Anthropocene 17 (2017) 1–12

Contents lists available at ScienceDirect

Anthropocene

journal homepage: www.elsevier.com/locate/ancene

A spatial model for evaluating the vulnerability of water management in Mexico City, Sao Paulo and Buenos Aires considering climate change

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ARTICLE INFO

Article history:
Received 27 January 2016
Received in revised form 16 November 2016
Accepted 14 December 2016
Available online 15 December 2016

Keywords:
Infiltration
Land use
Natural areas
Water management
Floods
Watershed

ABSTRACT

Water management in cities commonly focuses on reducing the risk of flooding and ensuring water supply by improving infrastructure locally. The supply of water and the process of flooding are directly related to the hydraulic dynamics of the watershed, however, and tools are lacking to evaluate and visualize hazards and solutions at the larger watershed scale. This paper presents a spatial model that evaluates the roles of water infiltration capacities and flood risks in watershed where cities are established. Understanding these characteristics is essential for managing water in urban areas, since water infiltration is related to the rainwater that may arrive to the aquifer, and floods are among the biggest concerns in risk management. We used spatial categorical data for land use, slope, soil texture, elevation, and precipitation to create a model that yields graded areas with different potential infiltration capacities, indicating susceptibility to flooding. The model can generate scenarios considering changes in land use and climate change up to the year 2050. We tested this model in Mexico City, Sao Paulo and Buenos Aires, three of the largest Latin American cities with different type of watersheds but similarities in population and policymaking. We found that climate change will decrease the infiltration capacities in Sao Paulo, but in the other two cities it will increase. Change in land use is the key factor, however, in reducing infiltration capacities and increasing the risk of flooding in all three cities. The model is applicable to urban areas in other parts of the world. These types of spatial models should be used in cities to emphasize the importance of watershed dynamics in managing water for the future.

1. Introduction

Hydraulic dynamics in watersheds depend on variables such as topography, land use and type of soil texture (Cotler and Priego, 2004; Kollet and Redd, 2008). These characteristics or "land attributes" shape the water flowing throughout the watershed in rivers, lakes, wetlands and aquifers. Because cities are often established within watersheds, they are not isolated from these dynamics. Consequently, these characteristics of the land affect directly water management in urban areas (Burns, 2009). For example, natural areas are consistently noted as key regions that should be included when evaluating water management in urban systems facing climate change (Jiménez Cisneros et al., 2014; Kundzewicz et al., 2014). Forests promote the infiltration of rain water to aquifers (Jyrkama and Sykes, 2007) and reduce the velocity of water toward lowland areas, thereby reducing the risk of floods (Neris et al., 2012; USDA, 2008). Other characteristics affect the water runoff during extreme rain events, such as the gradient of the hills (Bradshaw et al., 2007) and the type of soil (USDA, 2008).

Precipitation is another factor influencing regional water dynamics, as it varies in different areas of the watershed. Adding to the precipitation heterogeneity, climate change is modifying rain patterns (Taylor et al., 2012). These changes affect the amount of water that falls into the watershed. Consequently, changes in rain patterns are able to modify the amount of water flowing to aquifers, thereby altering the risk of flooding in different areas (Green et al., 2011). Therefore, water infiltration and flood events are the emergent results of varying land attributes and meteorological inputs (Burns, 2009). They are particularly important in the "Anthropocene" where watersheds dynamics are frequently changing due to human influences, particularly in urban areas.

Consequently, the dynamics of large-scale watersheds must be considered in the managing water in urban areas, since most of the challenges are focused on ensuring water supply and reducing the risk of flooding for inhabitants. In most cases, however, the area of

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http://dx.doi.org/10.1016/j.ancene.2016.12.001
2213-3054/

the watershed is larger than the influence of the legal power of local governments, thus generating a mismatch between city policies and ecosystem dynamics that can be called as the "problem of fit" (Romero Lankao, 2007). Also, information obtained about climate and landscape traits is not always accurate enough to generate models at watershed scale (Field et al., 2012), posing additional challenges. Failure to consider land attributes in watershed dynamics may lead managers to disregard the importance of natural areas in providing water supply and protecting communities from hazards. Additionally, changing land use and climate are rarely considered in the context of water management within cities (Ryan, 2015), despite their importance.

Thus, a framework is needed to guide local policies and actions for managing water that considers the dynamics at the watershed scale. Proper analyses at this scale would help to understand the linkages and interactions in the ecosystem that affects water resources. One possible framework is based on generating spatial models that can determine keystone areas during infiltration and flood events. These models should be spatially explicit in order to visualize those areas that can affect, or be affected by, changes in the hydraulic dynamics.

Many quantitative models evaluate water infiltration and floods in cities, but numerous challenges make them difficult to apply. Most of these models are based on local information in specific place and rarely consider the dynamics of the watershed. For infiltration, mathematical models such as Green-Ampt model and the Richard's equation, with various adaptations, are commonly used, as reviewed by Clausnitzer et al. (1998) and Sonaje (2013). Such models rely on physical soil theory and land variability (Youngs, 1991). These models require large amounts of continuous data, such as rainfall, evaporation, or runoff. Another method is based on the Gravity Recovery and Climate Experiment (GRACE) satellites project, used to analyze the resilience of groundwater on large aquifers (Richey et al., 2015). These methods are recommended for areas larger than 100 km^2 (Landerer and Swenson, 2012), which is greater than many watersheds in which cities are established. Regarding groundwater, a consensus has emerged among researchers that models currently available are difficult for identifying changes due to anthropogenic causes (Green et al., 2011; Jackson et al., 2015). Also, in many countries, insufficient meteorological information is available to generate water balance models at the watershed scale (Abu-hashim, 2011; Green et al., 2011; Jackson et al., 2015). These challenges become more complicated with accelerated changes in land use in urban areas.

In models that simulate the risk of flooding, the difficulties are similar. The lack of continuous meteorological data, gauging stations, and data for flood occurrence limits analyses of flood risk in some regions (Pielke, 1999; Chen et al., 2009). Moreover, rainfall-runoff models applied to watersheds are often inaccurate (Versini et al., 2010). At this scale, a need exists for information about the local pipe system that modifies the flow and speed in which the water circulates below the surface (Smith et al., 2002). Therefore, information about saturation of the system should be included for more accurate predictions about the risk of flooding.

In the new "Anthropocene" era where land conversions are fast and abundant, building new ways of generating and visualizing essential information for decision makers is necessary in urban areas. Geographical Information Systems with landscape characteristics have been recently used to improve flood analyses (Liu and De Smedt, 2005; Versini et al., 2010). Here, we present a model that uses land attributes and rain patterns at the watershed scale to evaluate areas that are susceptible to water infiltration and inundation that may increase risks of flooding. We generated two qualitative spatial models at the watershed scale to describe these areas. These models are capable of generating scenarios by modifying land use or forecasting different type of precipitation caused by climate change. The variables in the model are categorical, and the output gives qualitative information about the characteristics of the areas related to infiltration and inundation. This model can apply to cities around the world, as it uses common databases accessible to the public.

We tested the model in three cities in Latin America with common characteristics: Mexico City, Sao Paulo and Buenos Aires (Fig. 1). The cities are highly populated (with the largest populations of all Latin American cities), making them vulnerable to climate change hazards. Additionally, these cities are conglomerates of neighboring counties with different water management policies. Recently, these three capital cities have suffered from water management issues, particularly the lack of water and flooding. Additionally, many watersheds are undergoing rapid conversion from natural lands to urban areas, with many cities often situated in watersheds with different characteristics. These situations are ideal in evaluating and comparing the accuracy of the model generated, when assessing the differences and similarities among the traits of the land surface to reducing vulnerability in water management.

2. Description of the study cities

2.1. Mexico City

The Mexico City Metropolitan Region is inhabited by nearly 20 million people (SEDESOL et al., 2012). The city produces the highest Gross Domestic Product (GDP) in the country and faces the harshest problems related to water (Maderey and Jiménez, 2000). The predominant land use in the area is agriculture, followed by urban development, with natural areas in the south. The main water source for the metropolitan population comes from an overexploited aquifer, which provides nearly 70% of water resources (Soto and Herrera, 2009). As a result, the dehydrated soil contracts and generates land subsidence in the low lands, which suffer from constant flooding in the rainy season (Pérez and Blanco, 2010; Sosa-Rodriguez, 2010). The Cutzamala system supplies water to the rest of the region (Lankao, 2010). More than 330 km of pipelines and seven dams provide nearly 20 m^3/s of water to Mexico City (Burns, 2009). One federal agency (Comisión Nacional de Aguas–CONAGUA-) and two local offices (Sistema de Aguas de la Ciudad de México –SACMEX–and the Comisión del Agua del Estado de México –CAEM–) manage water for the city. These offices must coordinate with at least a dozen of local municipalities established within the watershed (González et al., 2010).

2.2. Sao Paulo

The Brazilian Sao Paulo Metropolitan Region is the world's fourth largest agglomeration, with more than 20 million inhabitants (Kellas, 2010). This region belongs to the Alto Tietê river basin (Kemper et al., 2005), but the state of Sao Paulo has divided its territory into 22 Resource Management Units, which do not match precisely with natural watersheds (Tesch, 2012). This region is characterized as an urbanized environment undergoing rapid urban and industrial expansion (Kellas, 2010). The southern portion of Sao Paulo is characterized by rainforest, the north by savanna and the northwest by araucaria forest. The water supply is mostly from surface water (Ribeiro, 2011), but the use of groundwater is increasing (Hirata et al., 2007). Neither the extraction of groundwater nor land use are properly regulated (Ribeiro, 2011; Kellas, 2010. Recently, flooding seems to be a growing problem for the region (Haddad and Teixeira, 2014; Kemper et al., 2005). The first attempts to coordinate governmental offices, private sector and society for water management started

Fig. 1. Location of Mexico City, Sao Paulo and Buenos Aires in Latin America. Shades within each country refers to watershed in which each city is based.

in 1991, when the Sistema Integrado de Gerenciamento de Recursos Hídricos do Estado de São Paulo (SigRH) was created in the metropolitan region. In 2007, a new office was created with the State Council for Water Supply and Sanitation (CONESAN). Recently, a new attempt to coordinate with the Pacto das Águas aimed to include the effects of climate change on water management (World Bank, 2012).

2.3. Buenos Aires

The Metropolitan Area of Buenos Aires is Argentina's most important economic and industrial zone. The province is mainly flat and the predominant flow of water is horizontal (Scarpati and Capriolo, 2013). The region's hydrology is part of the Grand Plata watershed, the second largest in the world (CIC, 2015). The predominant vegetation in this region is grassland, with small forests at the center and to the north of the region. All watersheds are exoreic (Abeucci and Sarafian, 2006; Dente, 2006). The current growth of industrial and urban land areas has reduced the amount of infiltration surface available (Morello et al., 2000). The province has recorded major flood problems since the 19th century, which appear to be due to saturated soils (Scarpati and Capriolo, 2013). Two organizations manage water in the region: Agua y Saneamientos Argentinos SA, which is a state company, and the privately-owned Aguas del Gran Buenos Aires. Also, the Autoridad de la Cuenca de Matanza-Riachuelo (ACUMAR) coordinates 17 different governmental offices, and the Autoridad del Agua del Ministerio de Infraestructura de Servicios Públicos was constituted to supervise all the activities and works related to water management.

3. Methods and data

3.1. Information gathered

We built the qualitative spatial models on a basemap layer of the watershed limits in each city. In Mexico City, we obtained the map from the Comision Nacional para el Conocimiento y Uso de la Biodiversidad (CONABIO, 1998). Subsecretaria de Recursos Hídricos provided the map for Buenos Aires (Subsecretaría de Recursos Hídricos, 2011), and in Sao Paulo, we obtained it from the Ministerio do Meio Ambiente (2003). Most of the information was in vector format, but the model used algebraic maps. Thus, all maps were transformed to rasters (100 m per pixel). We standardized the scales because most of the information was at the 1:250,000 scale, and some was at the 1:500,000 and 1:1,000,000 scales. The three variables that were in raster format, including elevation, temperature, and precipitation, were resampled to 100 m using the nearest neighbor method.

To obtain qualitative approximations of the potential infiltration and high-risk flood areas scenarios in each studied city, we added four layers of variables. For infiltration, we used the following: 1) slope, 2) land use and vegetation, 3) annual precipitation and 4) soil texture. These variables give information about the areas characterized by high infiltration capacities. For floods, we used the same variables, together with soil texture (instead of elevation). The data for these variables identified areas with high possibility of flooding during a storm. The variables in the infiltration model were based on Burns (2009), and Schosinsky and Losilla (2000), whereas the variables in the flood risk model were considered based on methods proposed by Pérez and Blanco (2010), and (Kalantari et al., 2014; Kundzewicz et al., 2014).

3.2. Standardizing variables

Since the data for the variables are expressed at different scales, standardizing each variable was necessary to avoid overrepresentation. We standardized each variable from zero to one, resulting in a maximum value of four for each region of the map. The standardization was based on a ranking process in work sessions based on theoretical and geographical information to increase the spatial heterogeneity in each city. Thus, some of the relationships between values and ranks were proportional, but others were logistical or exponential relationships.

We standardized the slope variable equally in the three cities and the two models. It was divided into five ranks, using coefficients generated by Burns (2009) that were adapted from Schosinsky and Losilla (2000) and Chow et al. (1994). This variable is based on the amount of time water spends in a particular area (Green et al., 2011; USDA, 2008). Regions with the smallest slopes have the highest infiltration rates and the highest capacities to generate floods. The first two ranks of the model are based on the lowest two slope degrees. The following ranks span from two degrees up to 12° because the water moves faster. The infiltration ranks decrease in an exponential form. We used a Digital Elevation Model (DEM) with a resolution of 30 m per pixel, obtained from the Global Digital Elevation Map ASTER (JPL, 2011).

Land use also has the same categories along the three cities and in both models. To categorize vegetation, we used the classification proposed by Velázquez et al. (2002). In this case, however, the values were inverted in each model because land use types that allow higher infiltration also reduce flood risks. The categorization was generated based on infiltration capacities (Schosinsky and Losilla, 2000; Green et al., 2011) and flood processes (Kalantari et al., 2014; Kundzewicz et al., 2014; Lankao, 2010). They were divided into five types of land use based on Burns (2009) that is used for Mexico City, and they were adapted to the types of land in the other two cities. Forest cover has better infiltration properties than grassland, which has better properties than agriculture. Urban land has the lowest infiltration capacity, as urbanization creates impermeable and compact soil, and lacks organic matter and roots, which is a trait that increases infiltration properties (USDA, 2008). In this variable ranking scheme, values decrease proportionally, except for grass, which is similar to forests. We used maps from the National Geographic Institute of the Republic of Argentina at a scale of 1:250,000, the Brazilian Institute of Geography and Statistics at scale of 1:5,000,000 and the National Institute of Statistics and Geography for Mexico at a scale of 1:250,000.

The annual precipitation is different in the cities studied; in some cities the rainfall is one fourth of that in the other cities. Consequently, using similar rankings would result in a homogenous ranked map for those cities where precipitation is small. We ranked each city considering the major differences in rain patterns in each basin. The ranking was generated using the same logistical pattern to determine the intermediate ranks. This procedure strengthened the regional variances within cities, which are close to the lowest and highest precipitation values. WorldClim provided precipitation data with a resolution of 30 s (Hijmans et al., 2005).

We used the variable of Soil texture only for the infiltration model. We classified it into three ranks based on the infiltration rate in inches per hour generated by the tree types of soil texture used (USDA, 2008). Sand was considered as the maximum rate, and the other two types were obtained by proportional rates. Different institutions provided maps, including the National Agricultural Technology Institute of Argentina at a scale of 1:500,000, the Brazilian Agricultural Research Corporation at a scale of 1:1,000,000 and the National Institute of Statistics and Geography for Mexico at a scale of 1:250,000.

The elevation variable was used only for the flood model. The ranking process was different in each city because they have contrasting elevations. For example, Mexico City has mountainous areas, whereas low-lying delta areas characterize Buenos Aires. We obtained elevation values from the same source that provided data for slope. The highest value matches the lowest elevation, and the rest of the ranking decreases exponentially, based on a correlation between floods and elevation in Mexico City (Zambrano et al. in preparation). The same exponential decay function provided the ranks in the other cities. The first two ranks were generated at an elevation of five meters because this elevation represents areas with larger floods. The third rank was an elevation of 22 m, the fourth was between 60 and 300 m, and the lowest rank was above 300 m. Table 1 outlines the categories and coefficient values for the infiltration and flood risks models.

Once categorized, we generated the algebra map with the software ArcGis 10.1 v, using the following equations:

$$PI = \sum (SL_{C_i}, LU_{C_i}, ST_{C_i}, P_{C_i}) \quad (1)$$

$$FR = \sum (SL_{C_i}, LU_{C_i}, E_{C_i}, P_{C_i}) \quad (2)$$

where PI = potential infiltration, SL = slope, LU = land use, ST = soil texture, P = precipitation, FR = flood risk, E = elevation, C = coefficient and i = particular value of each coefficient based on Table 1.

The resulting scores are dimensionless, but a high PI value indicates better water infiltration and a high FR value correlates with greater flood risk. These variables were divided into five natural inherent groups using the ArcGis 10.1 v software, in which groups defined by data breaking points were identified in class distribution. To get the percentage of the potential infiltration and flood risk value of the model (Current Percentage –CP- in both cases), we used the median infiltration and flood risk values for

Table 1
Variables and coefficients in both, infiltration and flood risk models. Slope, land use and vegetation are adapted from Schosinsky and Losilla (2000). Soil texture is adapted from USDA (2008). Exclusive variables and coefficients for each model and city are specified; if not, they correspond to both models and three cities. Urb & Wat = Urban land & water bodies and Coeff = Coefficient.

Variable	Value	Coeff				
Slope degrees	<2	1				
	2–4	0.67				
	4–8	0.33				
	8–12	0.27				
	>12	0.17				
Soil texture (Infiltration Only)	Clay	0.25				
	Loamy	0.5				
	Sandy	1				
		Coeff (Infiltration)	Coeff (Flood risk)			
Land use	Urb & Wat	0	1			
	No vegetation	0.25	0.9			
	Agriculture	0.5	0.5			
	Grasslands	0.9	0.25			
	Woods/Rainforest	1	0			
Precipitation (mm)	México City	Coeff	Sao Paulo	Coeff	Buenos Aires	Coeff
	>600	0.1	<1100	0.1	<800	0.15
	601–800	0.15	1100–1300	0.15	800–1000	0.6
	801–1000	0.6	1300–1500	0.6	>1001	1
	1001–1200	0.75	1500–1700	0.75		
	1201–1500	0.9	1700–1900	0.9		
	>1500	1	>1900	1		
Altitude (Flood risk only) (m)	2200–2230	1	0–250	1	−92–10	1
	2230–2240	0.64	250–500	0.64	10–20	0.64
	2240–2260	0.36	500–750	0.36	20–40	0.36
	2260–2300	0.16	750–1000	0.16	40–60	0.16
	>2300	0.04	>1000	0.04	>60	0.04

each category in the current scenario, and assigned the value "1" to the "very low" category (μ_i). Subsequently, the value of the following categories was assigned as proportional to its median, based on the very low category (μ_{ij}). The resulting values of all categories are multiplied by their respective area (A), and the result of all categories is summed. Finally, this score is considered as 100% infiltration or flood risk Current Percentage.

$$CP = 100\%\text{CurrentPIorFR} = \sum_{i=verylow}^{j} \left(A_{ij} * \frac{\mu_{ij}}{\mu_i} \right) \quad (3)$$

3.3. Model scenarios

In the "Anthropocene," some of the variables used in the model are changing constantly, especially land use and climate. These variables can be modified in the model to generate scenarios that can evaluate the importance of each type of area, including how changing precipitation alters the hydraulic dynamic of the watershed. As a first approach for evaluating the importance of vegetated areas in the watershed, we generated two land use change scenarios. In one scenario, vegetation was entirely replaced by urban land use (ULUC). In the other, vegetation was replaced by agricultural land use (ALUC). These land use change scenarios do not rely on sprawl projections, but they consider land use dynamics and provide an example of the capacity of the model to simulate human-environmental changes. In the infiltration and flood models, the vegetation land use coefficients were replaced by urban and agricultural land uses.

We also modeled different precipitation scenarios at regional scale based on climate change through the year 2050 (Hijmans et al., 2005). To generate these scenarios, we used the most recent projections of Global Climate Models from the Coupled Model Intercomparison Project Phase 5 (Supharatid, 2015). These models represent the latest climate models generated by the Intergovernmental Panel on Climate Change (IPCC) group (Arora and Boer, 2001; Scibek and Allen, 2006; Sulis et al., 2011). Variables used in these models were based on the combination of socioeconomic data that produced an cumulative measure of human greenhouse gas emissions to generate a Representative Concentration Pathway (RCPs) (Moss et al., 2010). We used the RCP 8.5, which considered the same emissions of greenhouse gases as they are produced now. All the models were built using the General Circulation Model GFDL-CM3 generated by Geophysical Fluid Dynamics Laboratory of the National Oceanic and Atmospheric Administration, USA. The selected models proved to be accurate in Latin American regions (Cavazos et al., 2013; Gulizia and Camilloni, 2014). Nevertheless, this model shows underestimation of rain in South America (Yin et al., 2013). These scenarios cannot be considered forecasts, but they provide estimates of future precipitation (Scibek and Allen, 2006). Finally, we mixed land use change scenarios with climate change-based precipitation scenarios. We applied the same Current Percentage equation to each scenario. The percentage based on the final result was assigned proportionally, however, according to the former Current Percentage (CP) to obtain the relative percentage (RP) of each scenario.

$$RP = \frac{CP}{\left(\sum_{i=verylow}^{j} \left(A_{ij} * \frac{\mu_{ij}}{\mu_i} \right) \right) * 100} \quad (4)$$

3.4. Model validation

Regional infiltration values are difficult to obtain at watershed scale. Therefore, it was not possible to generate a quantitative validation of the model for the three cities. However, we were able to compare qualitatively the resulting map obtained by the model

for Mexico City with the one obtained by Lafragua et al. (2003). For the other two cities, it was not possible to obtain similar maps for comparing results.

We performed statistical validation for the flood risk model by adapting the Species Distribution Model (SDM) True Skill Statistic (TSS) and by chi-square statistic for flood event records. We obtained records for Mexico City by request from the Sistema de Aguas de la Ciudad de México (SACMEX) and from the Comision del Agua del Estado de México (CAEM), with 1365 flood events from the years 2008, 2010 and 2012. The Centro de Gerenciamento de Emergências (CGE) database (CGE, 2009) provided information from Sao Paulo, covering only the year 2009 with 647 events. We obtained data from Buenos Aires from Nabel et al. (2008), covering the period 1980–2005 with 40 events. We used the TSS model by generating predictions for absence and presence (Allouche et al., 2006), which are compared with validated flood sites, to determine the areas of presence and absence of floods. For Mexico, each categorical flood risk value was reclassified in absence (very low – low) and presence (mid – very high) area. For Sao Paulo and Buenos Aires flood risk categories were reclassified in absence (very low – high) and presence (very high) area. Reclassification was based on evenness of presence and absence territory.

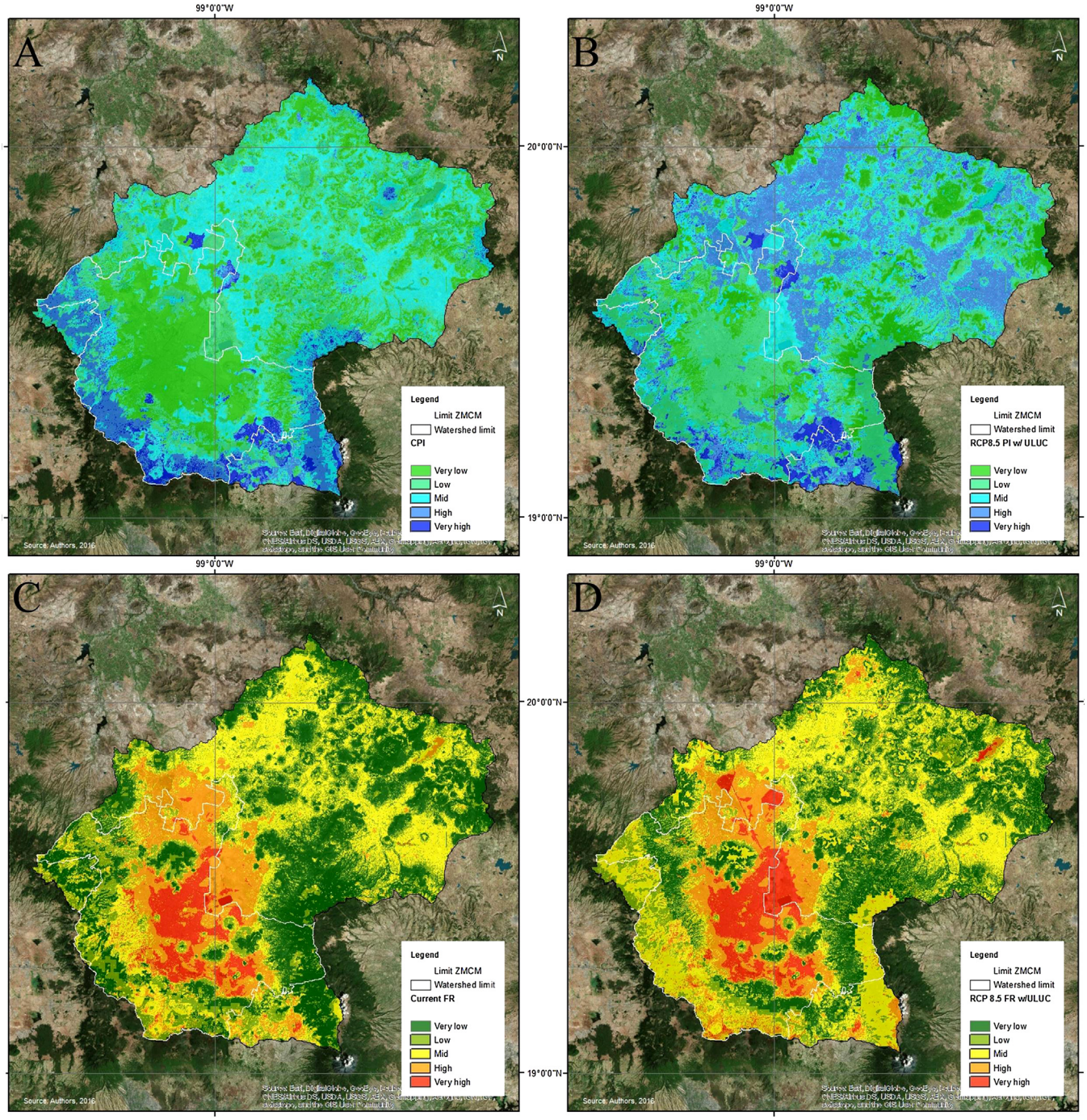

Fig. 2. Current potential infiltration of Mexico City (A) and potential infiltration scenario with change in land use and climate change (B). Current flood risk areas (C) and flood risk scenario with change in land use and climate change (D).

4. Results

4.1. Mexico City

4.1.1. Infiltration

The southern region of Mexico City has the largest area with high potential infiltration capacities (Fig. 2A). Most of the southern region is located on a mountainous surface, covered by forests that receive the highest precipitation. Another high infiltration area is the agricultural lowland at the southeast of the city. Here, high infiltration values are due to the sandy soil and the low slope. The north and east regions of the watershed, which are mostly mountain systems covered by forest, have very small areas with high infiltration values. Finally, the metropolitan area is mostly based on the central region, and has little or no infiltration capacity (Fig. 2A).

All scenarios in Mexico City have small changes in the watershed, but they suggest a reduction of infiltration capacity at land use change. In both scenarios of land use change (forest to urban and forest to crops), a reduction of 8% occurred in the whole watershed (Fig. 3). In scenarios with climate change with the current land use, areas with high infiltration values marginally increase. When scenarios involve changes in both climate and land use, then the potential infiltration is slightly reduced (Fig. 2B). The urban land use change causes the most critical reduction to the infiltration values in all scenarios. Our model results showed qualitatively similarities with Lafragua et al. (2003) in areas categorized as high, low and very low infiltration, whereas areas categorized as very high and medium infiltration were less similar (Table 2).

Table 2
Area similarity percentage of Mexico City's current potential infiltration scenario groups and Lafragua et al. (2003).

Groups	Shared area percentage
Very high	0,77
High	56,77
Mid	26,18
Low	42,60
Very low	88,67

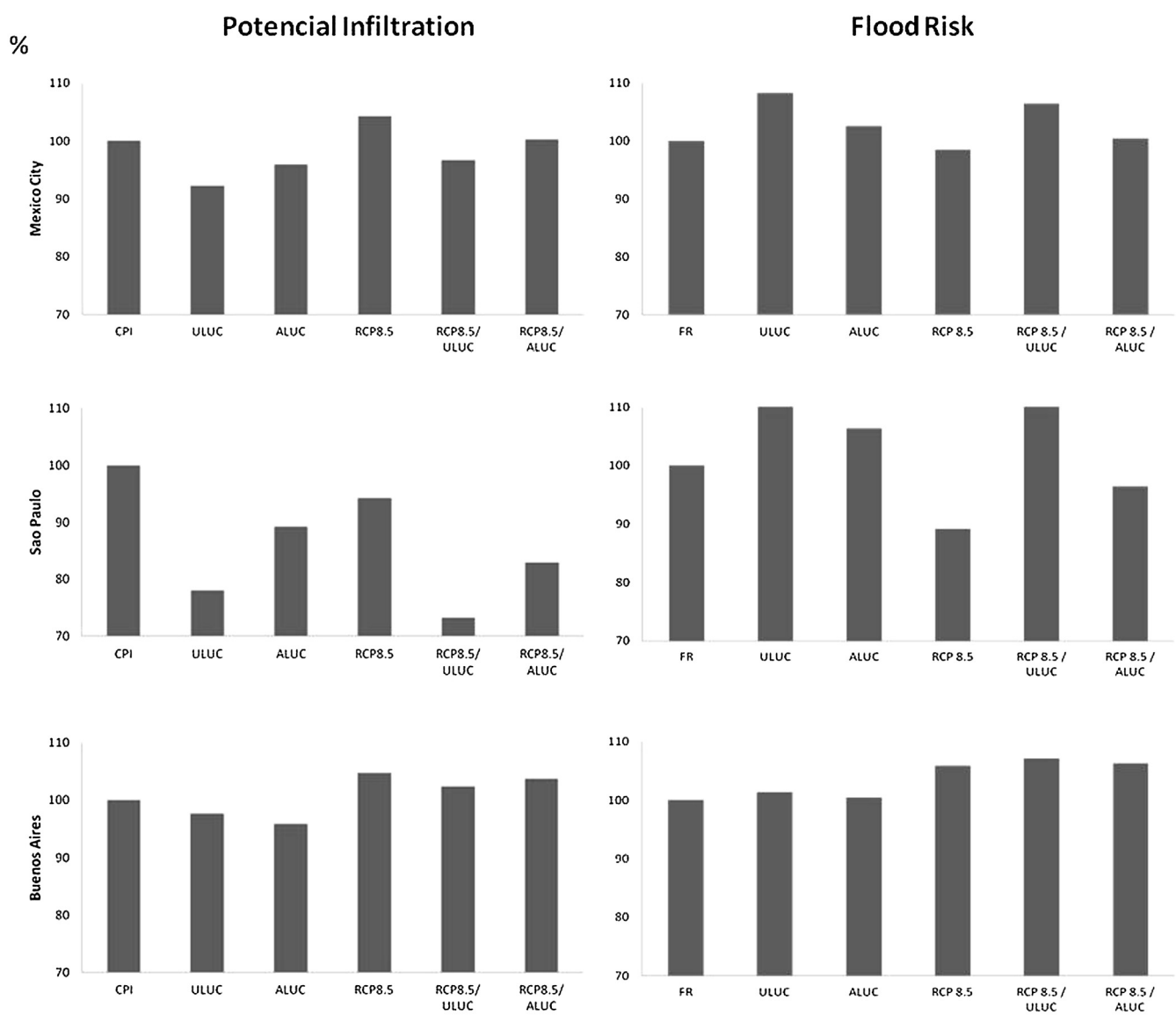

Fig. 3. Infiltration and flood risk percentages for Mexico City, Sao Paulo and Buenos Aires for current, climate change and land use scenarios. Current potential infiltration (CPI), Current Flood Risk (CFR), Scenario of urban land use change (ULUC), Agriculture land use change (ALUC) and climate change RCP8.5.

4.1.2. Flood risk

The current highest flood risk values in Mexico City are in the central region of the metropolitan area, as it has the lowest elevation and slope values (Fig. 2C). The morphology of the highest and medium flood risk areas resembles the shape of the former lake that used to cover the area before urbanization. The lowest flood risk areas scattered through the entire region are characterized by high slope and elevation values. Although elevation and slope seem to be the most important traits, land use plays an important role in producing risk of flooding. Both types of land use changes (forest to urban land and forest to crops) increase flood risk values by up to 10% in the entire region (Fig. 3). With scenarios considering only climate change but not land use change, the flood risk presents a slight decrease (<4%), mostly because of a reduction in precipitation in the southern valley. All scenarios using land use change and climate change models increase the flood risk between < 1% and 10%, and urban land use change produces the greatest increment on flood risk (Fig. 2D). The flood risk model validation gives a TSS = 0.6, Omission error = 0.33 Commission error = 0.5, and a significant values for Chi-square = 0.77, p = < 0.01, n = 2730.

4.2. Sao Paulo

4.2.1. Infiltration

Sao Paulo is mainly covered by rainforest, which represents most of the areas with high potential infiltration (Fig. 4A). The western region, dominated by sandy soils, has the highest infiltration values. Other areas covered by rainforest do not have these high values, mostly because they have clay and loamy soils. Small slopes seem to increase the potential infiltration in scattered areas throughout the watershed, such as the southwest and northeast regions. Therefore, these results show that the combination of vegetation, soil and slope are key attributes that modify areas of infiltration in Sao Paulo (Fig. 4A). The northwest region dominated by agricultural lands established on clay soils presents low potential infiltration values, as does the central region, which is dominated by urban land use.

Scenarios of land use change show a decrement in infiltration on both agricultural and urban lands of 17% and 30%, respectively. The RCP 8.5 model suggests a reduction in precipitation, resulting in lower values of infiltration in the city. Scenarios with combined climate and land use change follows the results as the ones in

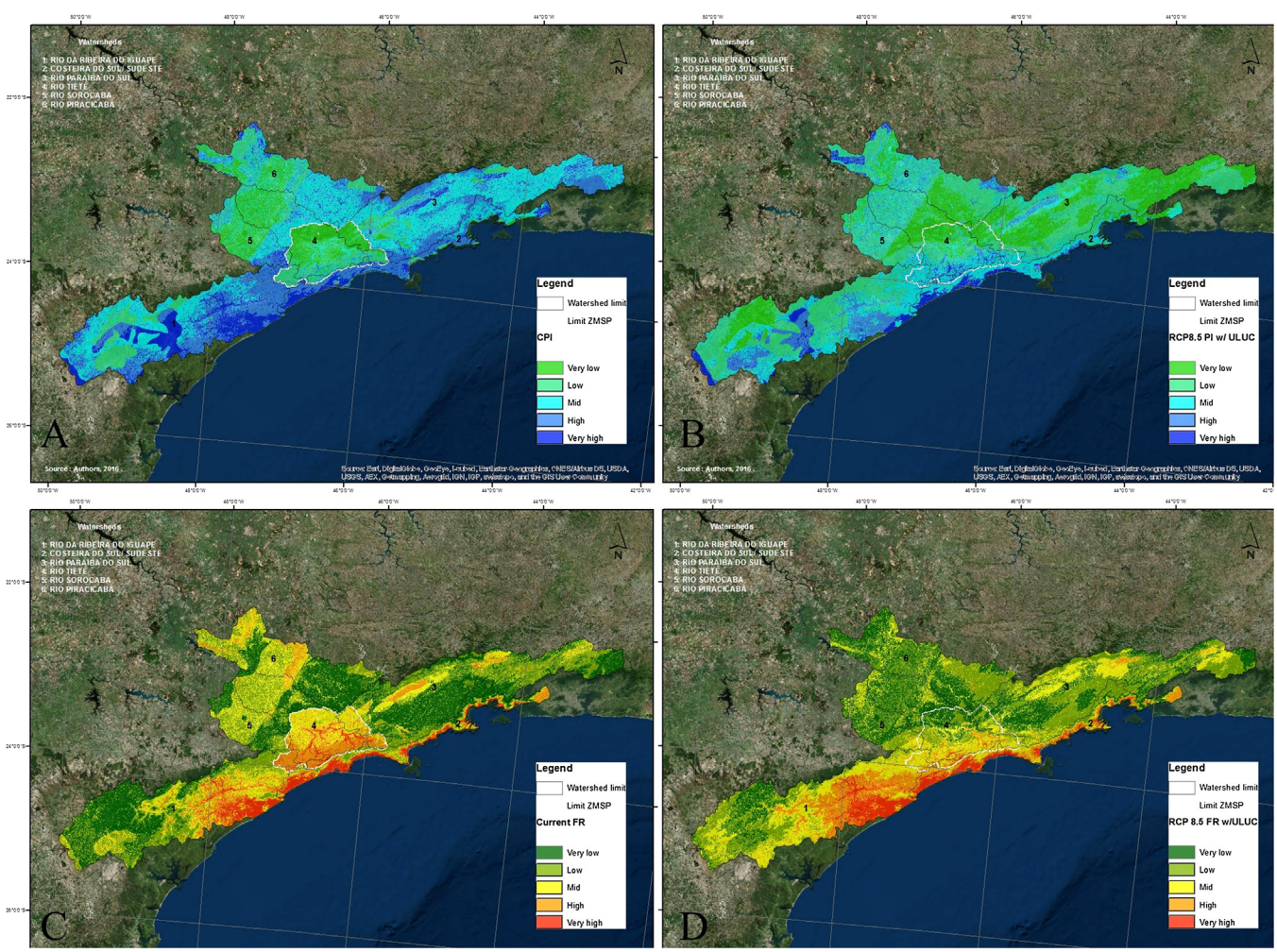

Fig. 4. Current potential infiltration of Sao Paulo (A) and potential infiltration scenario with change in land use and climate change (B). Current flood risk areas (C) and flood risk scenario with change in land use and climate change (D).

which only land use change was applied (Fig. 3). Most of the reduction is explained by the assumption of the depletion of the rainforest, as shown in Fig. 4B.

4.2.2. Flood risk

Sao Paulo's highest flood risk values are in the central and southeastern regions close to the coast, which have high precipitation, low elevation and slope (Fig. 4C). Medium flood risk values in most of the region are mainly attributed to small slope values. Areas with low flood risk are in the northeast and southwest region because they are characterized by low precipitation and high slope values. The central-north region generated moderate flood risk values that increase going to the south of the area. The urban land of the central region shows high flood risk values.

Both land use changes (forest to urban land and forest to crops) increase flood risk in the entire region (Fig. 3). The climate change scenario results show lower flood risk values. This scenario is based on lower precipitation in the entire region. Most of the combined scenarios (climate change and land use change) show an increment in flood risk, with some exceptions under the agricultural land use change (Fig. 4D). The flood risk model validation gives a TSS = 0.3, Omission error = 0.28, Commission error = 0.4 and a Chi-square = 106.56, $p < 0.01$. n = 1294.

4.3. Buenos Aires

4.3.1. Infiltration

Buenos Aires presents the most homogeneous values of slope in its watershed of the three cities. The high potential infiltration values are in the central and western regions (Fig. 5A). This result relates to high precipitation, sandy soils and agricultural, and the forest coverage in the area. Medium infiltration values apparently relate to the scattered agricultural areas. The north, far south and east regions have lowest infiltration values that are the result of low precipitation and clay soils.

In Buenos Aires, both scenarios of land use change produce a reduction of 8%–17% in the potential infiltration values compared to current values (Fig. 3). The climate change scenario predicts a lower precipitation and therefore has negative infiltration values in all related scenarios (from −18% to −3%).

4.3.2. Flood risk

The areas with highest flood risk in Buenos Aires are located in the central and northern regions, which are characterized by low elevation and high precipitation values (Fig. 5C). Other areas with high flood risk values, scattered through the region, are on water bodies or prone to flooding. Moreover, areas with low flood risk values are in the northwest and southwest, which have high elevation and low precipitation values.

In this watershed, all modeled scenarios show higher values of flood risk (Fig. 3). Considering scenarios of land use change (forest to urban land and forest to crops), flood risk increases in the central and northern region. Climate change scenarios increase flood risk in the same areas as well as in the western region, but the increment is smaller than in the combined scenarios (Fig. 5D). The flood risk model validation gives a TSS = 0.26, Omission error = 0.46 Commission error = 0.27, with a Chi-square = 521.15, $p < 0.01$, n = 80.

5. Discussion

5.1. Model performance

The models perform properly in evaluating both infiltration capacities and areas of flood risks areas. The model validation for infiltration in Mexico City, by comparing results with Lafragua et al. (2003), matches in most of the cases. The qualitative nature of the model and small amount of data used proved difficult in evaluating the certainty of the infiltration results. Thus, the model should be validated in other cities with better information for infiltration locally. Flood model statistical validation is significant for the three cities, and the TSS values of the models suggest that these models are able to describe properly the watershed dynamics.

These results suggest that the model is a good tool to generate scenarios to contrast conditions with specific land use changes. Also, by comparing results among cities, this model can help to evaluate the relevance of particular land attributes for hydraulic dynamics in different watersheds. In this case, maps generated by models reinforce the idea that watershed dynamics are highly affected by natural areas. The three cities studied are located in watersheds with different characteristics: Mexico City in an endorheic valley, Sao Paulo in a plateau, and Buenos Aires on a delta river. But two of the cities respond similarly in infiltration depletion at significant reductions of natural areas.

The results also suggest that the model is a good tool to understand hydraulic modifications caused by climate change in the watershed. In scenarios using only climate change, areas with higher water infiltration values decreased in Sao Paulo and slightly increased in Mexico and Buenos Aires. This variation is caused by the predictions by climate change models that reduce rainfall in Sao Paulo and increase it in the forested areas of Mexico and Buenos Aires, which may increase water infiltration (Burns, 2009; Lankao, 2010; Sosa-Rodriguez, 2010; Ribeiro, 2011). Therefore, these results suggest that climate change could be considered beneficial for water management in the cities developed later if natural areas are not urbanized. However, the model does not consider soil saturation or rain intensity. Consequently, the benefits of a higher precipitation could be smaller than the model predicts. These variables, when available, should be included in the model to generate a more precise forecast. These potential benefits of climate change in water infiltration contrast with the higher flood risk values in the three cities. This contrast is also caused by the increment of precipitation in the watershed. In this model, variables that are not included, such as soil saturation or extreme precipitation, may increase the flood risk areas, and therefore underestimates the effect of climate change.

5.2. Potential applications and policymaking

The model developed in this study was not intended to provide information about water balances in regions of the watershed, because its approach generates qualitative data. For more specific results, we should also consider soil water saturation, evapotranspiration, extreme events or spatial-specific urban growth models, which could potentially reduce the uncertainty in the results. But, the information generated by the model can be useful for decision makers. The qualitative model may help to stakeholders to evaluate urban planning and acknowledge the risks of modifying areas with high values of infiltration, or building in high-risk inundation areas. The specific parameters? of the general model can be modified to evaluate scenarios in which these valuable areas are modified, demonstrating the consequences associated with water availability or flood risk. For instance, in Mexico City, the model can be used to evaluate flood risk near the new international airport, which is planned for construction in the northwest portion of the city. Additionally, the model may help to evaluate whether the southern and southwestern areas of Sao Paulo should be considered priorities for conservation, as they are critical for infiltration and may increase the groundwater demand in the future. Finally, the lowest areas in Buenos Aires

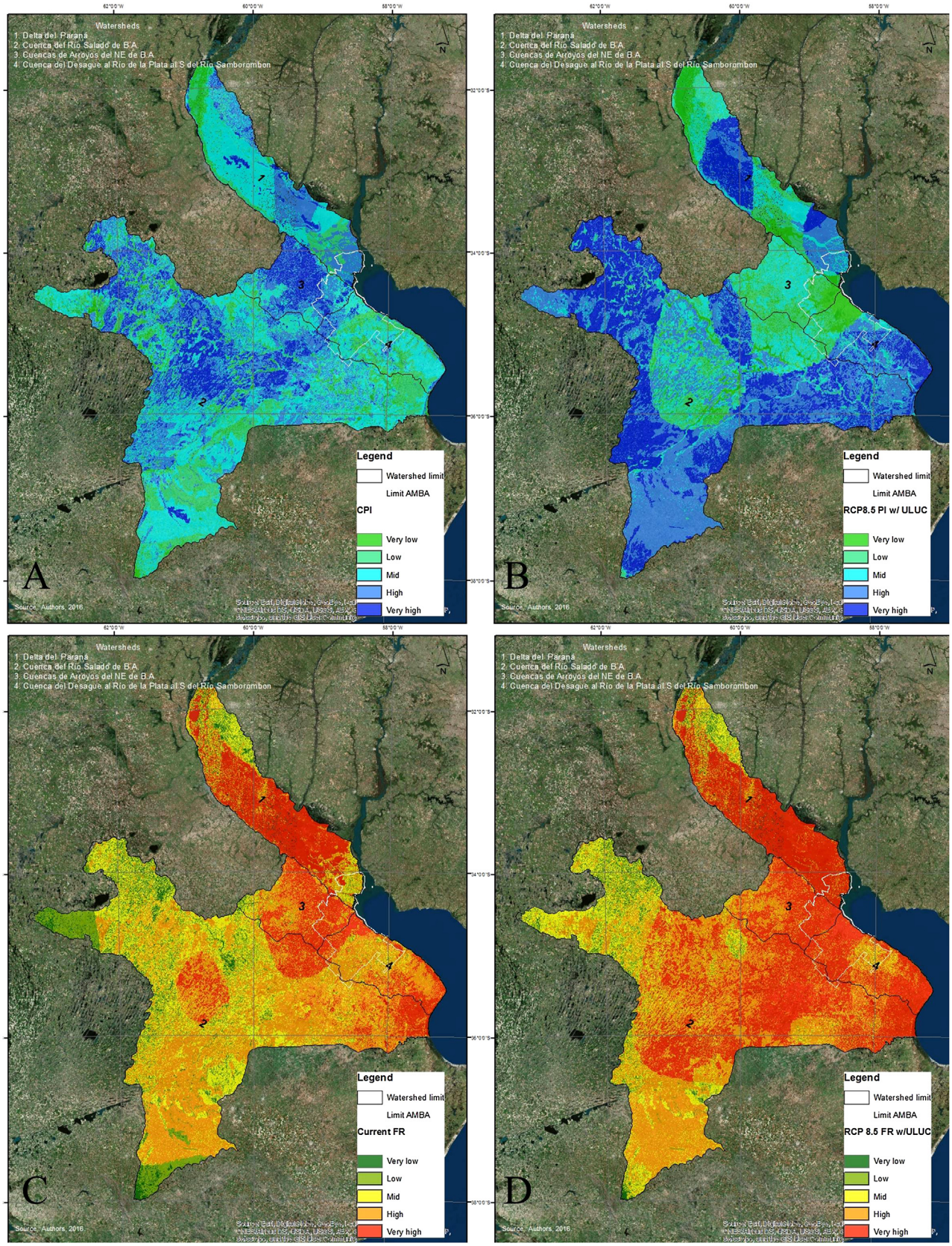

Fig. 5. Current potential infiltration of Buenos Aires (A) and potential infiltration scenario with change in land use and climate change (B). Current flood risk areas (C) and flood risk scenario with change in land use and climate change (D).

at the center of the region should be noted as flood risk areas during infrastructure development.

The model can be adapted to others cities easily with open access data. A framework such as this model provides a tool that supports the implementation of policies at the local level. Maps illustrating those important areas for water infiltration or vulnerable to floods can be effective to improve land management by local people (Dupuis and Knoepfel, 2013; Ryan, 2015). The land use change scenarios strengthen the argument that natural areas are highly important in reducing the vulnerability of urban water dynamics due to climate change (Magrin et al., 2014). Therefore, the model also may help to generate a more detailed analysis of water management policies at large scales.

5.3. Applying the spatial model in the Anthropocene

The fast growth in cities has increased the interaction of urban areas with the watershed dynamics (Tang et al., 2005). A new set of relations among variables within ecosystems is emerging in the Anthropocene era. The consequence is shown in new dynamics within the watershed, which also are affected by a changing precipitation patterns generated by climate change. These dynamics must be understood to provide water to a growing urban population that need to reduce flooding risk in extreme events, without affecting watershed dynamics. Isolated actions may solve short term problems locally but generate larger problems in the long term, and this has been proven in the studied cities. For example, in Sao Paulo, droughts occurred in 2014–2015 resulted in an increment of water extraction throughout unregulated wells that ensured the water supply in houses (Whately and Lerer, 2015), but increased the uncertainty of the amount of water extracted. In Mexico City, overexploitation of the aquifer has produced subsidence of up to 40 cm per year southern regions with high flood risk (Burns, 2009). Therefore, short-term infrastructure may increase the problems at the watershed level in the long term.

A new vision of management requires tools able to provide information for a fast response to manage urban influences in the watershed, facing climate change. The spatial model developed in this study considers watershed dynamics as a system able to provide information regarding the areas that are critical for water management. The model also helps to generate different scenarios of climate change to reduced negative effects in extreme events. With this tool, it is possible to analyze and compare those drivers that have greater influence on watershed dynamics.

Acknowledgements

This article was funded by the UK Department for International Development (DFID) and the Netherlands Directorate- General for International Cooperation (DGIS), through the Climate and Development Knowledge Network (CDKN). These findings are not necessarily those of or endorsed by DFID, DGIS or the entities managing CDKN, and are the sole responsibility of the authors. We also want to thank to Fundación Ambiente y Recursos Naturales (FARN), for their facilitations on the elaboration on this study, to SACMEX and CAEM for the information provided and to Angel Merlo-Galeazzi for his comments and reviews.

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