Water Demand and Supply Balance by Using Urban Spatial Development Model and System Dynamics

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Recently there has been increased tendency to pay attention in the impact of urban expansion in natural resources available to population requirement associated, in the particular case of water resources, as well not replaceable, the impact of the shortage is more critical. Many improvements in the field of water demand estimation have been considered, which are highly dependent on the criteria about the future population estimation in a city. In this study we face the evaluation of water demand through its relationship with urban expansion, which is observable through satellite information available nowadays. We estimate water demand using urban area considering proportionality to population growth and, balance water demand with water supply through a System Dynamics (SD)-based analysis. The study is applied to the El Alto city in Bolivia, for water supply from Tuni Condoriri reservoir system. In this case, the results show a correlation between urban expansion and population connected to the distribution system greater than 0.9, allowing us to apply it us explanatory variable for water demand. A forecast until 2050 shows that considering water loss as a variant factor in relation to infrastructure age, water demand is partially unsatisfied since specific point in time (2024) and considering current conditions of operation and losses there is no such us critical situation. Implication about maintenance policy and water demand growth rate are labeled as critical since those results.

Key Words: *Water demand Water supply, Urban expansion, Logit binomial model, SD model, Water loss*

1. INTRODUCTION

The water distribution systems (WDS's) in cities are currently subject to discussion. The great influence that these systems have on the daily lives of the population justifies paying attention to the conditions that they will offer in the future. The WDS are working under the influence of factors that are highly uncertain when our analysis approach is to future. On one hand the demand for water is based on the population, economic and social movement, in addition to climatic factors. On the other hand the supply of water is highly dependent on the topography of the area used as a water source (reservoir system) in addition to climatic factors as above. The point of view of analysis we perform determines the results we can offer, always within the framework of the provision of a scenario which is a function of the purpose of the analysis.

Considerations about the availability of information on general population data were limited due to the magnitude of the logistics of such a variable measurement, increases the degree of uncertainty about the estimation made using this information. In the particular case of water consumption in a city, there is a constant monitoring of the number of connections that the system has at each step of time. This monitoring is highly reliable and implicitly gives us a more reliable guideline about the actual population to which it is provided of water, hence the consideration of this variable has great advantages in terms of reliability.

A determining factor in cities with population under increase is the urban space development. This factor gives an indication of the trend of population growth and the corresponding increase in time. Monitoring urban expansion is relatively simple considering the satellite technology that is currently available and more accessible than population data in more continuous step time.

A spatial analysis of urban development must take into account factors that have an influence; these are economic in nature, location in relation to accessibility to public services such as hospitals, schools, commerce, etc. Another determining factor is the proximity of neighboring land uses which encourage the use of land in the same direction. In previous studies, all these features have been taken into account by using Discrete Choice Analysis; therefore we consider its application in our present study by the use of a logit binomial model to simulate urban development.

This analysis examines urban expansion parameters considering accessibility, neighborhood and suitability under comparison with land maps built by the use of satellite images (Landsat Thematic Mapper (TM)). The results are correlated with the change in population and water demand, to use in estimating water consumption versus water supply in future scenarios through the implementation of a system dynamics model, which is responsible for the relationships between variables and factors in the analysis for an overall balance in each step time.

(1) Background

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. Analysis of limited water resources and effects on the environment, due to urban expansion are characteristics of urban centers with rapid population and economic growth, with increasing per capita demand in both developing and developed countries. The scenario in which urban development is given defines government policies and appropriate planning of mitigation measures, both in terms of rational usage of water resources and the improvement of distribution systems in urban centers.

He Chunyang[5] use in an analysis of urban expansion in Beijing (China) using cellular automaton CA with a model of dynamic system (SD) for the assessment of demand scenarios corresponding urban land use implication in demand water resources.

The analysis of urban expansion can be applied in the field of regulation of economic activities influence by the land price and existence of certain land use conditions. Serneels[8] analyzed the effects and driving forces for the change of land use and the convergence of agricultural production areas related to the distance to the closest trade markets in urban centers in Kenya (Masai Mara Ecosystem International Park)

Haque S.M.[4] apply a statistical model based on geospatial variables and land price together with CA to simulate land use changes within a framework of strategic urban planning in the city of Hiroshima, Japan. Applicability of this kind of analysis is resilient to many areas for urban issues; in the case of this study we have specific attention to use Land Use Changes for WDS analysis in a city.

(2) Objectives and Scope

Based on previous framework, we decided to define our analysis based on the following objectives:

- Analyze the urban expansion patterns and forecast urban size taking into account jurisdictional land constraints.
- Estimate water consumption in future years with the help of urban expansion factors and consideration about population growth and per capita demand.
- Based on the results, and considering Water supply data define critical characteristics about water balance corresponding to a WDS in time.
- Set scenarios of infrastructure condition in order to define possible disruption in the system and availability of water in future years.

2. URBAN SPATIAL PATTERNS

The dynamics of urban spatial pattern depends on elements or factors that define the neighborhood in terms of proximity influence the suitability of a portion of urban land possess either land use. In that sense sorting using soil types is convenient if you want to evaluate and analyze behavior relationship and influence between them. As if our analysis is more focused on defining the overall pattern of urban space, has conducted an analysis of the relevance of each land use present and has been found useful to make a generalization or not depending on the results such analysis.

(1) Land use types in cities

According to land use, water consumption varies in value for specific type of users. If we consider the different types of land use in a city, the more representative are:

- Residential land
- Commercial land
- Industrial Land
- Public land

Macro analysis has to evaluate the relevance of differences and consider if we could aggregate them in order to make more feasible and simple analysis.

In case of total volume of water, the most relevant use is for residential (analysis from consumed water data showed that almost the 88% of total distributed water is assigned to residential use). Analysis of unitary per time levels of consumption shows industrial use spend more quantity, since the large amount of residential users is larger enough to any other use in consumers, we can consider in general, the water in a city as response to residential use, and many cases, factors which has effect on this user types can explain the whole water consumption itself.

(2) Spatial carrying Capacity

Municipal governments set their spatial jurisdiction in order to know the extension of services (in our case water distribution service) and policy regulation about land taxation.

Urban spatial patterns must to consider the feasible extension of urban land in each step time. However, this restriction is a product of policy implementation and not as a consequence of land users' natural behavior. Usually consumer under no land constraint tend to spread around land more influence by proximity to specific goods or services, which are provided by private companies or government, since that point, policy implementation makes effect on consumer and can be considered as a factor of influence in consumer behavior, since that analysis which take into account such us factors have implicitly the quality of setting policy makers as factor of the its results.

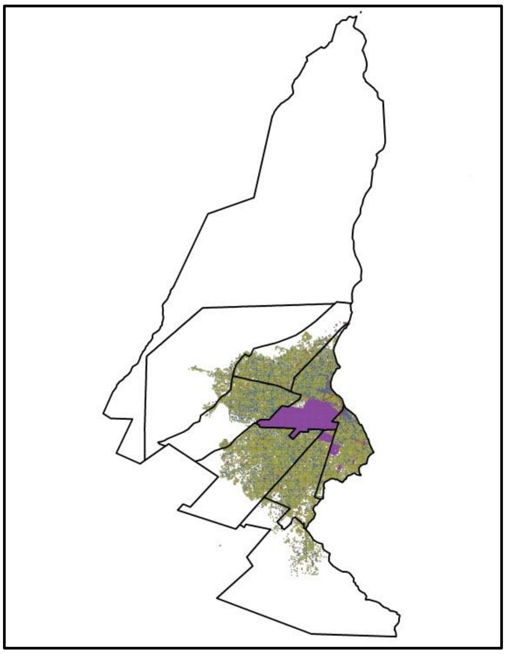

Fig.1 Urban development in yellow and municipal jurisdiction boundaries in black lines (source: ministry of land management – Bolivia)

3. WATER DEMAND AND OPERATION SETTINGS

(1) Per capita Water demand

Levels of socioeconomically status, water price, and climatic factors are the main explanatory variables for per capita water demand. All of them have a certain difficulty and uncertainty which leads to limit the knowing of water demand levels. In our case, urban expansion is also considered as a very good explanatory variable to estimate water demand at macro level (Fig. 2).

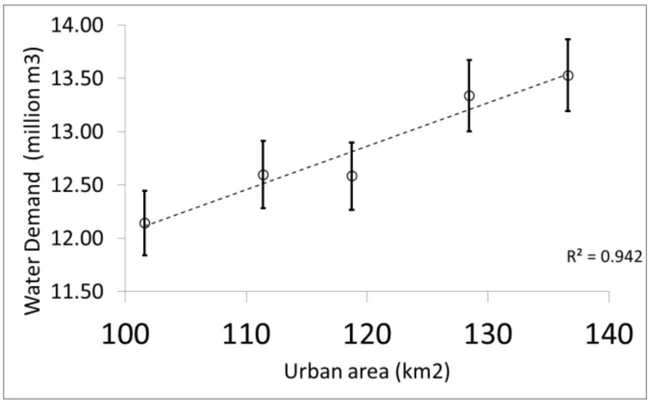

Fig.2 Correlation between urban land and water consumption data

In global balance we implicitly set per capita demand (as in the interval in which correlation analysis is carrying out) as constant especially, if we consider the oscillation in monthly or higher in daily data level around interval of analysis, due to spatial changes as general cause of water demand variation

(2) Population Growth

Population size is most important factor in order to know the global water requirement of a city; however, this value has much uncertainty for its estimation. Usually available information has an interval relatively large in the scale of analysis for resources evaluation issues. As a result of this limitation in availability of data the confidence and application of quantitative estimation based on population must to concern this kind of problems.

Alternatively, there is a clearly effective approach in terms of population, which is provided with drinking water by the WDS. Information on the number of connections and therefore the number of households is considered a priority because it is used in assessment of global production and utility balance month after month for the water distribution companies. The availability of this information is relatively easy to reach, not to mention the high reliability of it, why has greater degree of certainty than information given in the population census from the point of view of effective use of water. Interesting result of the comparison with data obtained for the present study shows a significant correlation between the number of connections to the WDS and the urban area (0.998 in fig. 3). With these characteristics, we can conclude that the urban area is a good indicator of the amount of effective population connected to WDS.

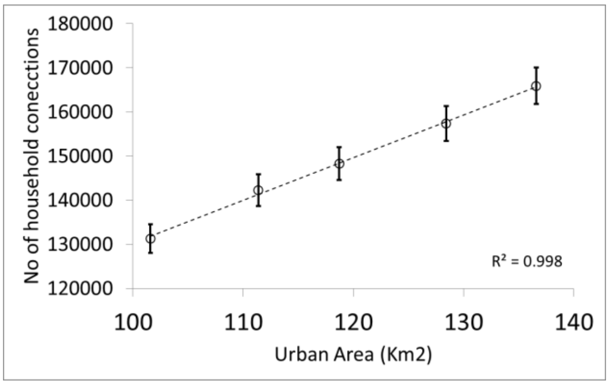

Fig.3 Correlation between urban land and number of household water connection

(3) Characteristic of Reservoir systems

The reservoirs are infrastructures to store water volumes for specific interval. We regulate the available water by setting the water level in reservoirs with its associate store volume. Information from topography analysis allows us to identify the potential of store in reservoir system (Fig. 4). Based on principle of conservation of mass and flow continuity, we can define volume in reservoir ($Volume_{Reservoir}$), if we know *outflow* (water required by city and excess water) and *inflow* (Runoff from source area or intake systems connected to reservoir) in time.

$$\frac{dVolume_{Reservoir}}{dt} = Volume_{Reservoir} + inflow - inflow \quad (1)$$

In expression (1), all of the components are implicit function of time, according to reservoir characteristics and can be solved numerically or deterministically according to the feasibility of solving equation (1).

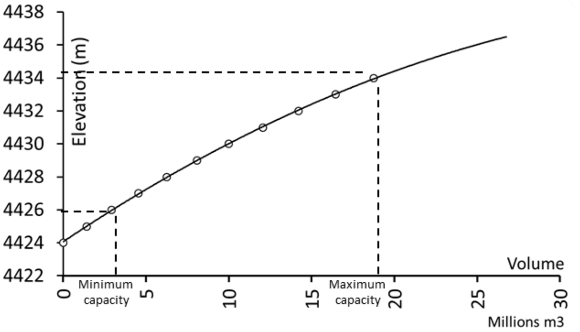

Fig.4 Reservoir capacity Vs Water level (Source: EPSAS, Bolivia, 2007)

4. MODEL

(1) Logit binomial Model for Urban expansion

The model for detecting changes in urban land should be as operational as possible, to give versatility and usefulness in a field in which policy intervention for land use management in a city have direct effect on the patterns obtained, this aspect is not far from reality, considering that the provision of infrastructure, services and prices are regulated by governmental institutions, and that these factors largely define the pattern of changes in urban land.

Land-user's expectations also depend on uncertain factors, such us financial, economic trends, etc., bid rent U_n^{Urban} for urban land use in location *n* is captured as average value V_n^{Urban} plus and statistically distributed error term ε_{nj}, Haque M. H.[4]

$$U_{nj} = V_{nj} + \varepsilon_{nj} \quad (2)$$

Due to the influence of unobservable factors represented by ε_{nj}, the problem cannot be solved deterministically; however we can estimate from the observable factors, the probability of a transition to use of urban land use occurs by the following expression:

$$P_n(urban) = Prob(U_n^{Urban} > U_n^{Vacant}) \quad (3)$$

If we assumed ε_{nj} as extreme value, and considering mutually independent and identically distributed under Gumbel Distribution, we have:

$$P_n = \frac{e^{V_n}}{1+e^{V_n}} \quad (4)$$

This is the Logit model for binary selection choice of land use. The bid rent function is defined in feasible set of parameter which can be visualized by satellite images and master plans documents for urban land cover restraints.

$$V_{nj} = \sum_1^m \beta_{A_{mj}} \cdot A_{mj} + \sum_1^o \beta_{S_{oj}} \cdot S_{oj} + \sum_1^p \beta_{N_{pj}} \cdot N_{pj} \quad (5)$$

Where A_{mj} ,S_{oj} and N_{pj} are accessibility, suitability and neighborhood factors respectively. Accessibility and neighborhood factors are generally inverse distance functions from respective location *n* to facilities and neighbor land uses *j*, while suitable factors are function of value in location about some specific suitable index (for instance, soil strength capacity for construction, level of slope of land in location *n*, etc.). Parameters $\beta_{A_{mj}}$, $\beta_{S_{oj}}$ and $\beta_{N_{pj}}$ are estimated using maximum likelihood algorithm using as observed data from land use maps for urban expansion in respectively transition points in time.

$$L(\beta) = \prod_n {P_n}^{y_n} \cdot (1 - P_n)^{1-y_n} \quad (6)$$

L(β) is the likelihood function of over all probability of urban transition n which must to maximize considering the observed data represented by y_n as binary variable. Previous analysis has proven that likelihood function in globally concave for linear in-parameters bid rent function (1).

$$\frac{\partial LL}{\partial \beta_i} = \sum_k x_i^k (y^k - p^k) \qquad (7)$$

$$\frac{\partial^2 LL}{\partial \beta_i \partial \beta_j} = \sum_k -x_i^k \cdot x_j^k \cdot P^k (1 - P^k) \qquad (8)$$

Equation (7) and (8) are the gradient and the hessian of log likelihood function which can be used to find parameters using Newton Raphson Method (NR) given the characteristics of likely and as consequence of log likelihood functions.

(2) Water balance using system dynamics model (SD)

The results of urban expansion give urban area in time with the correspondent spatial distribution of it.

As we showed in section 3, urban expansion is intimately linked to effective population supplied by the WDS. Since that, water demand can be estimated using urban expansion instead of population and considering that the per capita demand is constant given that usual yearly balance can omit the oscillation produced by monthly and daily data.

Urban expansion model give us urban area, and consequently *water demand* (see fig. 2), water demand can be evaluate in terms of *distributed water* and correspondent *water loss* using a hydraulic simulation (solved by NR as in Ayala T.[1]) to represent the WDS dynamics in each step time. Additionally losses in main line and water plant can be added in order to find *total required water*. The dynamic of balance between *water available* in store system and *total required water* is settling by reservoir dynamics which leads to make balance giving us the current *supplied water* in the system as we show by the Dynamic System (SD) diagram in fig. 5.

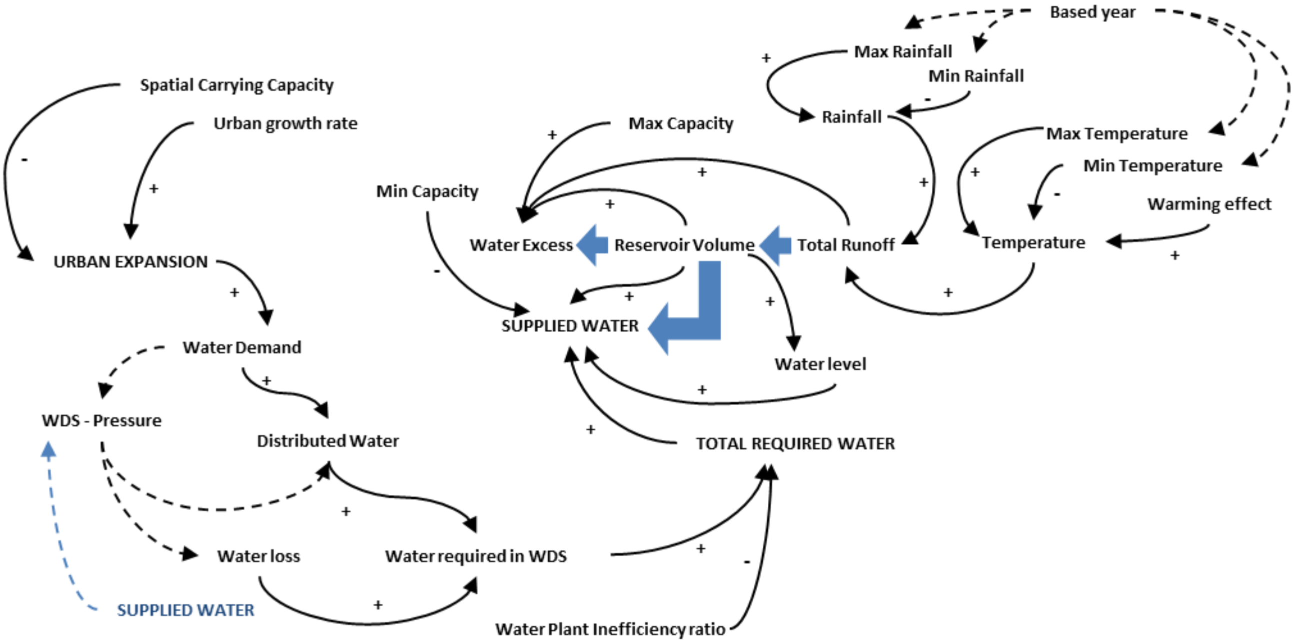

Fig.5 SD diagram for system quantitative balance of Water demand and Water supply

In the case of this study we pay attention in the evaluation and implication of urban expansion and water demand evaluation, since that we have not implemented a hydrological model in order to evaluate total runoff. Instead, we found that runoff from historical data is very good explained using climatic data directly in a multiple linear function rather than physical based model (fig. 6).

The balance in the reservoir between *store volume*, *inflow* (Water excess and Supplied Water), *outflow* (Total runoff) is explained in section 3, part (a). The SD model allocates water supplied in the city according to water demand and water supply dynamics.

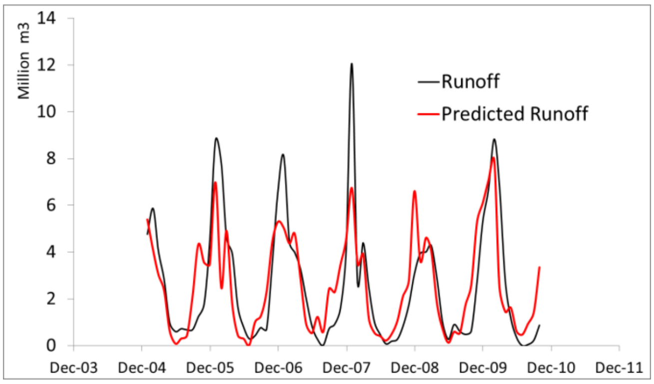

Fig.6 Multiple linear regression results for runoff estimation

5. METHODOLOGY

(1) Pooling data for Logit binomial model

If the unobserved factors which affect transition are independent over changes in times, Logit model can evaluate Panel Data in the same way as purely cross-sectional data in the called “Pooling Data” arrangement. This assumption is strong because we are considering not influence of previous year about land uses in future transition of land, which in many cases it is not true, however, and because of lack of information, we decided to implement such assumption here.

Data from land use changes is available in years in black color. Considering observed transition between one year of interval, 3 monitored transitions have been used as pooling data for calibration of urban spatial development model.

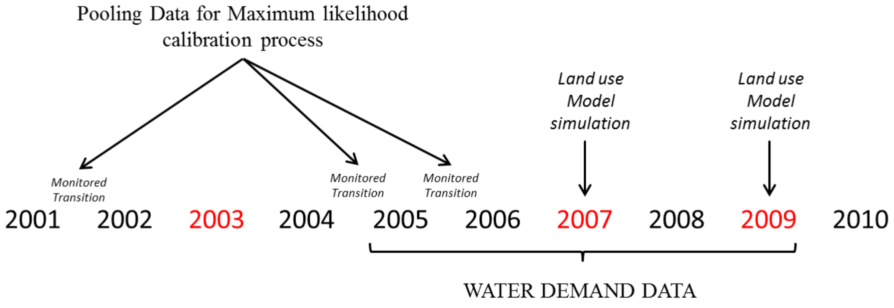

Fig.6 Availability of satellite imagery data for Logit binomial model

The results have been used to forecast urban land expansion until the period of 2050, to find water demand and balance it with water supply.

(2) Scenarios for Water Demand and Supply balance

While one of the variables that define the water requirement by a city's water demand effective population, this requirement is not the only one who answered the WDS. From the point of view of infrastructure, water losses are volumes of water that must be covered by the system as necessary. Proper keeping system maintains this requirement under certain percentage of permissible limits. This phenomenon is highly sensitive to the age of the infrastructure, renovation and maintenance processes, and especially the level of pressure in the system to locate critical points with critical levels of water loss factor.

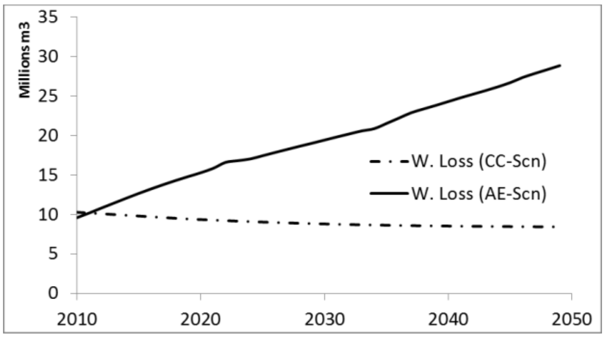

Fig.7 Scenarios for infrastructure conditions in WDS

The factor of water loss from a perspective of evaluation of condition can be defined in the following operating scenarios.

- We set constant loss features in time assuming that infrastructure is maintained and renewed with same frequency as in the current period (positive scenario ***CC-Scn***).
- We set water loss features under constant influence of aging process and gradually corresponding system failures, regardless of maintenance at any time during the analysis period (negative scenario ***AE-Scn***).

CC-Scn has a behavior of decreasing loss over time because generally WDS's operating under increasing demand, which implies a decrease of pressure in general, generating a negative influence on the total loss that falls at the same rate.

AE-Scn defines the characteristics of the aging network are proportional to the age of the infrastructure elements and therefore are increasing. Consequently suffers loss associated positive effect and increases in the same proportion. The total water loss in this case is a balance between the effect of the pressure drop and the influence of the age of the infrastructure in each time step (Figure 7).

In both cases we analyze the availability index for comparison between distributed water and water demand in the network in order to allocate and see the configuration of availability spatially. This index is estimated based on:

$$\text{Availability index} = \frac{Distributed\ water_i^j}{Water\ demand_i^j} \qquad (9)$$

Where *i* represent the step time of estimation and *j* the location in the network, for *Distributed Water* and *Water Demand* (see fig. 5)

6. CASE OF STUDY

(1) Target Area

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 your WDS.

The water supply in the city is provided by two WDSs, located to distribute water in the north and south of the city.

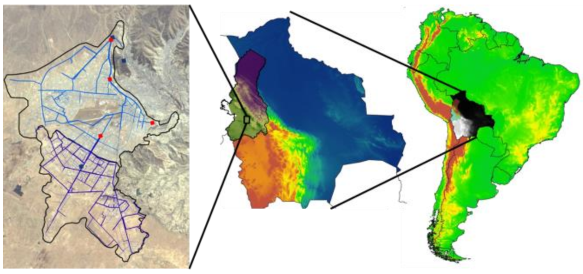

Fig.8 Location of study area, El Alto City, Bolivia

(2) Water Distribution System 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.

(3) Results

The results of maximum likelihood estimation are significant in general. Consideration about significance of average value of unobserved factors in the model must be analyzed under the fact that large numbers of unobserved factors which affect land changes are not considered in the model.

Table 1 Maximum likelihood estimation for logit binomial model

Parameter Name	Value	t-value	Pr(>|t|)	
Constant	-6.58737	-8.286	2.00E-16	***
Accesibility to roads	0.11979	11.589	2.00E-16	***
Accesibility to edu. infraestructure	0.53482	9.782	2.00E-16	***
Accesiblity to health care	-0.74734	-7.888	3.07E-15	***
Suitability by slope	2.88538	3.601	0.000317	***
Suitability by closeness to CBD	0.84589	2.546	0.010909	*
Suitability soil	0.05279	0.331	0.740674	
Neighborhood of residential land	33.95119	37.038	2.00E-16	***

Signif. codes: 0 ▪***▪0.001 ▪**▪0.01 ▪*▪0.05 ▪.▪0.1 ▪▪1
Newton Raphson iterations: 13
Tolerance level: 0.001
Sample: 12508

Due to the characteristics of model expansion and given the information used in the calibration process, a tendency to decrease the rate of increase in area, which exceeds the capacity limit established by municipal boundaries (2040) phenomenon is currently the city of El Alto and presents (invasion of the jurisdiction of the municipality in the area south-west, with the corresponding provision of water in the area invaded by the WDS of the city, see Appendix A2).

Table 2 Multiple linear regression analysis for runoff estimation

Parameters Name	Value	t-value	Pr(>|t|)
Intercept	−1077489	−1.133	0.261337
Precipitation	32027.78	5.951	1.08E−07 ***
Temperature	276440.7	1.934	0.057292 *

Signif. codes: 0 ▪***▪0.001 ▪**▪0.01 ▪*▪0.05 ▪.▪0.1 ▪▪1
Newton Raphson iterations: 7
Tolerance level: 0.001
Sample: 70

As expected, a consistent projection extension must consider the permitted limits, something that the model does not provide because of their dependence on the bid-rent, this function represents the behavior of users, which as we can visualize, do not take jurisdiction to consider the feasibility of defining settlement.

Urban area estimated by logistic binomial probability and bid rent's land users is disrupted since 2035, time in which it is expected that availability of land will give pressure in land users due to jurisdictional capacity limitation.

On the other hand we have been estimates runoff from data records for extended period of analysis using multiple linear regression model based on temperature and precipitation as main explanatory variables (table 2).

The use of multiple linear regression models involves considering increasing available water in proportion to the increase or decrease in rainfall and temperature (see Table 2). In a context of further analysis on this topic, this relationship is not always established under this proportionality. In reality the influence of topography, storage reservoir system and especially the characteristics of the water sources (Watershed, groundwater, glaciers, etc.) in these areas defined as resource availability.

A study on the impact of a disruptive agent in the sources requires first defining the scale effect on the amount of the source itself, and then assesses the feasibility of analyzing its impact on the people who use such area as a source of water resources. Subsequent studies established such characteristics (sensitivity analysis of supply given a specific demand), this analysis is focused on the estimation of demand and corresponding variations as a function of urban sprawl.

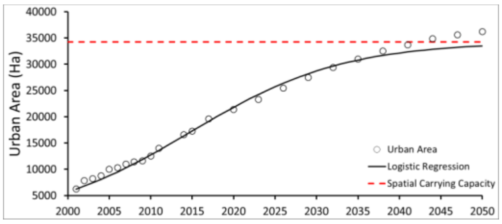

Fig.9 Spatial carrying capacity and logit binomial model results

For analysis, Water supply from Tuni Condoriri system has been contrast with water consumption estimated by model results.

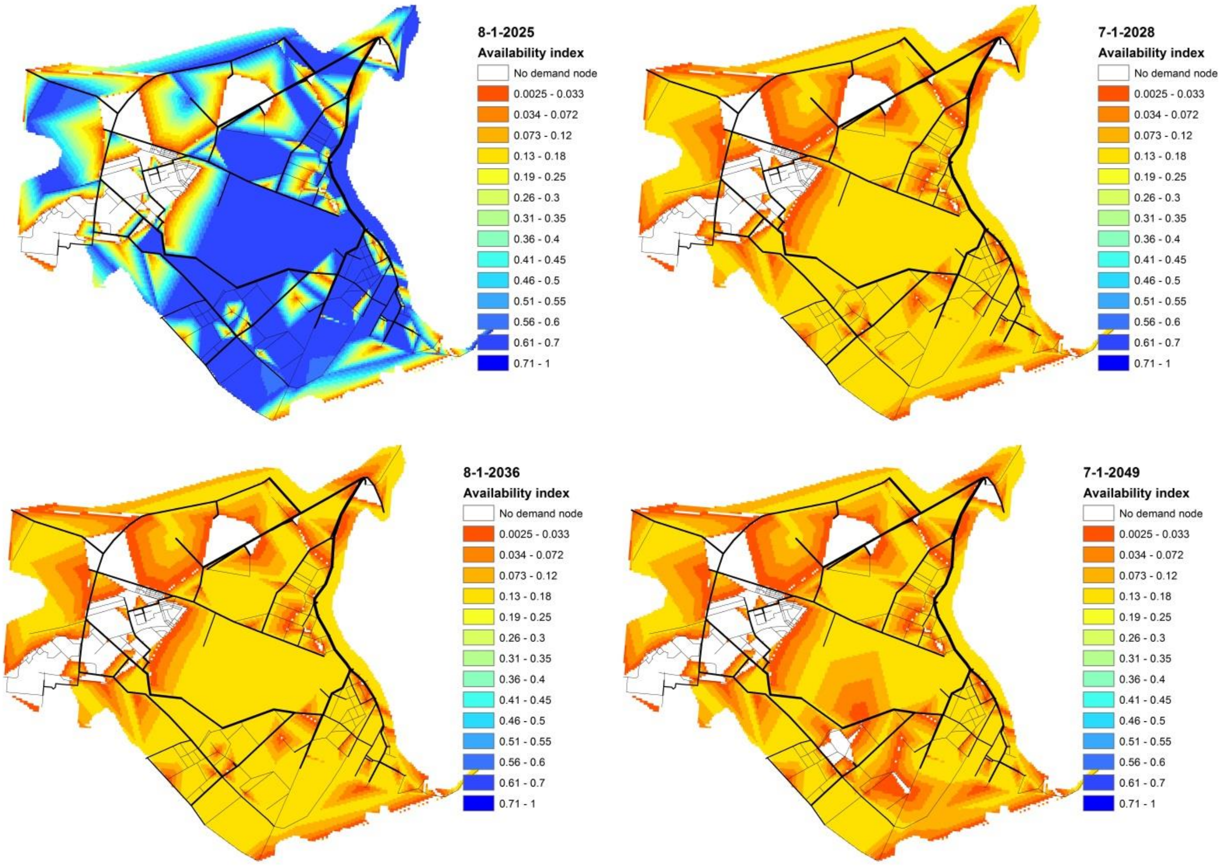

Fig.10 Availability index in network for AE-Scn in the period of unsatisfied demand (2020-2050)

This North system in El Alto city provides water to at least 75% of the entire city (North site). Eventually considering our forecast, it could supply water with no failure until 2024 (see appendix A1) if we consider a scenario of aging effect in the distribution system infrastructure (no maintenance during the period of 2005 – 2050 and consequently increment in water loss in the WDS)

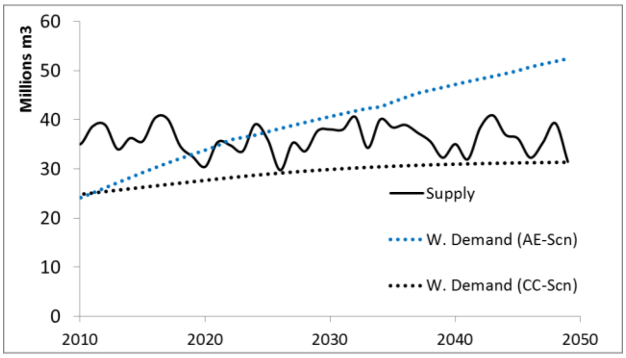

Fig.11 Water demand Vs Maximum Water Capacity incoming in the Reservoir system

The results of the use of system dynamics model show a monthly balance presented in this paper annually, by way of evaluating the effect on the period of study at annual time step.

The results show the dynamic that occurs between the volume stored in the reservoir system the incoming water from the water sources and the corresponding demand for water by the WDS.

There are periods in which demand is met continuously throughout the year given the scenarios studied here (CC-Scn and AE-Scn). In the case of AE-Scn imbalance scenarios occur during the dry season (from May to October each year). These imbalances can start in the period 2024 (to December under the required demand), lessened way, however, as the time period of monthly imbalance progresses, lengthens and the quantity of unsatisfied water increases (see Appendix A1).

7. CONCLUSIONS

It has established a model of urban expansion based development areal extent of a city based on the expectation of maximizing the benefit that each user receives a particular use to give each portion of land use in the area available for such use (above ground belonging to the corresponding municipal jurisdiction). The model features do not consider limitation of carrying capacity in the area that each urban government administers, why, in the case of our area of analysis (city of El Alto, Bolivia), such a limit is exceeded in a scenario prediction from 2010 to 2050 (in 2040 the city area equals the municipal area completely). This phenomenon is characteristic of the city of El Alto, which expands even today in municipal jurisdiction outside the set limit (see appendix A2, urban expansion in 2005 and 2008), giving an indication of the behavior of the population similar to the model's characteristics proposed in this study; reason why looks convenient for using it practically in this case.

The result of urban expansion model have been applied to estimate water demand in the city of El Alto, given the conditions of the information handled by the authorities involved in the administration of the WDS (Section 3 part 1). This information has been used under a SD model which simulates the inherent dynamics of a WDS to balance demand with supply of water (section 3, part 3)

The results show a period of scarcity of water relative to the balance of supply and demand of water (2024-2050, see Appendix A1) in the Scn-AE scenario (increased water loss in WDS), while for the CC-Scn (Current condition of water loss in WDS keep along time), the allocation is sufficient to meet the demand as realized distributed water. If we focus our attention in the worst scenario, we can establish the conditions presented by the WDS given the shortage. To evaluate the conditions of scarcity we can study the behavior of availability index values, which as can be seen in Figure 10, shows a downward trend over time and expandable in space. Both features express the conditions on which the lack of water affects the city if no maintenance process (AE-Scn) is applied and water demand increases according to urban expansion during the period of analysis.

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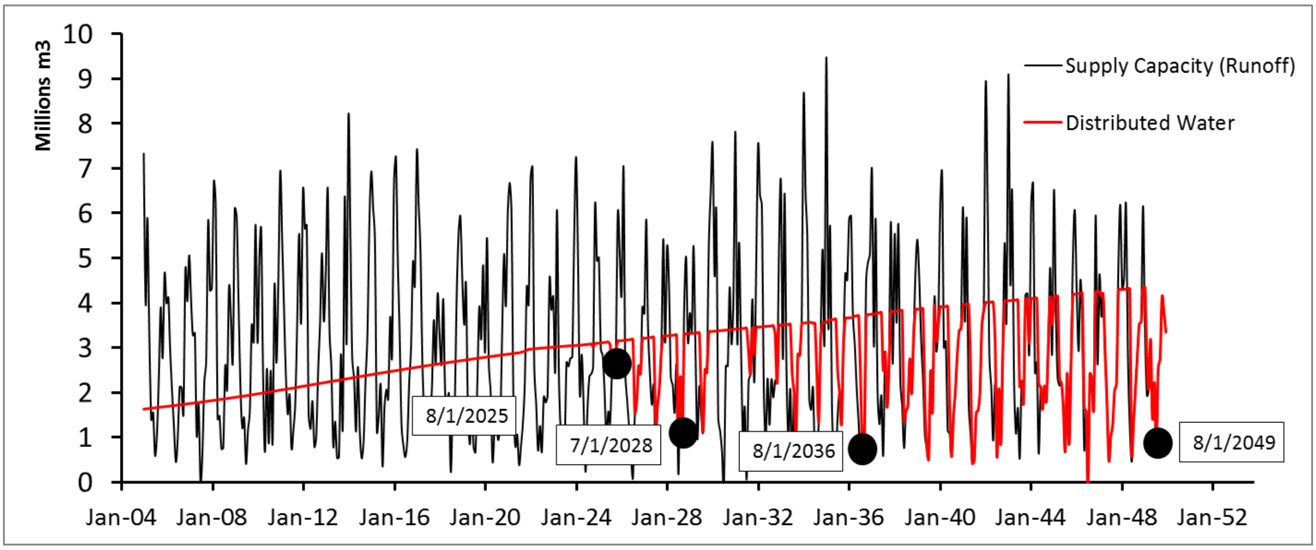
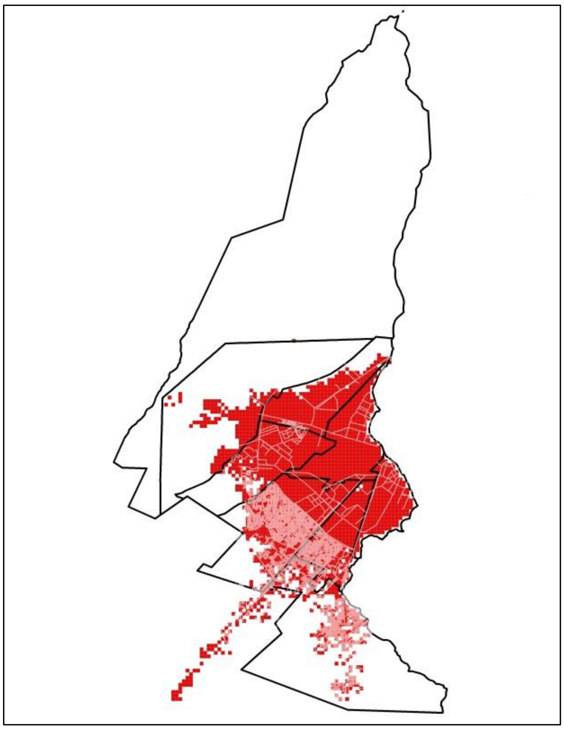
APPENDIX

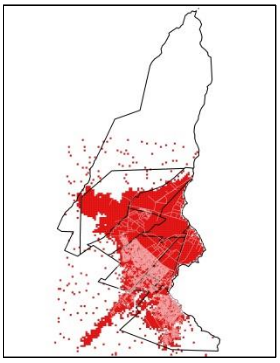
A1. SUPPLY CAPACITY AND SUPPLIED WATER INFORMATION FOR AVAILABILITY INDEX EVALUATION PRESENTED IN SECTION 6



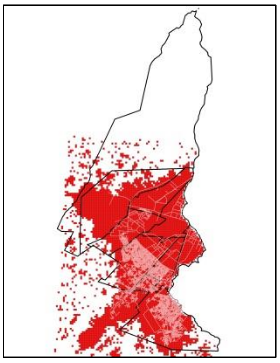
A2. URBAN EXPANSION USING LOGIT BINOMIAL MODEL



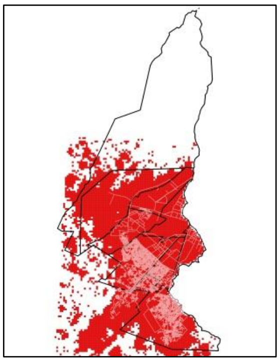
2005



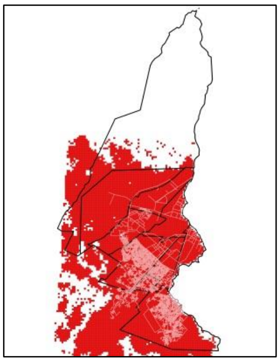
2008



2020



2035



2050

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