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Water and Urban Growth in Tucson Metropolitan Region: a Remote Sensing Approach

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Cover picture captions:

Top picture: Shapes of Urban Growth (Arrowhead Ranch in Glendale, Arizona)
Source: developers brochure

Bottom picture: San Pedro River, National Geographic 2000
Source: National Geographic, 2000

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1. INTRODUCTION

The relationship between urban growth and water/wastewater infrastructure is very significant in today's urbanized world, particularly in a water scarce region like the US Southwest[1]. The State of Arizona is especially illustrative of this relationship. The urban population of Arizona is growing at some of the highest levels observed in the United States and the two largest cities, Phoenix and Tucson, anchor an urban corridor of about two hundred miles containing six million people. Portions of this urban corridor, known as the Sun Corridor, even extend south into Mexico (Figure 1).

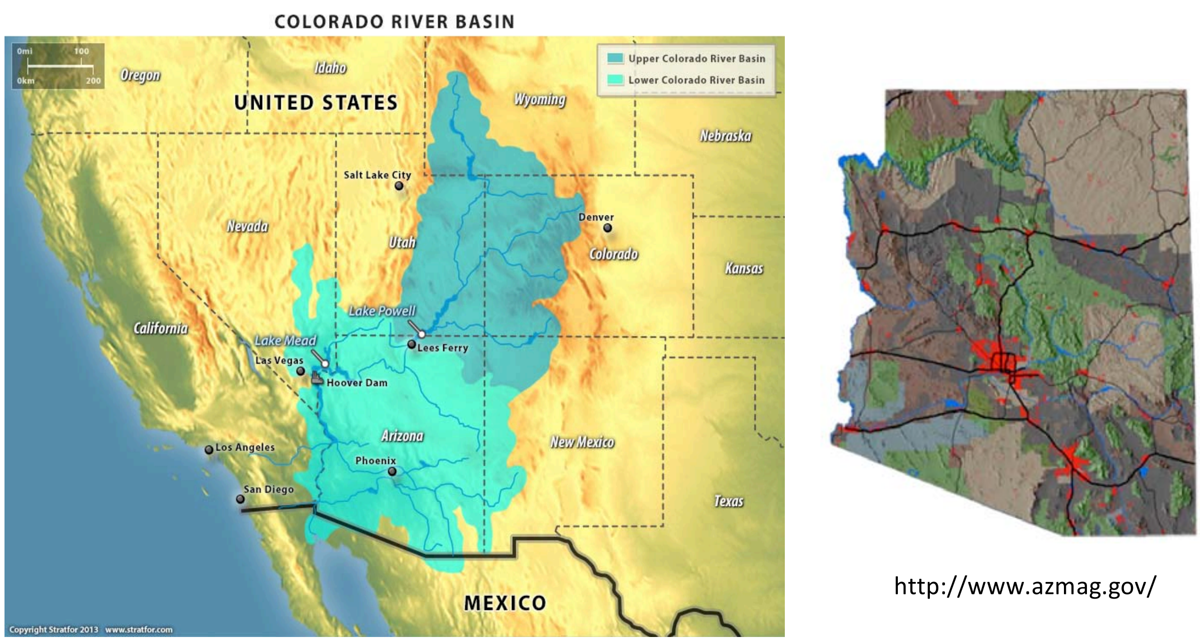

Figure 1. Arizona and the Desert Southwest

This study utilized remote sensing to understand the impact of urban growth on the natural environment in the Tucson Basin. Our study aimed to show how multi-temporal remote sensing could demonstrate the impacts of the built environment, particularly water and wastewater infrastructure, on the natural desert habitat.

The accuracy of multi-temporal maps derived from remote sensing data has improved significantly with the application of new classification algorithms. Recent work has been

[1] The arid west is defined by rainfall with Tucson averaging around 12 inches of precipitation annually between 1981 and 2010 (http://www.wrh.noaa.gov/twc/climate/tus.php).

particularly helpful in demonstrating the added value of utilizing new Object Oriented and Classification and Regression Tree (CART) classifiers. This research created a multi-temporal (1984-2010) view of land cover change along the Tucson – Phoenix urban corridor focusing on an area of significant growth within Pima County and utilizing Landsat Thematic Mapper data with CART classification techniques.

These classifications created multi-temporal maps of changing urban residential, urban commercial/industrial, agriculture, roads, bare ground, natural desert cover, riparian, and water. These data were then integrated into an ongoing analysis of changing urban and water policy and allocation within the region which provided an enhanced ability to evaluate the correlation of water availability and use, socio-economic drivers, and the direction and magnitude of land use/cover change.

2. BACKGROUND

The Tucson Metropolitan area[2], with a population of more than one million people and more than 200 square miles is located in the Sonoran desert, a water-scarce region rich in biodiversity and culture. The metropolitan area includes the historical City of Tucson as well the newly incorporated towns of Oro Valley, Marana, and Sahuarita along with unincorporated urban areas of Pima County.

Tucson was started as an agricultural settlement by Native Americans, along the Santa Cruz River which flows north through the area. In the 18th century, missionaries and settlers from Spain established a fortified town, the *Presidio*, which forms today's urban core. [3] Prior to becoming a part of the United States, Tucson was a classic Mexican frontier town particularly in the downtown areas known as the "Old Pueblo". The Anglo pioneers definitely changed Tucson through the gold and silver mining, the railroad, and warfare with Indian Tribes. During the twenties, federal expenditures (university, defense) and the economic activities associated with copper, cotton, cattle, citrus and climate (the five C's) fueled its growth. At the end of World War II, the metropolitan area included two cities, Tucson and South Tucson and many new subdivisions in the unincorporated area. As a whole, in the fifties, the metropolitan area had around 122,764 residents on 25 square miles (Akros, Inc. Wilson Preservation Coffman Studios).

After World War II, Tucson went from a small Southwestern city to a metropolitan area, with the transition of ranchlands to subdivisions. Increasing difficulties with ranching, such as drought or legal challenges to grazing leases, combined with growing expectations of lucrative land sales, fueled the development of an active real estate market. The urban core developed around the Hispanic town and mostly expanded eastward in the valley through construction and annexations. Infill came later with new construction within developed areas.

Tucson also experienced major changes due to the expansion of the defense industry and tourism which brought workers (blue and white collar) and retirees to the area. Between 1970 and 2010 Tucson's population nearly doubled, while the population of the county (Pima County)

[2] From its incorporation as an American territory to World War II, the Tucson region has phenomenally changed. With a strong military presence and the development of agriculture and mining plus commercial activities (the stage route - railroad), Tucson became noted for the five C's: "Copper, Cotton, Cattle, Citrus and Climate."

[3] Michael F.Logan speaks about a shared regional identity between Tucson and Albuquerque, New Mexico.

tripled [4]. The city expanded on the valley floor, eastward and gradually outside its boundaries, into unincorporated areas. Two-thirds of the Metropolitan Area population lived in subdivisions which sprang up around its corporate limits and, in the 1970s, subdivisions began to press against the federally owned lands to the east - the Saguaro National Park. During the 1980s, the city annexed approximately 76 square miles of land, mostly uninhabited lands in the east and south east, doubling its total size. However, due to the socio-spatial distribution of residents inside and outside the urban core, its per capita income is 33 percent lower than suburban per capita income (US Census Bureau 2000). The three newest towns of the metropolitan area were incorporated at different moments and have experienced significant residential and commercial growth. The Town of Oro Valley, incorporated in 1974, has 41,000 residents in 35 square miles and has become an affluent enclave on the north which emerged as a regional center for the biotech industry. The Town of Marana, incorporated in 1977, includes 35,000 residents on almost 120 square miles and is primarily an agricultural center (cotton) which is rapidly developing into a suburban community. [5] Marana began to grow through an aggressiveannexation policy (it currently has four times the surface area of Oro Valley with approximately the same population) which has important implications on water, wastewater and reclaimed water management. The latest of the new incorporated areas is the Town of Sahuarita which is located 15 miles south of Tucson and east of the Tohono O'odham Nation on the way to the Mexican border. Sahuarita was incorporated in 1994 and has 25,000 residents, but does not include nearby Green Valley, one of the first retirement communities in Arizona.

Even though the entire metropolitan area constitutes a functional unit, there is not a centralized metropolitan government, and each city and town has expanded following its own growth strategy based on its history, economy and socio-political characteristics. Water supply follows this pattern and several major water agencies/companies serve the area. Wastewater management is chiefly the responsibility of Pima County which provides integrated regional service.

[4] It has been estimated that each year new construction consumes approximately ten square miles of desert.

[5] Indeed, the 2007 American Community Survey showed that—at that time—the median income for a household in the town of Oro Valley was $74,015, which was more than 50% higher than Tucson median ($36,752) although It is also nearly 50% higher than the US median ($50,007). The estimated average household income in Marana is $64,332 per year (2007), which is nearly 50% higher than Tucson median ($36,752)

3. THE STUDY AREA

The remote sensing study area included the four jurisdictions that form the Tucson metropolitan area: the City of Tucson (COT), Oro Valley (OV), Town of Marana (M) and Town of Sahuarita (S) as shown in Figure 2.

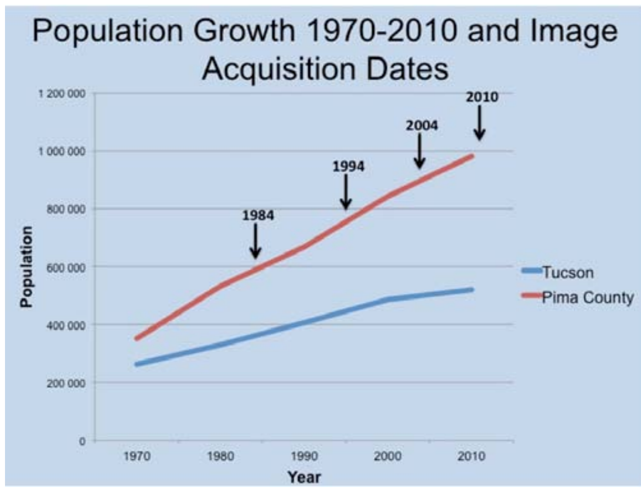

Figure 2. Population growth 1970-2010 and image acquisition dates.

The impact of population growth on the environment, infrastructure, and regulatory structure was explored using historical Landsat 5 Thematic Mapper data from May and June of 1984, 1994, 2004, and 2010.

The image data were radiometrically calibrated, atmospherically corrected, and orthorectified prior to performing a land use/ land cover classification. A CART algorithm was utilized to create a map with nine classes encompassing the natural and built environment within the study area.

All four maps produced had overall classification accuracies above 91%. The built environment was then singled out to measure the growth and impact of man on the natural environment within the four jurisdictions. Figure 3 and Figure 4 compare 1984 and 2010 land cover classification maps showing the changes in the study area. Over the 26 year time period the percentage of the built environment increased in all four regions.

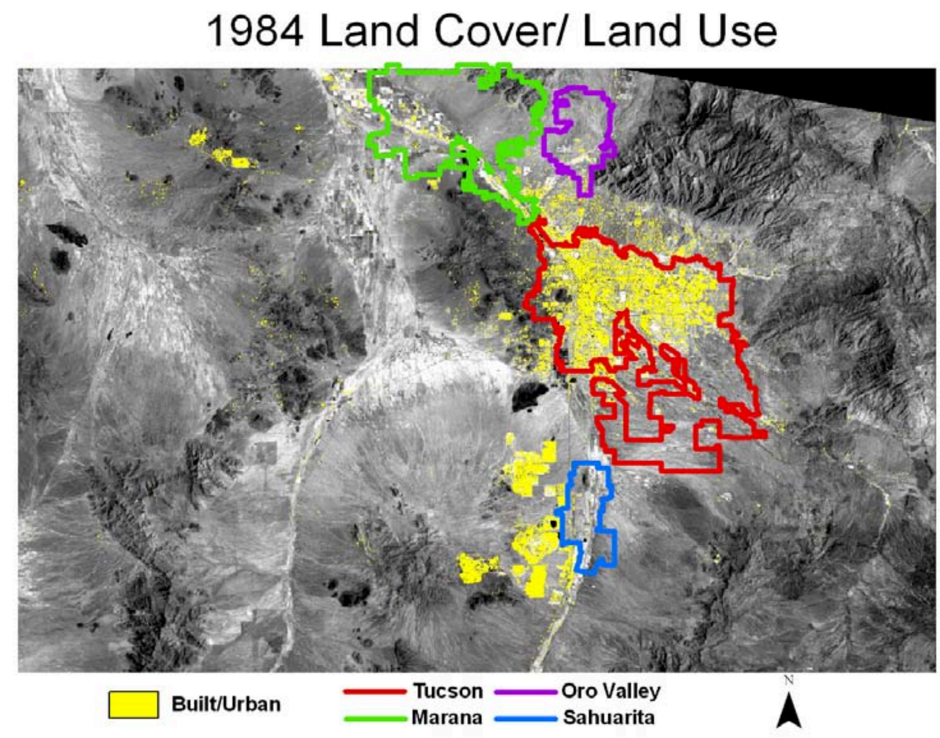

Figure 3. 1984 Land cover/Land use

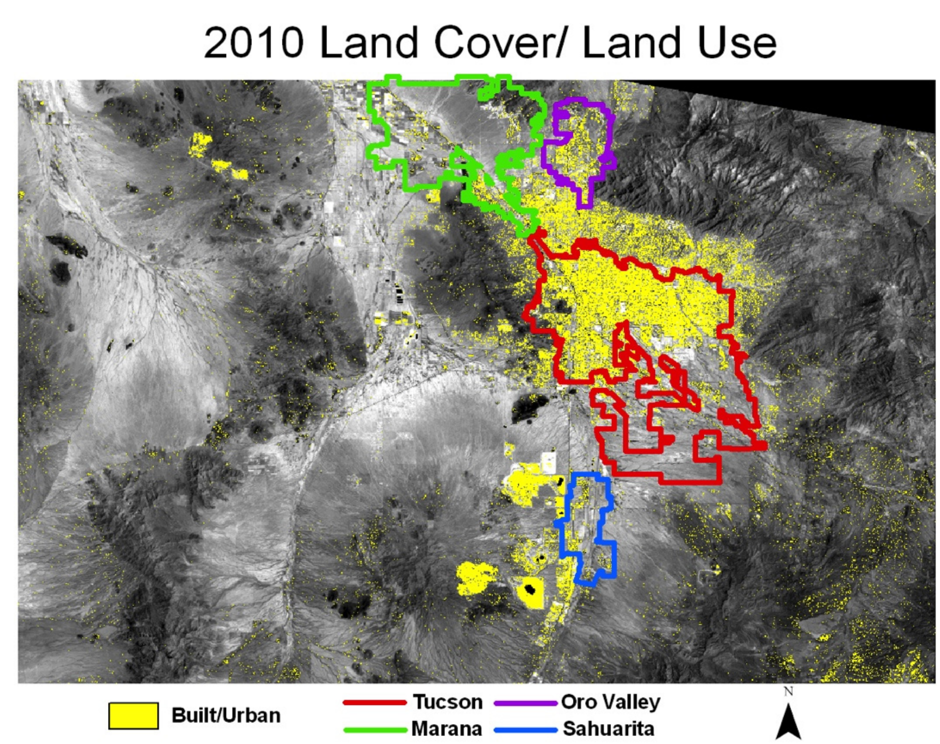

Figure 4. 2010 Land cover/Land use

The remote sensing analysis shows how the growth of the built environment has clearly altered the natural environment (evident through comparison of the land cover classification maps).

A more detailed analysis of the remotely sensed images identified what types of land cover were most impacted by the growth of the built environment. The majority of this growth between 1984 and 2010 came at the expense of the natural desert environment. Housing developments have replaced agriculture and golf courses have been placed over desert landscapes. The population boom and urban sprawl have impacted many aspects of the natural environment, particularly water resources and supply.

Some urban growth occurred on the edges of rivers and washes altering riparian areas (blue area on Figure 5). As Hayden said, “The built environment interferes with natural processes. An impervious surface – concrete highways, asphalt roads, housing developments, commercial malls, industrial areas – prevents rain from penetrating the ground, causes heavy runoff that can provoke erosion and also put toxic waste in the soil and in the aquifer” (Hayden, 2003). In addition “heat islands” develop in built areas where air circulation is not possible i.e. no trees. Built environment also stops habitat corridors and provokes the disappearance of species from the urban area unless they can adapt.

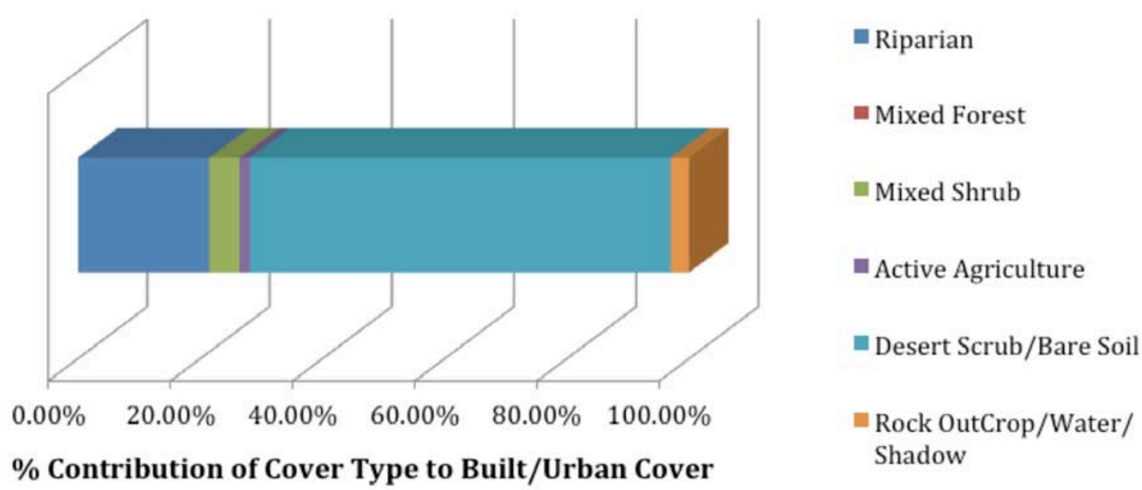

Figure 5. Contribution of natural cover types and urban cover (%)

4. PATTERNS OF URBAN GROWTH AND WATER/WASTEWATER INFRASTRUCTURE (1984-2010)

The natural landscapes have little by little been threatened by urban encroachment and fragmentation as a consequence of the conversion of ranch lands into urban landscapes. To go further in understanding the relationship between urban growth and water /wastewater, two major structural elements were explored: infrastructure and governance.

The increase in infrastructure over a 26-year period comes along with the increased amount of residential and commercial buildings as well as the construction of elaborate destination resorts for the tourist industry. This pattern repeats itself throughout Pima County and is evident in all four study areas (Tucson, Oro Valley, Marana and Sahuarita). The amount of urban growth was shown by the water and sewer connections and the number of wells. The increase in the amount of water connections was very high in all four jurisdictions. Oro Valley for example, went from having around 2000 water/sewer connections in 1984 to approximately 11,000 in 2010. Wastewater infrastructure (new treatment plants and conveyance lines) expanded as did the reclaimed infrastructure that allowed golf courses and resorts to multiply (Clavreul et al., 2011).

4.1. Water supply

Throughout its history, Tucson[6] relied on surface water but, beginning in the 20th century, and especially with the post-war urban development, it shifted to groundwater, located mostly between 100 and 500 feet deep. The groundwater was provided by two main aquifers, the Tucson Basin (or Upper Santa Cruz aquifer) and the Avra Valley aquifer on the west. However, despite natural recharge of the aquifers, since the 1950s the water demand became higher than the replenishment, provoking a general decrease in groundwater level (Benites-Gambiriaso et al., 2010). The increases in population, along with the copper mining and farming activities, within the region have also increased the demand for groundwater pumping, leading to subsidence and the significant degradation of the riparian habitat that once existed.

As regards the water demand, the main factor has been the shift since the 1980's from agricultural demand to municipal demand. Water production and distribution is a mosaic in

[6] The name of the city is connected to water : « Stook-zone » means « water at the foot of Black Mountain »

Tucson Metropolitan Area which counts about 150 different providers. The biggest provider is Tucson Water which provides 75% of the water in the Metropolitan Area within and outside the city limits. Several other public water providers, controlled by their own elected board of directors, serve the area as well as 20 very small private water companies.

Urban activities had a large impact on the water table. Decreases in water levels lead to land subsidence jeopardizing infrastructure and water storage capacity. Urban activities also polluted the aquifer (like TCE near the airport) and several landfills raised contamination issues. All these events fuelled the search for new water resources like the Colorado River's allocation through the Central Arizona Project (CAP)[7] or the idea to reuse treated wastewater as a new resource.

The first CAP delivery in 1992 created a large social conflict because of quality issues[8]and its direct use was halted in 1994. Tucson Water developed a technology for groundwater recharge in central Avra Valley to recover a blend of water (groundwater + CAP) which is delivered to customers after treatment. The aim is to decrease groundwater mining and avoid subsidence. Treated wastewater has been utilized as a new water resource since 1984 to irrigate golf courses and public parks through the reclaimed water system – "the purple pipe network".

To control water demand, the City started in the 1980's an intensive awareness campaign that made Tucson a poster-child for water conservation in the West. Now, the residential water use (indoor and outdoor) GPCD (Gallons per Capita per Day) for Tucson Water customers is 89 GPCD which is less than other major Southwest cities like Las Vegas at 222 GPCD in 2011 or Phoenix at 123 GPCD in 2008.[9] Currentlys, new projects are implemented in Tucson with several aims: increase the reclaim water use, catch storm water to control flood and use that water or at a smaller scale develop harvesting water or grey-water use.

[7] The CAP is a system of canal pumping stations and storage facilities that enable water to be brought from the Colorado River to central and southern Arizona. The project was completed to Tucson in 1992. To reach the terminus of the canal south of Tucson, the Colorado River water runs 336 mile and has to be lifted 2900 feet.

[9] Source: Arizona Water Meter: A Comparison of Water Conservation. Programs in 15 Arizona Communities, Western Resource Advocates, 2010 and Source: http://www.lvvwd.com/conservation/drought_measures.html, 2013

4.2. Leap-frog development[10]

Post-war growth in Tucson was largely a private endeavour. Developers simply acquired parcels of land and formed subdivisions with varying degrees of care and skill.

The major growth pattern that is evident from the remotely sensed data is that of leap-frog development - dense suburban developments that skip over empty land to establish a new urban fringe (Hayden, 2003). Newly urbanized areas, along with water infrastructure, spring up beyond existing urban boundaries so that developers avoid paying the higher costs of urban land and obtain more flexibility in developing larger tracts of land.

The real estate market started to boom with the massive arrival of migrants from the Eastern and Midwest United States. Moreover, the customers have always showed a preference for single-family housing - the ranchette lifestyle and the retirement communities (like Green Valley in the 1960's).[11] These preferences together with cheap land and water had important consequences. Indeed, developers and builders would buy lots where the land was cheap (in non-urbanized Pima County) and build subdivisions. Growth developed to the east and northeast and then to areas northwest of the City of Tucson.

The northwestern and northeastern portions of the Tucson metropolitan area were continuing to grow most rapidly (Figure 6). It is estimated that in 1992 two thirds of all residential permits were issued north of the north boundary of Tucson (the Rillito River), in the higher elevations of the Catalina Foothills. Although these low-density communities are expensive to service, Tucson Water supplies water and Pima County provides wastewater services as they are an integral part of the urbanized area.[12]

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[10] Like in the game where one player crouches down and another player vaults over the first.

[11] The 1960s saw the establishment of retirement communities, special age-restricted subdivisions catering exclusively to the needs of senior citizens who wanted to escape the harsh winters of the Midwest and the Northeast. Green Valley, south of Tucson, was another such community and was designed to be a retirement subdivision for Arizona's teachers.

[12] In 1970 a slow-growth movement appeared in Tucson with elected officials advocating infill and a limit to the expansion of the city. One facet of the slow-growth movement was the effort to revise water utility practices, including raising water rates and charging residents' service fees that were related to delivery costs. The political resistance to growth lasted only a few years and ended with the electoral defeat of most of the slow-growth proponents. Recently, Tucson Water has established requirements, so no building permits are issued in areas without adequate infrastructure.

The earlier north-south direction of growth continued to expand following Interstate 10 and Interstate 19 in relation to transportation and trade activities with Mexico.[13] The abundance of cheap private land in the unincorporated areas located next to large blocks of state trust lands (which have not been released for development) has also encouraged leapfrog development.[14]

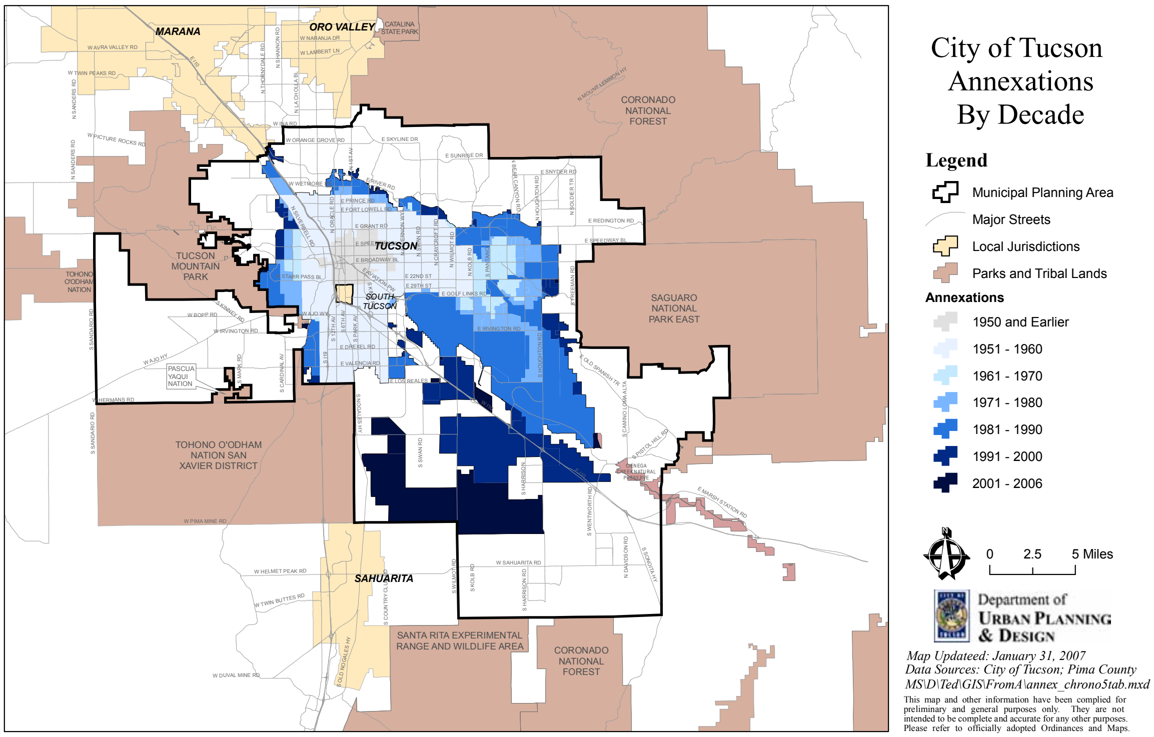

Figure 6. City of Tucson annexations by decade.

4.3. Water regulation

To cope with groundwater issues, during the 1980s, the state of Arizona established Active Management Areas (AMA) - Tucson Metropolitan Area is located in the Tucson AMA – which have specific regulations enforced by the state via the Arizona Department of Water Resources.

The aim is to control water demand and reach the “safe-yield” (balance between withdrawal and replenishment into the aquifer) within the AMA limits which include the metropolitan, mining and

[13] The City of Tucson. 1993. Tucson, *The People and the Place-Highlights from the 1990 Land Use Survey*.
[14] Over time, this has left vacant or underdeveloped land throughout the City’s urban core.

agricultural activities. Subsequently, another regulation obligated all new developers in the AMA to prove that 100 years of water supply is available in the area under construction.[15]

Many neighborhoods were built beyond the reach of existing water and sewer services. The builder therefore created a private water company to serve the development's homeowners or financed the extension of the infrastructure (Logan, 2006). The Rita Ranch development, in far southeast Tucson just north of the Town of Sahuarita, is a good example of this procedure. The area that now contains the Rita Ranch housing development had no water connections in 1984 and by 2010 had nearly 10,000 connections (Figure 7).

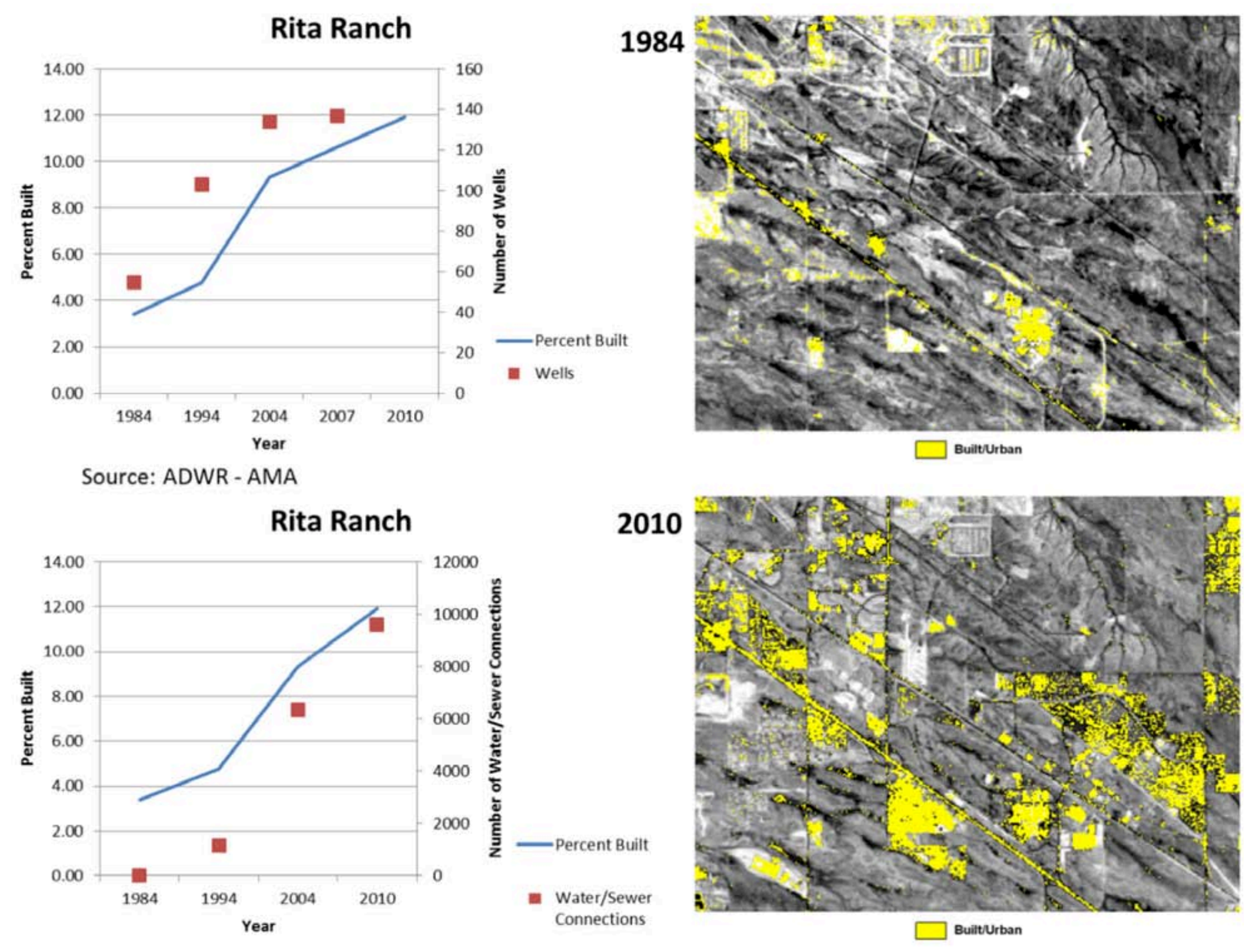

Figure 7. Rita Ranch housing development and water connections evolution (1984 and 2010)

[15] In the Tucson Region two kinds of water exist: wet water and paper water (water credits, assured water supply designations, water rights…). That separation can lead to hydrological contradictions like recharging the aquifer in one place to have the right to withdraw water in another.

Another example would be Dove Mountain in Marana that went from 0 to almost 10,000 water/sewer connections by gaining water and wastewater services even though the development was many miles from the urban boundary (Figure 8; Clavreul et al., 2011).

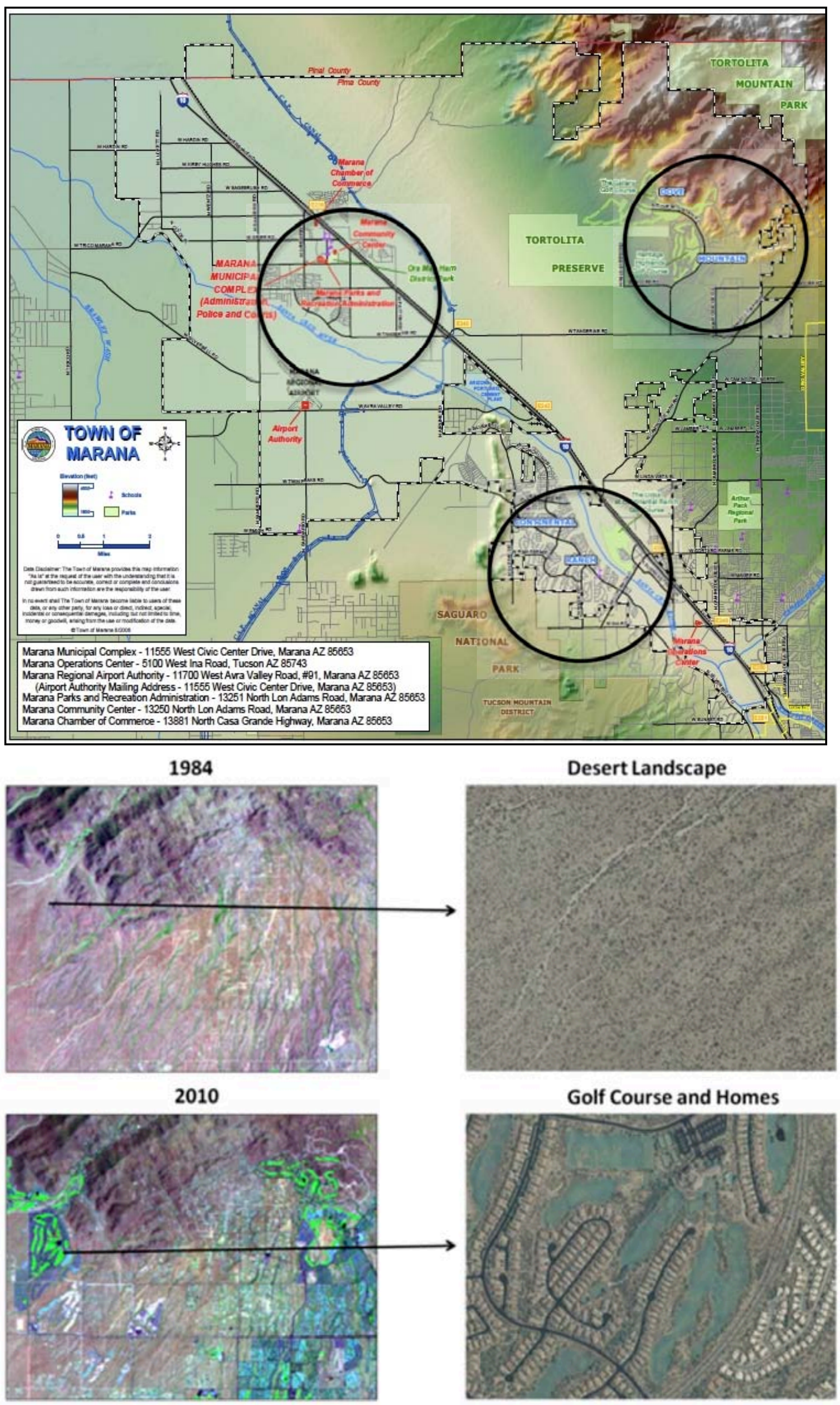

Figure 8. The picture on the top shows the Marana's Urban Development: three poles of growth (downtown (NW), Continental Ranch housing developments (S) and Dove Mountain (NE). The bottom pictures highlights an area in Dove Mountain that went from completely undeveloped in 1984 to containing two golf courses in 2010.

4.4. Wildcat development

In addition to regulated development, unregulated development or “wildcat subdivision”[16] became common in the areas outside the metropolitan area, particularly to the south and west of Metropolitan Tucson where little subdivision activity had occurred by that time. This creation of new residential parcels, without the limitations of subdivision regulation, results in development devoid of any basic infrastructure or improvements typically paid for by the developer.

In regulated development, impact or development fees are charged to new development as a means of paying for the facilities and infrastructure needed to serve that development (Tucson and Pima County, 2008). Each new house must pay these fees to its governing jurisdiction. Legal framework for how municipalities and counties set impact fees is set by state law. All jurisdictions have guidance for assessment of impact and development fees.[17]

Despite its negative implications, wildcat subdivision, or lot splitting, is directly encouraged by State law, which maintains that a parcel division of less than six portions is not considered to be a “subdivision”, and prevents any jurisdiction from denying approval or requiring a public hearing for these parcels.[18]

Wildcat development often devalues property, and can create significant hardships and sometimes real hazards for its residents. As the value of land increases there is a growing trend for private ranchlands and rural holdings to be developed as wildcat subdivisions: in 1997, 41% of the new residential dwelling units were not part of platted subdivisions and most of these were issued in “ex-urban” areas, or rural area outside the metropolitan area.

[16] The expression wildcat development refers to the independent and solitary nature of the « wildcat » which is actually a bobcat, a medium sized member of the mountain lion family.

[17] The City of Tucson currently assesses impact fees for water, roads, parks, police, fire, and public facilities. The County has impact fees for transportation only. Impact fees apply to all new developments and have specific benefit areas, for example, the Southwest Infrastructure Plan (SWIP) and the Houghton Area Master Plan (HAMP).

[18] What is often not realized is that lot splitting can proliferate into many more “splits” of the same parcel For example, if a property owner of 100 acres were to first lot split his parcel into five 20 acre parcels, each of the five subsequent owners would also have the right to lot split their 20 acre parcels again five times, so that now there are 25 property owners of four acres each. Depending on the minimum zoning, which could be as small as one acre per house, these four acre parcels could be again split, perhaps resulting in a wildcat subdivision of as many as 80-100 parcels and perhaps 200 or more residents, all without basic improvements, particularly potable water.

5. CONCLUSION

The knowledge gained from this research aims to inform future urban planning and water /wastewater policy. Multiple challenges exist, particularly for urban sustainability and water resources. This research demonstrates that the authorization (and financing) to build long sewer outfalls (+/- 8 kilometers) to existing urban infrastructure is most highly correlated with successful patterns of “leap-frog” development. In addition, the rapidly growing access to land use mapping and the increased accuracy of remote sensing analysis allows a new level of scientific precision in the exploration of significant policy and growth questions.

For example:

- In the 1980s the Groundwater Management act was enacted in Arizona that stated all wells must be registered. Using remotely sensed data we can examine whether this registration process impacted growth rates at all.
- We can also use similar classification techniques utilized in this study to explore additional issues with urban growth in the Sun Corridor near the US-Mexico border.
- Impervious surfaces also impact aquifer recharge and the amount of impermeable materials can be estimated using land cover classifications.
- Concrete surfaces have also been shown to contribute to the urban heat island effect which impacts water usage due to increased temperatures. Remote sensing can be used to estimate temperature changes in the Tucson Basin over the last two decades and whether there is a correlation with water usage.

Remote sensing can significantly assist in the analysis of urban growth patterns and the underlying causes and impacts. This adds a very important and powerful tool to our toolbox for research and discussion of these very important topics.

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