Water Management in the Upper Laje River Basin

Rebecca Leonardson
Rosey Jencks
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Abstract

Urban water management in Portugal will grow increasingly challenging over the 21st century, due to the combination of urbanization and climate change. Development of high-density housing and commercial areas increases both the probability and the economic costs of flooding. Climate change will reduce overall water supply. We propose to address both of these issues in the Laje River basin by harvesting stormwater for domestic use. We develop a precipitation model, a rainfall-runoff model, and a cistern usage model to estimate the effects of urbanization and moderate implementation of cisterns on streamflow. These models are applied to precipitation records from a recent wet year (1989-90) and a recent dry year (2005-06). During these model runs, it was estimated that urbanization from 1983-2008 would increase peak runoff by up to 35% in the wet year and 85% in the dry year. Assuming a 2008 level of development, implementation of cisterns into high-rise residential buildings would reduce peak flow by an average of 4% in the wet year and 0.5% during the dry year. Furthermore, cistern use was found to supplement water supply by 0.25 million cubic meters (mcm) during the dry year and 0.36 mcm during the wet year, or 3% and 5% of the in-building annual water demand. However, cistern use also reduces base flow levels in the basin, which can negatively affect the aquatic and riparian ecology. It is recommended that infiltration is increased in other projects in the basin in conjunction with cistern use, in particular routing the cistern overflow into infiltration basins.

Introduction

On November 18th-19th of 1983, a severe rainstorm near Lisbon, Portugal caused significant flooding in the Laje River Basin (Figures 1 and 2). Despite the subsequent implementation of flood control basins, we predict that the same rainstorm today would cause worse flooding problems in the Laje Basin due to urbanization and development on the floodplain since 1983.

Climate change predictions indicate that total precipitation in Portugal will decrease significantly over the 21st century. We propose that the region use new techniques in anticipation the two extreme outcomes of drought and flooding. We explore scenarios which could address these challenges. Specifically, we propose the implementation of cisterns to reduce runoff and augment water supplies.

The project team examined current build out to estimate the increases in impervious surfaces of the Upper Laje basin. In conjunction with this, a set of hydrologic models was developed to study the impact on peak storm flow due to urbanization. We analyzed how the implementation of cisterns in the basin could potentially mitigate some of negative consequences of urbanization to better utilize the existing infrastructure.

Figure 1: Area map. The Laje River Basin is located on the Estoril coast, West of Lisbon.

Figure 2: Extent of 1983 flooding in the Laje River Basin overlaid on 2008 development.

Effects of Climate Change

There has been a concerted effort in the past decade to predict the impacts of climate change on hydrology in Europe. Studies based on Global Climate Models (GCMs) and Regional Climate Models (RCMs) agree that there will be a significant increase in average annual temperatures and decrease in precipitation in the Mediterranean region [e.g. *Giorgi and Lionello*, 2008; *Hertig and Jacobeit*, 2008]. Precipitation will decrease due to a Northward shift of the Atlantic storm track, which currently sends wet winter storms into the region from the ocean. Increased temperatures will increase evaporation, further reducing the amount of water available for water supply and ecological uses. On a seasonal scale, multiple RCMs run under a variety of carbon emissions scenarios agree that precipitation will decrease during the summer [*Giorgi and Lionello*, 2008]. There is more uncertainty [*Hertig and Jacobeit*, 2008] between models for winter precipitation, with predictions varying between moderate increases and significant decreases [e.g. *Hertig and Jacobeit*, 2008; *Kilsby, et al.*, 2007].

For most of Europe, RCM studies predict that large storms will grow more extreme, leading to greater flooding [*Giorgi and Lionello*, 2008]. However, there is significant fine-scale variability due to local topography and seasonal wind patterns. For the Iberian peninsula, fine-scale RCMs predict either a decrease in the intensity of extreme storms or no significant change [*Frei, et al.*, 2006; *Gao, et al.*, 2006; *Pal, et al.*, 2004].

Study Site

The study site is located in the Upper Laje Basin in the town of Algueirao-Mem Martins, a town within the municipality Sintra approximately 26 kilometers from Lisbon, Portugal. (Figures 1 and 2) The sub-basin is about 10% of the entire Laje watershed and has an area of 4.47 km^2. The project team chose this sub-basin for the following reasons:

- The population density is the highest in Portugal and is approximately 3,821.4 inhabitants/km^2, meaning that:
  - The ground is highly impervious, increasing flood risks
  - The cost of flooding is high in terms of health and economics
  - There is a large local demand for water
- The basin is small and wide relative to its length, simplifying hydrologic modeling
- Flood risk has already been addressed in the Upper Laje in the form of detention basins, and we wanted to analyze cisterns as an alternative.
- The runoff model can be compared to results found in earlier runoff studies. The study area corresponds to *Bacia 1* in a flooding report by the Portuguese Public Works Ministry [*LNEC*, 1987].

Data

Streamflow and precipitation data were downloaded from the website of the Portuguese National Information System for Water Resources (SNIRH) (http://snirh.pt/). There is one streamflow gauge in the basin and several rain gauges near to (but outside of) the basin (Figure 3). The analysis is limited to daily streamflow and precipitation measurements because there was overlapping data available.

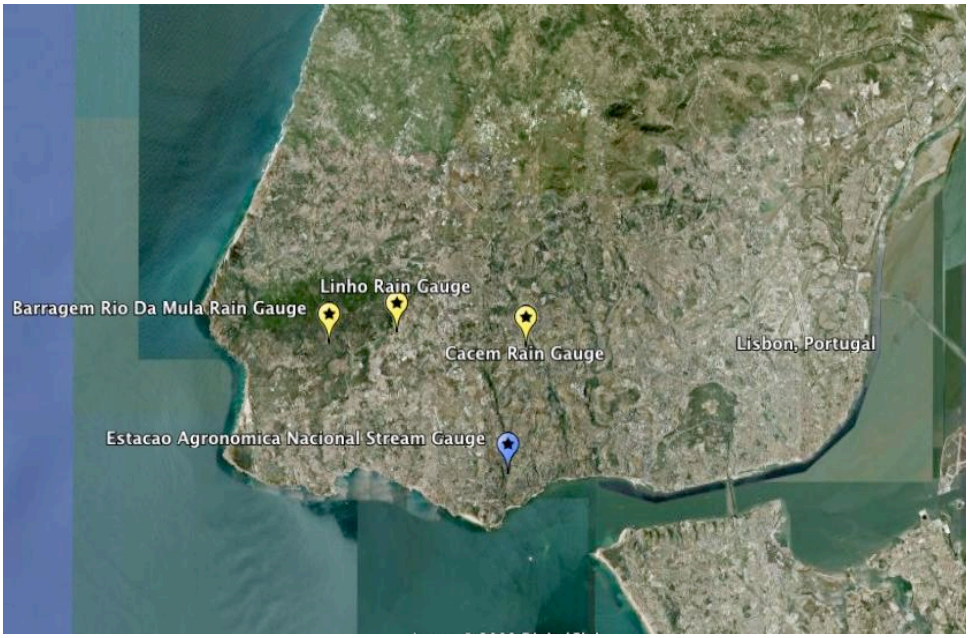


Figure 3: Rain and stream gauge sites

Study Period

Two years of daily precipitation data were chosen to represent wet and dry conditions, October 1989 – September 1990 and October 2005 – September 2006, respectively. These two rain records were used to estimate runoff with urban development levels from 1983 and 2008, and with 2008 development and stormwater harvesting with cisterns.

Methods

Streamflow data from the Estação Agronómica Nacional (EAN) in Oeiras were analyzed with precipitation data from nearby rain gauges (Figure 3) to develop a precipitation model and a rainfall/runoff model for the basin. Linear regression was used to correlate daily precipitation with streamflow EAN; the analysis was limited to days with streamflow values greater than $4m^3/s$, when rain contributes much more water than groundwater and sewage to total streamflow. This regression was used to develop a precipitation record for the Laje basin from a weighted average of the rain data from Cacém, Linhó, and Barragem Rio da Mula, with respective weights 0.56, 0.31, and 0.13.

Daily precipitation from the period 1-Oct-1989 to 30-Sept-1990 was then compared to streamflow measurements at EAN (including low-flow values) to develop the rainfall-runoff model. Runoff was modeled using the Soil Conservation Service (SCS) curve number model [pp. 389-393 *Dingman*, 1994]. This model uses soil moisture, geology and land use characteristics to estimate runoff. A previous study (LNEC 1987) had estimated the class II curve number (CN) for the Upper Laje as 86.3 when the 1983 flood occurred.

Using CN=86.3, the SCS model yields a reasonable storm response for the entire basin for 1989, but it does not recreate base flow. Base flow was estimated using linear regression of streamflow on consecutive days, which yielded the following model:

$$Q_{EAN}(n) = B(n) + Q_{SCS}(n) \quad (1a)$$
$$B(n) = 0.942 \times B(n-1) + K \times Q_{SCS}(n-1) \quad (1b)$$

where K is a parameter and $Q_{EAN}(n)$, $Q_{SCS}(n)$, and $B(n)$ are measured streamflow, modeled runoff, and estimated baseflow for day n. Equations (1a) and (1b) overestimate storm response when the ground is dry and underestimate it late in the season, when the ground is wet (the green line in Figure 4). These can be addressed partially by altering the response time of soil moisture to rainfall; this is illustrated by the blue line with markers in Figure 4. Further parameterization of the model is limited by the data record. Details of model calibrations and model runs are given in Table 1.

Model	Ppt period	Dev. level	Area (km^2)	CN	K	SM Response	SM thresholds
Calibration							
SCS	1989-90	1983	33.8	86.3	0	5 days	36, 53
SCS + Baseflow	1989-90	1983	33.8	86.3	0.08	5 days	36, 53
SCS + Bf + Rt	1989-90	1983	33.8	86.3	0.08	7 days	50, 100
Runs							
Dry Reference	2005-06	1983	4.47	86.3	0.08	7 days	50, 100
Wet Reference	1989-90	1983	4.47	86.3	0.08	7 days	50, 100
Dry Developed	2005-06	2008	4.47	88.2	0.05	7 days	50, 100
Wet Developed	1989-90	2008	4.47	88.2	0.05	7 days	50, 100
Dry Cisterns	2005-06	2008	4.26	88.2	0.05	7 days	50, 100
Wet Cisterns	1989-90	2008	4.26	88.2	0.05	7 days	50, 100

Table 1: Details of model calibration and runs. Ppt is precipitation. Dev. is development. K is the parameter in equation 1. CN and SM (soil moisture) are parameters for the SSC model.

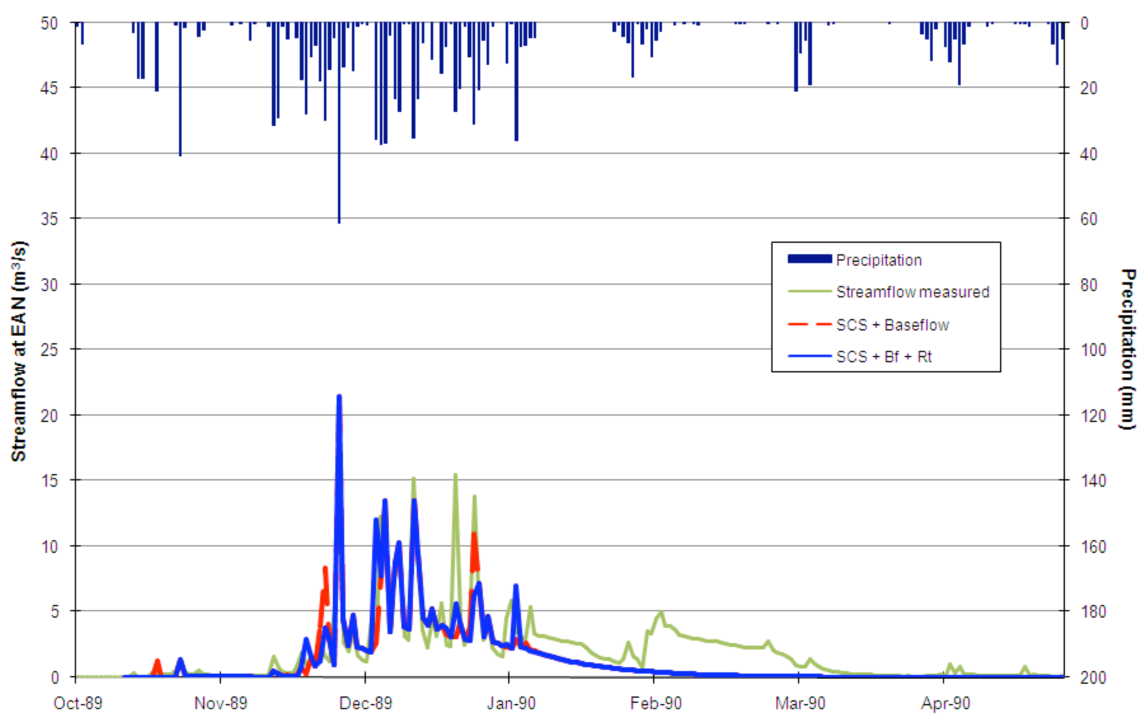


Figure 4: Validation of the rainfall runoff model. Precipitation is shown on the top axis. Along the bottom axis are streamflow values at EAN. *SCS* is the standard Soil Conservation Service model with CN = 86.3 for the basin. The *Baseflow* model is given in equation 1. *SCS + Bf + Rt* has a longer response time of soil moisture than the standard SCS model, as described in Methods.

Population growth on the Estoril Coast has been at least 1.5% annually since 1981, with development centered in the coast regions and upper watersheds and with the increase of impermeable areas outpacing population growth [*LNEC*, 2000]. Therefore, 1.5% per year, or 45% between 1983 and 2008, was taken as a conservative estimate of increased impermeable area. Assuming that the areas of both high-density housing and commercial districts increased by 45% and that the land was taken equally from low-density housing, orchards, gardens and forested areas, this leads to a new SCS curve number of 88.2 for 2008.

The parameter K represents how fast a storm hydrograph recedes after the rainfall stops. This recession time reflects water transport through surface channels and shallow groundwater flow. A K value of 0.08 gave a reasonable fit to the 1989 data at EAN (the red line in Figure 4). Recession should be faster (smaller K) in 2008 than in 1983 due to urbanization, but there was no basis for estimating it. Instead, K was chosen so that the annual evaporation (the difference between precipitation and runoff per watershed area) would remain constant. Model parameters are shown in Table 1.

Estimating Impervious Surfaces

The current type of development occurring in the upper Laje basin is largely the conversion of farmland to highly impermeable high rises. To estimate the relative ratios of impervious cover associated with the three major land development patterns in the basin, (farms and open space, low rise residential, and high rise and industrial lands)the team used aerial photos and AutoCAD to develop figure ground drawings of representative developments. The three development types were imported into AutoCAD at the same scale and the areas of roofs and paved areas were traced and calculated using the area calculation function. This same method was used to estimate the proportion of various land uses throughout the basin.

Cistern Model

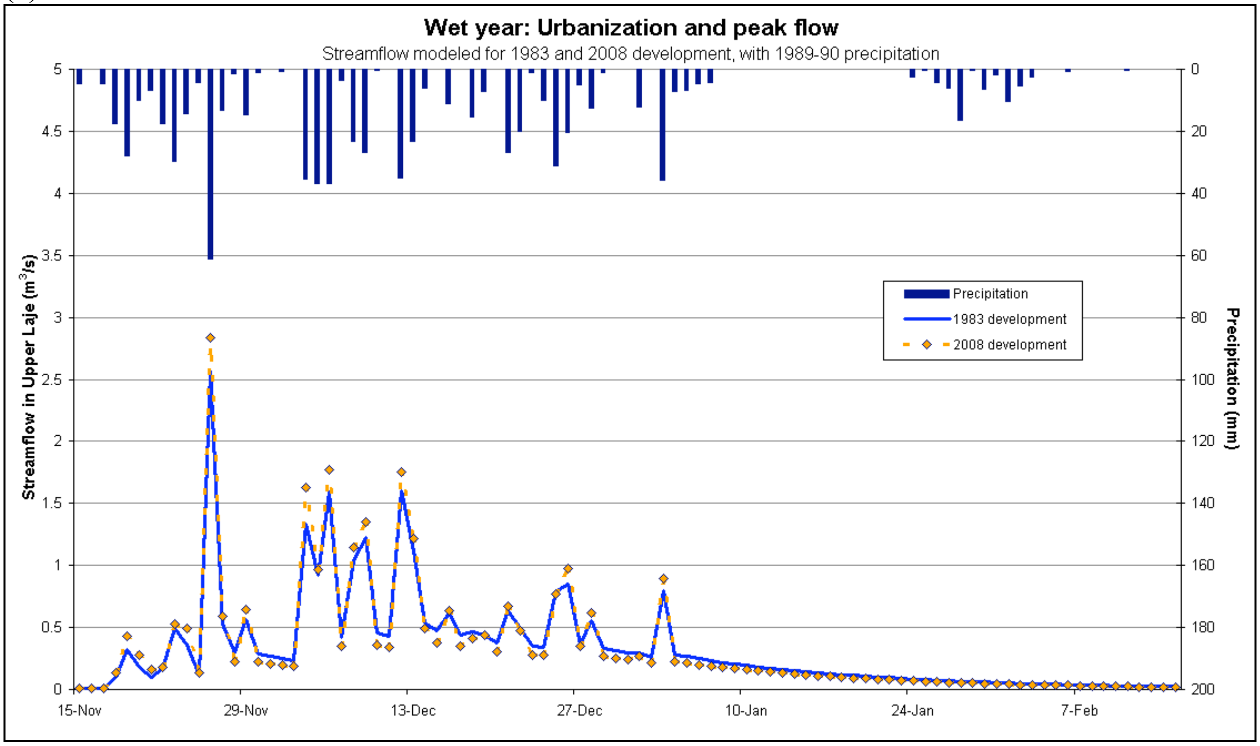
A “cistern model” was built to estimate the effects of collecting rainwater from rooftops on water supply and peak storm flow. Housing in the Upper Laje basin is largely comprised of apartment buildings (Figure 5), where it is presumed there is both space for a large storage tank (10 m^3) and a significant, constant demand for water for flushing toilets. Based on analysis of aerial and ground-based photographs, it was estimated that there are 540 apartment buildings in the study area, each having a roof area of 630 m^2 and 99 residents. It was estimated that all of the water hitting the roof is added to a cistern until it fills. Overflow is routed to an open area that has the same imperviousness as the basin average. The cisterns will be drained by toilet flushing at a rate of 6 flushes per day per resident using low-flow toilets (6.05 liters per flush) [Imhoff 1995]. The roof area represented in this study represents 9% of the land in the study area. The population of the buildings represents 52% of the population of Algueirão - Mem Martins.

Figure 5: High-density housing in the Upper Laje Basin

Results and discussion of hydrologic analysis

Modeled streamflow for the Upper Laje for the 1989-90 and 2005-06 rainfall patterns are given in Figure 6. Urbanization increases the estimated peak flows. During the wet years, the average peak flow increase is 12%, with increases up to 35% for individual events. Peak flow during the dry year is increased an average of 85%, although the overall flow volume is still quite small.

(a)



(b)

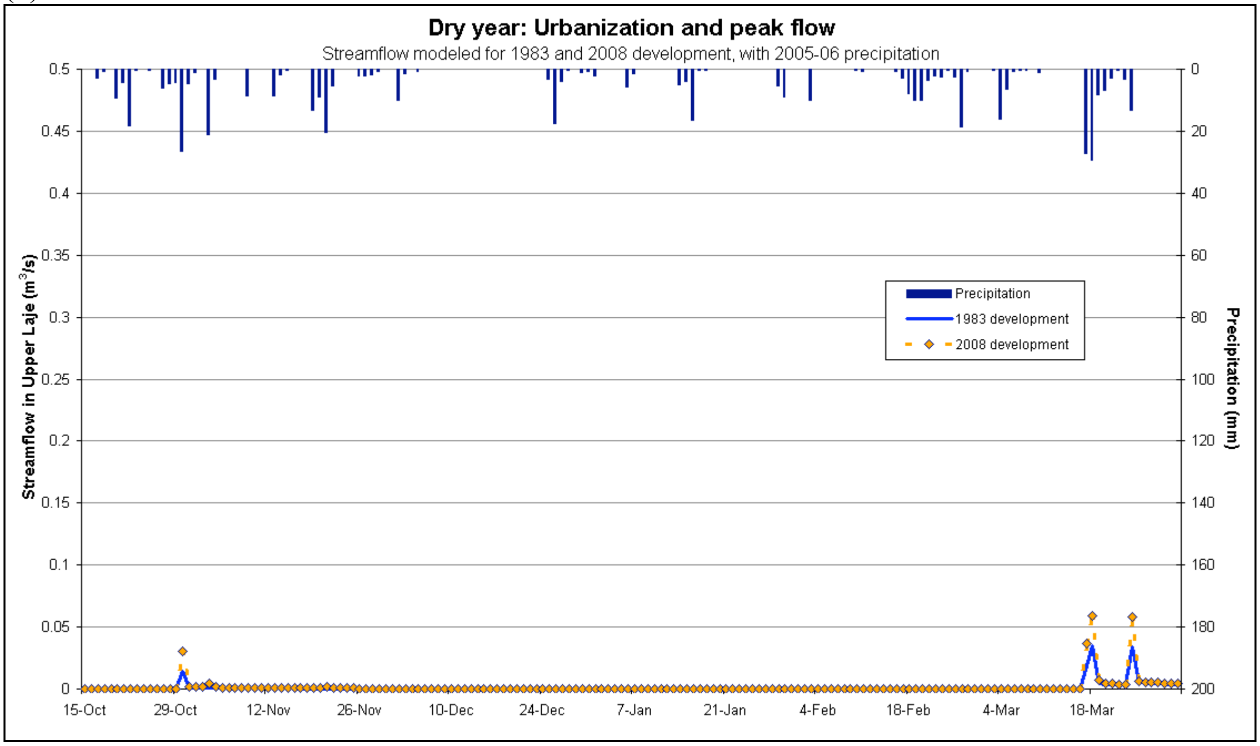


Figure 6: Modeled runoff for (a) wet year and (b) dry year rainfall under 1983 and 2008 levels of urban development in the Upper Laje.

Implementation of cisterns can reduce runoff by up to the percentage of land that feeds into cisterns (9% in this case). The actual reduction in flow is limited by the amount of water left in the cistern from the day before. During the wet year, the model predicted that cisterns decrease peak flow by 2.6%, with a 0.4% reduction for the largest peak flow (Figure 7). During the dry year, the peak flow was reduced by up to 7%, but most flows were unchanged. Moreover, the cisterns were able to supplement the local water supply with 194,000m^3 of water during the dry year and 245,000m^3 during the wet year, or 6.8% and 8.2% of total in-building water demand, respectively.

Extremely large floods, such as the 1983 event, tend to occur after a number of days of heavy precipitation, when the ground is saturated. In such an event, the cisterns are likely to fill before or during the heaviest rainfall. This limits their ability to absorb water and reduce peak flow. This could be mitigated by coordinating emergency releases of water from the cisterns into the storm or sanitary sewers in anticipation of the heaviest rain. Coordinating such an effort would require appropriate plumbing, education of building managers, and a weather monitoring/emergency notification protocol.

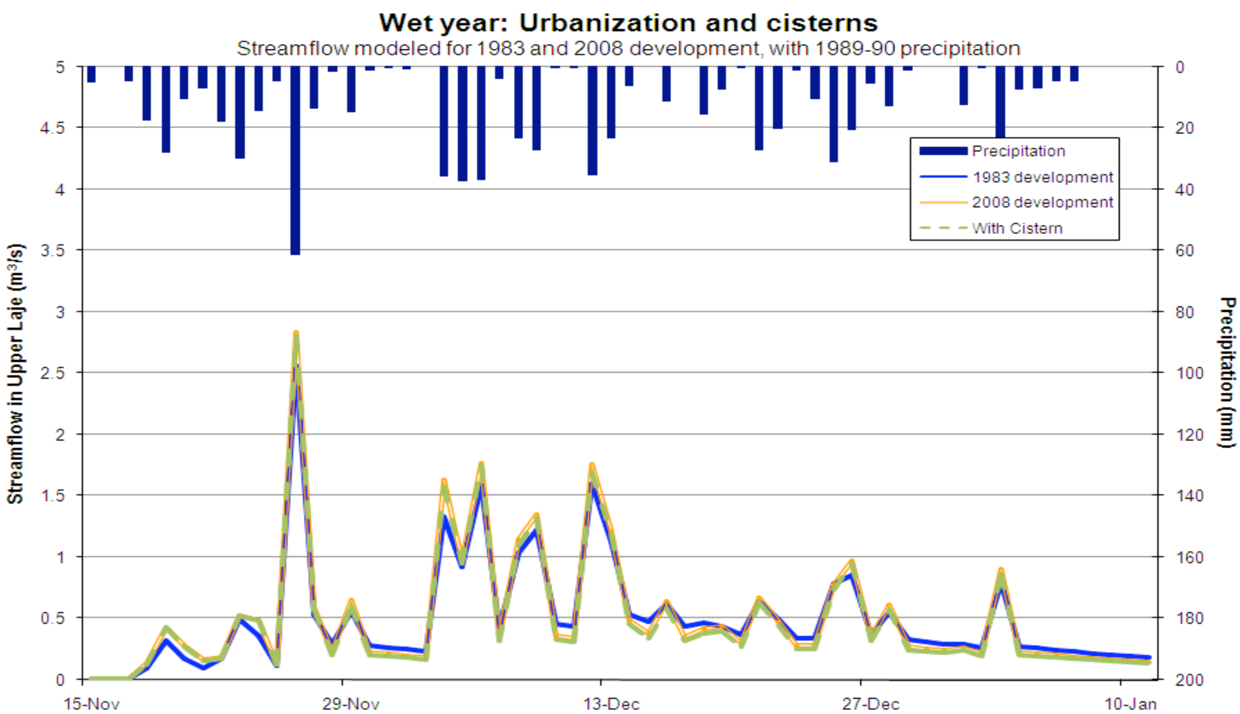


Figure 7: Effect of cisterns on streamflow during a wet year.

Stormwater management in arid regions

To date, many stormwater management technologies have been implemented in temperate climates with ample rain with the intention of protecting the water quality and the geomorphology of downstream receiving water bodies. Arid communities have always confronted the challenges of flashy rain events, flooding and water scarcity, but climate change forecasts predict greater water scarcity, necessitating a new approach.

The rapid development in the Laje Basin has greatly increased impervious surfaces. Urbanization decreases the infiltration capacities and increases the potential for localized. large-scale runoff and erosion events. Stormwater management professionals in other arid regions are now seeing the need to consider stormwater as a resource and begin to design systems to assist in efforts to meet water demand. This is in addition to the typical stormwater management goals of decreasing peak runoff flows and protecting receiving water bodies.

Other Arid Cities

Cities in the American Southwest that have been implementing stormwater management strategies to comply with Federal Stormwater Management rules are now facing drought and water scarcity. They are increasingly using strategies for stormwater runoff which retain, harvest and reuse the captured stormwater.

The City of Tucson, Arizona, which receives approximately 11 inches per year, has created progressive policies that guide builders and designers to incorporate rainwater harvesting strategies into their designs. These strategies assist the city in reducing potable water demands, create additional water reserves and recharge the aquifers. Strategies recommended include micro basins, installing swales along the contours to direct runoff to planting areas and rainwater harvesting cisterns. The city also promotes low-water use gardening. Tucson receives the majority of its rain in a few events which can lead to flash flooding. These strategies assist in slowing and retaining the flows and protect property Drought stricken Santa Fe, New Mexico is developing legislation which will require landowners to harvest their runoff. Several new projects incorporate rainwater harvesting projects. The new public park, the Santa Fe Civic Center and Railyard Park, included 45,000 gallon cisterns and 75,000 gallon cisterns for irrigation. [Gunderson, 2009]

Conclusions

This analysis shows that recent development patterns significantly increases peak stormwater runoff. If another storm event like the 1983 rainstorm occurred today, the flooding would likely be much worse. While flood control basins have been installed in the upper Laje, development patterns have likely outstripped their ability to protect life and property.

Cisterns have the ability to reduce peak runoff from their connected roof areas. While, cisterns alone will not address water demands or protect the town from flooding; they can be part of a set of tools which meet and reduce water demands, reduce the impacts of impervious surfaces and contribute to groundwater recharge.

In the face of uncertain water futures, decision-makers should employ the following hierarchy of uses to the maximum extent practical. To reduce the demands on potable water supplies, municipalities and water utilities should promote conservation first through the use of low-flow toilets, sink and shower fixtures and landscaping. Next, onsite resources such as stormwater and greywater should be used for non-potable purposes. The remaining runoff should be infiltrated and treated through the use of Low

Impact Development technologies. Once all of these strategies have been implemented, communities should look at larger scale recycled water from municipal wastewater sources. Unmet demands should then be met with imported potable water.

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