to vegetated areas and contribute to the natural infiltration.

Church et al. (1999) showed that the runoff coefficients vary greatly between areas with the same percentage of impervious surfaces and soil type, leading to the conclusion that there is no universal runoff coefficient that can be used to estimate the runoff rate considering only the total extension of impervious surfaces. At the same time, the specific characteristics of the impervious surfaces are difficult to be measured with precision and many have been the methodologies adopted for their quantification. For example, Lee and Heaney (2003) conducted a study on the impact of different methods of impervious surfaces estimation and classification, where the result shows a difference in the modeled peak flows of the order of 265% according to the methodology adopted.

**Urban soil compaction** also has a great impact on water natural infiltration. The initial development activities, such as the importation of soils and subsequent compaction and rupture of their structure during earthworks and foundations, are the main reasons for urban soil compaction (PITT et al., 2009). In traditional projects, which do not adopt techniques of minimum soil disturbance, most, if not all, lots area are disturbed and deforested to receive construction and exogenous vegetation (HINMAN, 2012).

The soil compaction significantly reduces the porosity of the first layers of the soil, leading to a decrease in permeability, which may even hamper plant root penetration (PITT et al., 2003, 2009). Studies have shown that urban soil compaction can reduce infiltration rate of sandy soils by an average of 6 and a half times. While, infiltration into clayey soils can be rapidly reduce by up to 11 times, approaching zero (PITT et al., 2003, 2009).

**The reduction of tree cover** also affects the infiltration rates of the soil. The plants roots, insects and microbes, dig, penetrate and join the soil particles in such a way that improve their structure and porosity (HINMAN, 2012). The micro and macro pores created by these structures improve the soil retention and infiltration capacity. This happens mainly with tree cover. They have deeper roots and are better able to alter the soil structure in large areas around them. While, the porosity created by the roots of most grass species is only superficial, not contributing to the same degree to improve soil structure (AMARAL, 2015).

Kays (1980), analyzed infiltration rates in a low-density residential basin, which had most of the native vegetation removed and replaced by lawns and with much of the soil disturbed during urbanization. The study shows that, although impervious surfaces cover only 27.1% of the soil, the infiltration rate in lawn areas was reduced by up to 30 times, in comparison to the remaining forest area with the same type of soil, reaching infiltration rates lower than 0.45 cm/h.

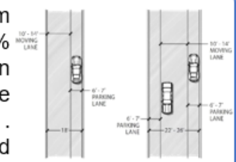
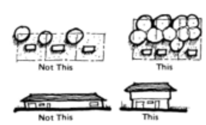
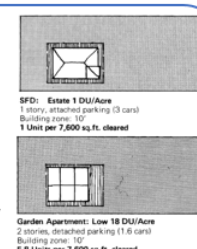
Another study by Kelling and Peterson (1974) sought to demonstrate that differences in infiltration between different grassland urban areas with the same soil type are mainly due to soil compaction. Out of this study (KELLING; PETERSON, 1974) one can conclude that not only areas with grasses naturally present lower infiltration rates, but that in urban areas these areas are usually associated to disturbed soils.

## Water-sensitive urban design guidelines and their connection to the factors that imply loss of natural infiltration

This section investigated the following manuals and directive documents in search of urban elements and parameters that most influence the maintenance of urban soil permeability: (i) Ian McHarg (1973); (ii) IHP - International Hydrological Program (ANDJELKOVIC, 2001); (iii) LID (HINMAN, 2012, PRINCE GEORGE COUNTY, 2000, EPA, 2000a); (iv) WSUD (MELBOURNE WATER, 2014); (v) and SuDS - Sustainable Drainage Systems (Ballard et al., 2015). The techniques, strategies and guidelines found were organized according to their utility to mitigate the 3 main factors identified in the previous section that lead to the loss of urban natural infiltration.

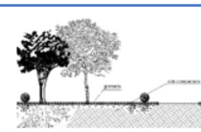
The guidelines of the manuals that apply to the **mitigation of the impact of urban impervious areas** can be grouped into 2 main strategies: (1) reduction of the total area of impermeable surfaces; and (2) disconnection of areas directly connected to the conventional drainage system. See the main guidelines in the table 1:

**Table 1 – Main guidelines for mitigation of urban impervious areas. Own authorship.**

| | Mitigation of the impacts of impervious areas | | |
|---|---|---|---|
| | **How** | **Implications** | **Example** |
| Reduction | Hybrid roads layout | The grid layout system can occupy an area up to 30% greater than curvilinear layouts (PRINCE GEORGES COUNTY, 2000). However, the grid layout promotes more mobility, while curvilinear systems are confusing and less connected. Thus, the integration of the two models is suggested (HINMAN, 2012). |  |
| Reduction | Reduction of roads sections | You can limit the number of park spaces, cul-de-sac size and low speed roads width. A reduction of 2m width can reduce the total impermeable area by 30% (HINMAN, 2012). This is important mainly in residential and services areas, since most roads are in this category and can have a low speed limit, E.g. . in USA it is estimated that 65 to 80% of the paved streets access residential areas (HINMAN, 2012). |  |
| Reduction | Smaller lots with smaller fronts | Grouped houses and lots with smaller fronts reduce the total area of streets, while larger lots lead to an increase in the total paved area required for each dwelling (HINMAN, 2012). |  |
| Reduction | Limit impervious surfaces within lots | Verticalization of constructions; reduction of frontal setback to minimize the length of access areas (MCHARG; SUTTON; SPIRN, 1973); and creation of shared garage entrances, limiting the access width. Studies show that the adoption of these strategies can increase the permeable area of a lot of 500m² up to 70% (PRINCE GEORGES COUNTY, 2000). |   |
| Reduction | Higher densities | The direct association between lower water impact and low densities is mistaken. The low-density areas have a larger number of impervious surfaces by residence, generating greater flow and less infiltration per person (EPA, 2000b). Thus, high-density sites have a lower impact on the hydrological regime in the regional scale. However, there is the caveat that, at the small-scale, larger areas of impermeable cover can increase problems in adjacent water bodies. |   |
| Disconnection | Disconnect streets from the drainage network | Elements such curbs should be lowered so that surface runoff flows to vegetated areas, with the potential of integrating sustainable drainage. In addition, roads side ditches can be replaced by vegetated infiltration ditches and semipermeable pavements can be used (HINMAN, 2012). |  |
| Disconnection | Direct runoff to vegetated areas | The impervious areas may still have their flow directed to vegetated zones with high permeability soils and sustainable drainage techniques can be introduced (ANDJELKOVIC, 2001). |  |

To **mitigate the impacts of compacted areas** the guidelines were grouped in two strategies: minimum soil disturbance and recovery of already compacted areas. See the main guidelines in the table 2:

**Table 2 – Main guidelines for mitigation of urban soil compaction. Own authorship.**

| | Mitigation of the impacts of compacted areas | | |
|---|---|---|---|
| | How | Implications | Example |
| Minimal disturbance | In lots | Avoid the need for earthwork by: limit the size of the construction site around the constructions; limiting the location of the construction next to the mandatory setbacks; preservation of natural topography runoff channels, orienting the largest axis of the buildings along the topographic contour (PRINCE GEORGES COUNTY, 2000); and adoption of low impact foundations that allow the native soil structure under the unit to continue to play a part of its hydrological function (HINMAN, 2012). |  |
| | In road systems | Curvilinear or hybrid roads layouts can facilitate the positioning of main streets aligned to topographic contour and avoid unnecessary ground disturbance (Andelkovic, 2001; Prince Georges County, 2000). |  |
| Recov. | Recovery of compacted soils | The implementation of lawns only allows a lower recovery of soil compaction (Andjelkovic, 2001). It is recommended to use medium and large vegetation, sustainable drainage techniques and soil composting. |  |

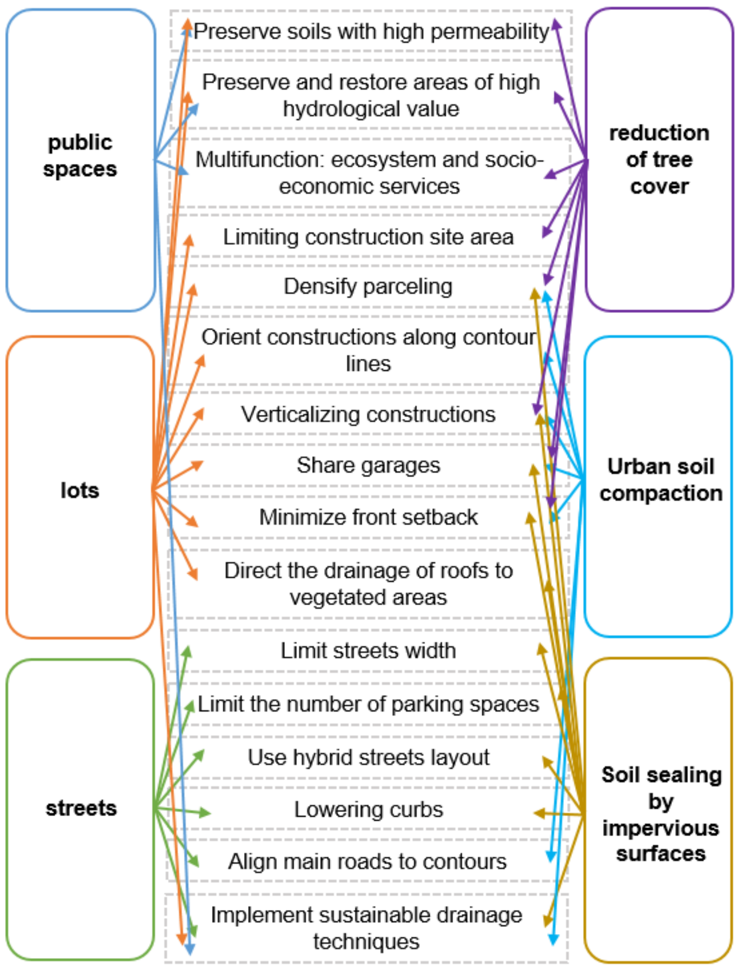
To **mitigate the impact of the reduction of tree cover**, it is important to prevent urban occupation and promote environmental recovery mainly in areas sensitive to the maintenance of hydrological functions: (i) water bodies and their buffer zones; (ii) natural wetlands; (iii) high permeability soils with high storage capacity; and (iv) natural drainage channels (HINMAN, 2012; PRINCE GEORGES COUNTY, 2000).
In this regard, urbanization should be prioritized in less permeable soils, preserving and using permeable soils for infiltration (PRINCE GEORGES COUNTY, 2000; MCHARG; SUTTON; SPIRN, 1973). However, public spaces, such as parks, recreation and leisure areas, which have greater potential to maintain large areas of vegetation, can be associated with areas of important hydrological function, and should be designed to integrate water management systems and spaces multifunctional systems with guaranteed performance of ecosystem functions.

<u>Methodological framework: relations between the urban form, intervening factors of infiltration and water-sensitive urban design guidelines</u>

This section will identify the morphological elements of the urban form capable of structuring the urban parameters relevant to an urbanization of lower hydrological impact. Lamas (2004) identifies eleven configurational elements that compose cities in general: (i) pavement; (ii) buildings; (iii) lots; (iv) blocks; (v) façades; (vi) public space; (vii) streets; (viii) squares; (ix) isolated monument; (x) vegetation; (xi) urban furniture. Panerai (2014) proposes an organization of these elements of the urban fabric in three groups: (i) public spaces, which involve public streets and public spaces; (ii) land parceling; and (iii) the buildings.

Among these sets of morphological elements, only those related to soil occupation are relevant for the analysis of potential infiltration, ie, public spaces and lots. Within the category of public spaces, it was decided to separate the streets from the public spaces. This is due to the importance of streets layout for urban water management. Given this, the sets of elements that will be used to construct the methodological framework are: (i) streets; (ii) public spaces; (iii) and lots. Strategies for water-sensitive urbanization and impact drivers factors revised permeate each of these elements, often relating to more than one of them at one time.

**Table 3 – Relations between elements of the urban form, intervening factors of infiltration and water-sensitive urban design guidelines. Own authorship.**




The combination of different characteristics of these three urban morphological elements can result in a multiplicity of urban typologies. In order to establish the characteristics that will be used as criteria to identify typologies that are more sensitive to the water cycle, it is important to know its relation with the phenomenon of urban infiltration opportunity based on the guidelines and factors studied in the previous sections. Factors indicate which parts of each element should be considered: (i) quantity and connection of impervious areas; (ii) signs of soil compaction; and (iii) amount of arboreal-shrub vegetation. In addition, the guidelines indicate how the soil occupation configuration of each of these elements influences one or more of these factors.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From this connection, it is possible to systematize the important characteristics to a more water sensitive urban design in each of the morphological elements and to identify better typologies, composed of a combination of characteristics of these elements, as a role. These criteria for assessing the soil occupation of each element are directly related to urban parameters, which can be used to evaluate existing urban typologies, to plan interventions, and for the planning, regulation and design of new areas. Table 4 presents the criteria identified for each of the elements:

**Table 4 – Methodological framework for evaluation and understanding of the relationship between the urban form and the hydrological impact. Own authorship.**

| Morphological elements | | Criteria for each morphological element | Criteria synthesis for the urban typology |
|---|---|---|---|
| Public | Streets | . % of area occupied in parceling<br>. % area occupied by parking spaces<br>. width of access and services roads<br>. area per inhabitant<br>. connection with conventional drainage network<br>. Type of layout | . % of impervious pavements<br>. impervious area per inhabitant<br>. % compacted soil<br>. % of area covered with arboreal-shrub vegetation |
| Public | Public Spaces | . % of area occupied in parceling<br>. % of impervious pavements<br>. % of area covered with arboreal-shrub vegetation<br>. association with environmental areas of high hydrological value | |
| Private | Lots | . % of area occupied in parceling<br>. lot size<br>. occupancy rate<br>. % of impervious pavements<br>. % of area covered with arboreal-shrub vegetation<br>. orientation of buildings along the topographic contour<br>. vertical replicability of buildings<br>. Setbacks<br>. impervious area per inhabitant<br>. area occupied by the garage and vehicle accesses<br>. connection with conventional drainage network | |

Analysis of the street element in a watershed in the Federal District, Brazil

The verification of the consistency of the built methodology and the research premises was based on the application of the methodological framework in the analysis of the Lago Paranoá Hydrographic Basin in DF, Brazil. The Lago Paranoá Basin was chosen because it is the most densely urbanized in DF (48.34%) and, simultaneously, 83.02% of its urbanized area is over recharge areas. In the study all the morphological elements were analyzed, however in this article will be presented only the results for the streets system due to space issues[1].

[1] For more information, see SERAPHIM, 2018.

Several methodologies can be used to evaluate the criteria identified in the methodological framework. The use of georeferenced cadastral data and image processing in GIS - georeferenced information system was chosen to analyze them in this study. In the first part of the analysis the urbanized area of the Lago Paranoá Basin was classified into five zones of similar constructive density: (1) very high, above 80% of impervious surfaces; (2) high, between 60 and 80%; (3) mean, between 40 and 60%; (4) low, between 20 and 40%; and (5) very low, below 20%. The identification of these similar urban typologies was based on a visual analysis of aerial photogrammetry images of 2016.

**Figure 1 – Distribution of the homogeneous constructive density in the Lago Paranoá Basin. Own authorship.**

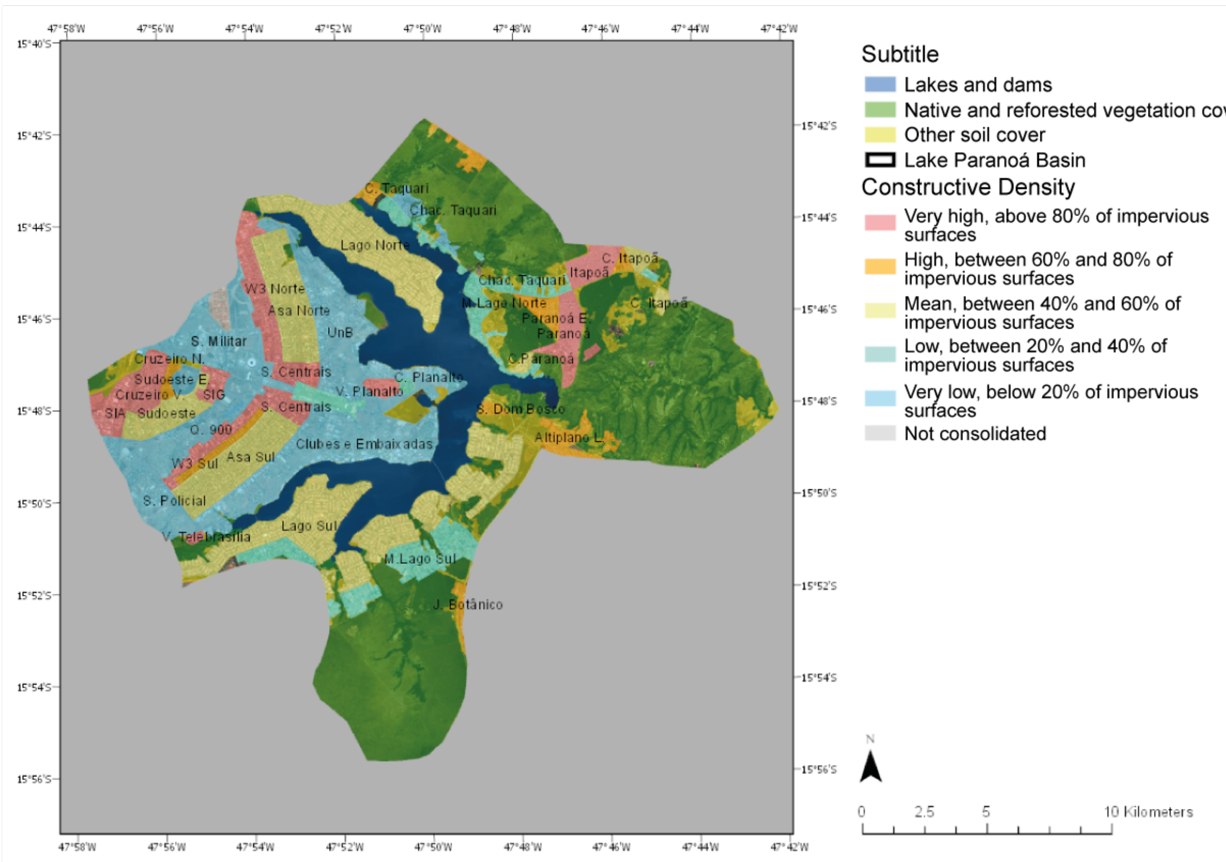

**Table 5 – list of the zones of homogeneous constructive density in the Lago Paranoá Basin. Own authorship.**

**(i) Zone 1**

| Q. 900 | S. Comerc., Banc., Autarq. e Hotel. | Cruzeiro Velho | Cruzeiro Novo |
|---|---|---|---|
|  |  |  |  |
| SIA e SIG: | V. Telebrasília, V. Planalto, Paranoá e Itapoã | | |
|  |  | | |

**(i) Zone 2**

| W3 Sul e Norte | Sudoeste econ. | Exp. Paranoá | J. Botânico, Altiplano L., S. Dom Bosco, Taquari e Itapoã |
|---|---|---|---|
|  |  |  |  |

**(i) Zone 3**

| Asa Sul e Norte | Sudoeste e Octogonal | Lago Sul e Norte | Cond. Itapoã e Paranoá |
|---|---|---|---|
|  |  |  |  |

**(i) Zone 4**

| M. Lago Sul e Norte | Chác. Taquari e Cond. Vila Planalto |
|---|---|
|  |  |

| **(i) Zone 5** | |
|---|---|
| Chácaras Taquari | Emb., Clubes, UnB, S. Policial e Militar, Esp. e Parques |
|  |  |

From this first screening 18 urban typologies were identified and had their road system analyzed according to the criteria of analysis previously listed, within the possibility of cadastral data and image processing. It was used the shape "streets" of the *Siturb - Sistema de Informações Territoriais e Urbanas* of the DF, which was transformed from line to polygon and later adjusted manually according to the aerial photogrammetry of 2016, by the authors. These areas include roads and parking spaces outside lots. Population data were also used for analysis, which were extracted from the 2010 Census to verify the number of street area per person. The comparative results of the analysis of the road characteristics within the same group of constructive density are presented in table 6.

**Table 6 – analysis of the street system in the Paranoá Basin Lake, according to the methodological framework developed. Own authorship.**

| Typology Name | Use | % of area occupied in parceling | width of access and services roads | area per inhabitant | connection with drainage network | Type of layout | Blocks |
|---|---|---|---|---|---|---|---|
| **Zone 1** | | | | | | | |
| Quadra 900 | mixed use | 18,20% | ~20m - 2 ways | 103,56 | yes | grid | big |
| S. Comerc., Banc., Autarq. e Hotel. | commercial | 33,55% | ~15m - 1 way | 792,55 | yes | grid | medium |
| Cruzeiro Novo | residential | 33,64% | ~20m - 2 ways | 23,89 | yes | grid | very small |
| Cruzeiro Velho | residential | 19,59% | ~6,5m - 2ways | 38,80 | yes | grid | small |
| V. Telebrasília e Planalto, Paranoá e Itapoã | residential | 17,64% | ~7m - 2 ways | 18,46 | yes | grid | small |
| SIG e SIA | industrial | 19,80% | ~30m - 2 ways | 278,51 | yes | grid | very big |
| **Zone 2** | | | | | | | |
| W3 Sul e Norte | mixed use | 17,65% | ~16m – 2 ways | 87,73 | yes | hybrid | medium |
| J. Botânico, Altiplano L., S. Dom Bosco, Taquari e Itapoã | residential | 11,97% | ~6,5m – 2 ways | 151,34 | yes | grid | medium |
| Expansão Paranoá | residential | 20,65% | ~17m – 2 ways | 2.279,27 | yes | grid | very small |
| Sudoeste Econômico | residential | 31,53% | ~15m – 2 ways | 39,68 | yes | hybrid | very small |
| **Zone 3** | | | | | | | |
| Asa Sul e Norte | residential | 24,16% | ~12m – 2 ways | 29,70 | yes | hybrid | small |
| Condomínios Itapoã e Paranoá | residential | 10,41% | ~9m – 2 ways | 139,54 | yes | grid | big |
| Lago Sul e Lago Norte | residential | 9,05% | ~10m – 2 ways | 101,02 | yes | curvilinear | big |
| Sudoeste e Octogonal | residential | 21,85% | ~10m – 2 ways | 25,22 | yes | hybrid | small |
| **Zone 4** | | | | | | | |
| Chácaras Taquari e Condominio Vila Planalto | rural | 6,16% | ~7m – 2 ways | 281,99 | no | curvilinear | big |
| Mansões Lago Sul e Norte | residential | 6,92% | ~10m – 2 ways | 295,83 | yes | curvilinear | very big |
| **Zone 5** | | | | | | | |
| Emb., Clubes, UnB, S. Policial e Militar, Esp. e Parques | institutional | 12,72% | ~7m – 2 ways | 964,02 | yes | grid | very big |
| Chácaras Taquari | rural | 4,95% | ~6m – 2 ways | 439,17 | no | curvilinear | very big |

The analysis confirmed the relevance of the characteristics studied in the total percentage occupied by the street element in the parceling. Given that in typologies with very similar constructive densities, the total area occupied by the street varied up to 2.5 times according to width of the access roads, street layout and size of the blocks. This confirms the importance of considering these characteristics in the hydrological impact when evaluating interventions in existing areas, proposing urban parameters for planning and management, and designing new areas.

## Conclusions

The main factors involved in the natural infiltration of water in urban areas were identified, namely: soil sealing; soil compaction and loss of tree-shrub cover. The systematization of these factors was relevant for the establishment of the first causal links between forms of land occupation and impacts on natural infiltration. As a result, we drawn a conclusion that in planning and designing urban areas, one should try to reduce the extension and connectivity of impermeable surfaces, reduce soil disturbance, recover compacted soil and increase the extent of urban forest. To complement this understanding, practical examples of water-sensitive urban design guidelines have been sought in manuals of the IHP, LID, WSUD and SuDs and organized according to their correlation with intervening factors of infiltration.

The identification of constituent elements of the morphological patterns allowed to constitute a methodological framework capable of assisting in the understanding and evaluation of the impacts of different urban typologies on the natural infiltration of water, namely: the road system; free public areas; and lots. For these elements, it was proposed criteria which can be used to evaluate existing areas, in new projects or translated into urban parameters and management tools.

The analysis carried out in the Lago Paranoá Basin, used to verify the methodology consistency, confirms the relevance for the hydrological impact of the characteristics proposed for the street element in the methodological framework. Also demonstrates the importance of redesigning this element, due to its preponderance in the urban area. It occupy up to 35 % of the parcels studied, which can represent more than 50% of the total impervious areas.

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