

GEOLOGIC INVESTIGATIONS OF URBAN SEDIMENTATION IN TEMPE, AZ USING RETENTION STRUCTURES

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ABSTRACT

Urbanization-induced changes in landcover and hydrology affect erosion, transportation, and sediment storage. Understanding urban sediment production and composition in a desert region can be achieved by studying sediments in retention basins and mapping the landcover of their watersheds. How water and sediment flow through the urban system has consequences for flood control and riparian biota, both within the urbanized area and downstream.

Retention basins reduce stormwater volumes reaching channels and trap urban sediments. Through analysis of aerial photography and City of Tempe stormwater GIS data, we selected and mapped two internally-drained neighborhood retention basins and collected sediment stored in the retention basin structures to calculate yearly-scale sediment production rates. Sediment for each basin was sorted by size. The pebble size fractions were separated into organic material, rocks, and trash. Sediment production analyses indicated that ~ 0.002-0.400 ft³/yr per acre were produced from these neighborhood landscapes. These production rates imply a geologically-scaled erosion rate of 0.01-3 m/My for the urbanized desert.

Key Words: sediment production, urbanization, desert, landcover, neighborhood-scale, geomorphology.

INTRODUCTION

Humans have become powerful agents of geomorphic change. Agriculture, construction, and mining now move sediment at a greater annual pace than erosion modulated by tectonics and climate (e.g., Hooke, 1994; Wilkinson and McElroy, 2007). Not only are we increasing global erosion rates, but we are reorganizing where landscape change occurs. By modifying continental lowlands for agriculture and urban construction, we may transform relatively stable landscapes into ones out of equilibrium; making landscape change, ecological change, and hazards more difficult to predict. While cities have long been the socioeconomic driving force for regional agriculture production and resource procurement (e.g., Boone and Modarres, 2006), today more than half of the world's citizens live in urban areas (e.g., United Nations, 2005), thus decisions and actions by urbanites can affect local, regional, and global landscape change (e.g., Grimm et al., 2008).

Hydrologists, geomorphologists, engineers, and ecologists have made considerable progress in understanding urbanization's influence on fluvial systems (for comprehensive reviews see Chin, 2006 and Gregory, 2006). The fluvial response to urbanization is well-described by a conceptual model first outlined by Wolman 1967a and recently expanded in Chin's 2006 review. We paraphrase the ideas here:

First, forests are converted to agricultural fields to support urban areas. Tilled and pastured hillslopes have lower soil cohesion so typical hydrologic events now cause significant erosion. Sediments are transported into channels resulting in channel aggradation. Later, conversion from agricultural to urban land results in an even greater initial spike in erosion as ground cover is completely cleared for construction; this can cause severe channel aggradation. The urbanized landscape is covered by impermeable pavement, concrete, houses, and highly cohesive landscaping. Now urban river channels receive greatly increased stormwater runoff (volumes and velocities), but almost no hill slope sediment. Thus, the channels become prone to overbank flooding until they adjust by deepening and widening their channels to accommodate the urban flow regime (e.g. Trimble, 1997).

While the general procession of landscape response to urbanization is known, the majority of past research has focused on tributary channels in temperate region industrial cities (Chin, 2006). Variations in climate, geology, pre-existing hydrologic structure, urban form, ecological regime, and stormwater management practices all result in variations in the timescale and distribution of fluvial response. Recently, desert cities have been sites of population expansion and urban growth while older industrial cities have lost population (e.g., Auch et al, 2004). Therefore, improving our understanding of desert urban hydrology is of practical importance for stormwater management, ecosystem function, and sustainable urban design.

On site retention of runoff is a common stormwater management practice to reduce stormwater flows and associated pollutants from reaching riparian ecosystems. However, on site retention also prevents sediments and certain nutrient supplies from reaching urban channels; causing channel enlargement (e.g. Chin 2006) and altering riparian ecosystems (e.g. Grimm et al, 2004; Roach et al., 2008). Choices in stormwater management are value laden and have trade offs. We

hypothesize that sediments trapped by stormwater retention structures contain information about the quantity and composition of urban sediments transported during stormwater runoff. Measuring sediment production rates and understanding how different landcover types respond to hydrologic events will help us better understand the fluvial response to urbanization and provide practical information for stormwater managers.

Herein we present a pilot study that measures annual-scale sediment production and composition from two internally-drained neighborhood catchments in Tempe, AZ (figure 1). The data suggest a low recent sediment production rate for this part of the urban system and that certain residential landscaping choices are more prone to erosion during urban stormwater events. First, we outline a modified conceptual model for the fluvial response to urbanization in a desert regime (figure 2). Then we discuss the details of our pilot studies (figures 3-6 and tables 1-2) and how the results fit into this conceptual model. We also place these sediment production rates in the context of geologic erosion rates. Finally we outline how future studies could be coordinated with stormwater managers and academics to answer both practical and theoretical questions.

A CONCEPTUAL MODEL

The Phoenix metropolitan area has grown substantially in the past few decades due in great part to urban sprawl. Not only has Phoenix expanded in area, but also the population increased tenfold between 1950 and 1999, and it continues to grow into the twenty first century (Heim, 2001). Its extensive metropolitan area and rapid population growth make Phoenix and surrounding cities such as Tempe, AZ (figure 1) prime natural laboratories for studying desert urbanization (e.g., Toke and Arrowsmith, 2006). Urbanization has been shown to induce an erosion (and sediment flux) trajectory that increases initially and then peaks, decreases, and stabilizes (figure 2; e.g., Wolman, 1967; Trimble et al., 1997). These conceptual models have not been thoroughly tested in arid environments (Chin 2006). Additionally, most exploration has focused on channel change. Understanding the magnitude and timescales associated with these erosion trajectories is important for urban stormwater and ecosystem management. This study begins to characterize the rates and spatial distribution of urban sediment production from urbanized desert hillslopes (low relief desert piedmont surfaces; not the fluvial channels).

Deserts are characterized by lower annual rainfall but with longer weathering periods separating intense hydrologic events resulting in periods of nearly zero sediment transport followed by sudden spikes in erosion during runoff events, thus the effects of urbanization on desert landscapes may be different than temperate regions. In the case of Phoenix, AZ, we postulate 5 geomorphic stages of hillslope erosion defined by changes in human landuse history following the classical conceptual model of Wolman postulated for land use change in Baltimore, MD in 1967 (figure 2, stages A-E).

Prior to modern urbanization, there were at least two periods of agriculture in the Phoenix area. The people of the Hohokam region constructed irrigation canals along the Salt River for an agriculture system that helped sustain as many as 40,000 people around 1200 A.D. (Abbott, 2003). We suspect that irrigation and relatively low impact agriculture might have increased root density relative to the natural desert vegetation having the effect of making desert soils more cohesive. More recently, European settlers supplemented canal irrigation with groundwater mining to sustain economic crops such as cotton and citrus (e.g., Gober, 2006). This type of agriculture is more intense and probably requires significant initial construction resulting in an early spike in sediment production, but with further development and erosion controls we suspect that the hillslope sediment production rate would decrease (figure 2, stage C). With the recent migration to Sunbelt cities, urban expansion is now converting both desert and agricultural lands to cityscape. Urban construction (stage D) usually results in large tracts of desert being cleared of vegetation and leveled (often stripping the upper soil layers). Loss of vegetative soil cohesion and manual shifting of soils should cause a drastic spike in sediment production from hillslopes. While construction in a city is an ongoing process, eventually most of the land is covered with pavement, concrete, buildings, and landscaping. During this stabilized period of urbanization (stage E), little erosion should occur from hillslopes. However, the urbanized landscape is a built and managed environment so the composition of sediment produced from the urbanized landscape may have an identifiable signature. This pilot study focuses on stage E of this conceptual model (figure 2). Next, we present our evaluation of sediment production and composition from two residential urban watersheds.

METHODS

While developing this project, we met with members of the City of Tempe storm water management team and discussed how their retention basins are designed. Initially, we thought to look for sites without drywells where we could study sedimentation in a typical geological fashion (that is, digging a stratigraphic column in a sedimentary basin). However, the City's stormwater system is sophisticated and we became convinced that it was a good idea to use retention basin sediment collection structures such as dry wells to study urban sedimentation.

Drywells are designed to infiltrate stormwater runoff efficiently. Typically there are multiple drywells along the edges of retention basins. Each drywell is paired with a trash/sediment collector so that the well itself does not clog and the retention basin park does not become unsightly. Neighborhood runoff from streets and yards is conveyed via pipes directly to these sediment traps at the edge of retention basins. Thus these structures collect most of urban sediment entrained in stormwater

runoff; of course some fine and buoyant material can be deposited over the retention basin surface during intense hydrologic events or if the system becomes clogged. Because these wells have to be cleaned regularly (so stormwater will continue to infiltrate) there exists the potential to collaborate with municipalities and collect detailed records of sediment production and composition.

The City of Tempe provided stormwater GIS data to help us choose candidate drywell basins. Interestingly, we learned that the city primarily oversees residential retention basins and drywells. Drywells that drain commercial and industrial areas are typically operated by the businesses themselves. Thus, this initial study was limited to residential watersheds. During retention basin reconnaissance, we observed that the northwest pipe entering the Gaicki Park retention basin (figures 1 and 3) spills into an above ground concrete apron (figure 4). We chose this atypical sediment trap for our first pilot study because of its easy access to the trapped sediment (figures 1, 3-4). This trap had not been cleaned for approximately one year. Later, we were informed of a drywell that needed cleaning in Celaya Park (figures 1, 5-6). It had not been cleaned for two years; so we worked with the city to observe its cleaning, sample the sediments, and measure the volume of sediment removed. Below we present the compositional analysis of our Gaicki Park pilot sedimentation study and annual-scale sediment production analyses for both Gaicki and Celaya Parks.

For each of the two sediment traps, we delineated its watershed using GIS layers of stormwater drainage pipes, stormwater flow vectors, and retention basin contributing areas and mapped landcover using 2007 color Digital Orthophoto Quarter Quadrangle aerial photography (1.5 ft resolution; figures 3 and 5). We performed basic aerial photographic interpretation and digitized 6 landcover classes for each watershed: *pavement*, *concrete*, *rooftops*, *greenspace* (grass and dense tree cover), *dirt lot/desert* (desert landscaping, dirt alleyways, and dirt lots), and *pools*. We further grouped these landcover classes for the sediment production analyses (table 2): Impervious surfaces (*pavement*, *concrete*, and *rooftops*), pervious surfaces (*greenspace* and *dirt lot/desert*), and desert landscaping. For each site, we collected representative samples of the trapped sediment in multiple gallon-sized zip lock bags. Sediments bags were left open to dry for more than 1 week. Sediments from Gaicki Park were then sieved into size fractions and the largest size fraction (pebbles and greater) were sorted by composition (table 1). From our measurements of the total quantity (mass and volume) of sediment accumulated in each basin's sediment trap we made area normalized calculations of annual-scale sediment production (table 2).

SEDIMENT COLLECTION AND MEASUREMENT

Gaicki Park (figure 1 and 3) is a small residential retention basin. Water running off the surrounding neighborhood is routed to drain into the retention basin via four concrete pipes. Most of the pipes discharge stormwater runoff into a combination trash collector/dry well. These systems collect most of the sediment entrained in runoff entering the basin, but are not accessible without confined space equipment and training. The northwest Gaicki Pipe drains 135,600 m² of the neighborhoods to the north and west of Gaicki Park (figure 3). This pipe discharges stormwater on to a concrete apron (figure 4). The apron has a ~5 cm dam that allows sediment to settle out stormwater entering the basin. Because of its ease of access we used the northwest Gaicki Park sediment trap as our first site for studying urban sedimentation.

On February 26, 2009, we collected half of the sediment on the concrete northwest sediment trap at Gaicki Park (figure 4 and table 1). The sediment was dried passively for 14 days. At that time, the collected sediment mass was 2.275 kg. The sediment sample was then sieved. During the separation process, we noted that some of the material was clumped and had sprouted roots because it was still moist. Thus it was manually crumbled before sieving. We separated the sample into four size categories: larger than 4mm (pebbles), between 4mm and 1mm (coarse sand), between 1mm and 0.125mm (fine sand) and smaller than 0.125mm (silt and clay). We sieved the sample in two iterations. Each time the sieves were shaken for 10 minutes until it was apparent that the size fractions were well sorted. We left the size fraction bags open to continue to dry for several days after the sieving. The dry weight of the sediment measured was 2.20 kg (table 1) suggesting that the total sediment eroded from the watershed was 4.4 kg. The pebble-sized material was separated manually into categories based on composition. Originally we separated it with six classes: matted leaf material and grass, unidentified rounded rocks, granite, trash, seeds, and tree bark and grass. However, for the purposes of this analysis, we reduced the six categories into four more general groups: 1) Rounded metamorphic and volcanic rocks with composition similar to those of the local Salt River watershed, 2) Angular granitic grus, 3) Organic material (consisting of grass, twigs, bark, seeds, and unidentified matted material), and 4) urban trash (such as glass, chewing gum, rubber and metal). Each sediment group was then weighed and broken down into percent composition (table 1). The rock fraction comprises 82% of the total mass, organic material 16%, and trash 2%. The different rock types included angular granitic grus, rounded metamorphic rocks and small pieces of concrete and pavement. It is important to note that these percent compositions are for only the sediment larger than 4mm. However, for the sediment production rate (and erosion rate) calculations, we assume that this compositional fraction is representative of all sediment sizes. Thus, we calculated one of the rates assuming that the eroded rock fraction (3.6 kg) was removed only from desert landscaped areas (21% of land area: 24,400 m²) yielding the maximum erosion rate estimates. The other calculations were made over the entire watershed and over only permeable surfaces using the total sediment mass of 4.4 kg. During compositional analysis of the plant matter it became apparent that the Gaicki sediment accumulated over at least one year's time because of the presence of multiple seasons of seeds in varying degrees of decay. While the city did not keep

a detailed timeline of cleaning records for this sediment trap (probably because it does not include a dry well) they did make a significant drywell cleaning effort in February 2008 which probably included Gaicki Park. Therefore we assume that this sediment accumulated over a single year.

The second site we studied was the trash collector and dry well system at the outlet to the concrete pipe on the west side of Celaya Park (figures 1 and 5). We were informed by the City that they would like to clean the sediment from this system because it had been just over two years since its last cleaning and was beginning to clog. The watershed for this pipe is also a residential neighborhood, but it is larger than the Gaicki watershed (332,500 m²) and has proportionally more pervious landcover (figures 3 and 5). On April 16th, 2009, we observed as a Tempe contractor evacuated the dry well system of sediment using a portable wet vacuum system. After cleaning drywells the sediment is transported to a city holding pad (figure 6). We went to this facility to sample the sediment for compositional analysis (Table 1) and to estimate the quantity of sediment eroded over the two year time span. Because the city sends these sediments to a landfill with other debris, we were unable to get them to measure the mass of sediment, but we were able to estimate the volume of sediment with simple geometric measurements and then make an assumption about the bulk density to calculate the sediment's mass (figure 6). Over the two years since it was last cleaned just over one thousand kilograms were eroded from the Celaya Park watershed suggesting an average yield of approximately half a metric ton per year.

Compositional analysis for Celaya Park followed the same procedure as Gaicki Park, first sieving into sizes, then separating the 4mm sediments into categories (tables 1 and 2). The collected sediment mass was 8.33kg. The rock mass accounted for 92%, organic material 5%, and trash 3%. During compositional analysis, we noticed the sediments from the dry well at Celaya contained a higher percentage of fine sediment than Gaicki Park. This is probably because the Gaicki Park apron overtops during runoff events and many of the finer particles are transported as wash load into the Gaicki Basin.

SEDIMENT PRODUCTION RATE

Combining watershed delineation and landcover mapping (figures 3 and 5) with estimations of total sediment eroded from Gaicki Park (over one year) and Celaya Park (over two years) allows us to calculate annual-scale area-normalized sediment production rates for these two residential watersheds (table 2). This is a simple calculation of:

$$\text{Sediment production rate} = (\text{sediment quantity/watershed area})/\text{time scale}$$

These calculations can be discussed in terms of mass of sediment/area*time [(kg/m²)/yr] or in terms of sediment volume/area*time [(m³/m²)/yr] or [m/yr]—the latter is simply an erosion rate. Typically, geologists or geomorphologists discuss erosion rates in the units of millimeters/year (mm/yr) or meters/million years (m/My). While the results presented here are not calculations of a long term erosion rate, these annual-scale sediment production rates do imply a short term erosion rate (table 2). Additionally, it is useful to view these sediment production rates in units that local stormwater managers use so we have also converted the production rates to (ft³/yr)/acre.

Compositional analyses suggest that most of the eroded sediments were rock material from the dirt lot/desert landcover type. One could also assume that most erosion is primarily taking place on permeable surfaces and not rooftops, pavement, and concrete. Thus, we normalized the sediment production rates in three ways: 1) The entire watershed area, 2) Permeable land area, and 3) Dirt lots/desert landcover area (table 2). This has the effect of increasing the sediment production rate for the smaller land area calculations and it is probably more representative because it is unlikely that erosion occurs evenly over the watersheds' area. These calculations result in a range of sediment production rates of ~ 0.002 – 0.01 ft³/yr per acre for the Gaicki Park watershed and ~ 0.1 – 0.4 ft³/yr per acre for Celaya Park watershed (table 2). These sediment production rates imply that erosion rates for urbanized desert landscapes with residential landcover is on the order of 0.01 – 3 m/My.

DISCUSSION

The sedimentation rates calculated for these two Tempe, AZ urban neighborhoods are low (0.01-3 m/My). Simple extrapolation of these rates would imply an erosion rate similar to those measured from bare bedrock surfaces in arid regions (e.g., Bierman and Turner, 1995). While conceptual models about the geomorphic response to urbanization predict low hillslope sediment production (e.g., figure 2; Wolman, 1967; Chin 2006), the rates found in this study appear to be even lower. One might expect that sediment production would be similar to that of stable, low relief soil-mantled arid hillslopes, but somewhat less because of the decrease in the percentage of mobile (permeable) landcover over the entire watershed. A compilation of studies, summarized by Bierman (1994), suggest that low relief arid climates have erosion rates of 4-40 m/My. Thus the annual-scale sedimentation rates calculated from these Tempe watersheds suggest that the stabilized urban landscape is less prone to erosion than pre-urban desert hillslopes and is on the order of 1 m/My.

A caveat with this interpretation is that these sediment production rates are averaged over only 1-2 years' weathering, precipitation, and erosion. Desert precipitation and runoff events are sporadic and thus these 1-2 years of data do not necessarily capture a representative long term erosion rate. Additionally, the sediment collected in the Gaicki and Celaya Park sediment traps may not represent all of the sediment produced from the watershed's surface. This is because cities often

practice street sweeping, which removes sediment from the streets (part of the urban landscape's channel network), thus these are minimum values of sediment production (table 2).

The sediment compositional analyses suggest that much of the pebble-sized erosion products come from desert landscaping. Crushed granitic grus, rounded metamorphic gravels, and small volcanic rocks are commonly used throughout these neighborhoods as yard coverings and made up most of the rocks comprising the pebble size fraction (table 1). These rocks are trucked into neighborhoods for an alternative to traditional mesic landscaping. This result implies that much of the eroded sediment is material that was recently added to the landscape. However, this conclusion is complicated by the fact that these rock types are found in regional rock outcrops and some of this material could be eroded from the local Salt River terrace stratigraphy. Despite this complexity, it appears that most of the material eroded from these small urban watersheds is actually material that has been added to the landscape by human modification (landscaping products and trash). This observation supports the commonly held view that urban landscapes are constructional and are net importers of materials.

Comparing the sediment production rates between the Gaicki and Celaya watersheds we see that Celaya's sediment production rate is at least a factor of ten greater than Gaicki's watershed. The Celaya sediment accumulated over the past two years instead of only the last year at Gaicki. However, the most recent year's rainfall total was greater (10 inches) than the previous year's (8 inches). Additionally, the most recent year experienced more intense rainfall events (Flood Control District of Maricopa County Rainfall Data, 2007-2009). It is plausible that the local rainfall intensities were greater near Celaya Park, thus accounting for the greater erosion. However, we do not have data to test this hypothesis. Landcover mapping showed that the Celaya Park watershed has proportionally more dirt/desert landscaping and less pavement/concrete than Gaicki watershed (figures 3 and 5). Not only is there more permeable landcover in the Celaya watershed, but there is also proportionally more dirt/desert landscaping relative to the more cohesive greenspace landcover (grass and trees). Thus one would predict with less cohesive landcover types that Celaya would have greater sediment production. This result shows that indeed differences in urban landcover may result in very different erosional responses to hydrologic events and suggests that more work is required to understand the magnitude of these differences over the range of urban landcover.

The result of low sediment production rates (table 2) in a fully developed urban environment (stage E; figure 2) is consistent with the observation that urbanization covers desert hillslopes with pavement, buildings, allotted green spaces, and organized landscaping. We strive to create a stable surface with virtually no erosion, but we are also creating smooth impervious surfaces for water to run off. This results in water flowing with less resistance, higher volumes, and higher velocities. By lowering erosion rates and seemingly stabilizing the hillslopes of our urban environment, we are enhancing stormwater volumes and velocities and the likelihood of damaging floods and channel bank erosion (e.g., Trimble, 1997).

Accounting for urban sediment transport and erosion is complicated by the human factor. People can dump sediment down a drywell, move a pile of dirt from their backyard to an alleyway that is in another retention basins' watershed, or haul in a truckload of new topsoil to cover their lawn. These factors are not necessarily negative, just part of the urban ecological system where humans appear to be the largest driver of change. The results presented here begin to uncover details about sediment production, erosion, and transport in desert cities. As we continue to urbanize, issues and questions about storm water retention and erosion will continue to be important to consider from the aspects of economics, ecology, aesthetics, and flood hazards. Better understanding sediment transport and erosion in the urban environment should help manage more efficient water retention and drainage because drywells, pipes and trash collectors fill up and need regular maintenance. If we understand more about these sedimentation patterns during the urbanization process, stormwater managers might be able to refine guidelines on when and how to best maintain retention and other stormwater conveyance structures. Municipalities already track, clean, and organize many of these human modified sediment transport ways; we suspect that it may prove academically, ecologically, and economically useful to team up municipalities and researchers to more deliberately track and reflect on our urban landform modification habits.

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TABLE 1. Analysis of sediment size fraction and composition collected from Gaicki and Celaya Parks.

sediment size ¹ analysis			
size (mm)	size (description)	Gaicki Park ²	Celaya Park ³
>4mm	Pebble and Greater	41 %	45 %
1-4mm	Coarse - Medium Sand	40 %	27 %
0.125-1mm	Medium - Fine Sand	18 %	23 %
<0.125mm	Silt and Clay	02 %	5 %

compositional analysis (pebble size fraction) ⁴		
material	Gaicki Park	Celaya Park
Organic Material ⁵	16 %	05 %
Granitic Grus	42 %	16 %
Other Rocks ⁶	40 %	76 %
Trash ⁷	02 %	03 %

¹ Sediment was separated by size fraction using geologic sieves.

² Percentage based upon a 2.2 kg sample, this was half of the sediment collected on the Gaicki Park apron over 1 year (figure 4 and table 2).

³ Percentage based upon a 8.33 kg sample, for total sediment see figure 6.

⁴ The compositional analysis was sorted by hand and only for the pebble size fraction (see table 2).

⁵ Organic materials consisted primarily of bark, twigs, leaves, and seeds.

⁶ Rounded metamorphic rocks are consistent with rock types observed in the gravels of the Salt River (figure 1).

⁷ Trash consisted of items such as glass, bubble gum, pieces of rubber.

TABLE 2. Calculations of area-normalized sediment production/erosion rate for Gaicki and Celaya Parks

	Landcover:	Watershed	Pervious Area ¹	Desert Landscaping ²
Gaicki Park				
Area (m ²) ¹		135,600	47,500	24,400
Sediment produced (Inorganic mass g/yr)		4,400	4,400	3,600 ³
Area-normalized sediment production (g/yr*cm ²) ⁴		0.32 x 10 ⁻⁵	0.93 x 10 ⁻⁵	1.5 x 10 ⁻⁵
Area-normalized sediment production rate (mm/yr) ⁵		0.16 x 10 ⁻⁴	0.46 x 10 ⁻⁴	0.74 x 10 ⁻⁴
Sediment production English units (ft ³ /yr per acre)		2.3 x 10 ⁻³	6.6 x 10 ⁻³	1.1 x 10 ⁻²
Implied erosion rate: Geologically-scaled and area-normalized (m/my) ⁶		0.016	0.046	0.074
Celaya Park				
Area (m ²) ¹		332,500	144,500	83,100
Annual sediment produced (g/yr) ⁷		545,000	545,000	501,400 ³
Area-normalized sediment production (g/yr*cm ²) ⁴		1.6 x 10 ⁻⁴	3.8 x 10 ⁻⁴	6.0 x 10 ⁻⁴
Area-normalized sediment production rate (mm/yr) ⁵		8.2 x 10 ⁻⁴	1.9 x 10 ⁻³	3.0 x 10 ⁻³
Sediment production English units (ft ³ /yr per acre)		0.12	0.27	0.43
Implied erosion rate: Geologically-scaled and area-normalized (m/my) ⁶		0.82	1.9	3.0

¹ Area was calculated from landcover mapping (figures 3 and 5). Pervious area includes greenspace and desert landscaping

² Desert landscaping includes areas covered with landscaping rocks/desert plants and unimproved dirt lots.

³ Total inorganic fraction of sediment produced over one year.

⁴ = sediment produced in one year/area

⁵ = area normalized sediment production/density; we assume that the density of the sediment mass is approximately 2 g/cm³

⁶ typically a geomorphologists might think of erosion in meters per million years.

⁷ Celaya Park sediments (figure 6) accumulated over 2 years this number represents the yearly average for that time period.

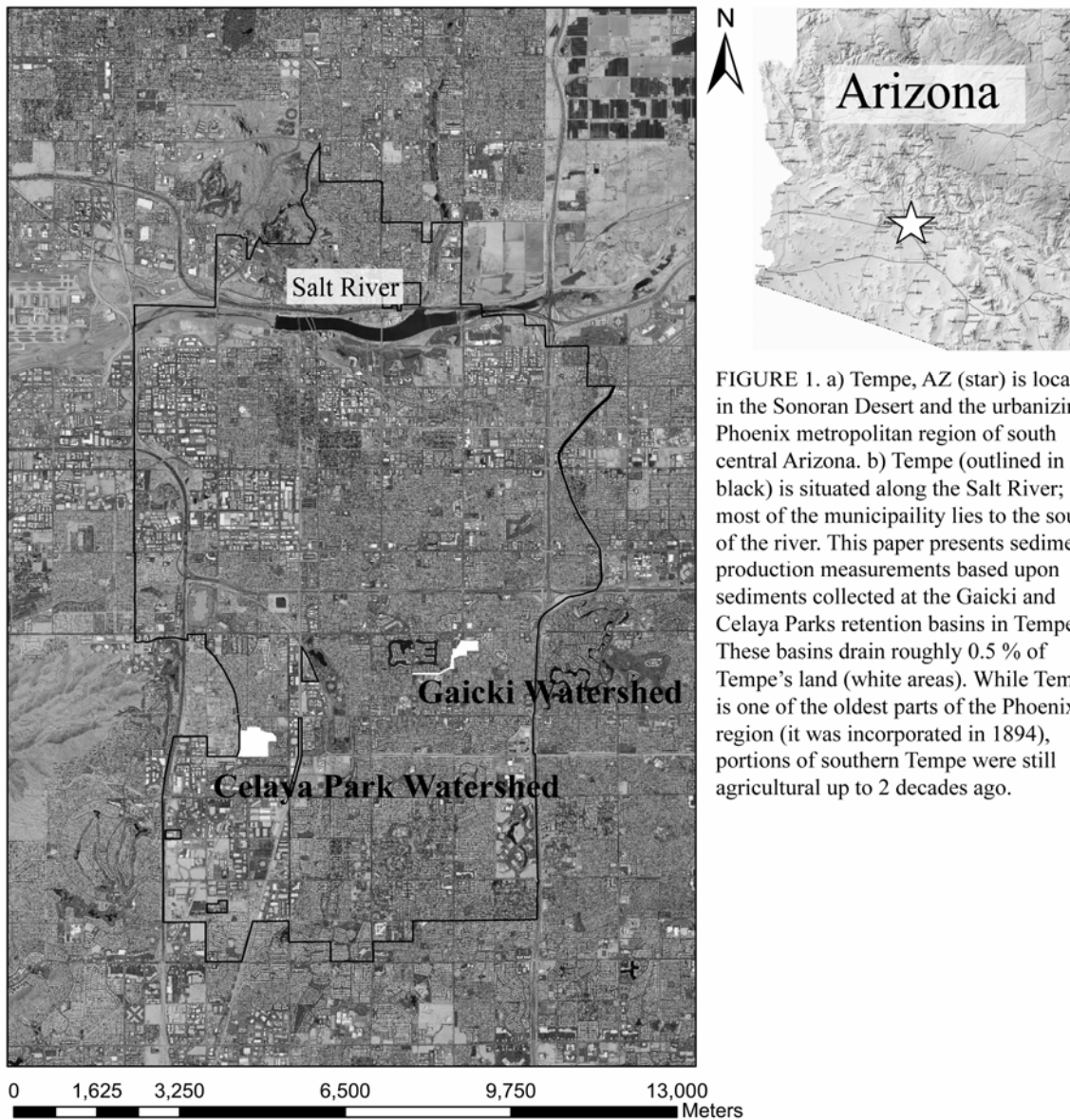


FIGURE 1. a) Tempe, AZ (star) is located in the Sonoran Desert and the urbanizing Phoenix metropolitan region of south central Arizona. b) Tempe (outlined in black) is situated along the Salt River; most of the municipality lies to the south of the river. This paper presents sediment production measurements based upon sediments collected at the Gaicki and Celaya Parks retention basins in Tempe. These basins drain roughly 0.5 % of Tempe's land (white areas). While Tempe is one of the oldest parts of the Phoenix region (it was incorporated in 1894), portions of southern Tempe were still agricultural up to 2 decades ago.

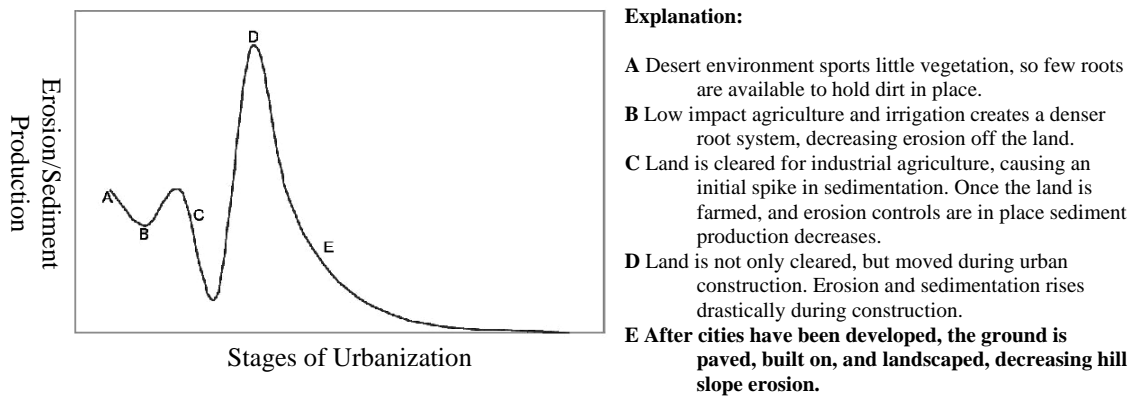


FIGURE 2. Hill slope sediment production trajectories during stages of urbanization (inspired by Wolman 1967a and Chin 2006). The analyses of sediment production at Gaicki and Celaya Parks (figures 3-5, table 1) in Tempe, AZ (figure 1) focus on stage E of the urbanization.

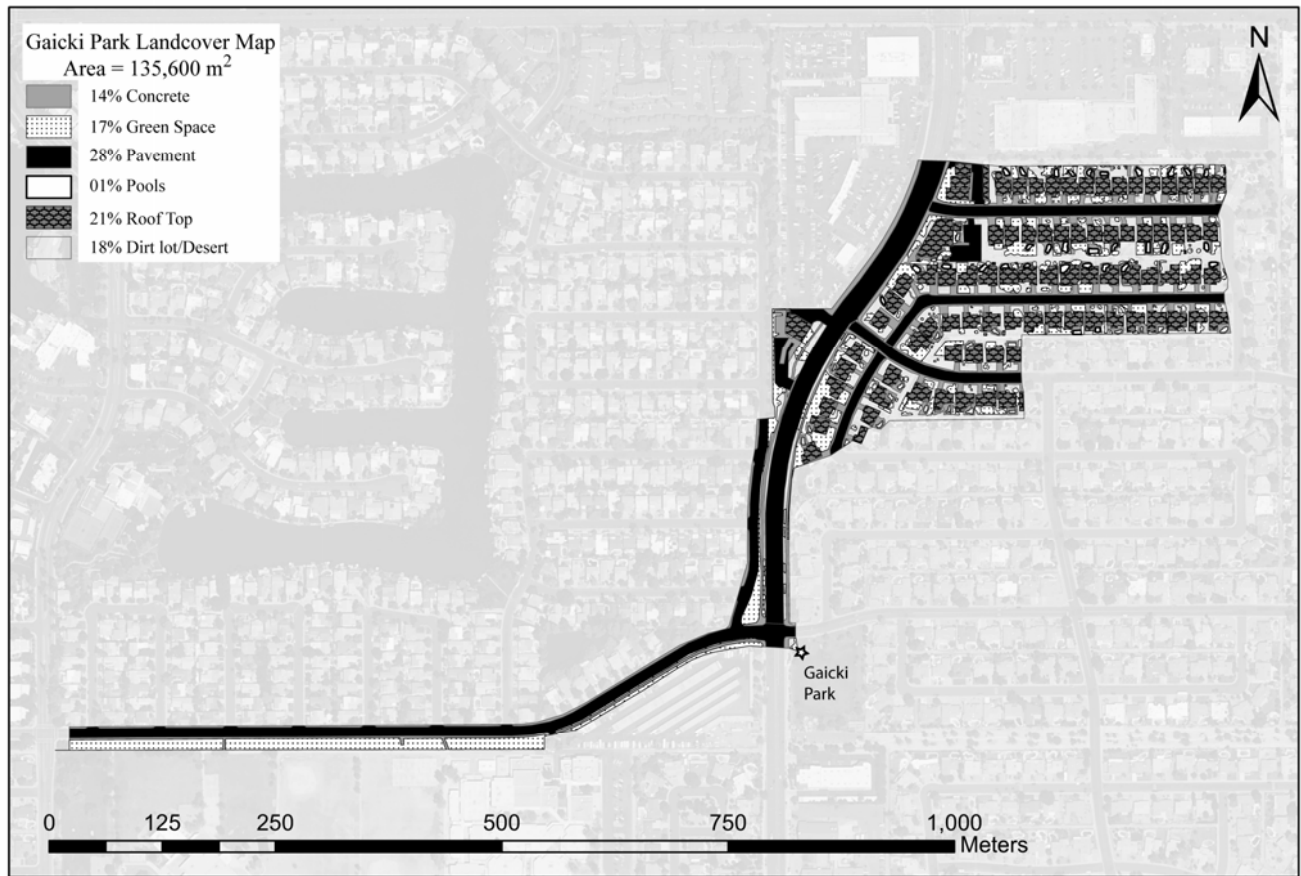


FIGURE 3. Landcover map for the watershed of the northwest drainage apron (location delineated by the small star) at Gaicki Park in Tempe, AZ (figure 1). Watershed delineation and landcover mapping was done in ArcGIS by human interpretation of 1.5 m color orthophotos (black and white version shown here in the background) and stormwater shapefile datasets provided by the City of Tempe (including locations of drains, stormwater flow vectors, and retention basin watershed maps). Our analysis of sediment production (figure 4 and tables 1-2) takes into consideration the total area of the watershed as well as the total pervious area of the watershed (dirt lot/desert landscaping, and greenspace).

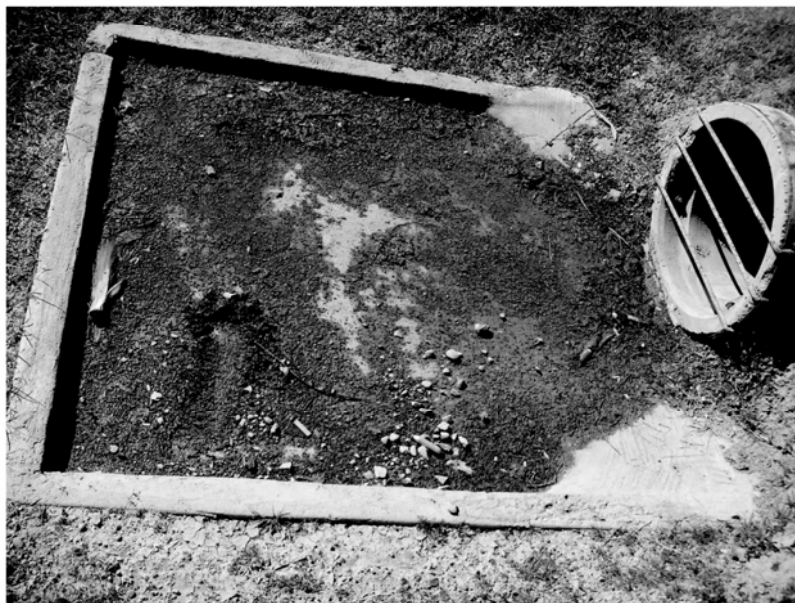


FIGURE 4. Photo of the concrete apron on the northwest side of Gaicki Park. This apron receives stormwater runoff from the watershed mapped in figure 3. Half of these sediments were collected and analyzed for composition and calculation of sediment production (tables 1-2). The apron's 5 cm dam likely does not trap all fine sediment so the sediment production rate calculated in table 2 is a minimum. The sediments in this analysis accumulated over approximately 1 year.

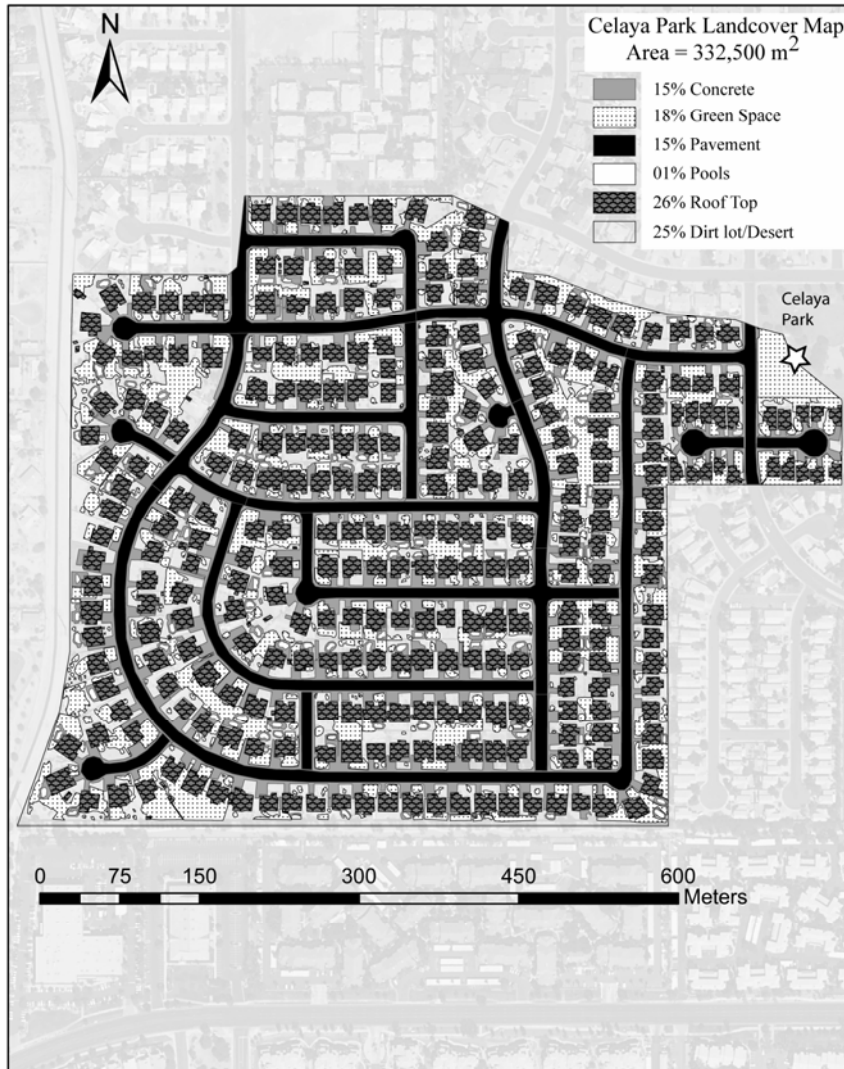


FIGURE 5. Landcover map for the watershed of the southwest drywell (location delineated by small white star) at Celaya Park in Tempe, AZ (figure 1). Watershed delineation and landcover mapping was done in ArcGIS by human interpretation of 1.5 m color orthophotos and stormwater shapefile datasets provided by the City of Tempe (including locations drains, stormwater flow vectors, and retention basin watershed maps). Our analysis of sediment production (figure 6 and table 2) takes into consideration the total area of the watershed as well as the total pervious area of the watershed (dirt lot/desert landscaping, and greenspace) and the area of the watershed that is only dirt lot and desert landscaping.



FIGURE 6. Photograph showing the volume of sediment collected from the southwestern dry well of Celaya Park in April, 2009. This sediment was collected after a 2 year period of deposition since the drywell was last cleaned. Two photographs have been merged with Laila for scale. The sediments were evacuated by a Tempe city contractor (we observed) and then dumped on a holding pad. The city later sent this sediment to a landfill. Because it was mixed with other material we had to estimate the volume and mass of the material. We estimated the volume by representing the material as a cone of coarse material sitting atop a thin deposit of fines. The fines (silt and clay) were about 1cm thick (see mud cracks) and were spread over a 200 cm radius. The cone of coarser sediments was about 40 cm in height and had a radius of 100cm.

volume_{sed} = volume of radial sheet + volume of cone:

$$v_{sed} = \pi r^2 h_{sheet} + 1/3 \pi r^2 h_{cone}$$

$$v_{sed} = \pi (200 \text{ cm})^2 (1 \text{ cm}) + 1/3 \pi (100 \text{ cm})^2 (40 \text{ cm})$$

$$v_{sed} = 545,000 \text{ cm}^3$$

If we assume a density of 2 cm³ we can estimate the mass of sediment:
mass = density * volume = 1,090,000 grams (Table 2)