LAND USE CHANGE DETECTION BY SATELLITE IMAGES AND ITS APPLICATION ON PIPE LINES AGE AND WATER LOSS ESTIMATION

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Abstract: Cities are complex systems and the understanding of relationship for their components is frequently required. The study about the factors which influence their evolution in terms of spatial development and densification process are very useful in order to support decision making issues, by municipal and governmental authorities. Studies in this category are required when it is necessary to consider the extent and equitable distribution of basic services. In the case of this study there is a specific attention in the distribution of drinking water in a city.

In the field of land use management, the use of satellite imagery is widely applied. The urban spatial pattern during time is easily visualized using satellite images. By capturing the changes in urban land use, additionally we can make a monitoring of changes in the corresponding water distribution system (WDS). The WDS can be classified by age and condition and thus identify areas with deficient physical situation and low service as a consequence, which leads to understand the distribution of water loss throughout the city and its implication in the WDS efficiency.

Key Words: *Satellite imagery classification, Water loss, Urban growth, Hydraulic simulation*

1. INTRODUCTION

There are several research conducted in the framework of the study about expansion of urban land and its implication in the exploitation of resources by the corresponding population mass. Scare water resources and effects on the environment, due to urban expansion are typical issue of urban centers with rapid population and economic growth, with increasing per capita demand in both developing and developed countries. There is a trend in many countries of the world to improve levels of efficiency to face a scenario of resource scarcity, increasing demand as the result of population growth. In a scenario of improving the efficiency of a system to ensure the rational and optimal use, quality and conditions of distribution infrastructure are a key factor to be addressed.

In the case of the infrastructure required to provide drinking water in a city, improvement the system efficiency is owing to the control of loss water, which is directly related with the age structure of the WDS (Water Distribution System) infrastructure. For cities with high population growth, the requirement of space by population is evident in the acquisition of larger area from the surrounding zones out of the city.

As a consequence of this expansion, a requirement of the current extent of the infrastructure for services are given, therefore expansion of both patterns are closely related. The extension of a distribution system gives us enough information for an analysis of both the spatial distribution of demand, and also the pressure exerted on infrastructure and the effect that expanded areas have on the system in global.

Information related to the infrastructure of a WDS is scarce, and in cases where there is no such information, it becomes very difficult to define the real causes of water loss rate which is a sensitive index to measure efficiency. One factor that determines the trend of renovation and new installation of pipes in a WDS is the expansion of urban land use. Information about monitoring urban land use is often more available and can be applied to estimate indirectly the characteristics (age of the pipes) in a WDS, (fig. 1)

The present study deal with the urban land expansion based on satellite image observations and applies the result in the characterization of infrastructure and corresponding extension of a WDS in a cities featured by rapid urban growth at the population level (water demand) and corresponding land usage.

(2) WDS's aging and Water Loss

WDS are infrastructure which is composed of a storage system (tanks, reservoirs, etc.), regulation system (valves, pumps, etc.) and distribution infrastructure. The distribution infrastructure consists of pipelines which are responsible to deliver water to different areas in the city to supply demand. The operating conditions, level of demand and the corresponding variation of land use in the city are the factors that influence the infrastructure of a WDS in time and space. The level of marginal urban land development is the addition of new water demand points and the corresponding supply through expansion of the system for this development. (Fig. 1)

The system response about water demands in different areas has direct implication in deterioration process of the pipelines within a WDS.

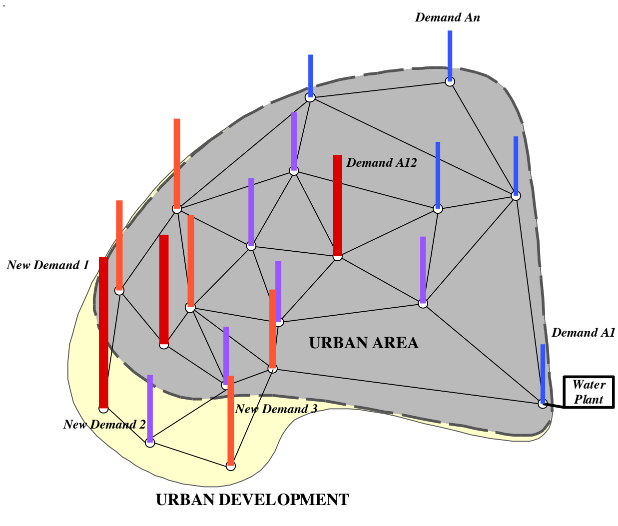

Fig. 1 Urban development and consequent new water demand points and infrastructure extension in WDS.

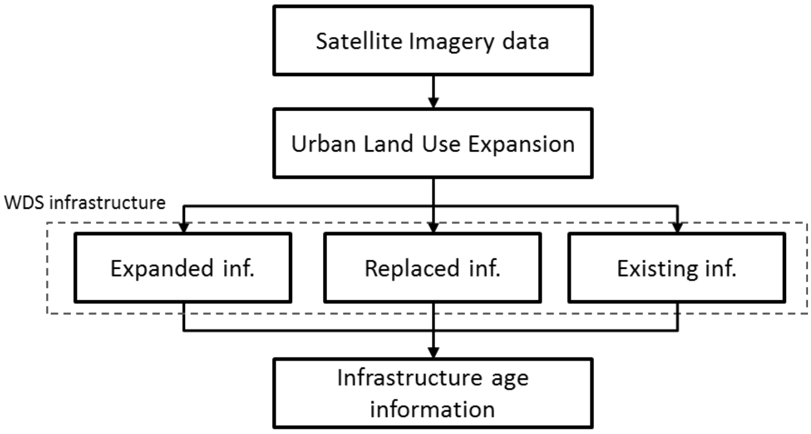

Fig. 2 Relation between Urban land expansion and WDS infrastructure

The infrastructure which is added to satisfy the expansion areas on the periphery of a city has a reducing effect on the rate of water loss from the WDS in general. Moreover the renewal of lines by excessive loss, by disruption caused by breaks in pipelines with different characteristics previously installed also reduces the rate of water loss. This dynamic between existing, renovated and newly installed infrastructure has an effect characterized by an aging process in the WDS.

When the efficiency in a WDS is analyzed in terms of water loss, it is necessary to know accurately its nature, in order to establish the factor that causes an increment or decrement. In terms of structural analysis, this is simplified to verify loss around the entire system, identify areas with critical losses and establish the common factor that generates them. Previous research has shown that WDS physical losses are a direct function of the age and the material of the pipes and elements of the WDS, and that age is given once we are able to classify the infrastructure in *expanded, replaced and existing* pipelines in time (fig. 2). Therefore the information related to the age of the pipes and their classes are key factors to identify the causes of losses in a WDS.

(3) Land use change detection and urban expansion influence in WDS infrastructure

In the field of monitoring urban land use changes, big progresses have been made to analyze the spatial distribution of a city during time. Studies in this category are required when it is necessary to consider the extent and equitable distribution of basic services

Herold M. et. al., (2003) applied aerial photography and IKONOS satellite imagery in order to assess the impact of urban development in Santa Barbara/Goleta region in USA, in response to topographical and mainly local planning policies as constraints. Satellite imagery data is available in large scale and types of ranges according to researcher's purpose, from those ones, Landsat Thematic Mapper (TM) images are widely used because of steps of collection interval and availability for historical dataset. Xiao J., et. al., (2004) uses TM data in order to evaluate urban expansion and land use changes in Shijiazhuang, China, in a temporal and spatial analysis based on information of 14 years land cover change.

The applicability of land use change in urban areas, specially the recognition of urban development allows us to understand the pattern of infrastructure requirement by population. One of the main problems in urban policy is related to proper allocation of infrastructure in order to operate under acceptable level of efficiency given the expansion of demanded areas and, in the case of WDS this seemly quit relevant for water loss rate development. Liu, J. et. al., (2013) use hydraulic simulation analysis in order to evaluate deficient water distribution as a response of pressure level in the system which is very sensitive to infrastructure configuration in space (expansion effect) and water demand level. In the case of this study we have specific attention to use Land Use Changes for WDS analysis in a city through water loss estimation.

(3) Scope and objectives

The main objective of this study is to define the characteristics of the water loss in a WDS, using the infrastructure age, classified through the use of satellite imagery data.

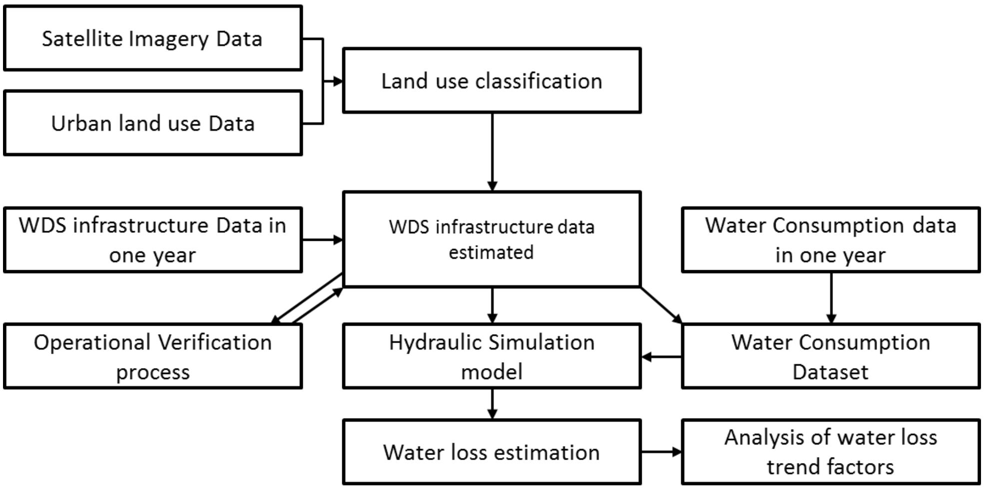

Fig. 3 Flow diagram for analysis process in Infrastructure data and Water loss estimation

It is assumed that the determining factors in the physical loss of water in the system are pipe material and age that the WDS possess.

The scenario in which the analysis is performed is defined in terms of the availability of infrastructure data. From this information, the infrastructure is classified in a retrospective process to define its characteristics in previous years and the corresponding size and degree of extension in relation of the year on available information.

The tool used for the classification process of the infrastructure is the expansion pattern of cities which can be estimated through the use of satellite imagery and its correspondent classification process for years in which infrastructure data is required.

2. FACTORS UNDER ANALYSIS

(1) Water Loss

Water loss in WDS is the product of several factors among which the infrastructure plays a fundamental role. From the physical point of view, factors such as material type, age of the structure, topography, etc., define the distribution of water loss. From the operational point of view, the water loss is a function of the pressure state of the system. The hydraulic analysis of a WDS has shown that areas with higher pressure have a greater loss of water, and having assessed that over 64% of these losses by physical leaks are located in the connections to private properties, whether residential, commercial, industrial or public, Abdullah, S. et. al., (2011)

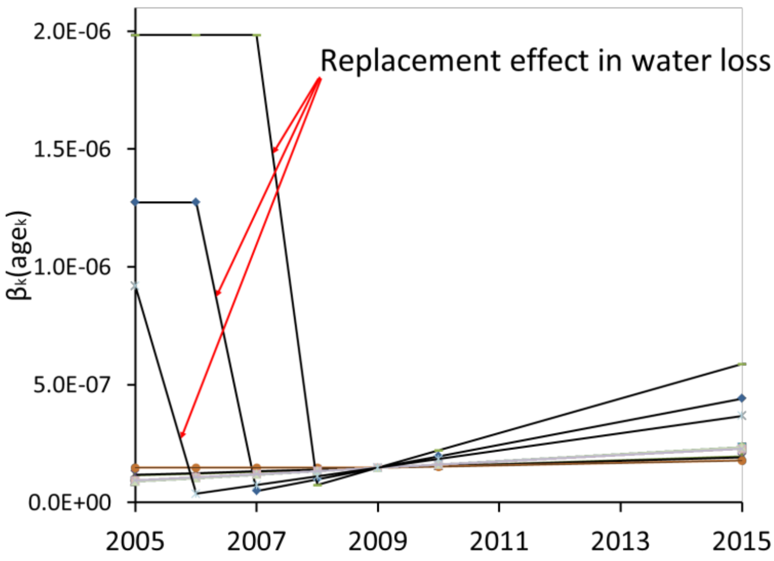

Fig. 4 aging effect in loss coefficient β

Considering the age of the system, the leakage rate or water loss 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, Abdullah, S. et. al., (2011)

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

$$\beta_k(Age_k) = \beta^{O}{}_k \cdot \frac{Age_k}{Utility_k} \tag{2}$$

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 of pipeline, Age_k is the age and $utility_k$ is the life of service which depend on the material for each pipe k, while $\alpha_k = 1.2$

The formulation explained above is expected to give the evaluation the natural effect on aging in the systems, which can be changed by maintenance procedure in time and implementation of new pipelines by urban expansion supply needs (fig.4).

(2) Infrastructure development in WDS

The spatial development of the infrastructure required to supply water demand of a city, follows the pattern of urban expansion in areas near to the periphery of the city. For this study we refer as "New pipelines" these kinds of pipes under the year we are analyzing development process. For example, if we start from the information available in a specific year i, and we want to know the extent of WDS in previous year's i-1, we use the information of urban expansion in order to classify, considering the year of installation.

If the extension related to the expansion in the year i has i year of installation, it is considered as infrastructure installed in year i (red solid line in Fig. 5), on the other hand if the infrastructure is into the urban area previously established, we consider this, as replaced in year *i* (red dashed lines in Figure 5.). The assignment of the year of installation for pipes replaced is considered equal to the year of the WDS's construction.

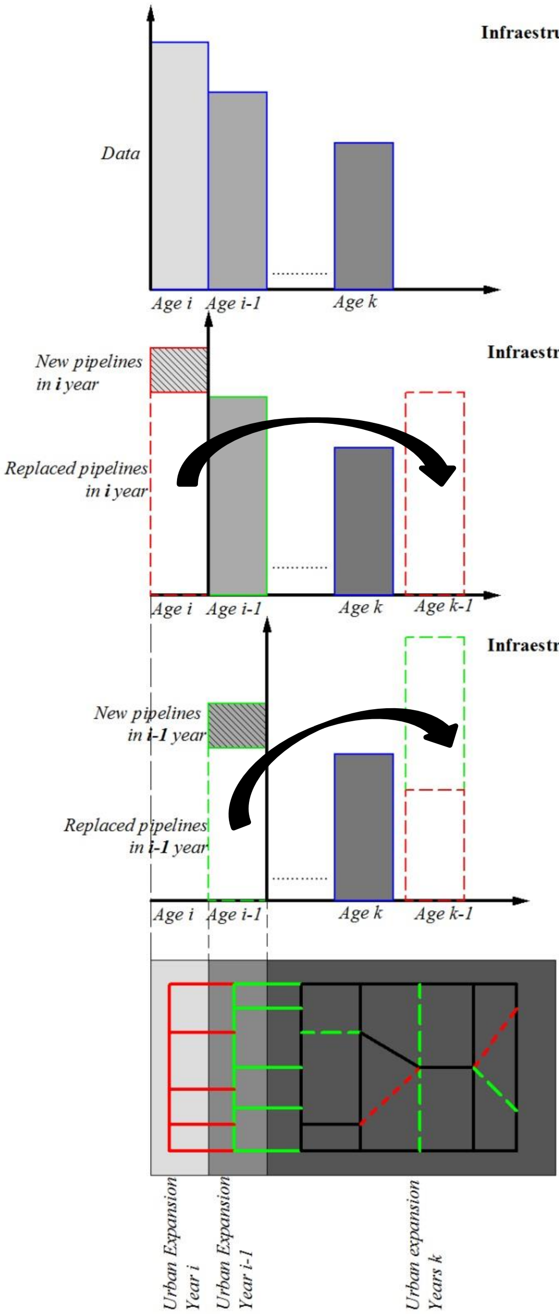

Fig. 5 Estimation process of age distribution of pipelines given infrastructure data in year ***i***

As can be seen, the classification process is in retrospective way, for years before the year in which information was obtained. The process is closely linked to the degree of confidence that the urban expansion change detection is characterized.

(3) Water Consumption

Water demand is linked to factors of population, economic, climatic region depending on growth conditions. The realized level of water demand, which is water consumption, is also influenced by the conditions of distribution in the WDS; this limits the potential consumption through state pressure in the system. Many studies have shown that water consumption is a function of the level of service in delivery system, it means, the configuration of system pressures, reason why, when nodal pressure drops to a certain level known as the *desired pressure* $P_{service}$, demand can be only partially realized, and when nodal pressure drops to a level termed the *minimum pressure* P_{min}, nodal demand outflow will be zero, Liu, J., et. al., (2013) formalized this relation as the change of service level in the system and corresponding consumption ratio.

$$\mathrm{C}_i = D_i \cdot R \tag{3}$$

$$\forall\, R = \begin{cases} 1 \quad if \quad P_i \geq P_{service} \\ f(\mathrm{P}_i) \qquad\quad f[0-1] \end{cases} \tag{4}$$

$$f(P_i) = \left(\frac{P_i - P_{min}}{P_{service} - P_{min}}\right)^{1/\varphi} \tag{5}$$

Equation (3) represents the relationship between the potential demand D_i, and realized consumption C_i, through service ratio R in a node i from WDS. This ratio is function of state of pressure in the system which is found using a hydraulic model around all the WDS in a simulation process.

3. CASE STUDY

(1) Area of study

The study has been applied to the city of El Alto, in Bolivia. This city is characterized by the rapid growth of urban land use, which puts a particular stress on its WDS. The water supply in the city is provided by two WDSs, located to distribute drinking water in the north and south areas of the city.

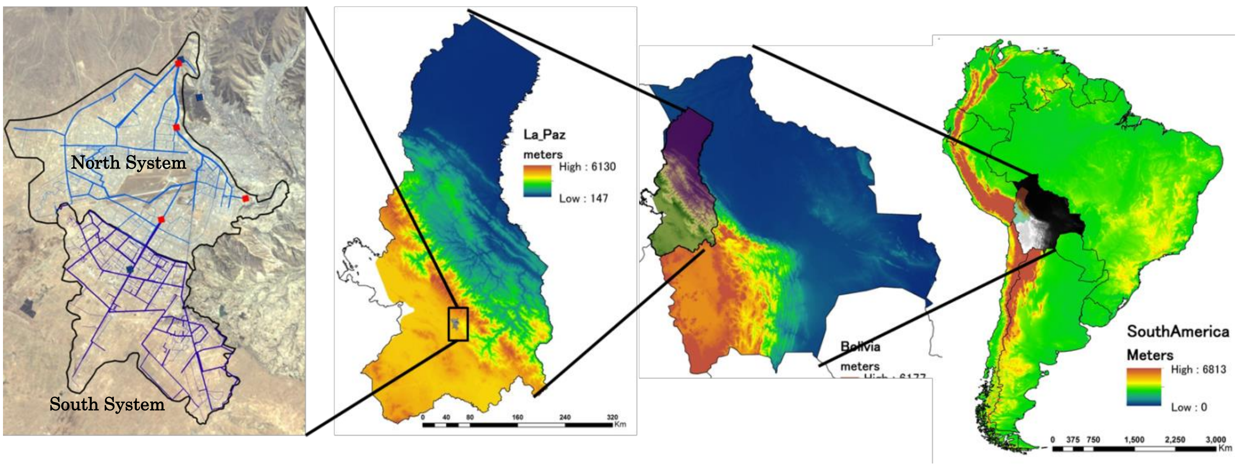

Fig. 6 Location of the Area of Study WDS of El Alto city, Bolivia

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 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 system (Fig. 6)

(2) Land use change detection

Water consumption data was available from 2005 to 2009, as consequence we focused the land use change detection analysis in that interval. Landsat 7 ETM+ data from El Alto City has been collected; however, data of 2007 and 2008 were not available, since that difficulty, we applied a land use transition model in order to interpolate the information in those years in which satellite data is not available. Following the classification process described in fig. 5, we could distinguish between expanded and replaced pipelines in each year within our interval of data consequently the WDS infrastructure and correspondent information about age were obtained for each year of analysis (fig. 7).

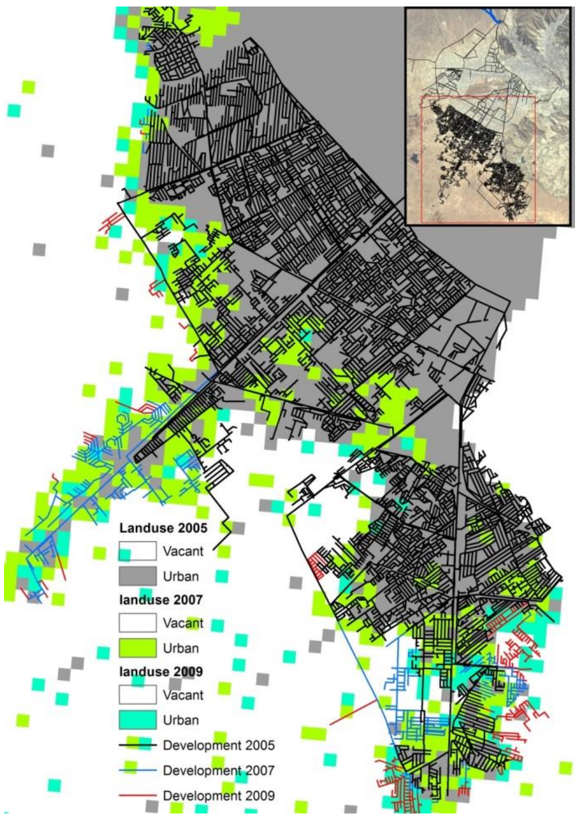

Fig. 7 Estimated Infrastructure size by yearly urban expansion (2005 – 2009), WDS (South system) in Alto city

(3) Infrastructure data and water loss estimation.

With the information about satellite imagery, water consumption data in 2005 – 2009 intervals and the information related to WDS infrastructure in 2010, the following steps were carrying out:

- We applied the TM satellite images using supervised classification method, maximum likelihood as in Murai S., et. al. (1996), for 5 years of analysis (from 2005 to 2009) except for 2007 and 2009. For these years a land use model was applied based on, Haque S. M., et. al. (2003).
- Expansion areas between years in study interval were recognized in order to analysis the urban expansion pattern.

- We performed a classification process based on the WDS data in El Alto city in 2010, following the steps outlined in Fig. 5

The classification process obtain WDS infrastructure in each year with the corresponding characterization about installed, replaced and operating pipelines. However for a subsequent use of these layouts of the WDS, it is performed a process of checking connectivity and hydraulic verification through a hydraulic simulation model which analysis is carrying out using equations (1) and (3) in a nonlinear matrix system to find discharges in each pipe and pressure in each demand node using the Newton-Raphson method as in Ayala et. al. (2014)

The result of the infrastructure data estimation process given the age is the data filtered as installed, replaced and operating pipelines. This information is applied to the hydraulic simulation model for estimating water loss once it was verified connectivity of the layout in each year of analysis. The actual water demand or consumption in the period of analysis has been obtained from historical records provided by the water company of the WDS in El Alto city

4. RESULTS

The classification of pipelines during the period 2005 - 2009 gives us important information when simulation of the WDS is carrying out for demands levels in these respective years (year of urban extension with the corresponding system expansion is detailed in Fig. 7). Following the estimation process described in fig. 4, the use of the classified information in hydraulic simulation allocates water loss in areas under pipes are older and pressure is higher. As a result we obtain the reduction of losses in periods in which the incorporation of new pipelines is higher and replacement ratio is low (fig. 8). An important characteristic of such behavior is that the simulation of water loss gives us evidence of the critical points where a replacement potentially will be required in advance, that may establish schedules based on priority areas, all of this in the space outside the periphery of the WDS (in areas established before 2005).

For areas in the periphery of the system, there is a widespread pattern throughout the simulation period. Because it is more distantly related to the water plant to supply zones, the pressure level in these locations is generally higher, leading to more concentrated lost. This phenomenon occurs in elements of the infrastructure which are within the area corresponding to the extension for current years and they have not been installed but remain operating since WDS construction stage or installation year near to this date, as a result, they have greater aging effect and consequent high water loss level. In the case of areas into the already settle down city, even water loss decreases in time, higher levels of loss spread year by year along on this places, which is also a consequence of aging on the infrastructure. (See corresponding schemes in Appendix).

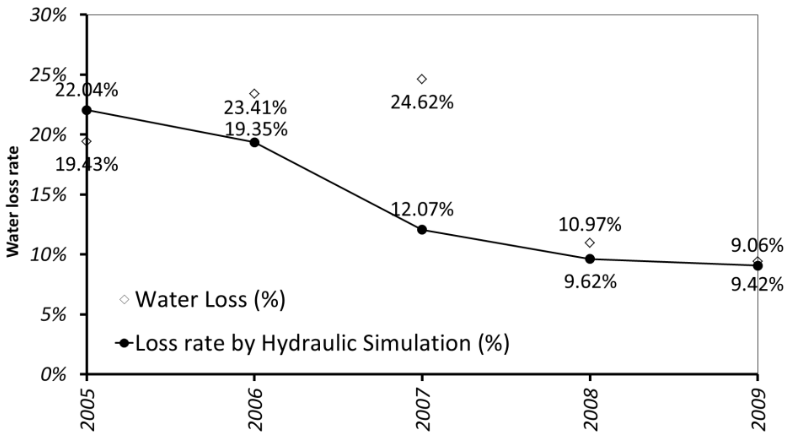

Fig. 8 Comparison of water loss ratio observed and estimated by Hydraulic Simulation Model in WDS (South system), El Alto city

Old pipelines in areas under critical pressure levels generate high water loss ranges, which reaches suggest that under ideal length, the periphery of the infrastructure should always be surrounded by recent or newly installed pipelines, to counter this phenomenon of potentiated loss.

The overall result of the classification and simulation of losses in the WDS has been compared with the records of water loss from the corresponding years, verifying simulation results with good fit near to the year in which the information is known (in this case 2009), this result is expected because of the estimation process conditions were generated synthetically and they are approximations of the actual condition the WDS infrastructure had at that time (fig. 8). However for planning purposes and verification of performance, the result shows good degree of fitness.

5. CONCLUSIONS

We have implemented a procedure of urban land use change detection to its corresponding application in the classification of the infrastructure of WDS. The results of such classification have been used to define the dynamic of WDS and its correspondent water loss over a period of 5 years of analysis. Important features related to the implementation of infrastructure replacements have been identified and differentiated.

One of the most important results in the classification, is related to the provision of new infrastructure or extensions, which, according to the results must be distributed continuously and must avoid including old pipelines in urban expansion areas, because of it is areas under high pressure levels, leading to a higher water loss levels in comparison with internal zones presented in the WDS.

As a particular characteristic of the WDS in the city of El Alto, we found that the major cause of the reduction over the years is the increase in demand which causes pressure drops in the system, due to low pressure, something that is not attributable to an improvement of the maintenance schedule, which can be corroborated by the classification made in this study which assumes replacement in areas with critical levels of losses, suggesting that the work of maintenance are carried out at the rate of infrastructure failures and not to previous maintenance planning for preserving the infrastructure service above optimal efficiency levels.

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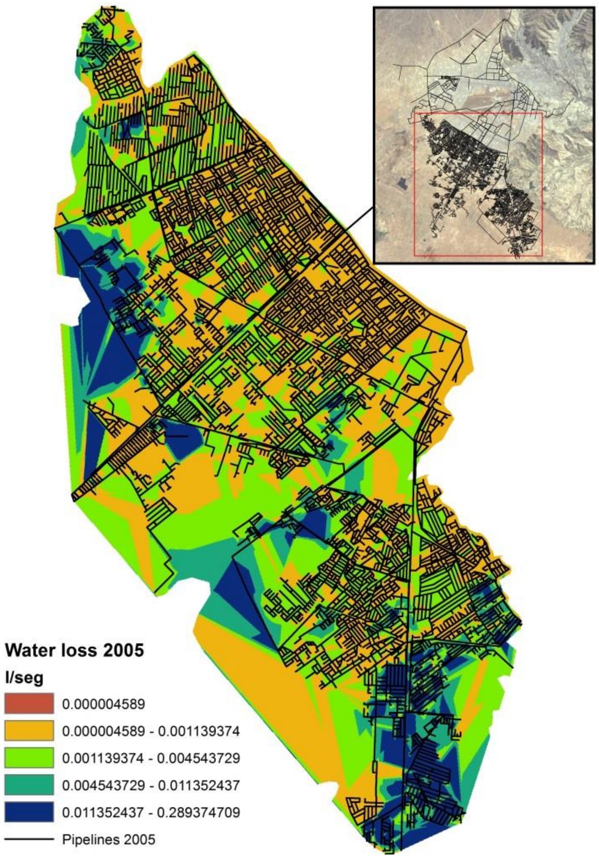
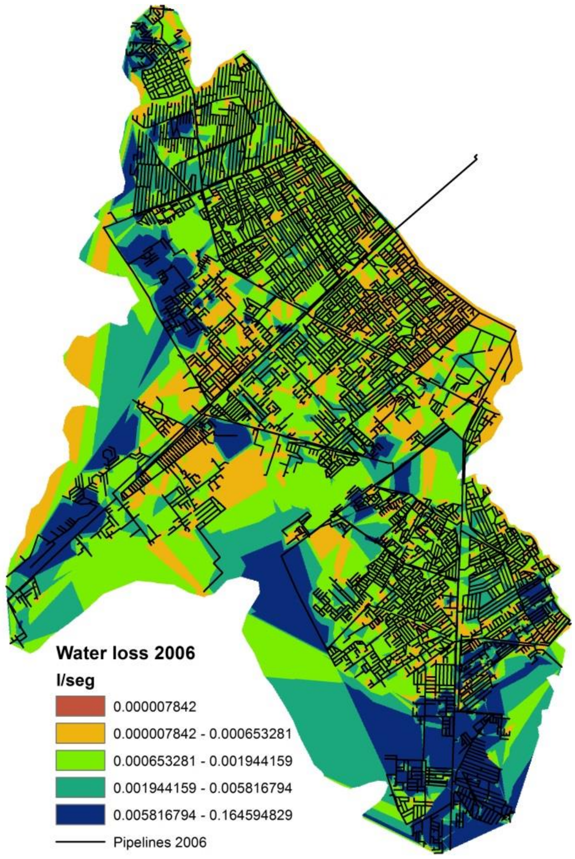
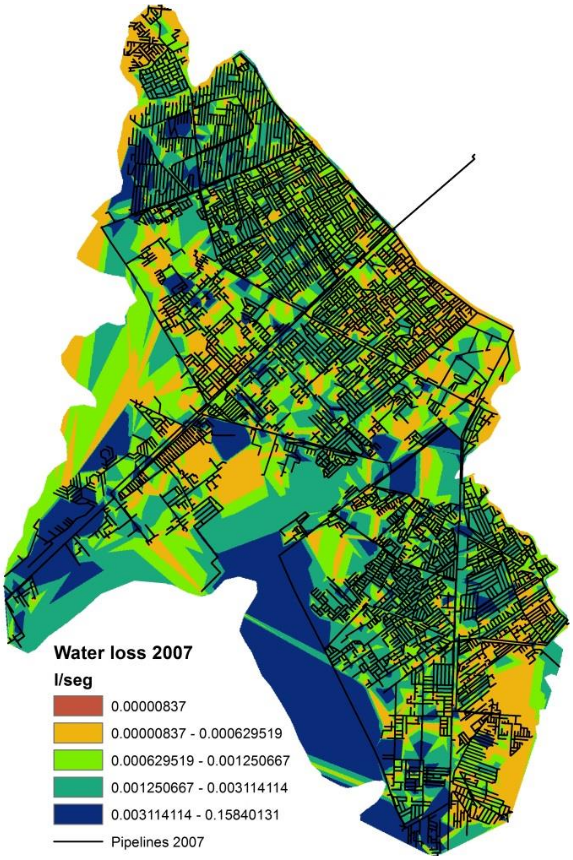
APPENDIX






Water loss 2007
l/seg
0.00000837
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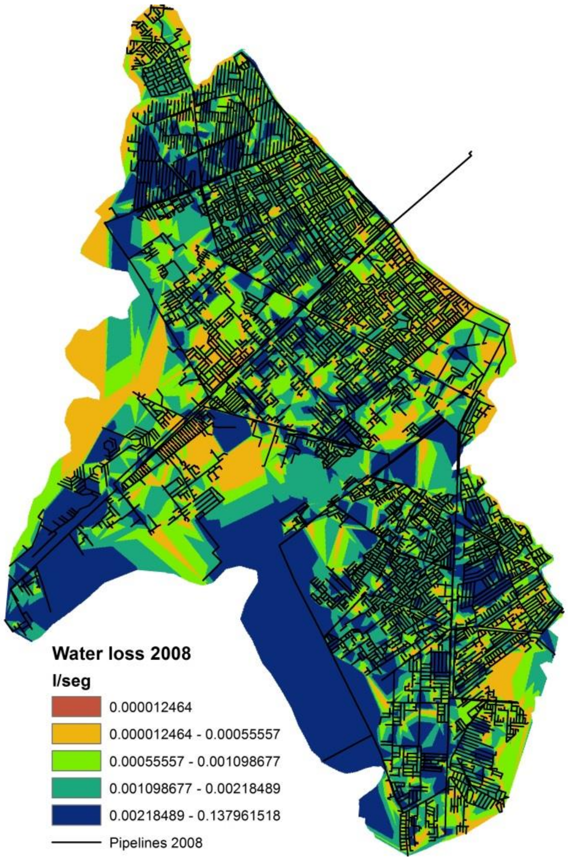
Pipelines 2007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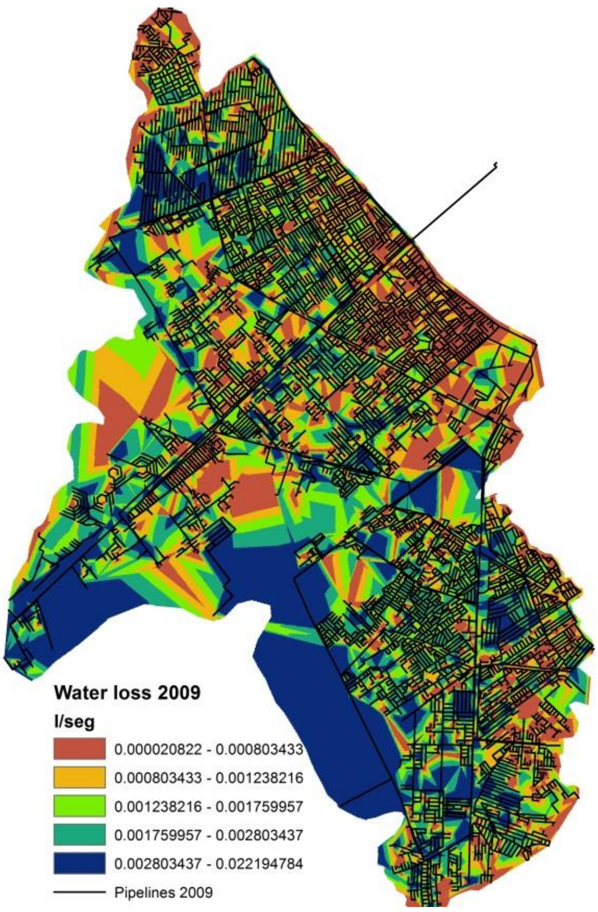
Pipelines 2008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0.002803437 - 0.022194784
Pipelines 2009

REFERENCES

1) Abdullah S., Al G.: Leakage – pressure relationship and leakage detection in intermittent water distribution systems, *Journal of Water Supply: Research and Technology – AQUA*, Vol. 60 No. 3, pp. 179-183, 2011

2) Ayala T., G.; Okumura, M.; Kim, J., Geographical Visualization of Water Shortage Effect in water Distribution System by Hydraulic Simulation Model, 49th *Annual conference of Infrastructure Planning and Management, Japan Society of Civil Engineers*, Vol. 49, 20 14.

3) Haque S. M. and Okumura M.: Simulation of land use changes for strategic urban management with a GIS based statistical model, *The 8th International Conference on Computers in Urban Planning and Urban Management,* CDROM, 9B-4, 2003.5.

4) Liu, J. and Yu G., Iterative Methodology of Pressure Dependent Demand based on EPANET for Pressure-Deficient Water Distribution analysis. *Journal of Water Resources Planning and Management* ASCE. Vol. 139, No. 1 pp. 34-44, 2013.

5) Martin H., Noah C. G., and Keith C. C.; The spatiotemporal for of urban growth: measurement, analysis and modeling. *Remote sensing of Environment*, Vol 86, pp. 286-302, 2003.

6) Murai S.: Remote Sensing Note, second ed. Nihon Printing Co. Ltd., Tokyo, pp. 220-221, 1996.

7) Tabesh, M.; Asadiyani, A. H. and Burrows, R., An integrated model to evaluate losses in water distribution systems, *Water Resources Management,* 23, pp. 477-492, 2009.

8) Wagner, J. M., Shamir, U., and Marks, D.H., Water distribution reliability: Simulation methods, *Journal of water resources planning and management*, Vol. 114 (3), pp. 276-294, 1988.

9) Xiao J., Shen Y., Ge J., Tateishi R., Tang C., Liang Y., and Huang Z.: Evaluating urban expansion and land use change in Shijiazhuang, China, by using GIS and remote sensing, Journal of Land scape and Urban Planning Vol. 75, pp. 69-80, 2006.