Geofísica Internacional (2012) 51-2: 157-167

Original paper

Subsidence risk due to groundwater extraction in urban areas using fractal analysis of satellite images

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Received: March 10, 2011; accepted: September 1, 2011; published on line: March 30, 2012

Resumen

La presencia de terrenos agrícolas en territorios urbanos de regiones semiáridas sin cuerpos superficiales de agua implica un intenso uso de agua subterránea. En la Cd. de Irapuato, México, existe una gran concentración de pozos agrícolas y urbanos. El intenso régimen de extracción está induciendo subsidencia. Se encontraron 18 sistemas de fallas por subsidencia con una extensión total de 27 km. Más de 200 casas habitación presentan daños. Concentraciones de tolueno en el agua subterránea demuestran que las fallas facilitan la migración de contaminantes. Se realizó un análisis morfológico de la distribución de los terrenos agrícolas dentro de la mancha urbana. Este análisis se aplicó a terrenos de cultivos segmentados derivados de una imagen de satélite. El análisis permitió calcular la distribución de terrenos agrícolas y confirmar la presencia de pozos usados para su riego.

Palabras clave: contaminación acuífera, fallas por subsidencia, análisis fractal, agua subterránea, subsidencia.

Abstract

Agriculture in urbanized areas of semi arid regions without surface water bodies depends on an intense use of groundwater. In Irapuato City, Mexico, there is a great concentration of agriculture and urban supply wells. The intense regional pumping regime is inducing subsidence. Eighteen subsidence fault systems were found with a total length of 27 km. More than 200 houses present damages. The presence of toluene in groundwater suggests that faults facilitate the migration of contaminants. A morphological analysis of agriculture land distribution in the urban area was carried out using satellite images. This morphological analysis shows the relevance of agriculture terrain distribution within the urban area. The morphological analysis is applied on previously segmented crop fields as derived from the satellite image. This analysis allowed calculation of agricultural land distribution and confirm the presences of wells used for irrigation.

Key words: contamination, faults, fractal analysis, groundwater, subsidence.

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Introduction

Urban water supply is the priority use of water bodies. In Mexico agriculture is the most demanding user (77 %), the second is urban supply with 13 % and industry with 10 % (CNA, 2004). Irapuato City in Guanajuato State, Central Mexico (Figure 1) has similar percentages. Water supply for about 450,000 inhabitants of Irapuato is provided by 55 wells of a total of 90 drilled wells. Irapuato belongs to a large agriculture area with more than 1,200 active wells. Abstraction in the whole region exceeds 650 Mm^3 per year (Lesser and Asoc., 2000).

Local aquifer systems are the main water source for all users in El Bajio Guanajuatense. El Bajio is located in the Transmexican Volcanic Belt, where volcanic rocks predominate. The absence of exploitable surface water bodies is the cause of the intense use of groundwater. Arsenic, As, from the volcanic environment and fluorine, F, from evaporitic layers alter local groundwater quality. As and F concentrations in excess of the Mexican standards for drinking water were detected in some urban wells (Mendoza, 1999; Gonzalez *et al*., 2003; Rodriguez *et al*., 2006). Subsidence was reported since the 70`s. A first mapping of subsidence faults was done in 2001 (FOSEG, 2001). Subsidence was associated to abstraction in early 2000 (Rodriguez and Rodriguez, 2006).

In order to quantify the influence of the spatial distribution of crop fields on supply wells, a digital image analysis procedure was applied to a satellite image from the Terra/ASter sensor. This procedure yields in a segmentation of crop fields that depicts the spatial relationship between the fields, the wells and the subsidence faults. Crop fields within and outside the urban network are considered.

Water and urban land management

Urban development

The City was build around a shallow lake formed by the Guanajuato and Silao Rivers. In early 1900 the lake was desiccated. In the lake domain fine sediments such as clay, limes and clayey lenses were deposited. The recovered land was used for agriculture and urban expansion. The Guanajuato riverbed was detoured to avoid Irapuato downtown. These changes caused flooding and building instability on former lake lands.

Agriculture is the main economic activity. Regionally, Irapuato is famed for strawberries. Urban growth did not expel the vegetable growing from urban area. On the contrary, vegetable processing plants were established in Irapuato. Until the end of the last century more than 50 hectares of agriculture lands using groundwater were located in the urban area.

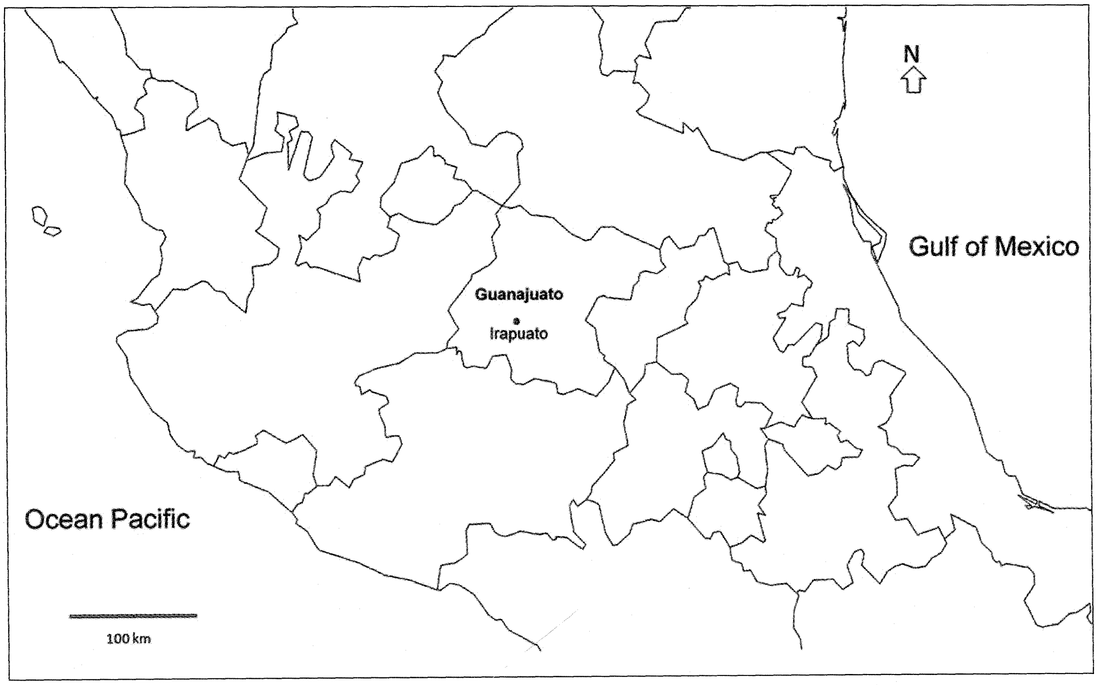

Figure 1. Location map, Irapuato City in Guanajuato State Mexico.

Subsidence and fault analysis

The first reports of land subsidence appeared in early 1970. Terrain breaks were associated with land instability. The first large fractures, locally called faults, were regarded as a natural phenomenon. Many geological faults are mapped in El Bajio although there is no evidence of active tectonic faulting in the area. There are no reports of seismic activity in the area.

The linearity of faults and fractures reveals a tectonic control because of their geometry. The dimensions and distribution of deformable materials such as clay and clayey layers obey tectonic and sedimentary processes. Water extraction causes the depressurization of clay layers and a consequent loss of volume. Subsidence has affected other cities in El Bajio such as Celaya, Salamanca, Silao and Abasolo (Borja and Rodriguez, 2004; Garduño *et al*., 2000).

Building damage by faulting did not become a major problem nor did it affect the population or the municipal authorities, but the frequent reparations of walls and floors represent an important economic invesment and losses to the population. The city also invests in repairing urban infrastructure. More than 200 houses have been affected until 2007. The economic losses are above 2 million dollars until 2007. A historical bridge located at the entry of the city is being demolished. In late 2007, 18 fault systems were detected with a total length of 27 km. A fault system is a main fault with its associated fractures. The accumulated vertical displacement in the urban area varies from 0.70 m to 2.1 m (Rodriguez *et al*., 2006).

Terrain subsidence affected also underground infrastructure. The differential displacements broke water pipelines and sewers. Irapuato neighborhoods with faults present frequent water shortage.

Methods

Groundwater sampling and chemical analysis

A groundwater monitoring was carried out at 23 urban and agriculture wells during spring and summer of 2006. Samples for As and BTEX index (benzene, toluene, ethylbenzene and xylene) determination were acquired. Chemical analyses were done at the Chemical Analytical Lab of the Geophysics Institute of the Universidad Nacional Autónoma de México. The analytical procedures followed Environmental Protection Agency (EPA) standard methods (Bloemen and Burn, 1993), with Gas Chromatography/Mass Selective Detector.

Satellite image processing

Segmentation of agriculture fields

A multi-spectral digital image from the Terra/Aster satellite (Marangoz *et al*., 2005) was used. The image covers the city of Irapuato and surroundings. This image was acquired on February 18, 2001, and the first 3 bands are taken into account. These bands feature a pixel size of 15′ 15 = 225 m^2. The other image bands are discarded since they feature a larger pixel size. Each of the 3 bands was input into a fuzzy clustering procedure with the following parameters: number of clusters = 30, movement threshold: 0.001, maximum number of iterations = 100. By means of an iterative procedure, the clusters are successively grouped until a fourth class image is obtained as follow (Figure 2): (1) small agriculture fields in urban area (black), (2) emerging agriculture fields (dark gray), (3) fully developed agriculture fields (light gray) and (4) the rest of the image (white). Some of the emerging fields are located in the urban area. This segmentation is overlaid with an RGB false color composite of the original bands (Figure 3), in order to determine the spatial context of crop fields. The segmentation of agricultural fields allows a quantification of morphologic parameters of these fields. Such morphology provides information related to the behavior of crop fields within the urban environment. In general, urban fields are small and regular because they are immersed in the urban network. Most of the emerging fields are medium size, and most of the fully developed fields are large size.

The a satellite image depicts the spatial distribution of crop fields. It establishes the spatial relationship between crop fields, urban environment and faults crossing the urban area. The segmentation of crop fields enable us to isolate areas devoted to agriculture within the urban network. Once this step is accomplished, a spatial connectivity of ground water extraction, crop field and subsidence is determined, and agriculture extraction for crop fields within the urban environment can be directly related to subsidence and faulting.

The segmentation of crop fields is necessary to evaluate morphological parameters associated to the spatial distribution of land devoted to agriculture. These parameters are used to assess the spatial state of crop fields, both within and outside the urban area. Clear differences are observed between these two groups of fields. In the following section we evaluate the morphology of agriculture fields. Based a such morphology, well defined differences may be observed among crop field classes as defined above. The

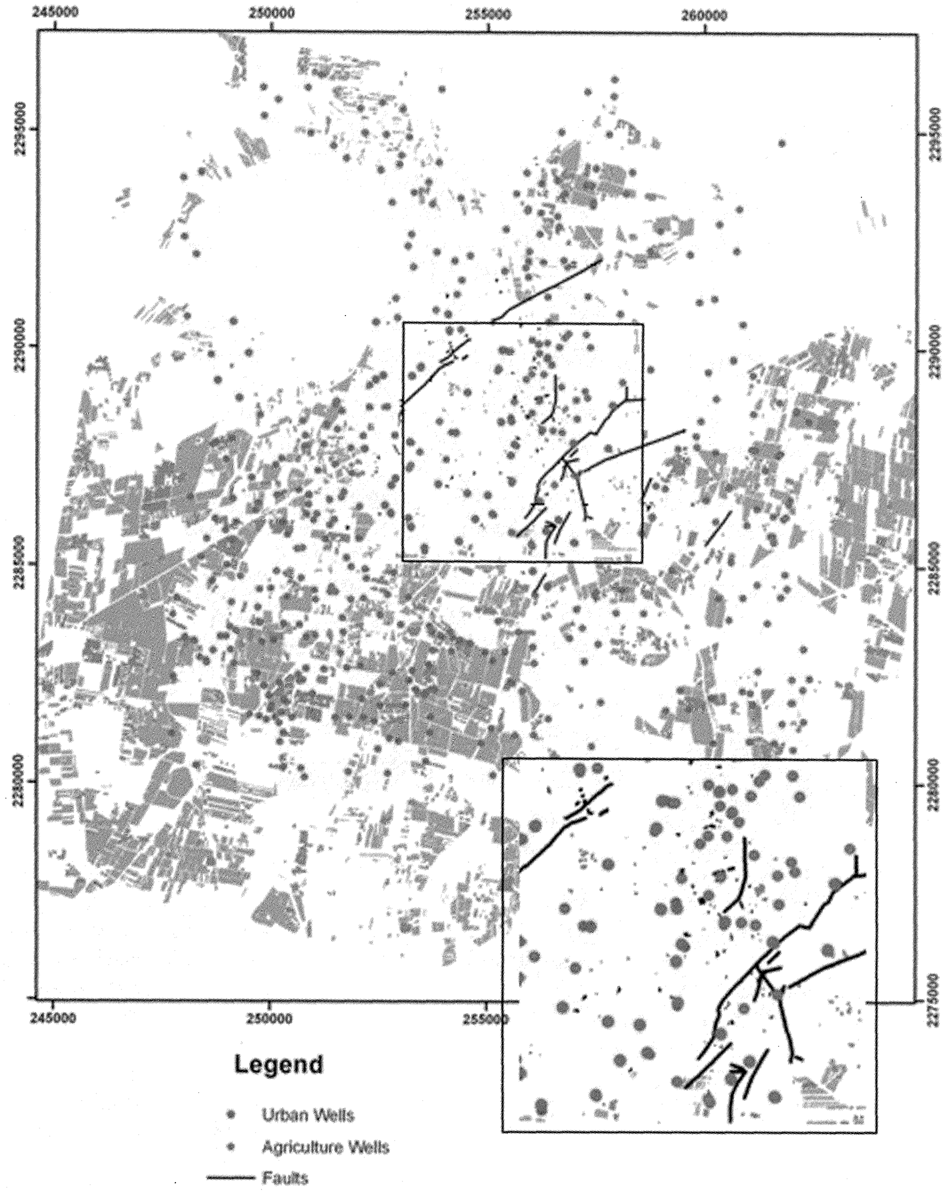

Figure 2. Bitmap of crop fields including wells and faults. Urban fields are depicted in black, emerging fields in dark gray and large fields in light gray.

morphology of urban crop fields is relatively simple as compared to those in open land outside the city, therefore, morphologic indicators are quantitative criteria to determine whether a crop field belongs to the urban area or not.

Morphology of agriculture fields

To evaluate the morphology of agricultural fields, the FragStats software was used (www.umass.edu). The procedure is as follows: image segmentation generates three images, and each image contains one class. These images dub the bitmap of each class. The bitmaps are input into the FragStats software and basic morphological parameters are calculated for each class. Figures 4, 5 and 6 show the distributions of perimeter, area and fractal dimension for the set of patches in each crop class.

Results

Faults increase locally the aquifer vulnerability due to the increasing in permeability around fault traces. The detection of toluene in areas with faults and gasoline stations proves groundwater contamination due to rapid infiltration of surface pollutants through faults. In six wells located near gas stations affected by faults low toluene concentrations were detected (Figure 7). In those areas there are no other potential sources of hydrocarbons. The maximum toluene concentration was 6.1 µg/L.

Agricultural terrains of small to large dimensions are scattered in the urban area (Figure 3). The fractal dimension is relatively high for large fields and decreases for medium and small fields (Figure 6). The distribution

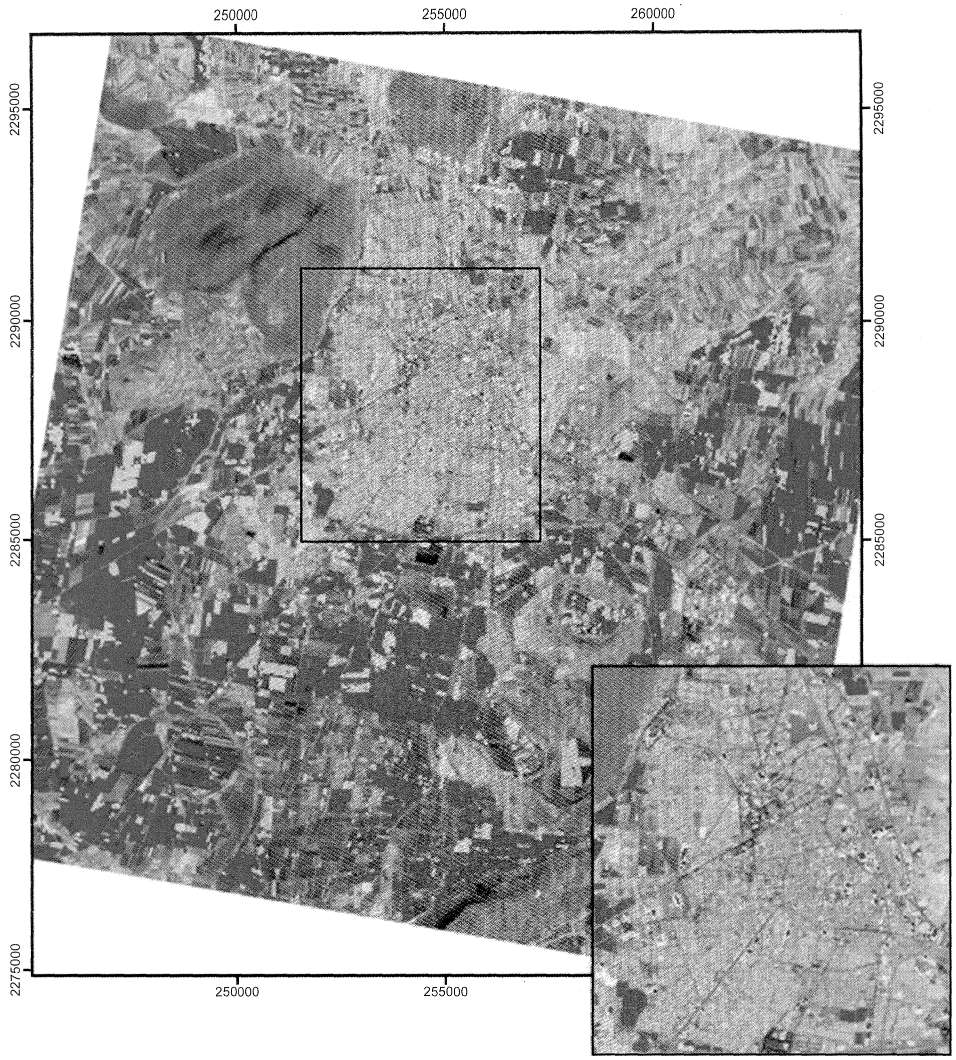

Figure 3. Overlay of crop fields with RGB false colour composite of an Aster image of the study area. Fields out of the urban area in red, fields into the urban area in blue.

by area shows a prevalence of relatively large areas in comparison to medium or small areas of less than 2,000 m^2 (Figures 6 a, b and c). Large agricultural lands require their own wells for irrigation.

The perimeter shows an exponential distribution for all classes; the larger the perimeter the fewer the patches. The area depicts a similar behavior. The fractal dimension, however, shows a certain variation for large crop fields, decreasing for emerging fields and even more for urban fields (Figure 6). The larger the field, the more fractal behavior it shows. On the other hand, urban fields are small and more rectangular-like; their fractal dimension shows less variation as depicted in Figure 6a.

In addition to the above morphology, landscape parameters were calculated. Landscape refers to the set of crop fields depicted in each bitmap. The definition of such parameters is the following

- Area (m^2) – Number of pixels of each class times pixel area: (225 $m^{2)}$.
- Patches – Number of pixel groups under 8-connectivity for each class.
- Patch density ($1/m^2$) – Number of patches divided by crop area.
- Landscape index – A measure of landscape heterogeneity.
- Perimeter/Area, fractal dimension (1/m) – Equals two over the slope of the regression line obtained by regressing the logarithm of patch area on the logarithm of patch perimeter.

The following table (Table 1) summarizes the value of parameters by crop class.

Table 1 shows that urban agriculture fields are few while emerging and fully developed fields

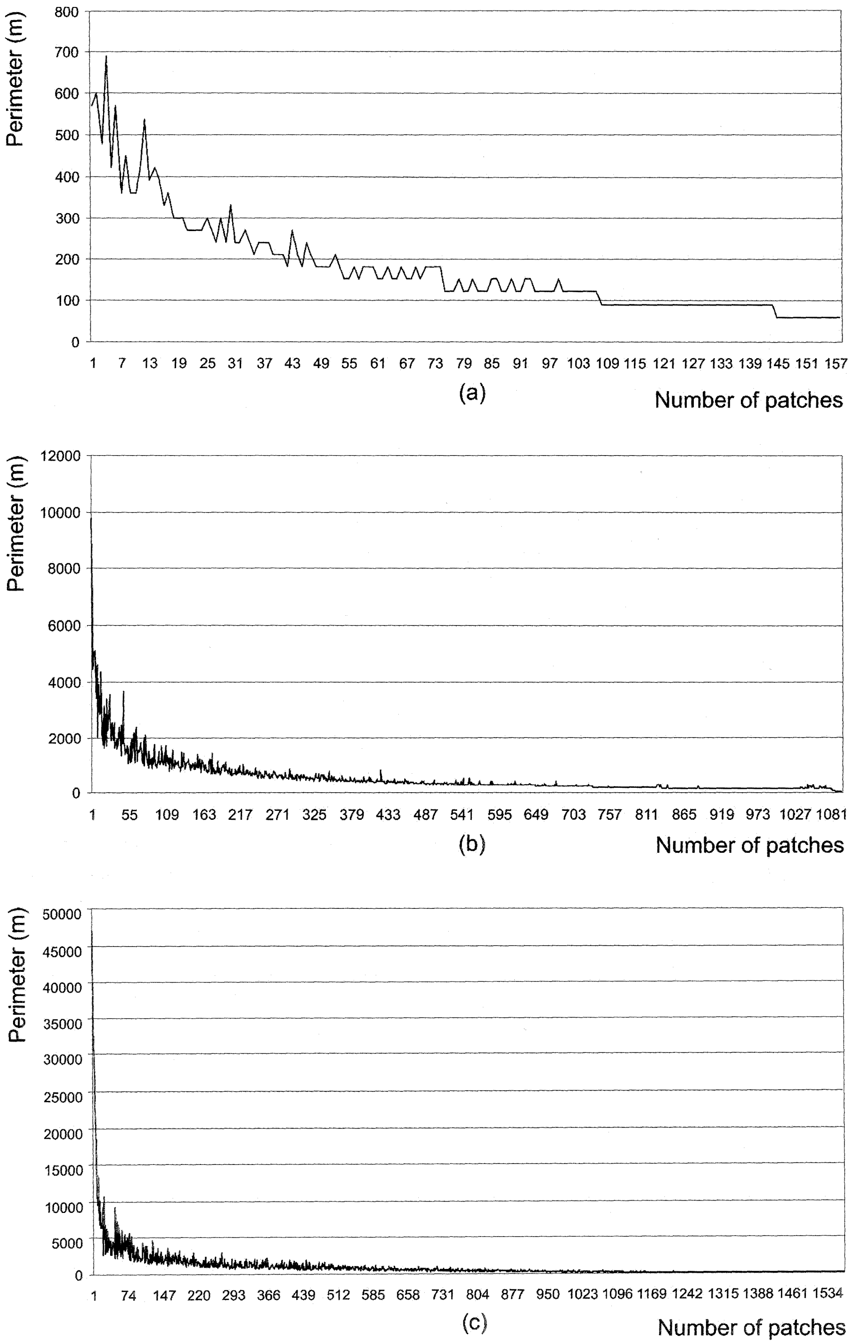

Figure 4. Distribution of perimeter for, (a) small fields, (b) emerging fields, and (c) fully developed fields. Number of patches in the *x* axis, the perimeter in m.

Table 1. Landscape parameters by crop field size.

	Area	Number of patches	Patch Density	Landscape index	Perimeter/Area fractal dimension
Urban fields	281,475	158	0.4155	13.4143	1.2167
Emerging Fields	15,940,575	1,096	2.8823	37.5422	1.3312
Fully Developed fields	57,357,450	1,956	5.1440	53.0515	1.2573

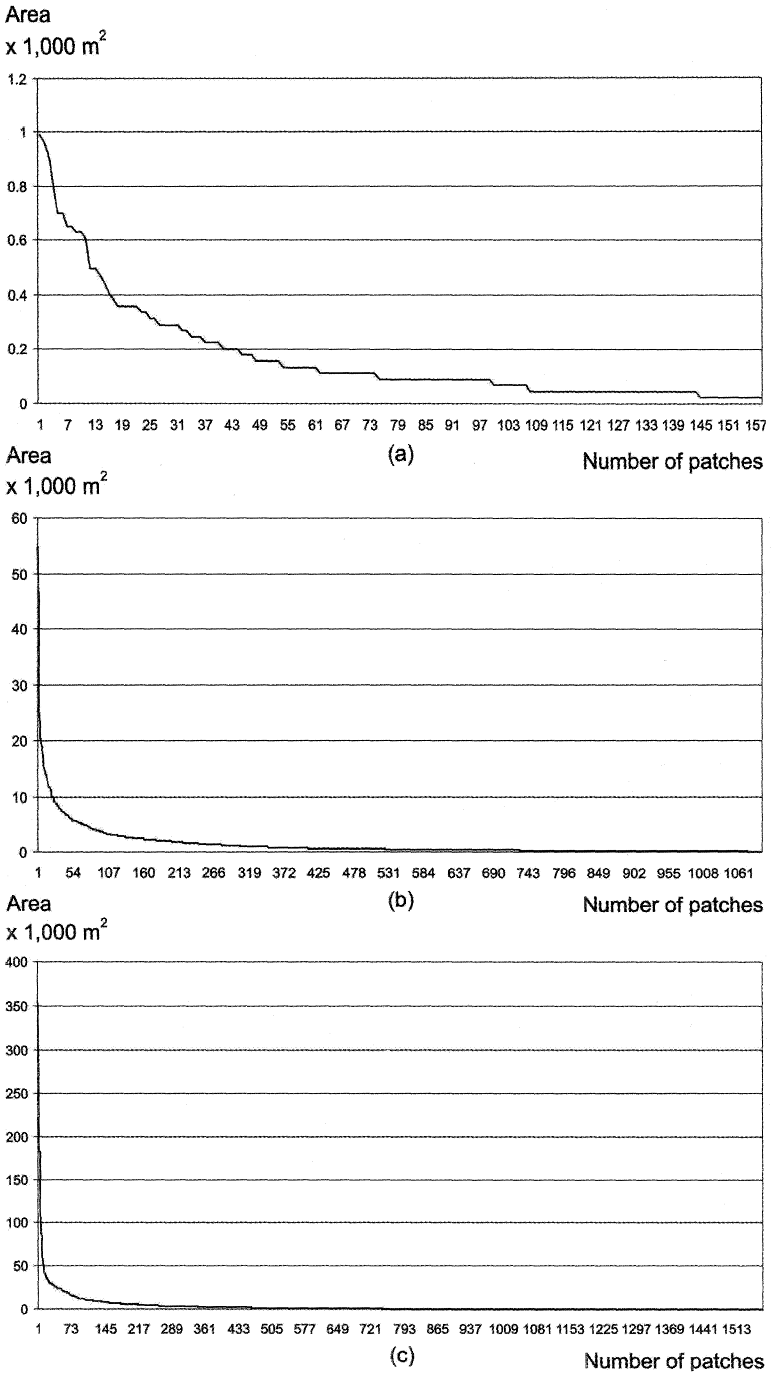

Figure 5. Distribution of area for, (a) small fields, (b) emerging fields, and (c) fully developed fields. Number of patches in the *x* axis, area in thousands of m^2.

consist of several hundred patches. Patch density varies according to this fact. The landscape index is a measure of landscape heterogeneity; the value of this index is relatively low for urban agricultural fields. As a result, the perimeter/area fractal dimension for these fields is relatively low. However, emerging fields present the highest complexity. Urban area includes all urban agricultural fields and a fraction of emerging fields and the total area of these fields is close to 50 Ha. This morphological analysis indicates that crop fields within the city present a distinctive spatial structure unlike those outside the city.

Discussion

The high dependence on groundwater for urban supply and urban agriculture in Irapuato City explains the high density of wells and the intense pumping regime. There are no municipal or federal regulations regarding or limiting the number or percentage of agriculture wells in urban areas.

The city is growing overextending on plastic and deformable lacustrine sediments. Abstraction exceeds recharge as it does in

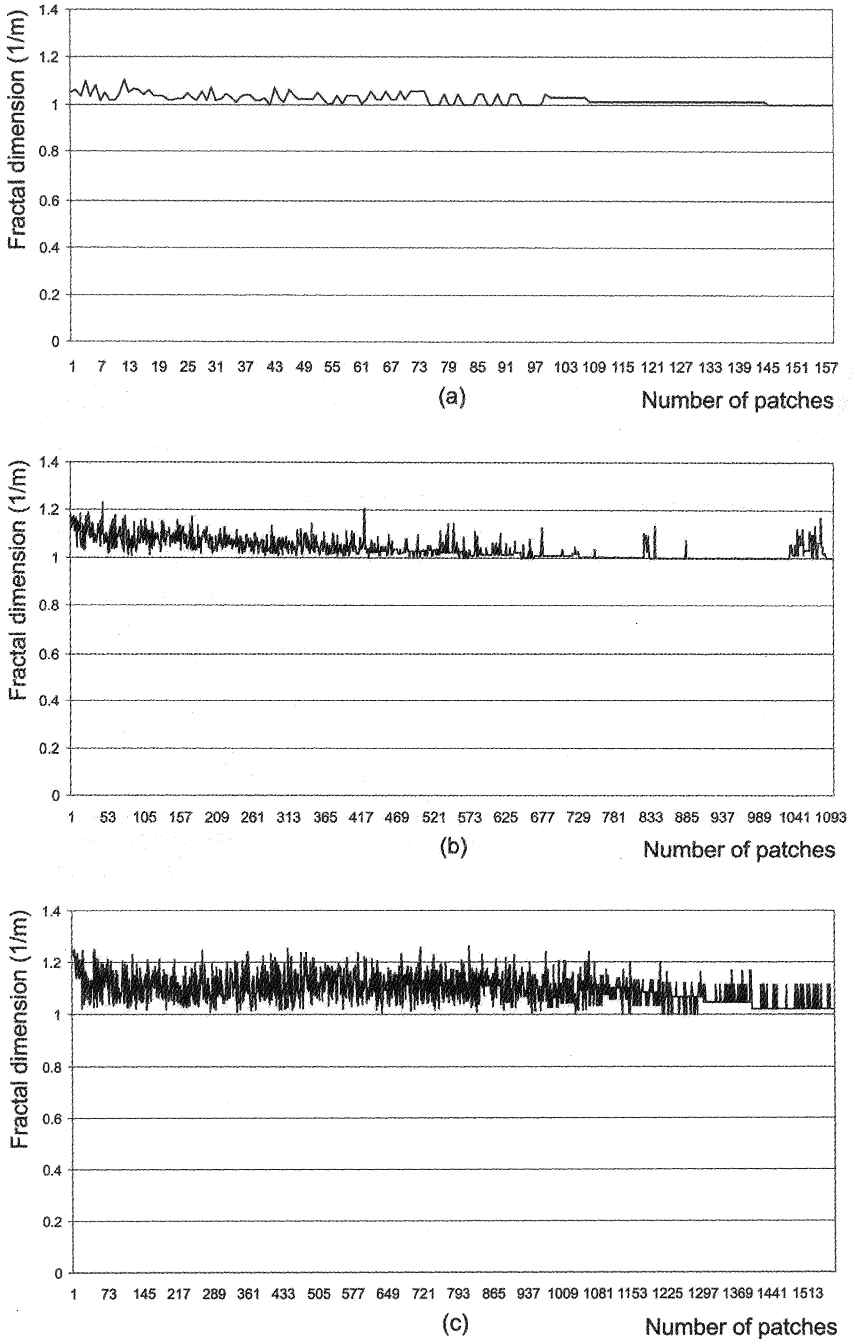

Figure 6. Distribution of fractal dimension for, (a) small fields, (b) emerging fields, and (c) fully developed fields. Number of patches is in *x* axis, units of fractal dimension are in 1/m.

most cities located in the Mexican High Lands (Esteller and Diaz-Delgado, 2002). Extraction is de-pressuring clay layers and originates land subsidence. Land compaction is irregular due to the irregular geometry and distribution of clay layers. The differential displacements rupture the terrain and form fractures that evolve into so called faults.

The well locations and rate of extraction did not take the related effects into account. The municipal water supply authority has drilled more than 80 urban wells due to the limited abstraction volume. Local producers drilled more than 1,200 wells on municipal land. The National Water Commission, CNA proposed an influence radius for wells of 400-500 m (CNA, 1993). The number of wells in the urban area shows a large interference of urban and agricultural wells (Figure 8).

The early reports of subsidence were not associated with groundwater abstraction. They were assumed to be an inevitable and natural phenomenon. There are no local studies demonstrating a relation between abstraction

Figure 7. Groundwater Toluene distribution.

and land subsidence, but the faults are well correlated with the location of lacustrine and clay layers. Vertical displacements were measured using a total station. A geological study corroborated the cause of subsidence (Rodriguez and Schroeder, 2010) Urban abstraction is much lower than regional agricultural extraction. There is no realistic abstraction assessment for wells located in the urban domain; even though they they have an influence on local subsidence. The subsidence faults facilitate the migration of contaminants into the exploited aquifer. The presence of toluene in groundwater near gasoline stations affected by faulting demonstrates the high aquifer vulnerability in faulted areas. There are no other potential sources of toluene in the area. Chlorine concentrations over regional background values were detected in areas around faults (Rodriguez *et al.*, 2006).

The use of morphological analysis shows the relevance of agricultural terrain distribution inside the urban area. This analysis indicates a difference between urban and non urban fields. Municipal authorities did not recognize the relevance of the distribution of agricultural fields in the urban domain. They did not associate agriculture fields with extraction or subsidence. We note that: (i) Urban fields are small and more rectangular-like due to the network of streets and avenues in the city, (ii) Some emerging agricultural fields are located within urban limits: the total area of crop fields within city limits is close to 50 Ha, (iii) The deviations from rectangular-like shape of urban fields causes fluctuations in the fractal dimension. Large fields are more irregular and feature a relatively high variation of fractal dimension. Urban fields do not show fractal behavior, but large fields do. In Figure 2,

Figure 8. Well interference in Irapuato.

among the two largest fault systems, there is a high density of small agricultural fields with active wells that contribute to subsidence along with urban wells. This analysis allows calculation of the distribution of agricultural lands inside the urban area and the presence of irrigation wells, and it shows the relevance of agricultural extraction in the subsidence processes.

In order to reduce the risk of land compaction, and the associated risk of infrastructure damage and aquifer contamination, municipal authorities should consider reducing agricultural abstraction or restricting agricultural water consumption located to lands outside the urban area.

Acknowledgements

The authors thank the financial support offered by DGAPA - UNAM, grant PAPIIT IN116010-2. Chemical analyzes were done at the IGF-UNAM Analytical Chemistry Lab by Aguayo A., Ceniceros N. and Cruz O.

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