Geographical Visualization of Water Shortage Effect in Water Distribution Systems by Hydraulic Simulation Model

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The operation of Water Distribution Systems (WDS's) is one of the most important services in urban area; therefore, it is vital to maintain the service level in distribution (required pressure level in the system) for any possibly situation. The variation of weather conditions in sensitive areas produces water shortage because fluctuations in the volume of water in its storage system harm the regular operations of WDS. To tackle with the shortage risk, public understanding of the shortage problem and appraisal for maintenance and improvement work in the WDS. In this study we present a geographical visualization of water shortage problem through distribution of zones with pressure below the required level, helpful to enhance the public understanding of the problem. This visualization is based on the analysis of a hydraulic simulation model considering pressure driven demand. Case study in the WDS of the El Alto in Bolivia (South America) will prove the explanatory power based on the proposed method.

Key Words: *Water shortage, Water Distribution, Leakage, Water Demand, Hydraulic Simulation*

1. INTRODUCTION

Water distribution in urban area is considered one of the essential needs in everyday life and other activities. A uniform distribution of water required to meet in a balanced way, to all areas of the same form, it means, in space and productive social sector (domestic, industrial, commercial, etc.). This requirement and equitable distribution of water is not only subject to many conditions of external nature (climate, availability of water resources), but also on internal (system infrastructure, topography of the city, condition of water storage system, etc.). To tackle with the deterioration of external factors, internal factors must be maintained and improved. In order to get the public approve for such investment, public understanding should be enhanced through developing the explanatory tools for the public.

(1) Background

Recently the climate change has been affecting regions with sources of water, particularly climate sensitive reservoir systems, for example with glaciers as main water source. The availability of water in the storage system, limited by the wider variations in levels or heights in tanks and reservoirs over time, influences the amount of distributed water at each user. This is reflected in the gradual reduction of pressure in the distribution system. Another important factor is the rate of water loss generated in the distribution stage. Both factors determine the volume of water handled by the distribution system, which is made available to the population and satisfy the demand for their daily life activities.

(2) Water Shortage

When the reservoir system does not have enough volume of water, the actual water volume that people get becomes less than the expected demand: that is "*Water Shortage*". Both less availability of resources in the storage system and water loss in the distribution system cause the lowered pressure at the demand point and reduce the available water volume. The result is a non-uniform spatial distribution of water within the city which result in water scarcity in some areas and excess water in another[1].

(3) Scope and purpose of the research

The authorities responsible for storing and distributing water (private and government) have proven to be limited to show the problem, only using the total quantification of loss, consumption and volume of water stored. In order to raise the public awareness, visualize the problem of *water shortage* is promising, through modeling the distribution system and after that makes a geographical presentation. The purpose of this study is to generate a better understanding of the shortage problem in public.

2. FACTORS AND VARIABLES

(1) Water loss

Water loss in a WDS is a result of the characteristics of the network infrastructure such as, material, age, network point elevations, etc. Based on these characteristics, a point in the network may tend to produce different types of leaks and breaks generating additional volume that should be covered within the allocation of water from the sources and storage system, then efficient and effective water loss control should be recognized as a first priority for improving water supply process[2]. Monitoring water leakage in WDS has been studied extensively and it was concluded that in most cases, the leakage occurs at the connections to users recurrently specially for urban distribution systems.

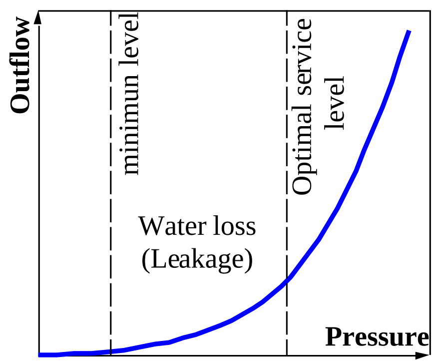

Fig. 1 Water loss and Pressure relation in a WDS

Some studies suggest that about 64% of the leaks were found to be at the property connections[3]. As a consequence, for practical analysis process, the allocation of leakage to consumption nodes has been a common practice for urban systems[4]. Considering the age of the system, the leakage rate was found to be linearly related to the age of the system pipe lines, and related to pressure raised to the 1.10 or 1.20 power[3] (Fig. 1). The water loss through leakage is assessed by using of equation (1) in which, l_k is the length of the pipe k, P_k is the pressure, β_k and α_k are coefficients to represent the characteristics given by the age of the pipe, building material, etc.

$$\mathrm{L}_k = \beta_k l_k (P_k)^{\alpha_k} \tag{1}$$

(2) Water availability

Water availability is a parameter that depends on the sources of water supply. The conditions of water availability of a storage system are dependent on rainy season, weather parameters such as temperature, which plays a key role in particular water sources such as glaciers, which alter the values of runoff getting into reservoirs temporally, product of a melting process. The equity of water distribution is expected to change in response to intern annual fluctuation in water supply[5], which affect the water volume in water storage systems. Usually WDS are driven by gravity because the high costs of a distribution system with pumping infrastructure. Localization of tools for energy dissipation in the storage system for water treatment and allocation of volumes to tank systems in urban centers creates a discontinuity in the direct effect that the availability of water exerts on the distribution to users, however the levels of tanks in the system are based on water availability and come into play when the distribution capacity of the system and the corresponding effect of water shortage throughout a city is evaluated.

(3) Water Demand

Water demand is a function of socio-economic factors, population, urban growth, and climatic parameters. All these variables play an important role to define the water demand in a certain area of a city. Quantification of demand is defined as an aggregate analysis, therefore when demand points are referred, it is related of requirements under a certain spatial unit with a defined population density. Ideally under an equal distribution in all areas, the demand can be satisfied in its entirety, but in reality the distribution systems have deficiencies in infrastructure and also it is subjected to the conditions of water storage and losses in the network, as a result the demand is not satisfied in some cases.

Many studies have shown that realized water consumption is a function of the level of pressure in delivery system, it means, when nodal pressure drops to a certain level known as the *desired*

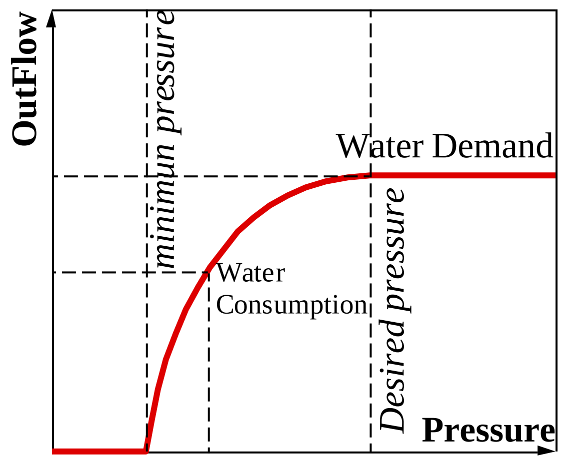

Fig. 2 Water Demand-Consumption and Pressure relationship

pressure $P_{service}$, demand can be only partially supplied, and when nodal pressure drops to a level termed the *minimum pressure* P_{min}, nodal demand outflow will be zero[6].

$$C_i = D_i \cdot R \tag{2}$$

$$\forall\, R = \begin{cases} 1 & if \quad P_i \geq P_{service} \\ f(P_i) & f[0-1] \end{cases} \tag{3}$$

Equation (2) represents the relationship between the demand D_i, and the realized consumption C_i, through service rate R, under the conditions of the equation (3) with a pressure at the point of i, P_i. $P_{service}$ defines a state of ideal pressure for service, and f (Pi) characterizes the limitation function of the pressures in the system and the following equation was analyzed by Wagner[7].

$$f(P_i) = \left(\frac{P_i - P_{min}}{P_{service} - P_{min}}\right)^{1/\varphi} \tag{4}$$

This relation has been assumed to be parabolic for many cities in previous studies ($\varphi=2$), therefore in the present analysis we assumed that also.

(4) Water Shortage Index

Water shortage is evaluated as a whole idea, because in a general balance can establish a simplified assessment of its impact and implement policies to maintain and improve service, however, when it is necessary to study areas with alarming population growth, and considering urban expansion without proper municipal control of urban land use, it becomes evident the need to assess the shortage from a distributed geographical point of view, in other to do that, we use the following factors:

$$N = \sum n_j \qquad (5)$$

$$\delta_{W\ shortage} = (1 - R_j) \qquad (6)$$

Where N represents the number of nodes under water shortage; while $\delta_{W\ shortage}$ is the rate of water shortage in the node of demand j.

A point is defined as a demand node under effect of water shortage if in equation (6), R becomes a function of the pressure of the system at the point of demand, or what is the same, R ranges between 0 and 1, we denote these nodes as n_j (Fig. 3).

3. METHODOLOGY

The methodology applied to the assessment of water shortage makes use of factors and variables previously explained, through a hydraulic model simulation which defines the behavior of the system against a certain demand level under the conditions of availability of water, the dynamics and the relationship between factors and variables is shown schematically in Fig. 4. The hydraulic simulation model is based on the equations (1), (2) and (3) for estimating water demands and water loss.

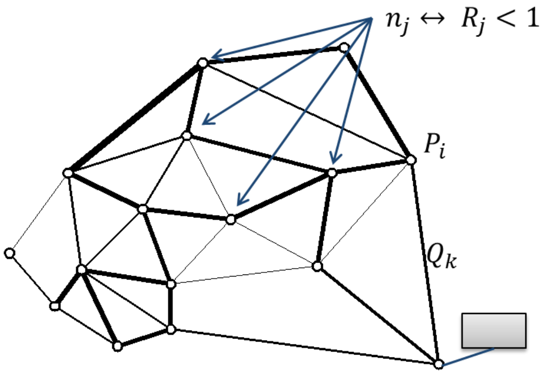

Fig. 3 Identification of demand nodes with water shortage

In data management for water distribution systems, the information available is water consumption and

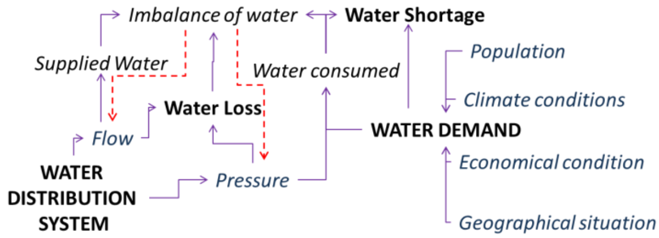

Fig. 4 Diagram of dynamics between factors and variables

water loss in the network, to estimate water demand; equation (2) can be used as a relation between two variables to estimate one in relation to the other.

The hydraulic simulation model used in this study is based on the equations of mass conservation law and energy conservation law throughout the matrix system, the representation of the formulation is shown in Fig. 5.

$$\boldsymbol{D}_{actual} = \boldsymbol{C}_{actual} + \boldsymbol{L}_{leak} \qquad (7)$$

Equation (7) represent the component water consumption and water loss in the hydraulic model, where D_{actual} represents the vector of consumption (2) plus the vector of water loss L_{leak} assigned to each node in the system using the following equation:

$$q_{l_i} = \frac{P_i}{2} \sum_k \beta_k l_k (P_k)^{\alpha_k - 1} \qquad P_k > 0 \qquad (8)$$

The matrix system is solve using Newton Raphson method, because of the nonlinearly equations involve in it. For more information about hydraulic model simulation see [9] in references

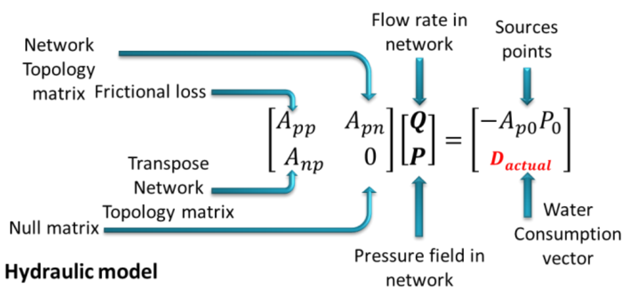

Fig. 5 Formulation of hydraulic distribution system model

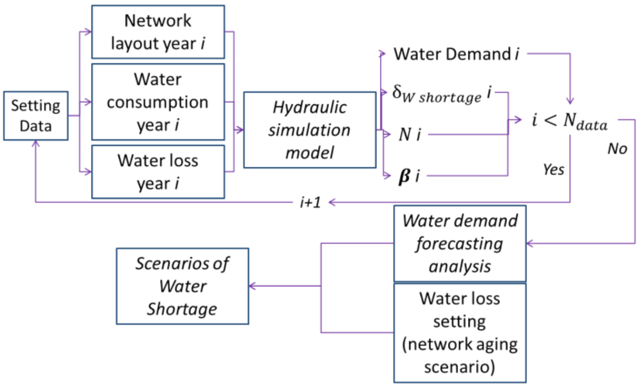

Fig. 6 Methodology for water shortage evaluation

All methodology detailed above is summarized in the scheme presented in Fig. 6.

4. CASE OF STUDY

(1) Target area

From cities with sources particularly sensitive to climate change, water resources, the city of El Alto in Bolivia (Fig. 7), is a city that has a set of glaciers (Tuni, Condoriri, Huayna Potosi glaciers) that are based source in its storage system.

Additionally, the city is characterized by one of the fastest population growth in the region, accompanied by an abrupt expansion of urban land leading to demand in the same rate of expansion for basic services such as the distribution system of drinking water and sewerage.

The assessment model of water shortage is applied on the two WDS from the city of El Alto (Systems assigned to provide the North and South of the city). The northern network has a

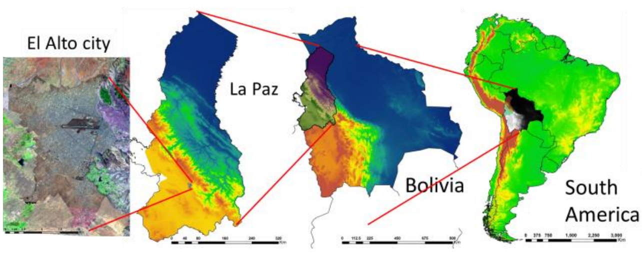

Fig. 7 Location of area for case of study – El Alto City

water source to the Tuni - Condoriri reservoir system, while the South System is supplied by a number of nearby wells located near at the South side of the city in this area. Both systems work in a connected way at certain point of service hours to satisfy the demand of the population, but since 2010 they have been working individually.

(2) WDS in El Alto City

The North System supplies water to a population of 1, 240,451 inhabitants in an area of 8.5 hectares, the system has an infrastructure consisting on 29,088 nodes and 32,503 pipes and a set of pressure reduction valves and tanks to regulate pressure around their network system. The South system provides 168.869 inhabitants in an area of 6.2 hectares with an infrastructure on pipelines 9,041 nodes and 10476 pipes with a set on pressure reduction valves and one source tank for the entire network (Fig. 8).

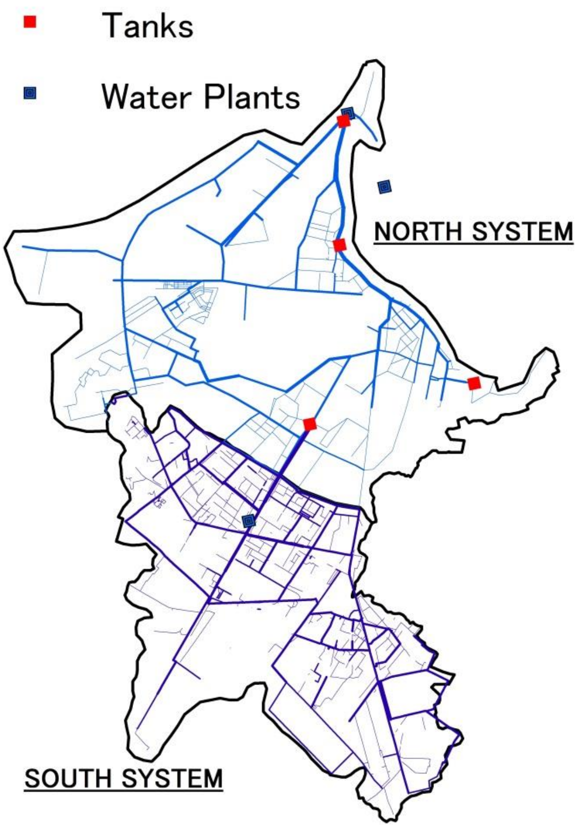

Fig. 8 Layout of two WDS for Analysis

The information of layout configuration of pipes, nodes and valves in 2009 was obtained from EPSAS. Leakage ratio of each pipe was assumed through equation (4).

(3) Future Condition Setting

Concerning the demand growth, the 2005 - 2009 trend was expanded and shows an increase over the next 20 years in demand of 146% in the southern system, and 54% in the northern system. This pattern can be validated by the fact that urban growth to the south of the city is due to greater access on inter-city route to the rest of the country and the consequent economic movement over these areas, not to mention the low cost of land, accompanied by a less restrictive altitudinal situation given at north of the city.

Another important factor in the south system is that accompanied the great growth of urban land is accompanied by the growth of the distribution system which has been assessed to be more representative than the system established in the north side of the city. Aging effect was also assumed in the calculation.

(4) Result

With the volumes of water demand estimated in the analysis during 2005 to 2009 and the water loss scenario characterized by the aging effect of the distribution system, it has been carried out a hydraulic simulation, then the rate of water shortage for all demand nodes was estimated, the corresponding interpolation of this information on the area around the city of El Alto is shown in fig. 9.

As a result, consumption is becoming a small fraction of demand rather than required amount to be equally under ideal conditions of distribution. The assessment of the number of points with water shortage can be visualized by the surface area of the areas under water shortage. In relation to the water loss, it has been found that the influence of pressure reduction is gradually decreasing the water loss in the WDS. The effect of the availability of water through varying levels and volumes of water stored in tanks in the system has shown a relatively low influence, which is significant, but is not comparable to the effect that other factors such as water loss and demand have on the rate of water shortage (0.06 of influence in relation to average 0.6 in regarding of loss and water demand).

Table 1 Number of demand nodes by level of water shortage rate in the interval of analysis

W. Shortage Index	2010	2015	2020	2025	2030
0 – 0.007	9842	9822	9747	9470	8725
0.007 – 0.019	2	2	17	35	87
0.019 – 0.0392	1	8	17	32	152
0.0392 – 0.066	5	3	20	43	127
0.066 – 0.105	5	8	15	59	166
0.105 – 0.231	2	9	24	151	316
0.231 – 0.36	2	4	10	47	149
0.36 – 1	1	4	10	23	138

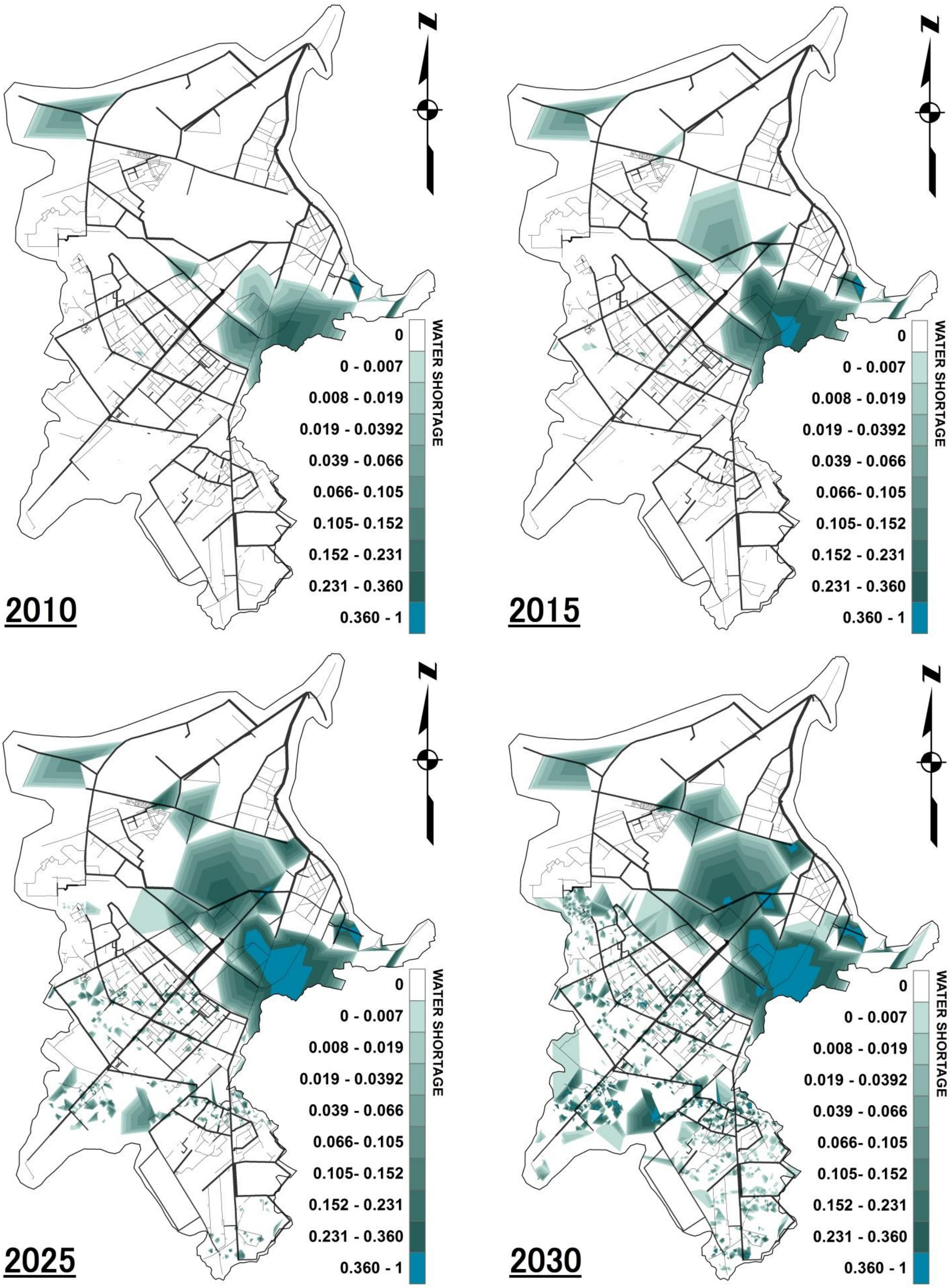

Fig. 9 Water shortage visualization in El Alto city – 2010-2030

5. CONCLUSIONS

We have developed a methodology to analyze water shortages through the hydraulic simulation of a water distribution system in a city. This methodology has been applied to two real systems with potential water supply problems in the future (North and South Systems in El Alto city). The results show a clear trend of increasing rate of water shortage in relation to demand projected in coming years (2010 – 2030) as seen in Fig. 9 and Table 1. We observed a trend of increasing water demand corresponded by the rapid expansion of urban land and the expansion of WDS.

The information of the distribution system of the city of El Alto is to be attributed the effect of reducing losses to rapidly increasing in water demand. A more detailed analysis of this topic should be approached from a more operational view of the system being monitored by a dynamic analysis which can use the results of this study as a starting reference, which can be applied to any system distribution having the characteristics mentioned up to this point.

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