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Methodologies for Analyzing Impact of Urbanization on Irrigation Districts

Rio Grande Basin Initiative

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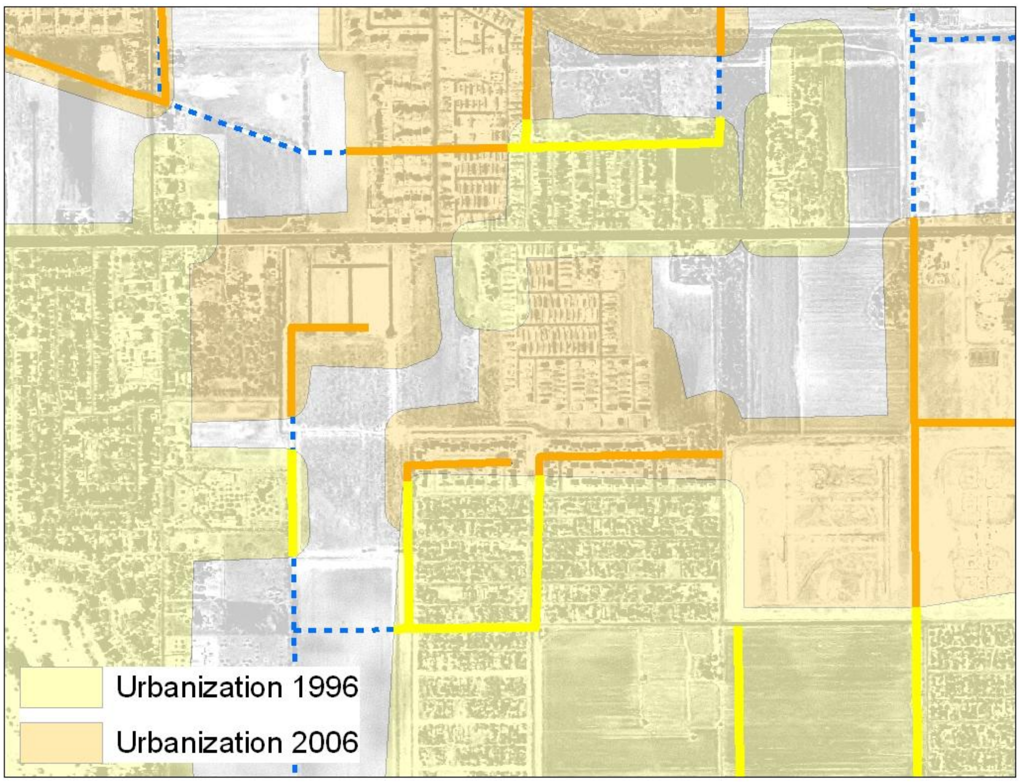

Rio Grande Basin Initiative
Irrigation Technology Center
Texas AgriLife Extension Service

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December 23, 2011

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EXECUTIVE SUMMARY

The region of Texas along the Mexican border has been experiencing rapid urban growth. This has caused fragmentation of many irrigation districts who are struggling to address the resulting challenges. In this paper, we analyze the growth of urban area and its impact on water distribution networks in three Texas border counties over the ten year period, 1996 to 2006. In particular, we discuss alternative procedures to assess such impacts, and we evaluate their effectiveness in identifying critical areas.

Identification of urbanized areas was carried out starting from aerial photographs using two different approaches: manual identification of areas "no longer in agricultural use" and automatic extraction based on the analysis of radiometric and structural image information. By overlapping urbanization maps to the water distribution network, we identified critical areas of impact. This impact was expressed as density of network fragments per unit area, or Network Fragmentation Index (NFI). A synthetic index per each district, District Fragmentation Index (DFI) was obtained by dividing the number of network fragments by the total district length of network. Results obtained starting from manual and automatic maps were comparable, indicating that the automatic urbanization analysis can be used to evaluate impact on the water distribution network.

To further identify critical areas of impact, we categorized urban areas with the Morphological Segmentation method, using a software available online (GUIDOS). The obtained categories (Core, Edge, Bridge, Loop, Branch, and Islet) not only improved the description of urban fragmentation, but also permitted assigning different weights to further describe the impact on the irrigation distribution networks. The application of this procedure slightly shifted the areas of impact and grouped them in more easy-to-interpret clusters.

We simplified urbanization analysis by identifying a probability of network fragmentation from network and urbanization density maps. Although results were comparable to the ones obtained with the other methods, additional validation is recommended.

These methods look promising in improving the analysis of the impact of urban growth on irrigation district activity. They help to identify urbanization and areas of impact, interpret growth dynamics, and allow for partial automation of analysis. It would be interesting to collaborate with irrigation districts to determine the correlation between the real impact on the district operation and the elements of the water distribution network included in the analysis.

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LIST OF ABBREVIATIONS

AUM: Automatic Urbanization Map
B-AUM: Buffered Automatic Urbanization Map
B-MUM: Buffered Manual Urbanization Map
DFI: District Fragmentation Index
DOQs: Digital Orthophoto Quadrangle Imagery
DPFI: District Potential Fragmentation Index
GIS: Geographic Information System
GUIDOS: Graphical User Interface for the Description of image Objects and their Shapes
MSPA: Morphological Spatial Pattern Analysis
MUM: Manual Urbanization Map
NDM: Network Density Map
NF: Network Fragment
NFa: Network Fragments obtained using B-AUM
NFI: Network Fragmentation Index
NFIa: Network Fragmentation Index calculated using NFa
NFIc: Corrected Network Fragmentation Index
NPFI: Network Potential Fragmentation Index
OO: Object-Oriented image analysis
PO: Pixel-Oriented image analysis
UFDM: Urban Fragments Density Map

Abbreviations for Irrigation Districts

Adams Garden: Adams Garden Irrigation District No.19
Bayview: Bayview Irrigation District No.11
BID: Brownsville Irrigation District
CCID2: Cameron County Irrigation District No.2
CCID6: Cameron County Irrigation District No.6
CCWID10: Cameron County Water Improvement District No.10
CCWID16: Cameron County Water Improvement District No.16
Delta Lake: Delta Lake Irrigation District
Donna: Donna Irrigation District-Hidalgo County No.1
Engelman: Engelman Irrigation District
Harlingen: Harlingen Irrigation District-Cameron County No.1
HCCID9: Hidalgo and Cameron County Irrigation District No.9
HCID1: Hidalgo County Irrigation District No.1
HCID13: Hidalgo County Irrigation District No.13
HCID16: Hidalgo County Irrigation District No.16
HCID19: Hidalgo County Irrigation District No.19
HCID2: Hidalgo County Irrigation District No.2
HCID6: Hidalgo County Irrigation District No.6
HCMUD1: Hidalgo County Municipal Utility District No.1
HCWCID18: Hidalgo County Water Control and Improvement District No.18

HCWID3: Hidalgo County Water Improvement District No.3
HCWID5: Hidalgo County Water Improvement District No.5
La Feria: La Feria Irrigation District-Cameron County No.3
Santa Cruz: Santa Cruz Irrigation District No.15
Santa Maria: Santa Maria Irrigation District-Cameron County No.4
United: United Irrigation District of Hidalgo County
Valley Acres: Valley Acres Water District
VMUD2: Valley Municipal Utility District No.2

INTRODUCTION

Individual irrigators and irrigation districts (districts) hold more than 80% of total water rights along the Texas Rio Grande (TCEQ, 2010). As districts urbanize, Texas water laws and regulations require that the associated water rights be transferred from agricultural to municipal water use. Thus, not only does urbanization reduce the size of service areas, but also reduces the amount of water districts have access to and which flows through their canals and pipelines.

Industrial, commercial and retirement community development are resulting in rapid urban growth within portions of the Texas Rio Grande River Basin. The fastest growing areas are Hidalgo and Cameron Counties. The four largest cities of Alamo, McAllen, Brownsville and Harlingen are among the fastest growing cities in the USA (Stubbs et al., 2003; City of McAllen, 2010). Texas is predicted to have the fastest population growth in the USA between 2010 and 2060, and Region M, which includes eight Counties in the South-Western area, is predicted to have the highest growth in Texas, with +182% (Texas Water Development Board, 2012). Within Region M, Hidalgo and Cameron are the most populated Counties, with an expected growth of +103 and +164% respectively between 2010 and 2060 (Rio Grande Regional Water Planning Group, 2010).

Urbanization in South Texas is causing the fragmentation and loss of agricultural land, with detrimental effects on normal operation and maintenance of districts (Gooch and Anderson, 2008, Gooch, 2009). In particular, districts have to abandon structures and invest in new ones to ensure proper operation, change how to operate systems when canals become oversized, and increase rates to address the challenge of reduced revenues from water sales. Districts in this region primarily operate their systems manually, with a canal rider personally moving from site to site. As a consequence, urbanization can create access to and maintenance of facilities difficult or more time consuming. Transfer of water rights from agricultural to other uses reduces the total amount of water flowing through the water distribution networks, which typically decreases conveyance efficiency and increases losses. Finally, the increasing presence of subdivisions and industrial areas in the vicinity of the delivery network increase the liability for canal breaks and flooding.

Most districts in the region do very little analysis of the effects of urbanization on their operation and management procedures, or incorporate urbanization trends into planning for future infrastructure improvements. Therefore, there is a need for identification of critical areas. There would be several benefits from such analysis, for example identify priority areas for conversion from open canal to pipeline (Lambert, 2011).

The objective of this paper is to compare alternative procedures and techniques to assess urbanization impacts on irrigation districts and to evaluate their effectiveness in identifying critical areas.

Literature review

Several methodologies have been used to identify urban area extent and growth. Many studies use satellite archive imagery as source of data (e.g. Landsat) which are becoming more readily available, are characterized by a multi-spectral data, and have good spatial resolution for landscape scale analysis. When analysis is carried out on smaller areas, results can be more accurate using aerial photographs which provide more detail on geometric information. Another advantage of using aerial photography is the precise identification of vegetation possible with infrared information. Analysis of imagery data for interpretation of land use and land cover dynamics can be performed with automatic procedures. The most utilized approaches are Pixel-Oriented (PO) and Object-Oriented (OO) analysis. In the last decade, several studies demonstrated that the OO method can give more accurate results compared to PO (Pakhale and Gupta, 2010). Furthermore, OO analysis gives better results when trying to fully distinguish roads from buildings (Chen at al., 2009).

Urbanization maps identify only the location of urban areas. To interpret the evolution of spatial patterns, Ritters, et al. (2000) proposed a model which distinguishes different types of forest fragmentation through an automatic pixel analysis of aerial photography. Ritters' analysis is used to determine the progressive intrusion of urbanization, classified into categories: edge, perforated, transition and patched. Vogt, et al. (2007) and Soille and Vogt (2009) proposed an improvement in Ritters method by analyzing the fragmentation on the base of image convolution, called the Morphological Segmentation method. This method helps to prevent misclassifications of fragmentation and can be easily applied using a free software (Soille and Vogt, 2009, GUIDOS, 2008).

Impact on districts can be measured not only with the size or the type of urbanization intrusion in their service area, but also with a specific analysis of the interaction between water distribution network and urban expansion. Little attention has been given to this aspect (Gooch, 2009).

MATERIAL AND METHODS

Study area

Six counties along the Texas-Mexico border have irrigation districts with Texas Class A water rights. Our analysis was carried out on the three southern counties of the basin: Cameron, Hidalgo, and Willacy (Fig. 1). These counties contain 28 irrigation districts with a total service area of 759,200 acres, and a canal system 3,174 miles long. Based on water rights, the districts vary greatly in size. The smallest active district has 1,120 ac-ft of Class A Water Right (Hidalgo County Municipal Utility District No.1), while the largest district has 177,151 ac-ft (Hidalgo and Cameron County Irrigation District No.9) (Table 1). Actual water allocations in any given year depend on the amount of water stored in the Falcon Reservoir.

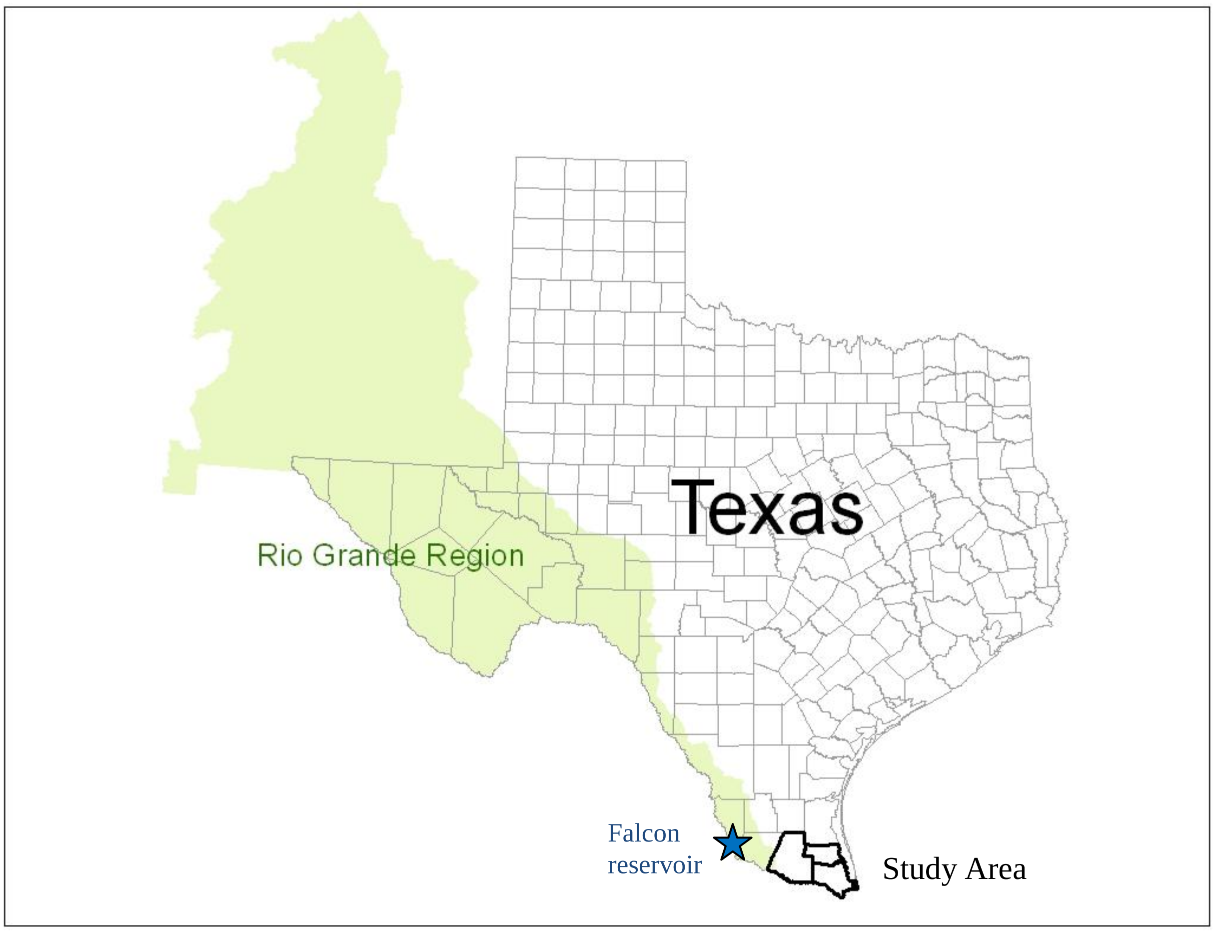

Figure 1. Location of the study area

Table 1. Class A Water Rights of districts in the Lower Rio Grande Basin

District	Class A Water Right (Acre-Feet)
Adams Garden Irrigation District No.19 (Adams Garden)	18,738
Bayview Irrigation District No.11 (Bayview)	16,978
Brownsville Irrigation District (BID)	33,949
Cameron County Water Improvement District No.16 (CCWID16)	3,713
Cameron County Irrigation District No.2 (CCID2)	147,824
Cameron County Irrigation District No.6 (CCID6)	52,142
Cameron County Water Improvement District No.10 (CCWID10)	8,488
Delta Lake Irrigation District (Delta Lake)	174,776
Donna Irrigation District-Hidalgo County No.1 (Donna)	94,064
Engelman Irrigation District (Engelman)	20,044
Harlingen Irrigation District-Cameron County No.1 (Harlingen)	98,233
Hidalgo and Cameron County Irrigation District No.9 (HCCID9)	177,152
Hidalgo County Irrigation District No.1 (HCID1)	85,615
Hidalgo County Irrigation District No.13 (HCID13)	4,857
Hidalgo County Irrigation District No.16 (HCID16)	30,749
Hidalgo County Irrigation District No.19 (HCID19)	9,048
Hidalgo County Water Control and Improvement District No.18 (HCWCID18)	5,318
Hidalgo County Irrigation District No.2 (HCID2)	137,675
Hidalgo County Water Improvement District No.5 (HCWID5)	14,235
Hidalgo County Irrigation District No.6 (HCID6)	34,913
Hidalgo County Municipal Utility District No.1 (HCMUD1)	1,120
Hidalgo County Water Improvement District No.3 (HCWID3)	9,753
La Feria Irrigation District-Cameron County No.3 (La Feria)	75,626
Santa Cruz Irrigation District No.15 (Santa Cruz)	75,080
Santa Maria Irrigation District-Cameron County No.4 (Santa Maria)	10,183
United Irrigation District of Hidalgo County (United)	57,374
Valley Acres Water District (Valley Acres)	16,124
Valley Municipal Utility District No.2 (VMUD2)	5,511
Total	1,419,282

* Water allocation under the Rio Grande Compact

Urbanization Maps and Network Fragmentation Index

Manual Urbanization Maps

Manual Urbanization Maps (MUM) were created manually starting from aerial photography (Fig. 2). We used the Geographic Information System (GIS) software ArcView 9.3 to draw urban areas, and Digital Orthophoto Quadrangle Imagery (DOQs), with a resolution of 1 m (year 1996) and 2 m (year 2006), obtained from the Texas Natural Resources Information System (http://www.tnris.state.tx.us). In this work, "urban area" is loosely defined as a continuous developed and/or developing area that is no longer in agricultural use. We included all residential communities and subdivisions (with or without homes) that are clearly identifiable from aerial photographs, and properties with more than one dwelling or other structure on a single piece of property. Single dwellings on large properties outside the city limits were excluded. Areas inside the city limits were not analyzed and were considered as completely urbanized. The methodology was presented with some preliminary results by Leigh, et al. (2009). By overlapping the MUM to the water distribution network, we then calculated the amount of elements including open canals, pipelines, reservoirs, and resacas that are engrossed by urban areas.

Network Fragmentation Index

In order to measure the overlapped water distribution network, we modified MUM by adding a 0.3-miles buffer, to obtain Buffered Manual Urbanization Maps (B-MUM). By overlapping B-MUM with open canals and pipelines we identified Network Fragments (NF) (Fig. 3). We then used the Kernel density to count the number of times in a given area that open canals and pipelines are overlapped by urbanization (mi/mi^2). This method is a data smoothing technique that gives more weight to points near the center of each search area and allows for creating a more continuous surface that is easier to interpret (Kloog et al., 2009). We used a 0.2-mile output cell size, and a 1.5-miles search radius. To facilitate comparison among the different study areas, we normalized the Kernel density based on the highest observed value. We obtained a scale that ranges from 0 to 1, and we called it Network Fragmentation Index (NFI):

$$NFI = \frac{\#\,fragments}{Sample\ area} = \#fragments/mi^2$$

For each district, we calculated the ratio between the NF and the total length of canals. This computation has the advantage of giving one number for each irrigation district. We called this ratio District Fragmentation Index (DFI):

$$DFI = \frac{\#\,fragments}{Total\ nework\ length} = \#fragments/mi$$

Further details of this methodology can be found in Bonaiti et al. (2010).

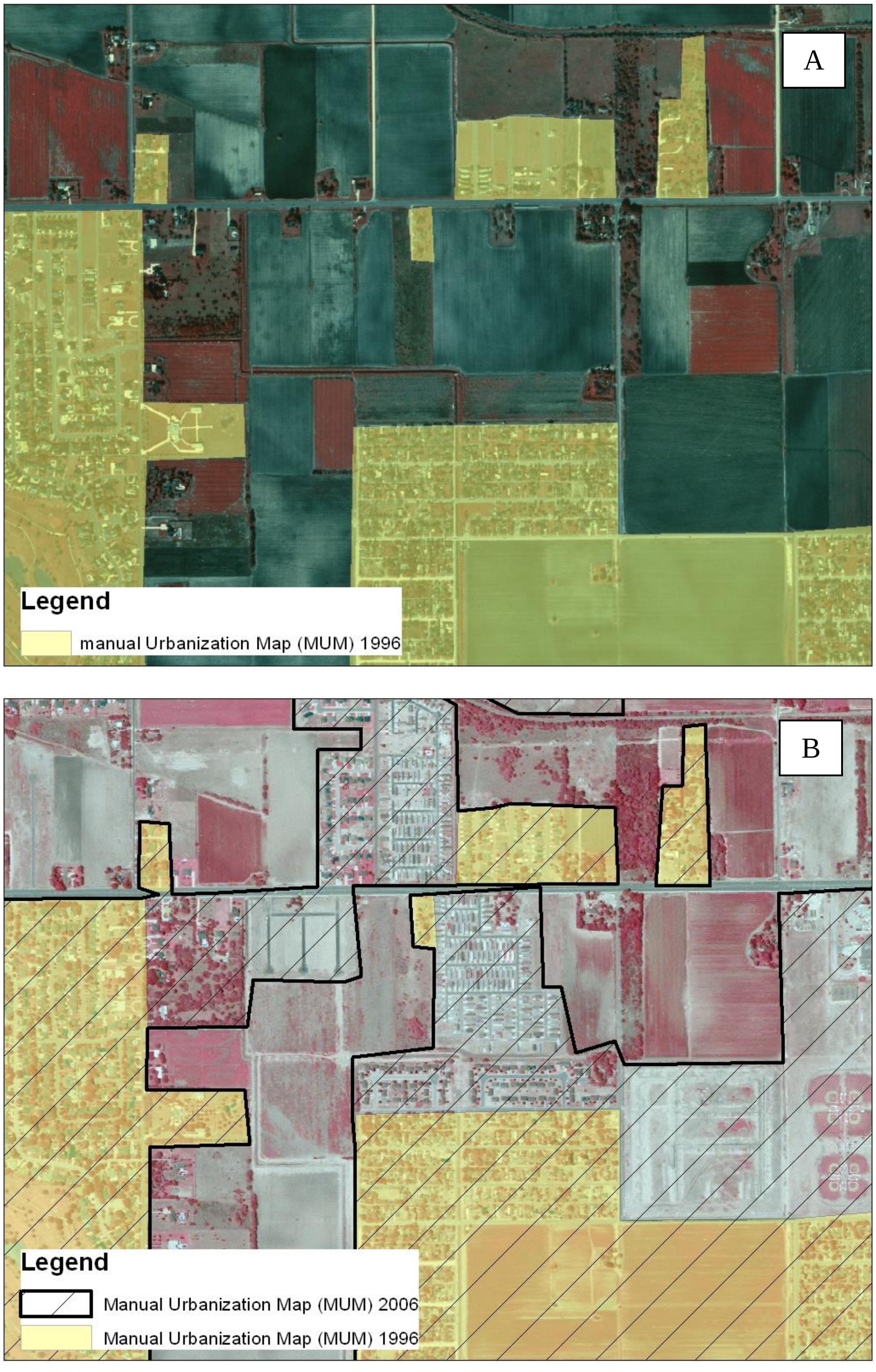

Figure 2. Urban area manually identified from aerial photography (Manual Urbanization Map, MUM): A) 1996, B) Expansion 2006.

Figure 3. Buffered Manual Urbanization Maps (B-MUM) obtained adding a 0.3-mile buffer to MUM. Identification of water distribution network overlapped (Network Fragments, NF)

Automatic Urbanization Maps

We created urbanization maps using the eCognition software, which is based on an object-based image analysis method. We called them Automatic Urbanization Maps (AUM). Since the preparation of aerial photography is time consuming, we applied the methodology only to the South Eastern portion of the Brownsville Irrigation District (BID) for the year 2006. The method was also applied to the area inside the city limits. This method is faster and give higher detail compared to MUM, but since is based on a slightly different approach (e.g. all houses are included) consistency between the two methods must be evaluated.

Similarly to what done with MUM, we added 0.03-mile buffer to AUM to create a Buffered Automatic Urbanization Map (B-AUM). Then we overlapped it with open canals and pipelines and we identified NFa. Finally, we applied the Kernel density to NFa and we obtained the NFIa.

Morphological Segmentation Method

In order to add information to the urbanization maps, we categorized them using the Morphological Segmentation Method. The categories that are defined by the procedure are: Core, Edge, Perforation, Bridge, Loop, Branch, Islet. We used the GUIDOS 1.3 software (Vogt, 2010). In particular, the software implements the Morphological Spatial Pattern Analysis (MSPA) and allows modification of four (4) parameters as described in the MSPA Guide (Vogt, 2010):

- *Foreground Connectivity: for a set of 3 x 3 pixels the center pixel is connected to its adjacent neighboring pixels by having either a) a pixel border and a pixel corner in common (8-connectivity) or, b) a common pixel border only (4-connectivity). The default value is 8*
- *Edge Width: this parameter defines the width or thickness of the non-core classes in pixels. The actual distance in meters corresponds to the number of edge pixels multiplied by the pixel resolution of the data. The default value is 1*
- *Transition: transition pixels are those pixels of an edge or a perforation where the core area intersects with a loop or a bridge. If Transition is set to 0 (↔ hide transition pixels) then the perforation and the edges will be closed core boundaries. Note that a loop or a bridge of length 2 will not be visible for this setting since it will be hidden under the edge/perforation. The default value is 1*
- *Intext: this parameter allows distinguishing internal from external features, where internal features are defined as being enclosed by a Perforation. The default is to enable this distinction which will add a second layer of classes to the seven basic classes. All classes, with the exception of Perforation, which by default is always internal, can then appear as internal or external (default value equal to 1)*

We applied the methodology to B-MUM, B-AUM, and AUM. We used default values for the four parameters except for the Edge Width with AUM, which was set to 10 to account for the smaller pixel size of this map. To be suitable for the software, the original files (shapefiles) had to be first converted to raster. To do that, we chose a cell size that looked reasonable for the type of detail of the original map. Therefore we used a cell size of 310 for B-MUM and B-AUM, and a cell size of 31 for AUM.

Based on the idea that network fragmentation has a different impact on districts operation according to the category that overlaps it, we also set up a procedure to correct the NFI using a categorization map. Using the 1996 B-MUM, we gave the following weights to categories: 1, 2, 3, 4, 5, and 10, respectively for Core, Edge, Bridge, Loop, Branch, and Islet (no results were obtained for the Perforation category in our maps). In other words, we assumed that the impact on district operation is greater if a new subdivision overlaps a canal in a remote area, where district personnel and farmers are not well organized to adapt to such changes. Using the Raster Calculator ArcGIS tool we multiplied the category weights by the NFI, and then normalized the results based on the maximum value. We called the result the Corrected Network Fragmentation Index (NFIc).

Network Potential Fragmentation Index

To avoid the burden of extracting NF and then combining them to urbanization maps to obtain NFI, we tested a simplified procedure based on a probable number of NF instead of the measured one. We first created an Urban Fragments Density Map (UFDM) by calculating the density of urban fragments in the 1996 MUM (i.e. the number of isolated urbanized polygons per area unit). To do this, we applied the "Feature to Point" ArcGIS tool to the urbanization polygons and then the "Kernel Density" tool to the resulting point map. In both cases we used default values. Secondly, we created a Network Density Map (NDM) by applying the "Line Density" tool (with default values) to canals and pipelines. Using the "Raster Calculator" tool, we multiplied the UFDM values by the NDM values, and then normalized the results based on the maximum value. We called the result Network Potential Fragmentation Index (NPFI). In analogy with DFI, we finally calculated for each district a District Potential Fragmentation Index (DPFI). This was done by calculating the ratio between the sums of NPFI pixels values and the total length of canals and pipelines.

RESULTS AND DISCUSSION

Urbanization Maps and Network Fragmentation Index

Manual Urbanization Maps

Results of the urbanization analysis include the following:

- Using the MUM, we estimated that from 1996 to 2006 the urban area increased at an average of 31% (from 9 to 12% of the total County area), with peaks values in the Hidalgo County (Table 2).
- We found that the urban area within districts increased an average of 45.2 based on total district service area (from 17.9 to 26% of the total district area), with great differences among districts (Table 3).
- The distribution networks were increasingly engrossed by urban areas. During the ten year period (1996-2006), about 800 more acres of storage facilities (reservoirs and *resacas*[1]) became a part of urban areas (28% increase), and an additional 360 miles of canals flowed through urban areas (from 23 to 27% of the total network length) (27% increase). No major differences were found among categories (main, secondary), materials (concrete, earth, PVC), or types (canal, pipeline) (Table 4).
- The method, although time consuming, clearly identifies and quantifies urban area fragmentation, and is easy to use and interpret.

[1] An area of river bed that is flooded in periods of high water; an artificial reservoir (Dictionary of American Regional English, 2011)

Table 2. Urban area within Counties in 1996 and 2006

County	Total Area (Acres)	Urban Area 1996 (Acres)	Urban Area 1996 (% of tot)	Urban Area 2006 (Acres)	Urban Area 2006 (% of tot)	Increase (%)
Cameron	613,036	66,189	11	81,635	13	23
Hidalgo	1,012,982	118,466	12	160,095	16	35
Willacy	393,819	3,084	1	3,509	1	14
Total/Average	2,019,837	187,739	9	245,239	12	31

Table 3. Urban area within districts as a percentage of total district service area in 1996 and 2006

District	Total Area (Acres)	Urban Area 1996 (Acres)	Urban Area 1996 (% of tot)	Urban Area 2006 (Acres)	Urban Area 2006 (% of tot)	Increase (%)
Adams Garden	9,600	532	5.5	1,380	14.4	159
Bayview	10,700	24	0.2	120	1.1	400
BID	22,000	8,724	39.7	9,915	45.1	14
CCWID16	2,200	260	11.8	415	18.9	60
CCID2	79,000	8,384	10.6	10,925	13.8	30
CCID6	33,000	4,439	13.5	7,948	24.1	79
CCWID10	4,700	135	2.9	224	4.8	66
Delta Lake	85,600	1,127	1.3	1,841	2.2	63
Donna	47,000	4,357	9.3	7,310	15.6	68
Engelman	11,200	144	1.3	331	3.0	130
Harlingen	56,500	14,662	26.0	16,955	30.0	16
HCCID9	87,900	16,721	19.0	22,716	25.8	36
HCID1	38,600	22,633	58.6	25,327	65.6	12
HCID13	2,200	117	5.3	469	21.3	301
HCID16	13,600	83	0.6	1,005	7.4	1,111
HCID19	4,800	0	0.0	1,908	39.8	
HCWCID18	2,400	15	0.6	300	12.5	1,900
HCID2	72,600	33,006	45.5	39,107	53.9	18
HCWID5	8,100	1,142	14.1	1,424	17.6	25
HCID6	22,900	5,677	24.8	9,595	41.9	69
HCMUD1	2,000	1,016	50.8	1,811	90.6	78
HCWID3	9,100	6,618	72.7	6,936	76.2	5
La Feria	36,200	2,626	7.3	3,809	10.5	45
Santa Cruz	39,500	2,889	7.3	3,715	9.4	29
Santa Maria	4,000	242	6.1	365	9.1	51
United	37,800	15,336	40.6	17,794	47.1	16
Valley Acres	11,200	162	1.4	162	1.4	0
VMUD2	4,800	1,142	23.8	1,142	23.8	0
Total/Average	759,200	152,213	17.9	194,949	26.0	45.2

Table 4. Percent increase in the length of canals and pipelines overlapped by urbanization from 1996 to 2006

	Category		Material			Type		
Irrigation District	Secondary	Main	Concrete	Earth	PVC	Canal	Pipeline	Total
Adams Garden	53	163	62	588	33	210	51	66
Bayview	432	39		130		225	279	255
BID	28	8	21		44		22	21
CCWID16		5		5		5		5
CCID2	69	37	42	50	163	52	51	52
CCID6	58	21	49	40		48	35	45
CCWID10		168		72		72		182
Delta Lake	104	107	111			94	110	104
Donna	41	74	49	14		70	18	46
Engelman	62	148	76			129	70	76
Harlingen	37	9	35	7		9	37	28
HCCID9	22	12	20	9		12	22	20
HCID1	11	12	12	6	22	8	13	11
HCID13	0	93	0		161		93	84
HCID16	780	294	752		262	387	808	648
HCID2	12	20	12	55	3	27	13	15
HCWID5		1	1				1	1
HCID6	28	38	37			32	27	29
HCWID3		22		81		31		21
La Feria	32	31	37	4		24	35	32
Santa Cruz	16	29	19			17	19	19
Santa Maria	103		103				103	58
United	9	18	10		41	14	9	10
Total	29	24	27	30	36	34	24	27

Network Fragmentation Index

Conclusions from the network fragmentation analysis include:

- The use of B-MUM clearly identifies network fragmentation (Fig. 4)
- The representation of NFI as a density map quantifies and identifies precise locations of fragmentation (Fig. 5)
- DFI helps to rate the District, and identifies the ones more affected by fragmentation (Fig. 5)

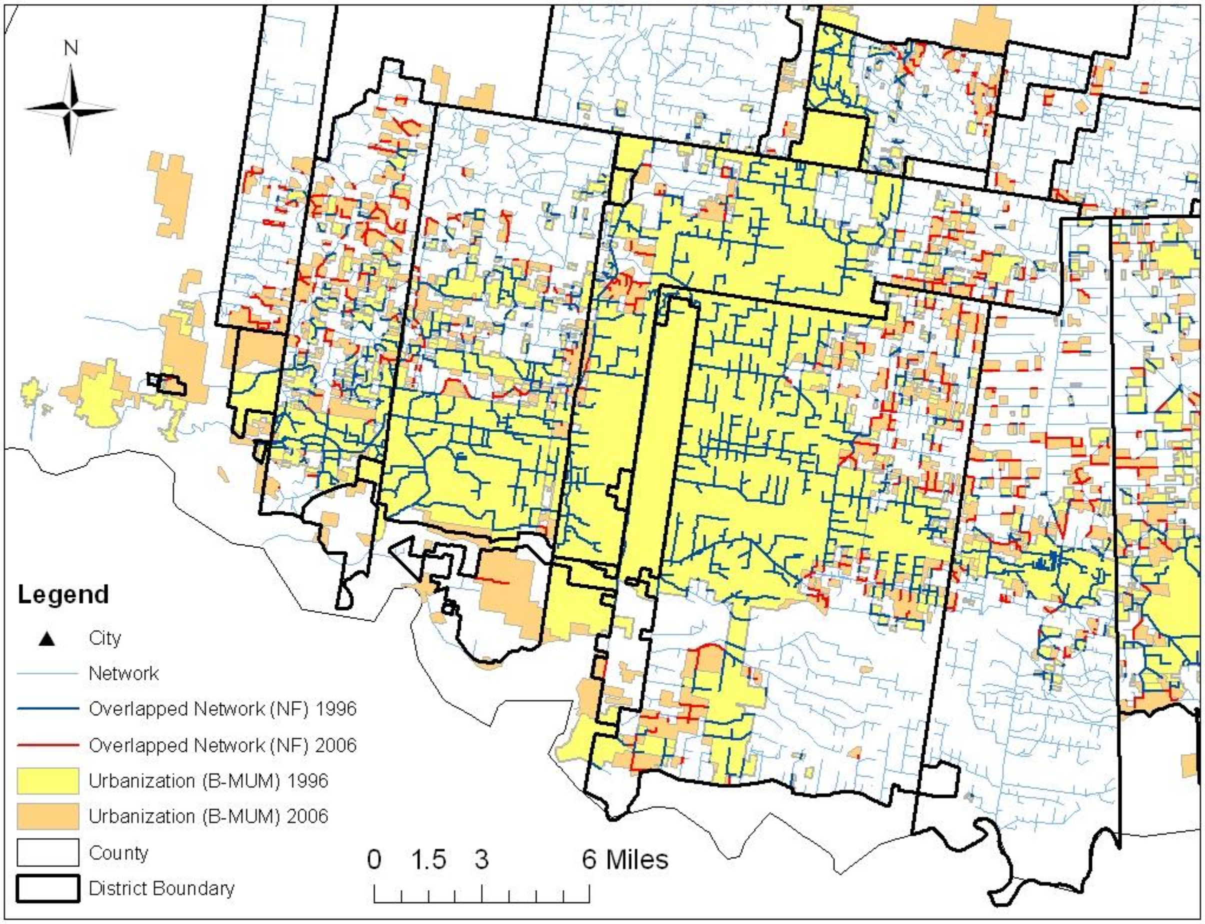

Figure 4. Increase in urbanization in the McAllen area of the Hidalgo County in 1996 and 2006 (B-MUM), and overlapped water distribution network (NF)

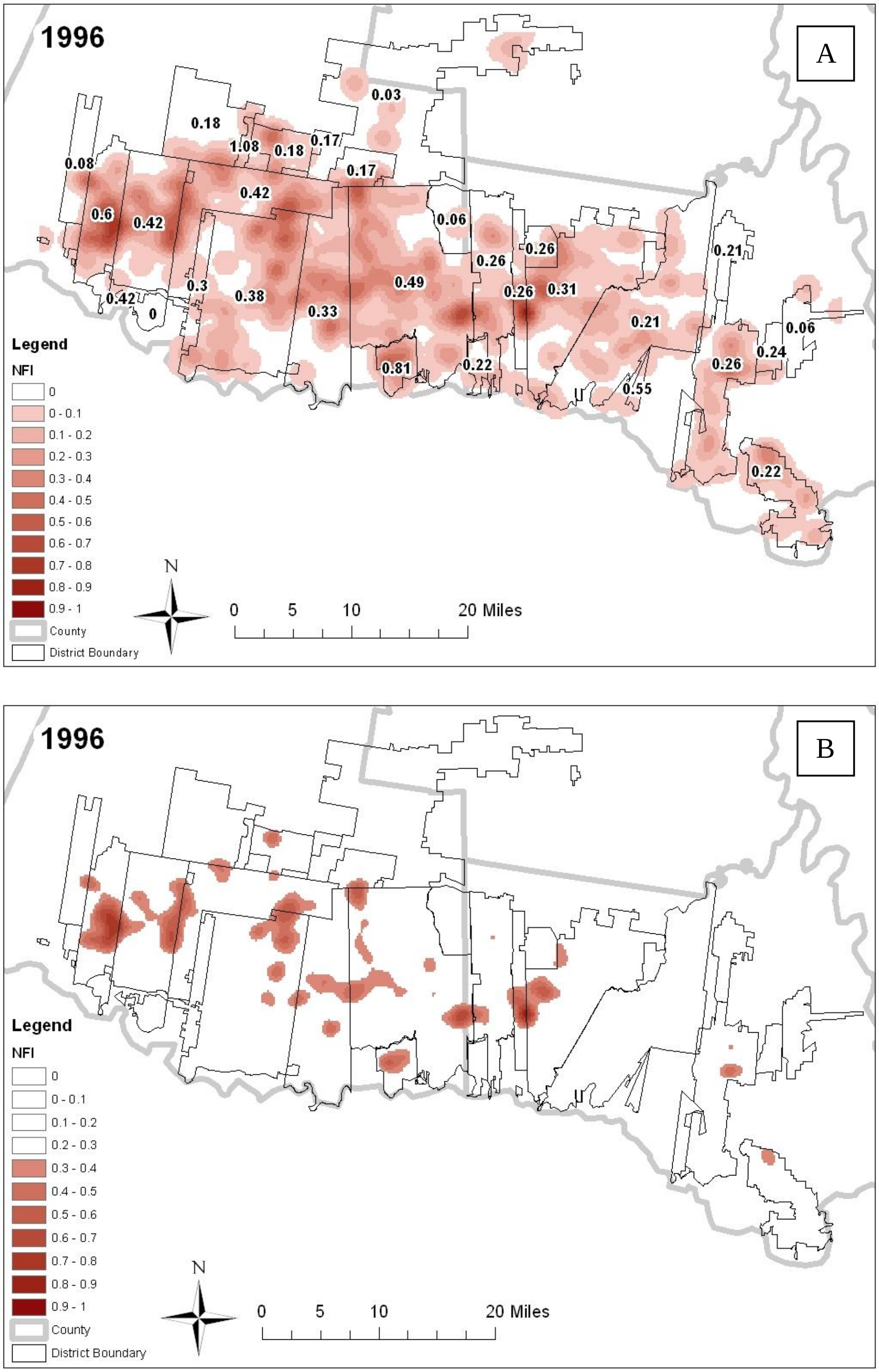

Figure 5. A) District Fragmentation Index (DFI) for each district along with the NFI (Network Fragmentation Index), shown as a density map, in the year 1996; B) Values >0.3 for 1996 NFI for easier identification of areas with higher fragmentation

Automatic Urbanization Maps

In Figure 6 we compare the urban areas identified with the manual (MUM) and the automatic (AUM) methods. Major urbanized areas are identified with both methods. Differently from MUM, AUM identifies individual buildings rather than urbanized area (Fig. 7).

Overlap to canals and pipelines of buffered maps (B-MUM and B-AUM) was performed only outside the city limits. We obtained a different number of network fragments (NF and NFa) in the two cases (Fig. 8). Although the highest values of NFI and NFIa are located in different areas, the two major areas of fragmentations are identified with both maps (Fig. 9).

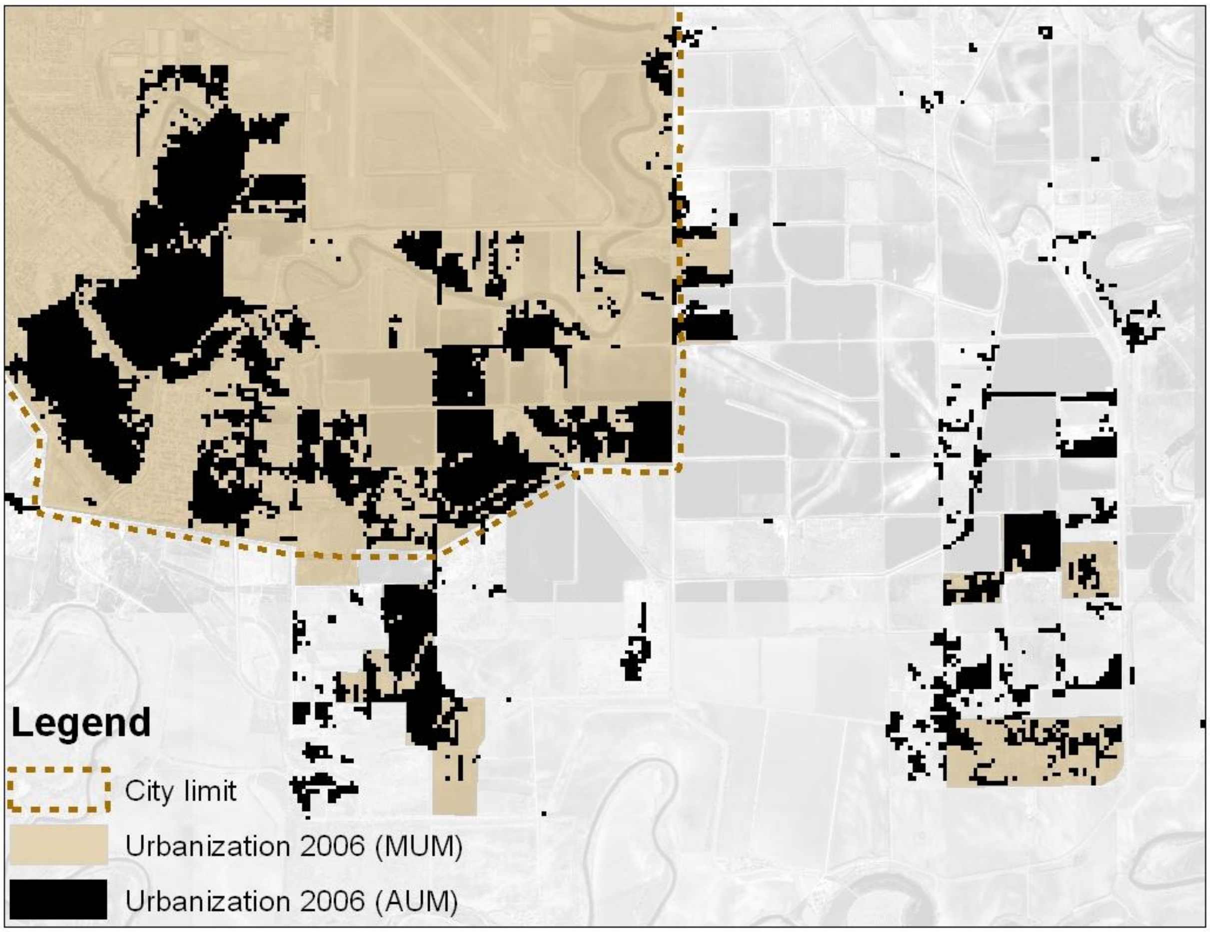

Figure 6. Identification of urban areas with the manual (MUM) and the automatic (AUM) methods, in 2006

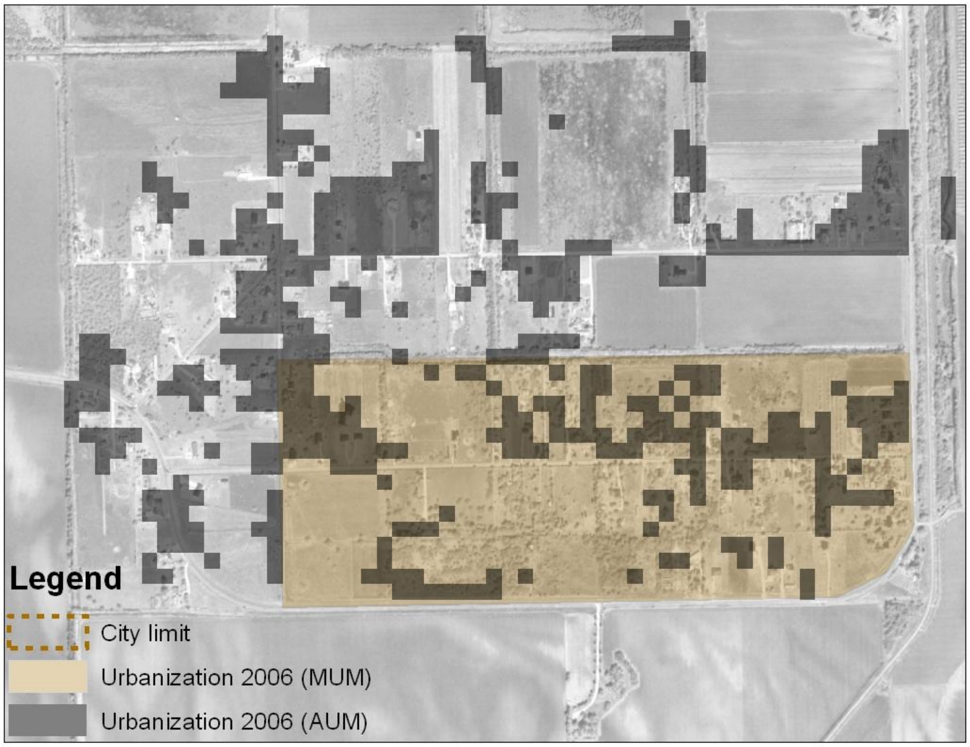

Figure 7. Detail of urban areas identification done with the manual (MUM) and the automatic (AUM) methods, in 2006

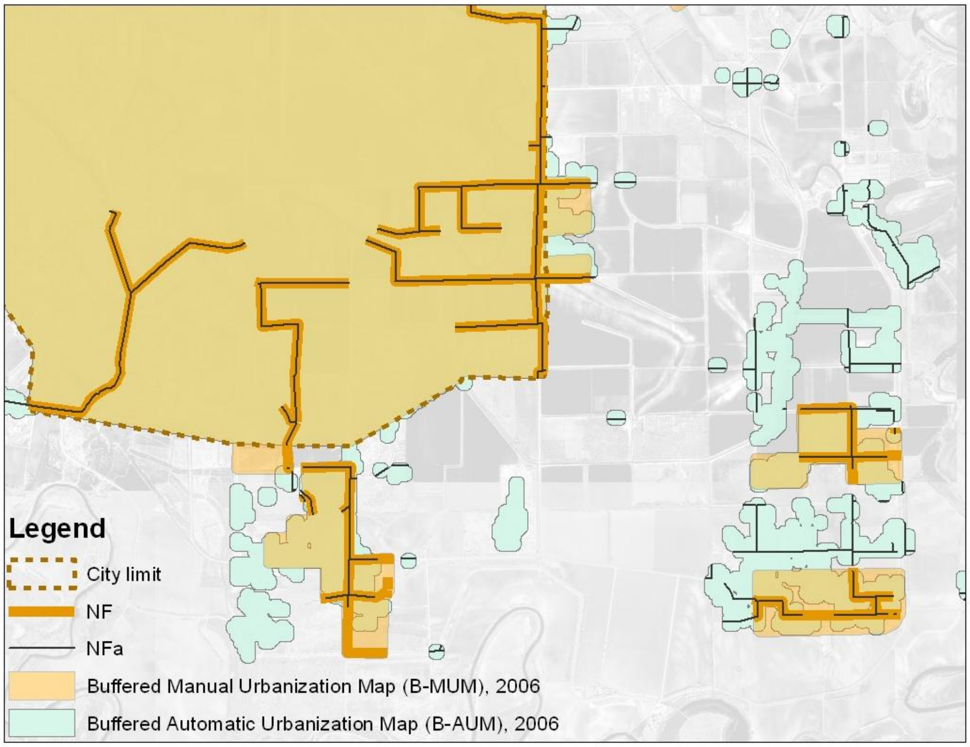

Figure 8. Fragments of canals and pipelines obtained by overlapping buffered urbanization maps (B-MUM, B-AUM) in 2006. Fragments (NF, NFa) are determined only outside the city limits.

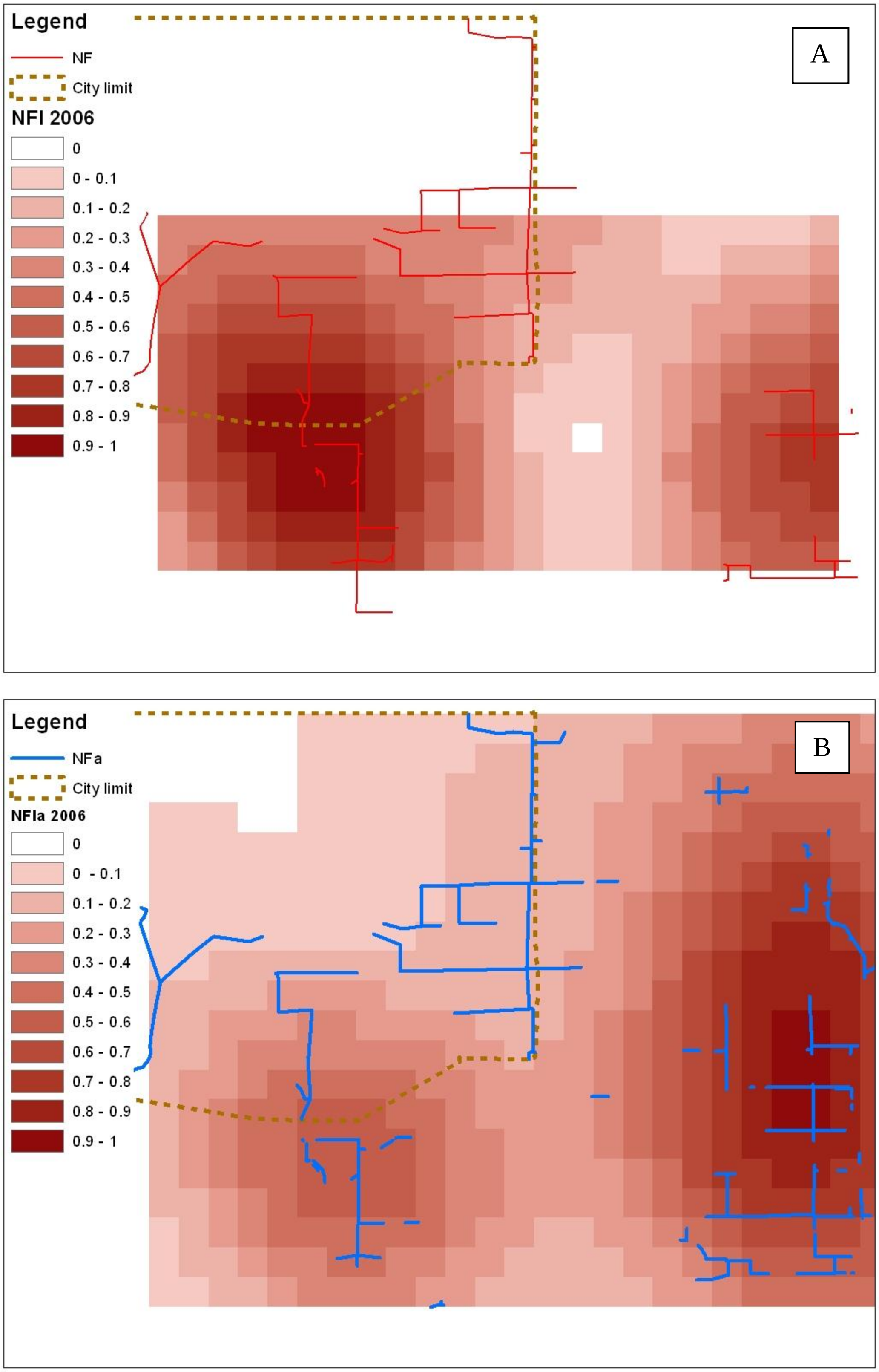

Figure 9. Network Fragmentation Index calculated for the year 2006. A) NF and NFI using B-MUM; B) NFa and NFIa using B-AUM

Morphological Segmentation Method

Categorization was found to be useful in highlighting specific urban areas. As an example, Bridges and Loops (red and yellow) identify areas that will be likely soon completely urbanized, while Branches and Islets (orange and brown) those most isolated (Fig. 10).

Figure 11 shows the results of categorizing different 2006 maps in a sample area (Southern BID). Some areas are classified differently when using B-MUM or B-AUM (charts A and B). For example, the urban area close to the city Core is classified as Islet in the first case, while Branch in the second case. When using a non buffered map, such as AUM, result is completely different due to the higher map definition (pixel is 10 times smaller) (chart C). This chart shows categorization being performed also inside the city limits.

Figure 12 shows the main steps of calculating a corrected NFI (NFIc) using the 1996 categorized B-MUM. As a result of applying weights to categories (chart B), NFIc is higher in remote areas compared to NFI. By showing results as density map, and excluding values <0.3, we were able to better identify the most affected areas (chart C).

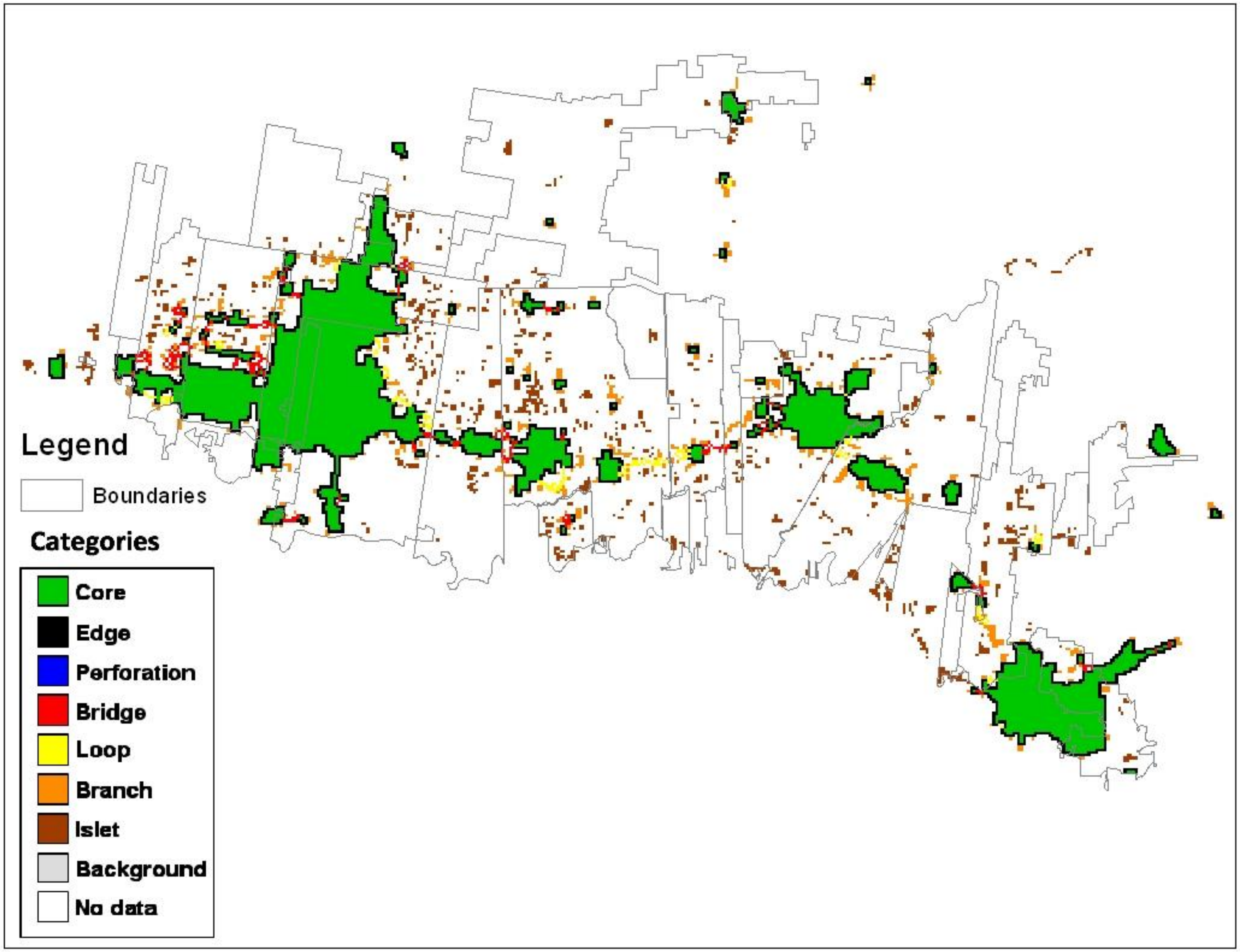

Figure 10. Categorization of 1996 Manual Urbanization Map (MUM) using the Morphological Segmentation Method

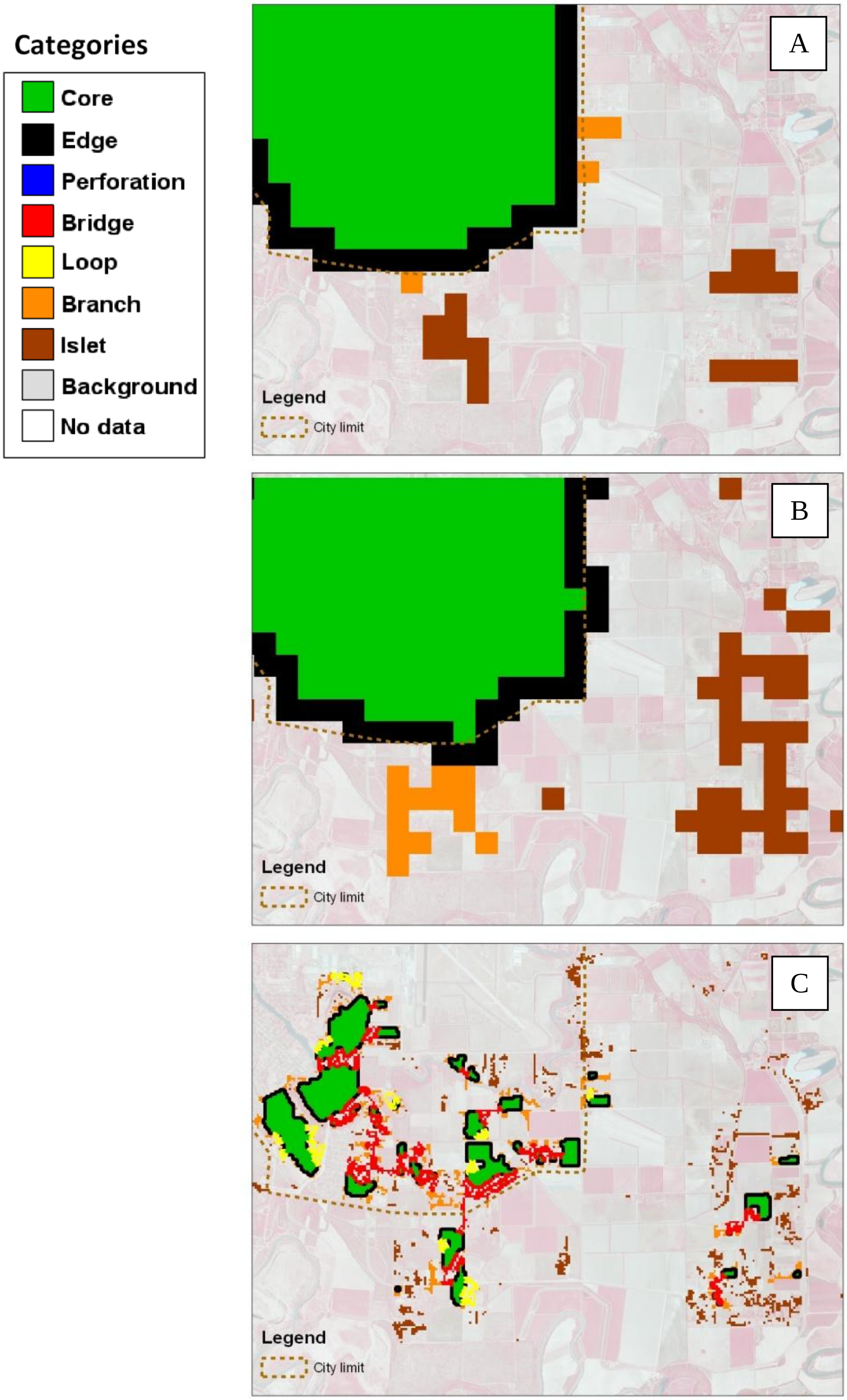

Figure 11. Categorization of 2006 urbanization maps using the Morphological Segmentation Method: A) B-MUM with cell size 310; C) B-AUM with cell size 310; D) AUM with cell size 31 (also area inside the city limit is analyzed)

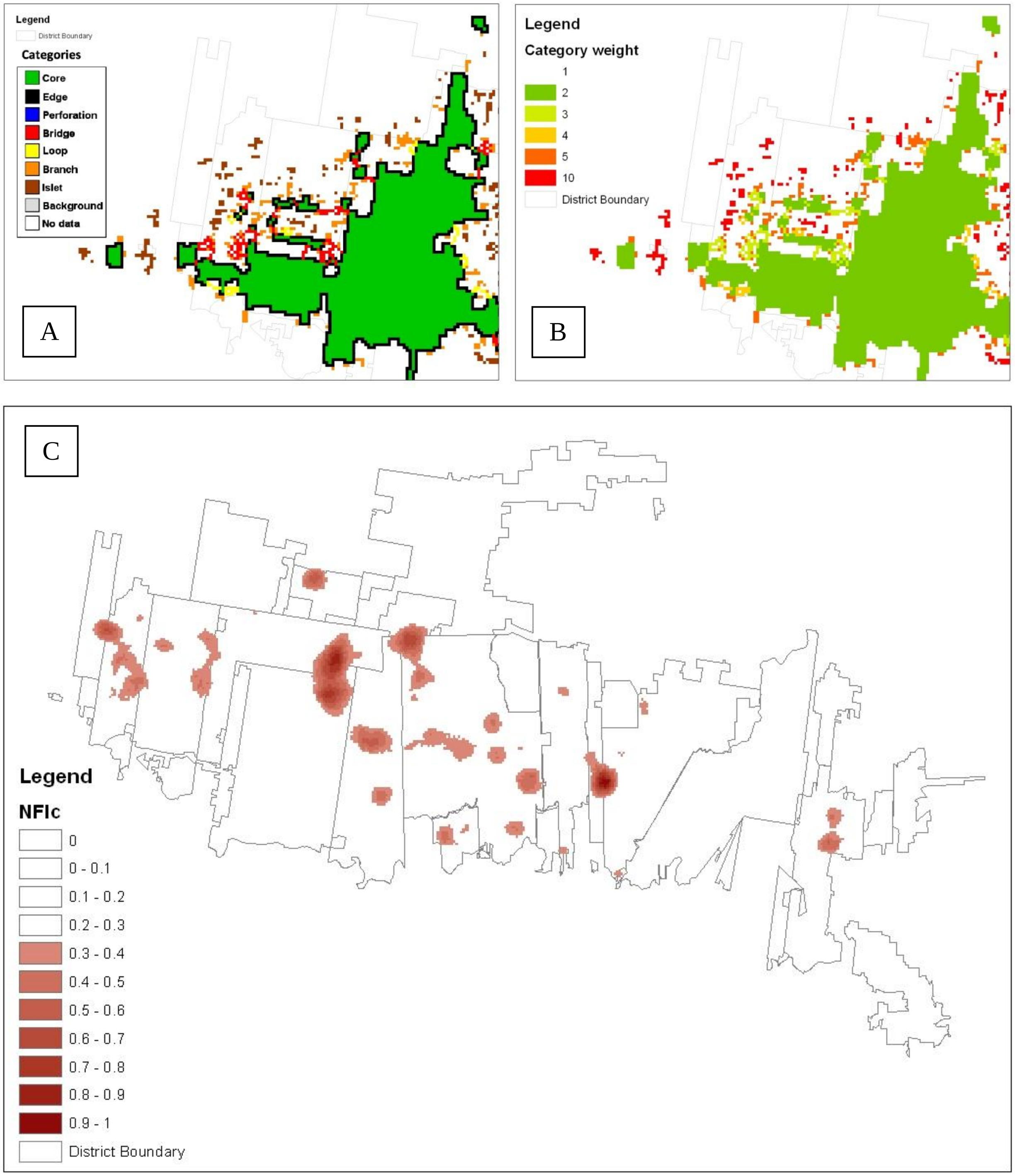

Figure 12. Steps of calculating a corrected NFI (NFIc) using the 1996 categorized B-MUM. A) Example of categorization of B-MUM; B) Example of weights assigned to categories; C) NFIc (only values > 0.3)

Network Potential Fragmentation Index

As shown in Figure 13, UFDM has localized areas of high fragmentation, whereas NDM (canals and pipelines) is pretty uniform with few areas with higher density (charts A and B). The combination of the UFDM and NDM gives a NPFI similar to NFI, despite the very different method utilized (chart C). Also DPFI resulted comparable to DFI.

Figure 14 shows that results are very different if NPFI is calculated using various elements of the distribution network (i.e. open canals and pipelines, or only open canals). It would be interesting to evaluate which case maximizes the correlation between NPFI and the impact of urbanization on district operation.

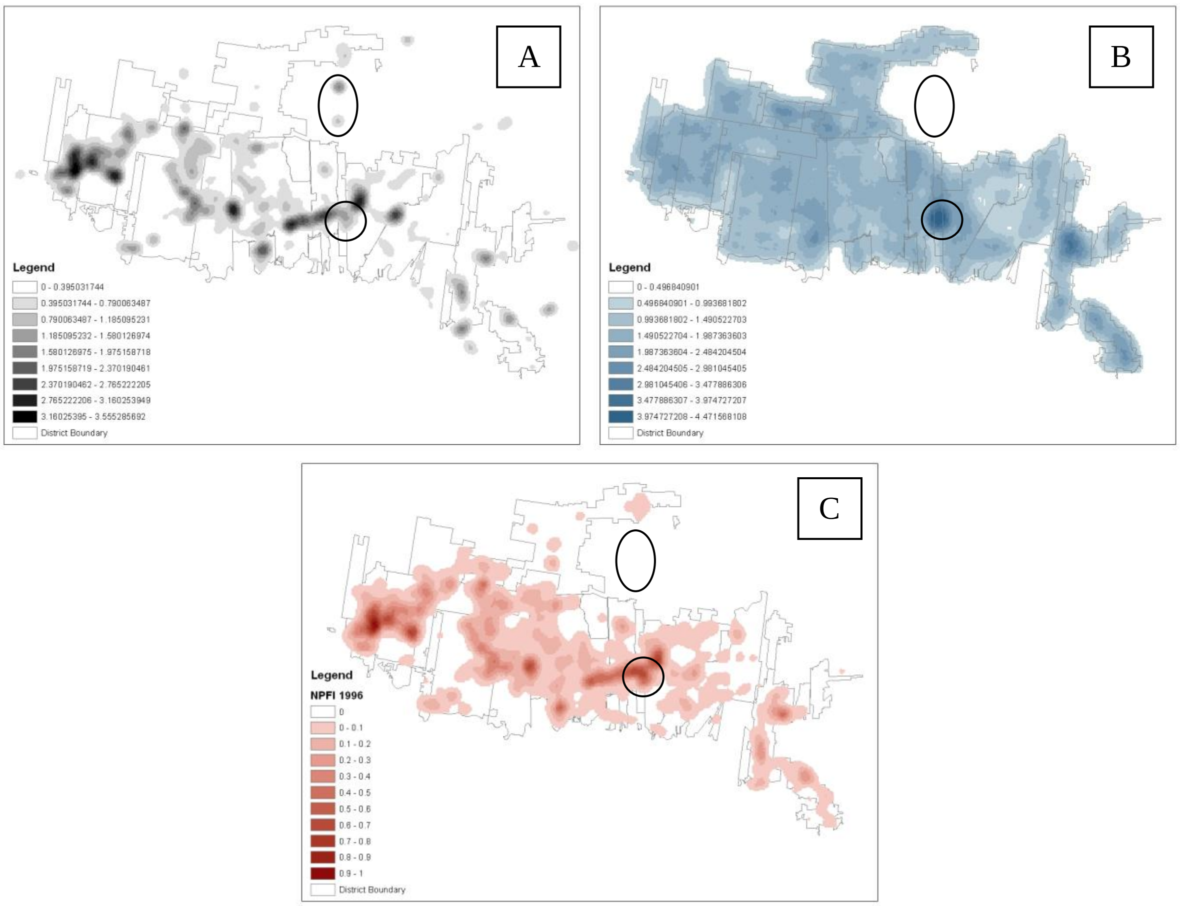

Figure 13. Steps of calculating a Network Potential Fragmentation Index (NPFI): A) Urban Fragments Density Map (UFDM) for 1996 MUM; B) Network Density Map (NDM) for open canals and pipelines; C) NPFI. Circles show major differences among charts

Figure 14. NPFI for different elements of the water distribution network in the year 1996. A) Open canals and pipelines; B) Only open canals. Circles show major differences between charts A and B

CONCLUSIONS

The following are our recommendations and conclusions:

- High fragmentation of irrigation districts due to urbanization existed in both 1996 and 2006 for our study area
- The different methodologies proposed for urban areas identification gave good results. Although a test on a larger area would be beneficial, results showed that Automatic Urbanization Maps can replace Manual Urbanization Maps, as the image processing phase is less time consuming
- The use of synthetic indexes helped identify areas where the water distribution network is impacted by urbanization. The Network Fragmentation Index identifies precise locations of impact, whereas the District Fragmentation Index synthesizes the information in one value per district
- Interpretation of urban fragmentation dynamics was improved by using categories defining the type of urbanization. By assigning weights to such categories, we obtained a corrected Network Fragmentation Index. This index is able to further identify areas affected by urbanization.
- The set up of a simplified procedure to calculate impact of urbanization (Network Potential Fragmentation Index) showed potential for application, even if analysis was based on probability of fragmentation rather than observations
- Recommendations for future work include:
    - Correlate analysis results to observed impact on district operation, especially when applying weights to urbanization categories
    - Further evaluate the advantages in term of computation of these analytical tools
    - Evaluate which elements of the distribution network (i.e. open canals, pipelines) have more impact on district operation when fragmented

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