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Runoff Modeling to Inform Policy Regarding Development of Green Infrastructure for Flood Risk Management and Groundwater Recharge Augmentation along an Urban Subcatchment, Ciudad Juarez, Mexico

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Abstract: Changes in land use patterns at expanding border cities along the U.S.-Mexico transboundary area have severe impacts on runoff coefficients and flood risk management. Severe rain is the most representative type of precipitation in the Paso del Norte (PdN) region (New Mexico and Texas in the United States and Chihuahua in Mexico), characterized by high intensity, low duration, and high volumes of rain falling in localized, small areas. Rains generate flooding and damage to urban infrastructure, putting at risk people and properties along the arroyos, which lack hydraulic design to control overflowing. While using a Geographic Information System (GIS), we applied the Hydrologic Modeling System (HEC-HMS) to model streamflow at the study site while building the hydrologic domain using ArcGIS with the Flow Area extension. Flood risk analysis was generated to evaluate potential sites for establishment of Green Infrastructure (GI) as a means of reducing risk and induce recharge to local aquifers. A hydrologic model was created using HEC-HMS under GIS tools and later using Flood Area® hydrologic software to evaluate flood risk analysis. For small-scale watersheds (< 10 km^2) runoff can be greatly reduced by using and developing an urban hydrology approach. Furthermore, using GI and applying an urban hydrology approach can generate synergistic benefits by reducing flood risk, enhancing recharge to aquifer formations, weakening urban heat islands, improving habitat for regional species, and generating a common site for social interaction between neighbors. Binational agencies have adapted a new policy to address and promote the generation of such sites while academia, local government, and Non-Governmental Organizations (NGOs) have taken up the challenge of promoting joint collaboration leading to local solutions to the ancient problem of flood risk.

Keywords: *urban hydrology, transboundary watersheds, green infrastructure, flood risk assessment, permaculture, social participation and education policy, aquifer recharge*

Cities are growing all over the world as people move from rural areas to urbanized areas. Demographic projections indicate that by the year 2050, close to 70% of the world´s population will live in cities (Barney 2015). Mass migration towards cities is changing land use/land cover (LULC) patterns, generating increasingly reduced infiltration on paved surfaces causing loss of native vegetation. Resulting changes in runoff behavior, combined with unplanned urban development, place new population centers at risk of flooding, an effect likely to be exacerbated as climate leads to erratic precipitation patterns.

The North American Monsoon (NAM) produces thunderstorms responsible for severe meteorological conditions, including flooding,

hail, wind, dust storms, and lightning in northwest Mexico and the southwest United States (Adams and Comrie 1997; Higgins et al. 2003; Adams et al. 2014). Despite the generally dry climate in semi-desert environments such as the PdN region, floods result from intense precipitation events linked to the summer monsoon. As population in a particular area increases, so do flood risk and degree of damage to urban infrastructure (Gil et al. 2009). Extreme flooding events have occurred in the past within the Paso del Norte (PdN) region (El Paso, Texas in U.S. and Ciudad Juarez, Chihuahua, in MX), where extreme precipitation events exacerbated by changes in LULC have generated loss of property and human life (Figure 1) (Granados et al. 2013a; Granados, et al. 2013b).

The concept of urban hydrology is not new (Leopold 1968; USDA 1986); however, the concept has developed greatly over succeeding years. An understanding of the effects of different types of urban development has emerged. Construction of broad impervious areas leads to increased runoff and decreased recharge in areas where much surface water would have formerly infiltrated (Day and Bremer 2013). Proper urban hydrologic designs, for instance with Green Infrastructure (GI), can manage the movement of water within an urban watershed, and in so doing, help to improve quality of life, reduce contamination, and decentralize water storage (Spatari et al. 2011). GI offers a contemporary approach to the management of landscape resources in urban environments in harmony with newly built infrastructure, or with traditional gray infrastructure. GI has developed rapidly in many southwest North American cities because of the opportunities it has provided in meeting the ecological, economic, and social challenges of spatial planning (Mell et al. 2009; Mell 2010; Zavrl and Zeren 2010; USEPA 2015). The concept is spreading rapidly within large Mexican cities along the northern border. In part, this is because of the support of the Border Environment Cooperation Commission (BECC) which seeks to provide important basic scientific information on the hydrology of the urbanized watersheds (BECC 2016).

In the context of GI policies, Ciudad Juarez, Chihuahua, Mexico, has been an entrepreneur city with vast experience in innovative policy. The maquiladora industry was first established there as a means of producing jobs and expanding the regional economy. Later, construction companies established large units in Ciudad Juarez in response to the need for housing and other urban infrastructure. Furthermore, as the city developed, important governmental institutions such as the Instituto Municipal de Investigacion y Planeacion (IMIP), and NGOs and international cooperation agencies, such as BECC and the North American Development Bank (NADBANK), began to focus some of their important operations on the city. BECC has taken leadership in promoting GI for the city as a policy design of a potential solution for small-scale flood risk and aquifer recharge. This policy approach has led to progress towards flood risk prevention, esthetic enhancement of urban infrastructure, improvement of green areas to promote environmental benefits for native species of flora and fauna, and development of community based collaboration and involvement towards a sustainable city. For example, BECC has promoted two major international conferences in which experts from the U.S. and Mexico presented their work on applied and working GI in different cities of both countries. A third international conference is planned for 2016. Additionally, BECC is promoting major investments in GI in other border cities. Furthermore, BECC has participated in studies of the potential for rainwater harvesting and management for GI and reduction of flood risk. GI policies approach environmental restoration through permaculture and positive feedback. For example, rain will produce runoff; runoff will move downhill and can be collected in basins, both large and small. Soils and other organic materials will also collect in the basins, generating a soil profile adequate for plant growth. In basins where water and nutrients are available, plants will develop the soil profile through root growth, with deep-rooted species providing the greatest benefit. The roots will promote infiltration into deeper layers, and, where the water supply is sufficient, recharge to subjacent aquifers. Additionally, plants will promote establishment of bird species that will enhance positive feedback by sowing native vegetation species from the wider region in their droppings. Communities will participate by adopting these green areas for social interaction among neighbors.

Crime rates are reduced as a result of community participation and involvement (Scott et al. 2013). Positive social outcomes will encourage the development of new GI sites. The development and maintenance of small-scale GI is well within the means of local communities (Figure 2).

The main aim of the study is to apply surface water modeling in order to gain a better understanding of the potential runoff of a small-scale watershed in Ciudad Juarez, Chihuahua, Mexico for 2, 10, and 25 year return period scenarios, under a Type II precipitation regime (USDA 1986). A return period is defined as the recurrence interval estimated from the probability of an extreme precipitation event; for instance, a 25 year return period relates to the largest precipitation event that is likely to occur within an interval of 25 years. Model results are interpreted in terms of flood assessment, and potential for enhanced recharge in an urbanized catchment. A further aim is to examine the potential for cooperation between local communities and government organizations in the development of GI as a means of controlling flooding and augmenting groundwater supply. This study focuses on one small catchment, but has implications for innumerous urbanized sub-watersheds in the semi-desert environment along the border between Mexico and the U.S.



Figure 1. Type II punctual precipitation and its potential for catastrophic flood events. Photos are from the June 2010 storm event in Ciudad Juarez, Chihuahua (Chaparro 2006; Diario de Juarez 2006).

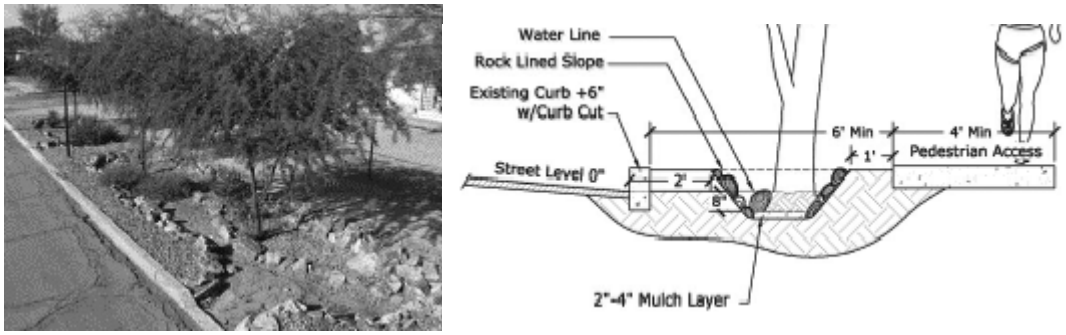

Figure 2. Green infrastructure and design prototype in Tucson, AZ (modified from WMG 2012).

Study Area

The study area is the catchment of an ephemeral watercourse known as Arroyo Tapioca, located at the geographic center in the City of Juarez, Chihuahua, Mexico (Figure 3). Arroyo Tapioca is about 21.78 km long, and the study focuses on an area of 11.65 km^2 in the upper part of the catchment. Slopes in the area range from 0.03% to 0.15%, resulting in laminar and sheet flow runoff.

The urban infrastructure of the study area dominantly features densely populated zones, particularly at the lower (northern) end. Impermeable areas range from 80 to 95% of surface area, which increases the runoff potential. This area is estimated to have a total population of 9,656. Much of the drainage density (Dd ~85 km/km^2) is controlled by major and secondary streets (Figure 4). The Arroyo Tapioca catchment, like most of Ciudad Juarez, is prone to flooding that results in severe localized property damage.

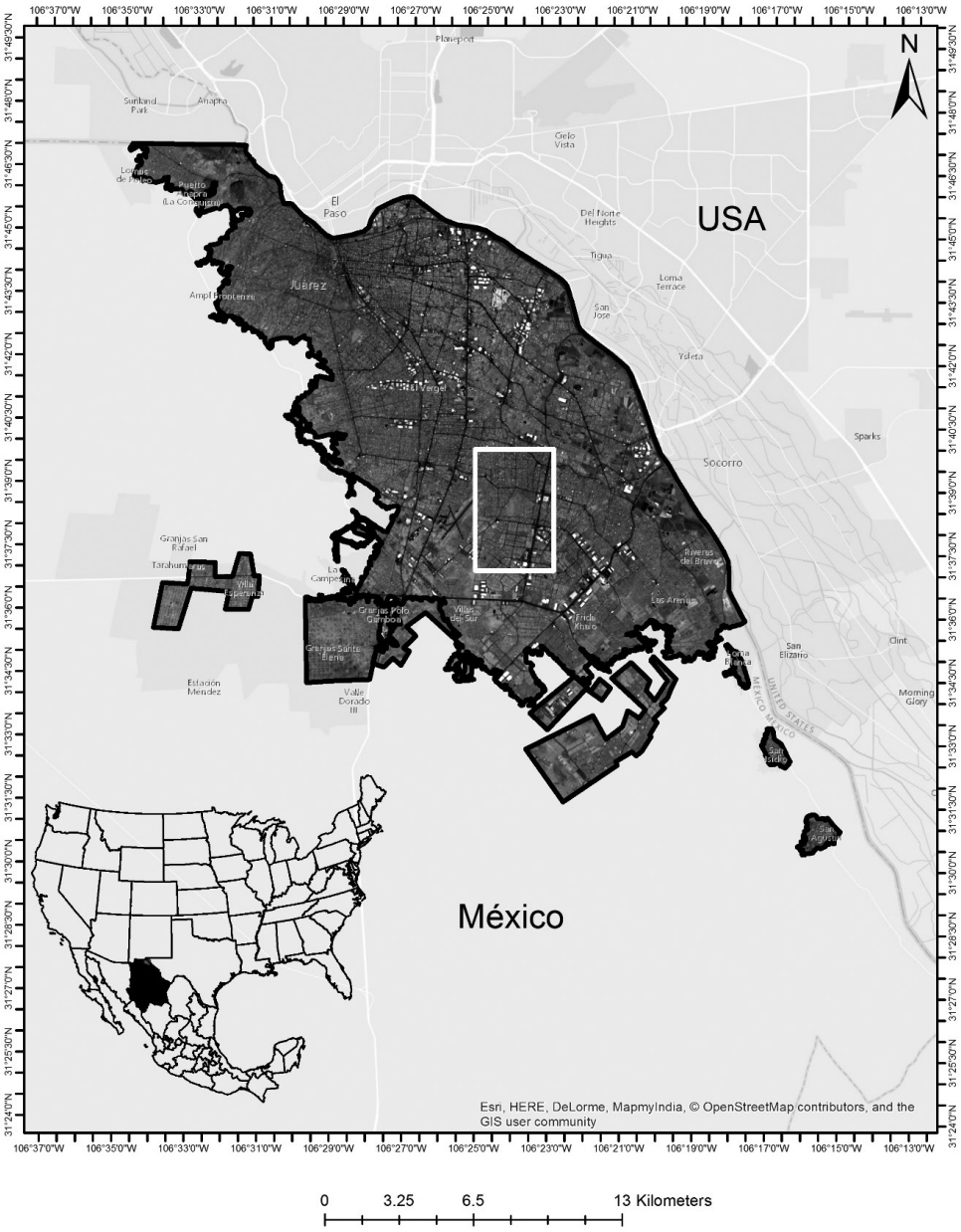

Figure 3. Location of the area of interest at Paso del Norte, Ciudad Juarez, Chihuahua, México.

Methods

Precipitation data from 1990 to 2010 were acquired from the National Water Commission of Mexico, the International Boundary and Water Commission, and the Autonomous University of Ciudad Juarez (UACJ) Meteorological Lab (UACJ-MetLab). A LIDAR (Light Detection and Ranging) survey undertaken in 2008 by the UACJ Geographic Information Center (UACJ-CIG) was used to prepare a Digital Elevation Model (DEM) with bare ground elevations; the resulting map has a resolution of 2 m per pixel. Physiographic parameters were then inserted into HEC-HMS v3.4 to calculate runoff volumes and other parameters such as watershed areas, main stream length, and average slope (Estrada-Leyva 2013). These parameters were calculated as an extension of a GIS project under ArcView v3.2 software which allowed the insertion of runoff coefficients and concentration and lag times for runoff measurements. Prevailing soil types, LULC, and impermeable areas were mapped from aerial photographs. These serve as the main source of land truth analysis and were used to estimate a Curve Number (CN) from which runoff coefficients were calculated. For this study, soils were considered type B (USDA 1986), characterized as soils that allow very little infiltration (i.e., Vertisols). Once the runoff volumes were calculated, potential flooding areas with estimated buffer zones were obtained using the Flood Area extension of ArcMap v9.3. This enabled determination of the extent of surface water pulses based on calculated return periods for each modeled flood event. The hydrologic models were run for a 24 hour torrential rain event (the

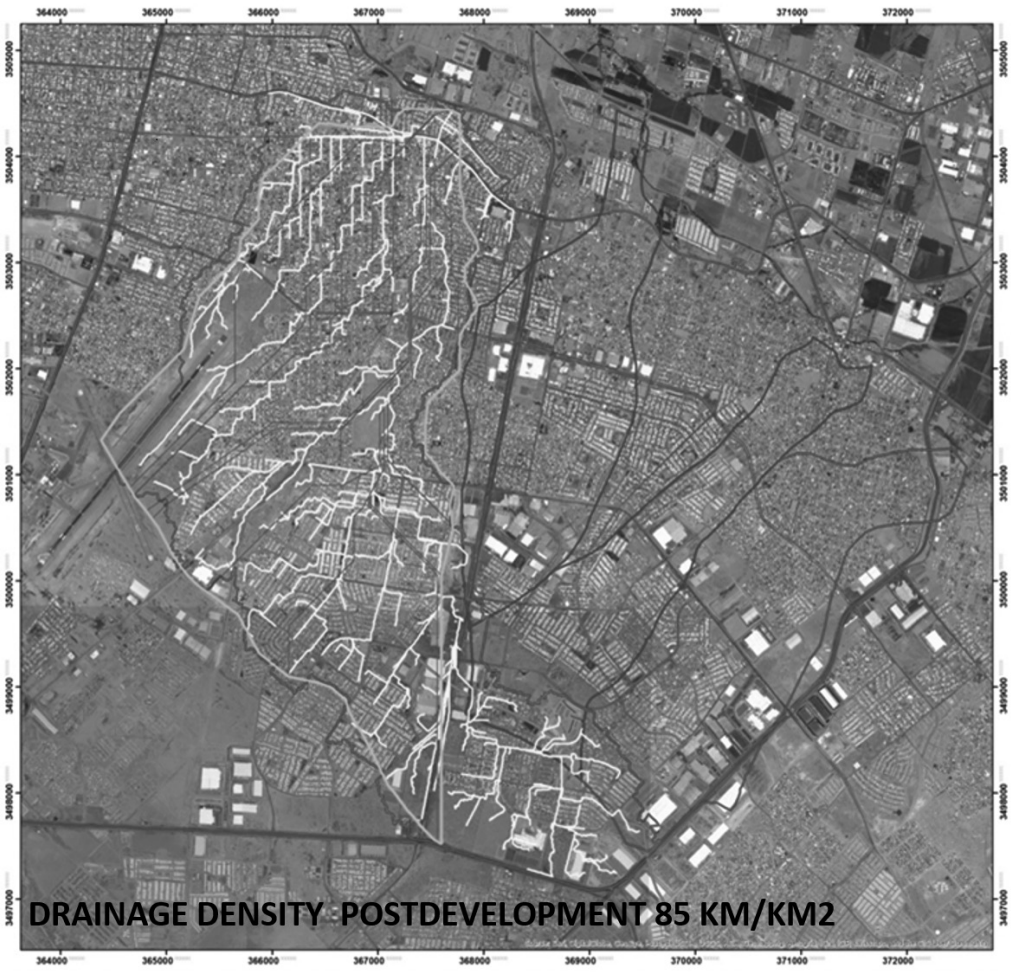

Figure 4. Drainage density (Dd) at area of interest Arroyo Tapioca (Modified from Estrada-Leyva 2013).

modeling criterion used by municipal authorities in Ciudad Juarez, Chihuahua, Mexico), using return periods of 2, 10, and 25 years.

Results and Discussion

The vegetation cover of the study area is less than 30% and the average CN is about 80. Hydrologic modeling results from HEC-HMS and ArcView v3.2 are displayed in Figure 5. The model shows the effects of urban features on the post-development locations of streams, junctions, sub-watersheds, and outlets in the Arroyo Tapioca Watershed. Divides between internal sub-watersheds are governed by major streets and the modified topography resulting from recent dense urbanization. Mainstream arroyos in each sub-watershed follow street paths; nonetheless, runoff at the scale of the entire watershed continues to follow the pre-development northward direction. The street-based drainage pattern has an important hydrologic consequence because flooding hazards are greatly increased at each of the 90° turns imposed by the street grid. Hazards are exacerbated by the changed LULC (removal of vegetation and construction of impermeable surfaces) and the densification of Dd.

Table 1 shows potential precipitation depths for each set of conditions. For a return period of 25 years, the accumulated precipitation depth is 84 mm, representing one third of the average annual precipitation estimated at 250 mm/yr. The model simulations include 2, 10, and 25 year return periods for a 24 hour torrential rain, matching the return periods used by local authorities in Ciudad Juarez, Chihuahua (IMIP 2004). These potential storm events can accumulate important volumes of water because of the transformation from precipitation to runoff linked to impervious areas, low roughness coefficients, length of main streams, and dominant slopes. Slopes and other physiographic parameters are listed for each sub-watershed in Table 2. Points 1 and 2 lie to the north of a paleolake that formerly drained in their direction, but urban topography modification has redirected surface flow to the southeast. Estimated volume and peak discharge were calculated for the junctions and outlets of each of the catchment sub-areas of the Arroyo Tapioca Watershed. Table 3 shows the accumulated

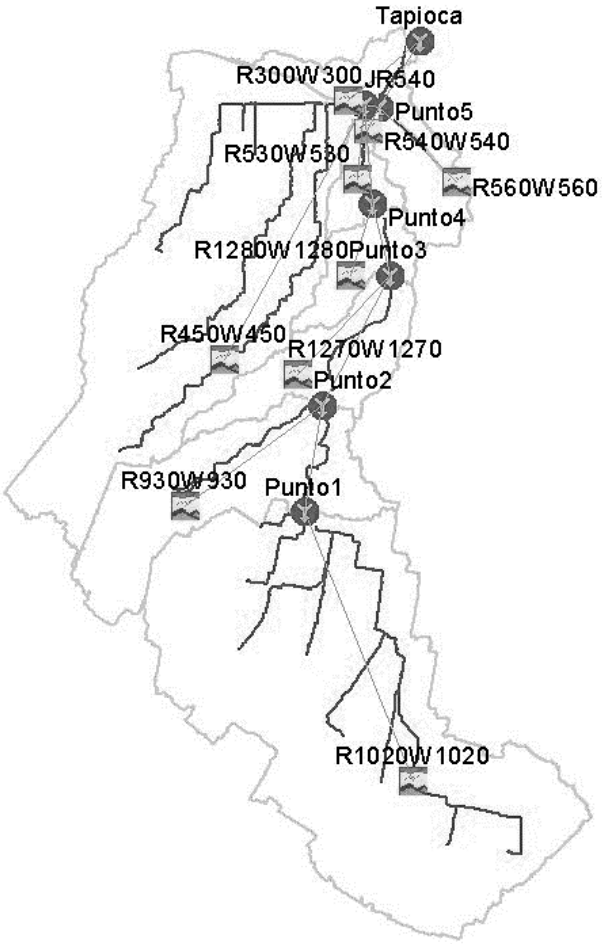

Figure 5. Hydrologic model generated under HEC-HMS showing catchment areas, junctions, and outlets for the area of interest.

Table 1. Potential rainfall depths (mm).

Duration	Return Period		
	2 yrs	10 yrs	25 yrs
5 min	8.30	12.80	15.30
15 min	16.50	25.40	30.40
1 hr	20.70	33.40	42.00
2 hr	24.00	38.90	48.90
3 hr	26.20	42.50	53.40
6 hr	30.50	49.40	62.10
12 hr	35.50	57.40	72.20
24 hr	41.30	66.80	84.00

volumes and peak discharges as functions of the return period. The main stream in Table 3 was defined from (Point 1) upstream to the final outlet at the Tapioca site (Figure 5, also shown as site 6 in Figure 6).

The biggest catchment area, corresponding to Point 1 in Table 3, is about 6.8 km^2 with an estimated impervious area of 80%. It has a long main stream that meanders through the streets for 6.5 km (Table 2). The Tapioca outlet has the most accumulated volume for a return period of 25 years (845,000 m^3), as well as, the maximum estimated peak discharge (44 m^3/s) (Figure 7). The outlet is small (0.5 km^2), but its impervious area is high (95%) and its slope is minimal (1%); hence, the concentration time (TC in Table 2) for runoff accumulation in that area is short, approximately 41 minutes, which consequently generates a higher danger of flooding. Only a small amount of runoff comes from the immediate 0.5 km^2; most originates in the rest of watershed. Therefore, the sub-watershed at catchment area R300W300 (Figure 5), is at higher risk of flood damage during intense storm events. In contrast, the upstream sub-watershed R1020W1020, with an area of approximately 6.8 km^2, has an estimated accumulated volume of 482,000 m^3 for a 25 year return period. In this case, peak discharge reaches about 25 m^3/s over a more extended area; hence, the flood risk could be distributed and significantly reduced.

Enormous quantities of runoff water are generated every year from extreme storm events in the PdN region. It has been demonstrated that flooding potential is a hazard risk within the Arroyo Tapioca, placing residents in danger. Nonetheless, potential solutions to this challenge can be achieved, with added advantages, from the application of engineering alternatives.

Aquifer recharge opportunities

PdN cities are dependent on groundwater for their supply of potable water. Even though rainfall is low (avg. 250 mm/yr.), huge amounts of runoff are generated from impermeable LULC areas resulting from urbanization, as demonstrated by the hydraulic modeling response of the Arroyo Tapioca Watershed. This runoff creates problems and flood risks along mainstream corridors. Aquifer formations and their water tables in the region are falling up to 1.5 m/yr. because of over pumping from deep groundwater wells (Hibbs 2004; Eastoe et al. 2008; Hawley et al. 2009; Granados et al. 2012; Eastoe et al. 2016). The need for innovative facilities for focused artificial recharge is enormous since most of the area has

Table 2. Physiographic parameters for mainstream and sub-watersheds at the Arroyo Tapioca study site.

Catchment Name	Total Area (km^2)	Slope (%)	Length (m)	Roughness Coefficient "n"	TC min	TR min	IS %
Point 1	6.8	0.003	6558	80	114	69	80
Point 2	2	0.007	3616	80	60	36	70
Point 3	1	0.01	3182	80	50	28	95
Point 4	0.5	0.01	1968	80	35	21	95
W530R530	0.3	0.01	1546	80	29	17	95
Point 5	0.02	0.01	568	80	14	9	95
W560R560	0.5	0.01	1957	80	39	23	95
Tapioca	0.5	0.01	2379	80	41	24	95

TC = Concentration Time; TR = Retention Time; IS = Impervious Surface

Table 3. Estimated peak discharge and accumulated volume per return period (RP).

Catchment Name	Hydrologic Elements	Drainage Area (km^2)	Peak Discharge 2 year RP (m^3/s)	2 years Accumulated Volume (*1000 m^3)	Peak Discharge 10 year RP (m^3/s)	10 years Accumulated Volume (*1000 m^3)	Peak Discharge 25 year RP (m^3/s)	25 years Accumulated Volume (*1000 m^3)
Point 1	Catchment Area R1020W1020	6.8	11	215	21	392	25	482
Point 2	Catchment Area R930W930	2	14	272	26	499	32	614
Point 3	Catchment Area R1270W1270	1	16	308	30	562	36	691
Point 4	Catchment Area R1280W1280	0.5	17	326	32	594	38	730
Junction 540	Catchment Area R530W530	0.3	17	338	32	614	39	755
*Point 5	Catchment Area R540W540	0.02	.	.	.	.	.	.
	Catchment Area R560W560	0.5	18	356	34	646	41	793
Tapioca	Catchment Area R300W300	0.5	20	375	37	680	44	835

*Most of the estimated peak discharge and accumulated volume at Point 5 comes from Catchment Area R560W560 (0.5 km^2); Catchment Area R540W540 (0.02 km^2) is not representative.

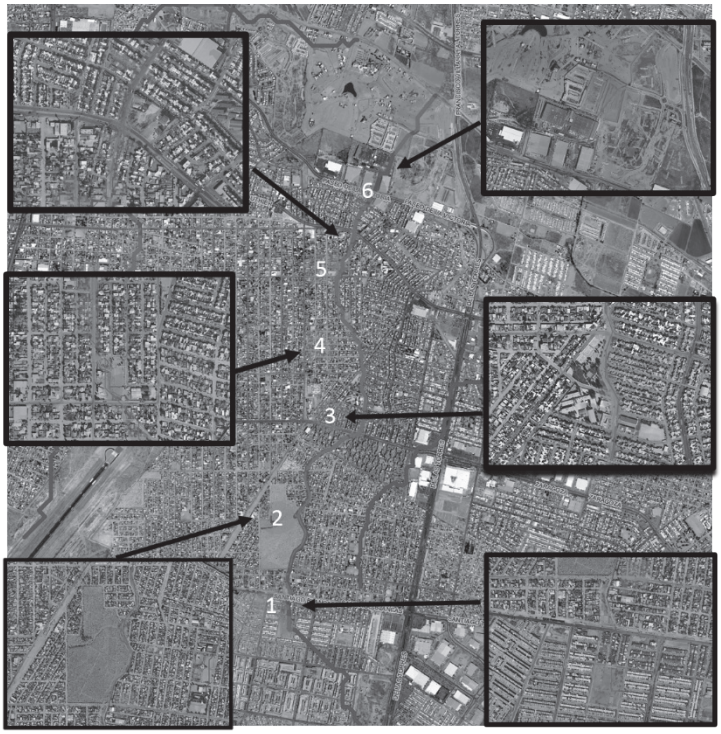

Figure 6. Modeled potential flooding areas within the Arroyo Tapioca for 25 year return.

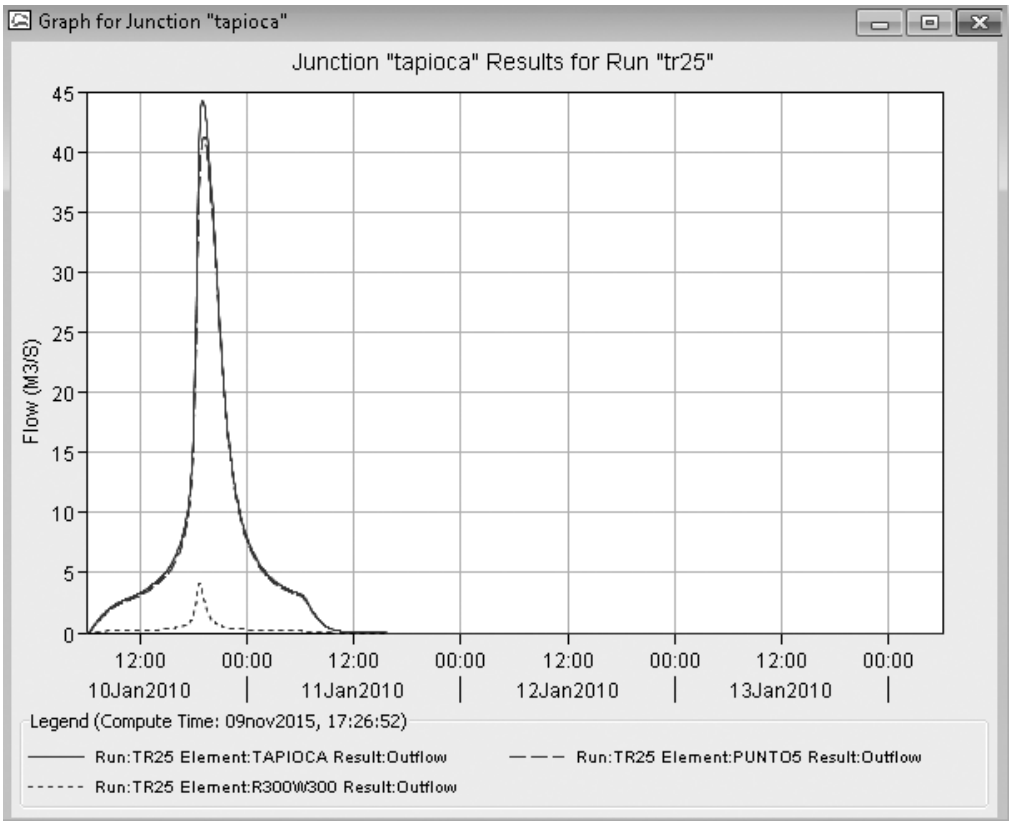

Figure 7. Hydrogram peak discharge for the January 10, 2010 torrential rain event.

been urbanized with high percentages (80 to 95%) of impermeable surfaces. Finding large areas for traditional recharge facilities is almost impossible because the price of land is too high; hence, there is a need for a different approach to reduce flood risk while enhancing recharge. The implementation of GI is a potential solution, and has the added advantage of encouraging and enabling a basic level of community involvement.

Conclusions

An understanding of urban hydrology in small watersheds is becoming more important for flood control and prevention of damage to urban infrastructure in regions where climate change is altering precipitation. For the region of interest in this study, it is clear that extreme precipitation events have already put human life, property, and urban infrastructure at risk. Furthermore, unplanned urban growth has not taken into consideration the importance of urban hydrology in building safe and viable communities. The increase of impervious areas has produced excessive runoff volumes focused into densely populated parts of the lower catchments. If proper runoff control infrastructure is generated, different volumes of water may be put to use in improving the urban environment, while reducing flood risk in lower elevation areas and enhancing recharge. The use of GI to promote flood control is a strategic approach using a permaculture concept in which small local instances multiplied many times can generate a better result than the construction of massive and costly infrastructure. Furthermore, such sites can have a positive impact on the environment, native flora and fauna, and community interaction and wellbeing. All of the findings of this study are applicable throughout urban areas of the PdN region and in other regions of similar climate.

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