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RESEARCH ARTICLE

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Soil erosion from urbanization processes in the Sonoran Desert, Arizona, USA

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Abstract

Cattle stock ponds on the fringe of metropolitan Phoenix, USA, experienced a wide range of land-use changes over the period from 1989 to 2009. This research measures soil erosion from watersheds of different rock types, variable relief, and land uses. Monitoring sediment accumulation behind 18 earthen berms at each major land-use transition enabled calculations of soil erosion rates. Compared with the first decade of study with more precipitation and cattle grazing, accelerated urbanization in the drier second decade increased soil erosion from wildfires by up to 4.2×, from exposure of bare ground due to building construction by up to 3.4×, and from bare ground exposure due to road and pipeline construction by up to 3.1× overgrazing alone. Stock pond watersheds underlain by granite experienced statistically significant higher erosion rates compared with watersheds underlain by metamorphic, basalt, and other rock types. Global sediment yield data for warm desert (BWh Köppen-Geiger) sites reveal that our data plot consistently with other grazed study areas with a tendency for higher area-specific sediment yields in smaller drainage areas. These sediment yield data, however, do not support previously published generalizations of anomalously high or low sediment yields from warm desert settings. Desert urbanization processes accelerate soil erosion, resulting in the need for regulatory agencies to impose new erosion mitigation strategies.

KEYWORDS

desert climate, erosion rates, natural and anthropogenic causes of erosion, road building, urban sprawl

1 | INTRODUCTION

Soil erosion contributes to land degradation at large (Balaguer-Puig, Marqués-Mateu, Lerma, & Ibáñez-Asensio, 2018; Nyssen, Poesen, Moeyersons, Haile, & Deckers, 2008) and small (Shi, Huang, Ai, Fang, & Wu, 2014) scales in all habitable ecoregions (Lal, 1994). Soil erosion in arid lands is the focus of this study and is often attributed to overgrazing (Al-Awadhi, Omar, & Misak, 2005), wind erosion (Dong, Wang, & Liu, 2000), and overland flow of water that generates substantial loss even with low-intensity events (Marques, Bienes, Pérez-Rodríguez, & Jiménez, 2008). Critical transitions that greatly increase erosion often involve exposing bare soil through unpaved roads (Marchamalo, Hooke, & Sandercock, 2016; Nyssen et al., 2002; Villarreal et al., 2016) and human-caused wildfire (Martínez-Murillo & López-Vicente, 2018).

Compared with other arid regions, the Sonoran Desert in Arizona, USA, has been the location of minimal research on land degradation in general and soil erosion in particular. After Post-Columbus contact, grazing and mining were major agents of land degradation (Radding, 2005), and grazing is still common (Fleischner, 2010). Prior to European invasive grasses, Sonoran Desert wildfires were very infrequent

Short informative containing the major key words: This paper explores natural and anthropogenic influences on erosion in a desert climate. Urban sprawl on the growing margins of the Phoenix metropolitan area, USA, enhances soil erosion rates by exposing bare ground through such processes as road building and wildfires.

and of low intensity (McLaughlin & Bowers, 1982). Invasive grasses such as *Bromus madritensis Pennisetum ciliare*, however, now generate an abundance of fuel following winter rains that greatly increases the frequency and intensity of Sonoran Desert wildfires (Balch, Bradley, D'Antonio, & Gómez-Dans, 2013). Arid urban populations in the metropolitan Phoenix and Tucson areas, Arizona, USA, also degrade the surrounding Sonoran Desert through off-road vehicle activity (Villarreal et al., 2016).

This study focuses on soil erosion in a Köppen-Geiger BWh climate at the interface of the Sonoran Desert and the sprawling metropolitan area of Phoenix, Arizona, USA. Relatively sparse published data exist on sediment yield in a BWh setting. In the Negev Desert, for example, extremely high sediment yields can occur in small catchments (Schwartz & Greenbaum, 2008), where evidence exists that sediment yield exceeds sediment production by 53–86% (Clapp et al., 2000). More generally, Einsele and Hinderer (1997) predicted very high specific sediment yields of 4,000–5,000 t km^{-2} yr^{-1} at small arid catchments. Scholarship in BWh climates reveals several factors thought to influence erosion rates, including rock type in the Indian arid zone (Sharma & Chatterji, 1982) and slope in southern Arizona (Abrahams, Parsons, & Luk, 1988). Poesen, Torri, and Bunte (1994) highlighted the effects of rock fragments on soil erosion. At microplot (4×10^{-6}–10^{0} m^2) and macroplot scale (10^1–10^4 m^2), sediment yield decreases with percent rock fragment cover due to the protection of the underlying soil and the interception of soil particles by rock fragments. Nearing et al. (2005) investigated a humid and a semiarid watershed to better understand how changes in precipitation and vegetation parameters such as rainfall amount, rainfall intensity, rainfall duration, vegetation cover, and canopy cover influence erosion. Zhang et al. (2012) and Dorn (2015) emphasized that extreme precipitation events result in a jump in soil erosion in southwestern USA.

A reason for the selection of Phoenix as a BWh study site is that prior to an expansion of urbanization, lands managed by the US Bureau of Land Management, Arizona State Trust Lands, and the US Forest Service gave permits for cattle grazing. Thousands of berms built across ephemeral desert washes created stock ponds to collect water for cattle (Langbein, Hains, & Culler, 1951). Starting in 1989, the second author initiated the monitoring sediment accumulation in 25 stock ponds that had not yet experienced urbanization but were in locations where political entities planned urban expansion. Periodic observations of sedimentation in these stock ponds before and after land-use transitions took place over the next two decades, recording changes in sedimentation.

This paper analyzes four hypotheses related to over two decades of monitoring soil erosion on the urban fringe of metropolitan Phoenix, USA:

H1 :*During the period of cattle grazing prior to urbanization, the sediment yield would be influenced primarily by natural variables such as drainage area, slope, vegetation cover, precipitation amount and intensity, and rock type.*

H2 :*Sediment yield would increase substantially during the period of land-use changes associated with urbanization including human-set wildfires, exposure of bare ground due to home and commercial real estate development, and exposure of bare ground due to other infrastructural development such as road and pipeline construction.*

H3 :*The sediment yields of small basins in a warm desert Köppen-Geiger BWh climate setting would not meet the expectations of some scholarship in the literature. Einsele and Hinderer (1997, p. 295) plotted specific sediment yield versus drainage area for different climate types. In this idealized plot, arid and semiarid drainage areas had some of the highest sediment yields. In contrast, in an analysis of just three BWh catchments, Jansson (1988) found some of the lowest sediment yields. Rózsa and Novák (2011) mapped sensitivity to human factors globally from the perspective of different Köppen-Geiger climate types and predicted that arid regions with minimal relief (plains and hills) would be amount the least sensitive.*

H4 :*In a compilation of all available sediment yield data from BWh catchments, we hypothesize that the general trend of increasing specific sediment yield in smaller basins observed in Europe (Vanmaercke, Poesen, Verstraeten, de Vente, & Ocakoglu, 2011), Africa (Vanmaercke, Poesen, Broeckx, & Nyssen, 2014), and global comparisons (Einsele & Hinderer, 1997) would hold true for warm desert BWh Köppen-Geiger settings.*

2 | MATERIALS AND METHODS

2.1 | Study site

The Sonoran Desert in central Arizona experiences precipitation averaging 208 mm split evenly between summer and winter maxima (Climate Office of Arizona, https://azclimate.asu.edu/climate/climate-of-phoenix-summary/). Winter rainfall occurs when the westerlies generate Pacific cold fronts and low-pressure systems. Moist air masses from the Gulfs of Mexico and California, combined with surface heating and upper level tropospheric disturbances, produce summer thunderstorms during the July–September monsoon season. This climate supports Sonoran Desert trees grow along ephemeral washes and on hillslopes where overland flow concentrates, including palo verde (*Parkinsonia microphylla*), ironwood (*Olneya tesota*), and elephant trees (*Bursera microphylla*). Desert scrub vegetation found on slopes includes creosote bush (*Larrea tridentata*), brittlebush (*Encelia farinosa*), triangle-leaf bursage (*Ambrosia deltoidea*), catclaw acacia (*Acacia greggii*), desert globe mallow (*Sphaeralcia ambigua*), and ocotillo (*Fouquieria splendens*). Piedmonts and hillslopes also host succulents such as saguaro (*Carnegiea gigantea*), barrel (*Ferocactus cylindraceus*), and hedgehog (*Echniocereus engelmannii*) cactus.

Thousands of stock ponds, also called stock tanks, throughout Arizona collect water for grazing cattle (Langbein et al., 1951). Most consist of an earthen dam blocking small ephemeral channels. Researchers use these stock tanks to study erosion and sedimentation rates in nondesert ecoregions in Arizona such as a semiarid mesquite grassland (Nichols, 2006).

Twenty-five stock ponds were selected for a study of erosion and sedimentation associated with urban expansion with their locations determined by areas targeted for urban growth. The goal of the study initiated in 1989 rested in developing a better understanding the role of land degradation associated with urban sprawl in a warm desert region. Seven of the stock ponds experienced overflow events leading to breaching and loss of the sediment record, and these sites are not included in this paper. However, 18 stock ponds recorded changes in sedimentation associated with major land-use changes on the urban fringe.

Phoenix, Arizona, is the fifth largest USA city. The population of the metropolitan area grew dramatically after World War II with the advent of air conditioning, and the aerial footprint sprawled commensurately with migrants seeking employment and low-cost homes. Because Phoenix is located entirely in the Sonoran Desert, the stock ponds on the urban fringe had the potential to yield unique insight in a warm desert ecoregion. The USA National Science Foundation selected metropolitan Phoenix as a type urban site to analyze land use–land cover change (LULCC) in an arid climate. Thus, extensive documentation exists on LULCC for the study period from 1989 to 2009 (Fan, Myint, Rey, & Li, 2017) that can be accessed at https://sustainability.asu.edu/caplter/.

Figure 1 superimposes the location of the 18 studied stock pond drainage areas on a map showing the expansion of urbanization from 1985 to 2010. Data S1 provides overview of the supporting information files. Data S2 presents a Google Earth KMZ file of the stock tanks and their associated watersheds. Figure 2 illustrates typical shifts in land use as the urbanization expanded out into areas formerly occupied by cattle grazing.

2.2 | Field sampling

Nine 0.3-m segments of steel rebar were inserted into the sediment accumulation area of the studied stock ponds in a 3 × 3 grid (Figure 3) to understand variability in sedimentation. The rebar was flush to the surface, covered by dirty cardboard. Upon experiencing a major land-use change, each stock pond was revisited to measure sediment accumulation depths on top of the rebar. The rebar was relocated with the assistance of a metal detector. Because sediment bulk density varies with sediment texture, multiple sampling assists in analyzing variability over space and time (Verstraeten & Poesen, 2001). Like others (Bellin, VanAcker, Wesemael, van Solé-Benet, & Bakker, 2011), we anticipated that there would be no significant increases in bulk density with depth, but this assumption was tested by collecting bulk density samples at the same time when the sedimentation was measured.

2.3 | Laboratory measurements

We sampled three points for each stock pond as others have also done for bulk density and particle-size analysis (Bellin et al., 2011). The cylinders method determined the bulk density of all samples (Blake, 1965). The hydrometer method measured the percent silt and clay of all samples (Bouyoucos, 1962). The reported error term derives from the standard deviation.

2.4 | Calculation of soil erosion rate

Calculating annual soil erosion rate in meters requires the area of the stock pond watershed in square meters (A_D), the surface area where the sediment accumulated behind the berm in square meters (A_b), the depth of sediment accumulation in meters (D), and the number of years of sediment accumulation (Ys).

$$= (A_b{*}D)/A_D)/Ys.$$

We converted soil erosion rate to millimeters per thousand years by multiplying the annual soil erosion rate in meters by 10^6.

A major error concern involves how to analyze the aeolian contribution. Dust storms transport desert dust in the Sonoran Desert (Péwé, 1981). Because an analysis of soils in southern Arizona

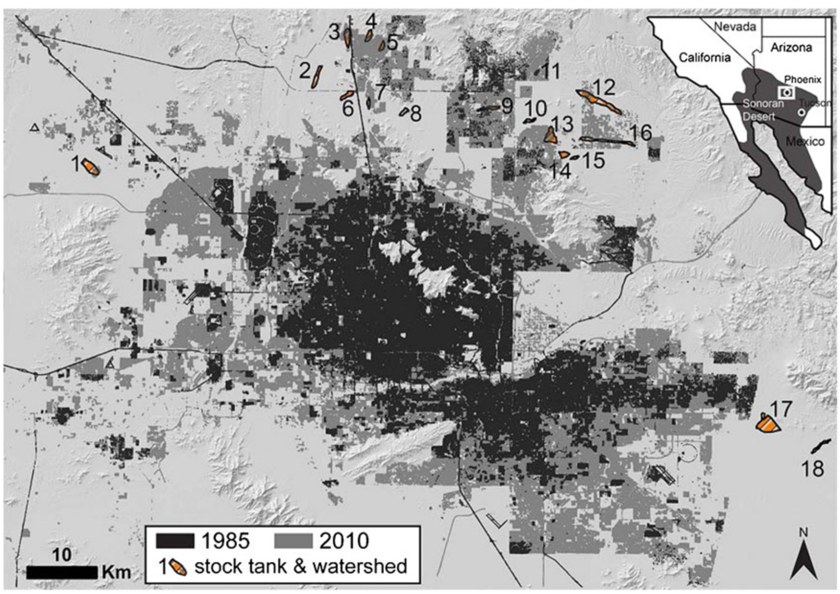

FIGURE 1 Map contextualizing the scattered locations of the stock tanks around metropolitan Phoenix. The studied stock ponds are situated in the Sonoran Desert. Urban boundaries in 1985 and 2010 are extracted from land cover classification by Central Arizona–Phoenix Long-Term Ecological Research. Data available at https://sustainability.asu.edu/caplter/data/view/knb-lter-cap.650.1/. The numbers refer to stock ponds identified in this paper's data tables. Data S2 provides a Google Earth KMZ file of the stock tanks and their watersheds [Colour figure can be viewed at wileyonlinelibrary.com]

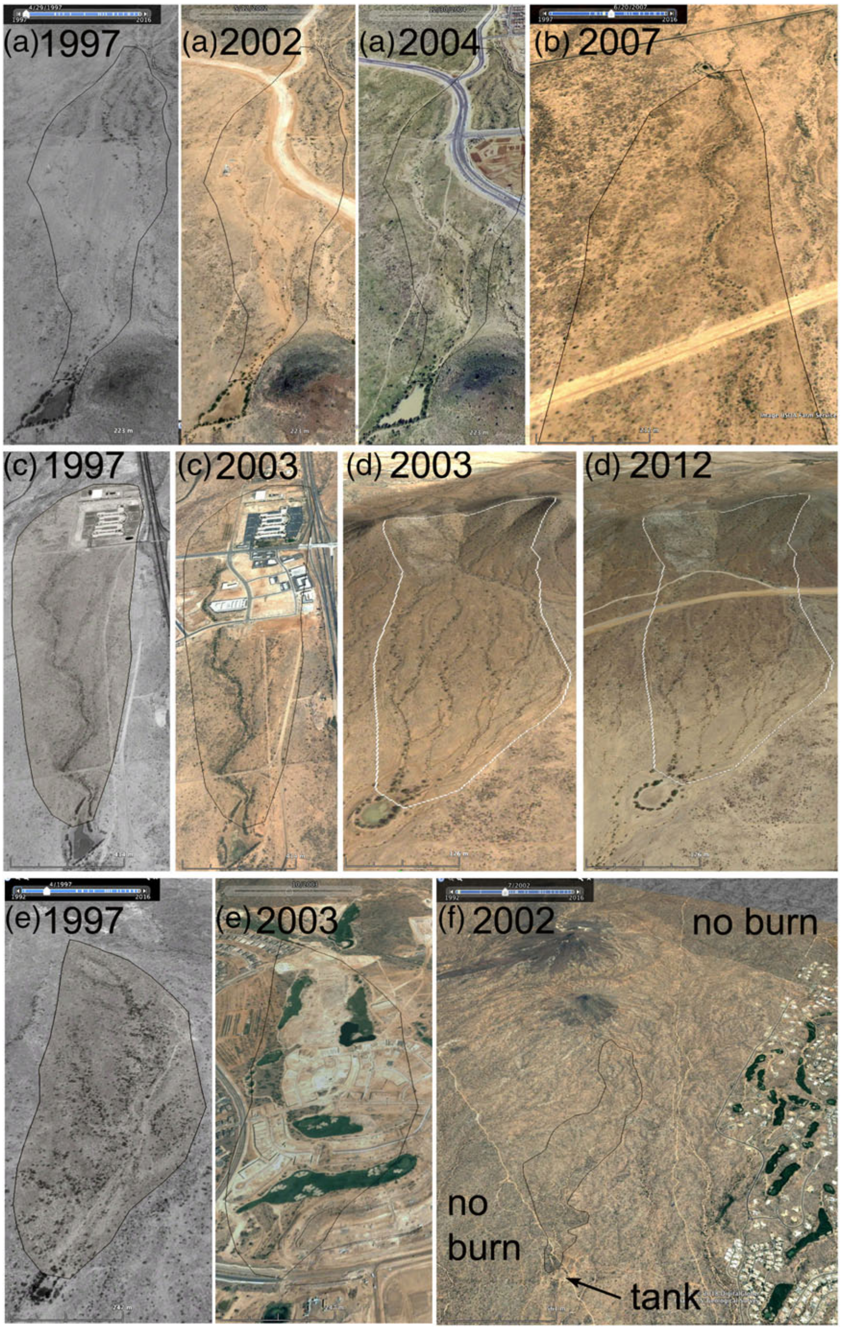

FIGURE 2 Examples of land-use changes in stock pond watersheds of the sort that can be explored in greater detail and higher resolution by the reader using the Google Earth KMZ Data S2. Roads provide a sense of scale. Dates of the Google Earth screenshot imagery are annotated in the upper left corner. (a) Transition from cattle grazing to road construction and housing subdivision development, (b) pipeline construction and proximity to the tank, (c) transition from grazing to commercial development, (d) road construction, (e) wildfire and subdivision development, and (f) stock pond drainage area that burned without urban encroachment [Colour figure can be viewed at wileyonlinelibrary.com]

suggests that up to 20% of the mineral material could derive from dust (Lybrand & Rasmussen, 2018), the silt and clay accumulating in the stock ponds could potentially all derive from aeolian dust deposition, or it could derive weathered bedrock. Thus, two sediment yields (and erosion rates) are presented. One is the maximum with the assumption that there was no aeolian dust deposition. One is the minimum with the assumption that all of the silt and clay derived from aeolian deposition.

For both the maximum and minimum sediment yields (erosion rates), there is a ± assigned from the standard deviation of nine depth measurements for each time slice. This standard deviation of the average depth then translates as a ± percentage the reported sediment yield.

2.5 | Determination of specific sediment yield

The area-specific sediment yield in the studied 18 stock ponds is calculated as follows (Verstraeten & Poesen, 2001):

$$SSY = SM/(A_D{}^*TE^*Y)^*10^6,$$

where *SSY* is specific sediment yield (t·km^{-2} yr^{-1}), *SM* is sediment mass (t), *dBD* is average dry bulk density of the sediment (t m^{-3}), A_D is drainage area of the watershed of each stock pond (m^2), *TE* is sediment trap efficiency (%), and *Y* is time period of measurement (y). In the case of the 18 stock ponds, the sediment trap efficiency (*TE*) is 100% because we rejected all seven stock ponds that breached. We found no

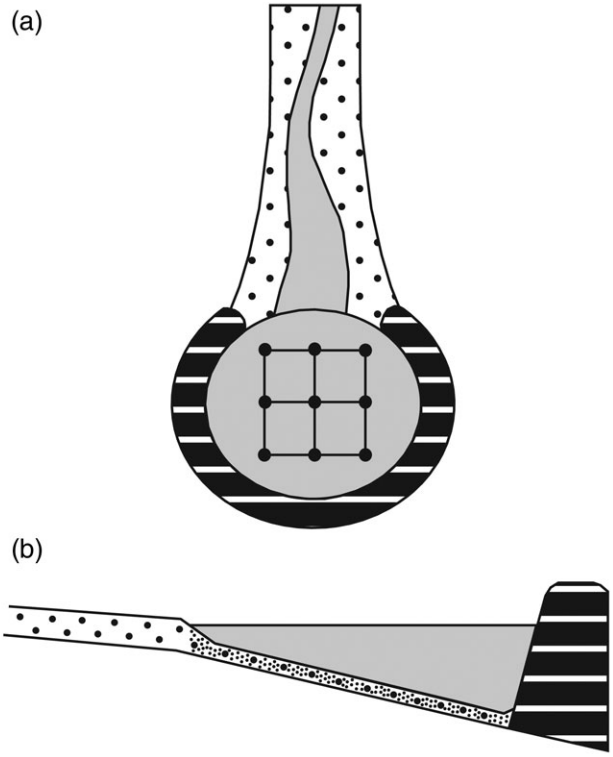

FIGURE 3 Generalized diagram presenting 3 × 3 grid of sediment sampling and rebar placement locations in an idealized stock pond. (a) Plan view and (b) cross section illustrating the course nature of sediment in channels just prior to entering the stock pond. However, where water ponds, the clays and silt in the suspended sediment load mix with bedload

evidence that the studied stock ponds were excavated during the period of study.

The maximum sediment (SM_{max}) can be calculated as follows:

$$SM_{max} = SV_{max}{}^{*}dBD = Ap^{*}D_{avg}{}^{*}dBD,$$

where Ap is sedimentation area and D_{avg} is the averaged depth of the sediments measured from nine grid points (Figure 3). SV is the measured sediment volume in the stock pond during the given time period Y (m^3). The minimum sediment yield is then calculated as follows:

$$SM_{min} = SM_{max}{}^{*}(1 - \text{percent silt and clay}).$$

2.6 | Data acquisition and correlation between catchment properties and erosion rate

We collected quantitative data for each of the selected catchments (Table 1) with the goal of determining statistically significant correlations between a catchment property and erosion rate. Data S3 presents all data used in the correlation analyses. Pearson's pair-wise correlation was calculated for all pairs of quantitative variables to measure linearity between and among catchment properties (cf. Shi et al., 2013, p. 173).

The digital elevation model with a resolution of 10 m delineated morphological characteristics of each catchment. ArcGIS software generated data on drainage area, average slope, and maximum relief. ImageJ software converted historical aerial photograph images in different time periods to 8-bit images to determine percent perennial vegetation cover. The Maricopa County Flood Control District gathers precipitation data at a variety of rain gauges (Maricopa County Flood Control District, n.d) (http://alert.fcd.maricopa.gov/showrpts_mc.html), typically within a few hundred meters of each catchment. Using this rainfall data, we calculated mean annual precipitation (MAP), summer convective (monsoon) seasonal precipitation from 6/15 to 9/30. Study of a well-monitored semiarid watershed in southern Arizona (Polyakov et al., 2010) revealed that sediment transport occurred when rainfall exceeded 10 mm for 30 min (I_{30}). Thus, for each sediment accumulation interval, we compiled the total amount of rainfall with I_{30}. Additionally, we split the study period into approximately two decadal periods (Period 1: 1989–1999; Period 2: 2000–2009) and calculated MAP and I_{30} from three nearest rain gauges to all stock tanks to reduce the influence of dry and wet years (Table 1).

The largest potential error in carrying out a correlation between catchment property and erosion rate involves land-use uncertainty. All of the catchments experienced cattle grazing, and almost all of them also experienced potential land degradation events such as wildfire, dirt road creation, and construction. In order to tease out the significance of catchment properties, we rejected all time intervals that involved land use other than cattle grazing.

2.7 | Collecting qualitative catchment properties

Two important influences on soil erosion rates cannot be analyzed using a linear correlation, because rock type and land uses do not translate into interval data. To better understand the importance of rock type and land use on erosion, we used a difference of means *t* test. For rock types, we obtained lithological information by ground truthing geological maps. Whereas granitic rocks break down into grus, or sand-sized particles, the other rock types (basalt, ignimbrite, metasedimentary, and metavolcanic) decay into a mixture of fines (clay and silt), some sand, but also cobbles and boulders. Thus, an unpaired *t* test evaluated whether the specific sediment yield or erosion rate was significantly different between stock pond watersheds that were only granitic and those that were nongranitic.

We identified different land-use and land-used changes using prior research (e.g., Fan et al., 2017), field observations, and historic aerial photographs. We classified different land uses into grazing, low-density residential, high-density residential, commercial, construction, and mixed use. We also classified nonurbanized areas as impacted by either cattle grazing or a wildfire event. Because the same stock pond watershed experienced different land-use changes, each time slice was treated as a separate data point. An unpaired *t* tests compared the specific sediment yield from basins experiencing grazing; building construction of houses, subdivision, and commercial properties; infrastructure of road and pipeline building that exposes bare ground; and wildfire.

TABLE 1 Sonoran Desert, Arizona, USA, stock tank catchment characteristics and data on soil erosion rates and sediment yields

Stock tank	Time period	Dominant land use	Different rock types	MAP (mm) I_{30} (mm) P1	P2	Coordinates	Ad (km^2)	At (m^2)	Max. ER ($mm\ ka^{-1}$)	Min. ER ($mm\ ka^{-1}$)	Max. SSY ($t\ km^{-2}\ yr^{-1}$)	Min. SSY ($t\ km^{-2}\ yr^{-1}$)
1. Cigar Tank	1990–2004	Grazing	Metamorphic, basalt, granite	207 (20.9)	170 (15.4)	33.685117, −112.534267	2.60	6,000	66 ± 5.8	57.7 ± 2.8	89.2 ± 9.7	77.3 ± 3.8
	2005–2009	Grazing and off-road vehicle use							75.8 ± 6.4	66.4 ± 2.4	102.4 ± 9.8	89.6 ± 3.2
2. Saguaro	1990–2004	Grazing	Metamorphic, basalt, granite	222 (25.1)	181 (14.1)	33.800925, −112.20405	1.40	5,800	35.0 ± 4.8	29.7 ± 2.3	48.7 ± 7.6	41.4 ± 3.2
	2005–2009	Grazing and pipeline construction							95.3 ± 6.6	84.3 ± 3.0	143.2 ± 26.0	126.7 ± 4.6
3. Cline	1989–1995	Some construction	Metamorphic, basalt, granitic	222 (25.1)	181 (14.1)	33.853465, −112.149325	1.50	9,500	33.7 ± 3.7	28.8 ± 3.5	52.0 ± 6.9	44.4 ± 5.4
	1996–2003	Commercial construction							75.9 ± 4.6	67.8 ± 2.2	103.7 ± 6.4	92.7 ± 3.1
	2003–2004	Subdivision construction							102.7 ± 11.1	94.1 ± 6.4	174.7 ± 25.4	160.0 ± 10.9
4. Anthem	1989–1992	Grazing	Metavolcanic	222 (25.1)	181 (14.1)	33.862595, −112.123726	0.88	3,000	84.2 ± 5.6	74.8 ± 9.8	136.7 ± 14.6	121.4 ± 15.8
	1993–1997	After wildfire							203.6 ± 5.1	188.6 ± 16.7	334.0 ± 25.4	309.3 ± 27.4
5. Anthem 2	1989–1992	Grazing	Metavolcanic	222 (25.1)	181 (14.1)	33.850572, −112.101617	0.58	2,700	59.6 ± 4.0	51.6 ± 2.3	77.5 ± 7.1	67.1 ± 2.9
	1993–1995	After wildfire Period 1							184.5 ± 24.9	169.4 ± 16.4	276.7 ± 45.8	254.0 ± 24.6
	1996–1998	After wildfire Period 2							197.8 ± 17.2	184.4 ± 34.9	330.9 ± 32.8	308.6 ± 58.4
	1999–2002	After wildfire Period 3							91.2 ± 3.9	85.2 ± 11.7	156.2 ± 14.9	146.0 ± 20.0
	2002	Housing							172.8 ± 16.5	155.5 ± 8.7	255.7 ± 41.4	230.1 ± 12.8
6. Pepe	1989–2008	Grazing and ongoing house construction	Metamorphic, basalt, granite	222 (22.8)	181 (11.5)	33.786100, −112.159939	0.99	3,300	34.0 ± 5.6	27.7 ± 3.3	38.4 ± 10.0	31.3 ± 3.7
7. Bronco	1989–1998	Grazing	Metamorphic, basalt, granite	222 (22.8)	181 (11.5)	33.774765, −112.117174	0.45	4,100	37.9 ± 5.8	32.4 ± 4.7	43.7 ± 8.0	37.4 ± 5.4
	1999–2003	Road construction							117.4 ± 22.2	96.1 ± 9.5	137.4 ± 32.4	112.5 ± 11.2
8. Circle	1990–2010	Grazing	Metamorphic	222 (22.8)	181 (11.5)	33.767891, −112.069517	0.60	5,000	46.8 ± 11.6	39.0 ± 3.8	51.0 ± 13.7	42.5 ± 4.1
	2010–2013	Road construction							82.7 ± 18.7	72.3 ± 3.2	128.5 ± 31.1	112.3 ± 4.9
9. Charlie	1989–2004	House construction	Granitic	276 (40.4)	237 (28.0)	33.773722, −111.949346	0.91	10,500	164.5 ± 25.8	146.6 ± 6.9	264.3 ± 49.1	235.6 ± 11.1
10. Rock	1989–1992	Grazing	Granitic	276 (40.4)	237 (28.0)	33.758838, −111.877228	0.54	2,800	45.3 ± 4.5	38.6 ± 3.0	53.6 ± 8.8	45.7 ± 3.5
	1992–1997	After wildfire Period 1							169.7 ± 14.7	150.7 ± 10.8	224.0 ± 25.3	199.0 ± 14.3
	1998–2003	After wildfire Period 2							102.9 ± 5.9	93.3 ± 14.6	175.7 ± 11.7	159.3 ± 24.9
	2004–2009	After wildfire Period 3							56.6 ± 3.3	52.9 ± 10.7	90.9 ± 9.3	85.0 ± 17.2
11. Cave Creek	1989–1992	Grazing	Granitic	276 (15.4)	237 (22.9)	33.821477, −111.860042	0.19	1,200	73.0 ± 8.3	63.7 ± 7.7	102.2 ± 15.4	89.1 ± 10.8
	1992–1999	After wildfire							151.8 ± 10.5	142.4 ± 23.4	258.5 ± 18.0	242.6 ± 39.8
	2000–2003	House construction							91.8 ± 8.4	81.4 ± 6.2	128.8 ± 23.6	114.3 ± 8.7
12. Buckhorn	1989–1999	Grazing	Granitic	305 (40.4)	260 (28.0)	33.771593, −111.726559	4.40	4,100	76.1 ± 2.3	65.6 ± 3.9	106.2 ± 17.1	91.6 ± 5.4
	2000–2002	House construction							108.8 ± 4.9	94.3 ± 12.4	133.4 ± 17.4	115.7 ± 15.2
13. The Rocks	1989–1996	House construction	Granitic	310 (40.4)	248 (28.0)	33.735184, −111.843395	2.36	6,500	128.6 ± 13.2	120.3 ± 15.8	227.6 ± 25.7	212.9 ± 28.0
14. 128th St	1989–1994	Grazing	Granitic	310 (40.4)	248 (28.0)	33.719610, −111.80591	0.85	7,000	72.6 ± 17.5	62.3 ± 8.9	110.3 ± 27.1	94.7 ± 13.6
	1995–2000	After wildfire							198.5 ± 12.0	175.4 ± 6.3	342.0 ± 40.4	302.3 ± 10.8
	2001–2008	Road construction							105.0 ± 13.6	92.7 ± 4.9	159.9 ± 29.4	141.3 ± 7.4

(Continues)

TABLE 1 (Continued)

Stock tank	Time period	Dominant land use	Different rock types	MAP (mm) I_{30} (mm) P1	P2	Coordinates	Ad (km^2)	At (m^2)	Max. ER (mm ka^{-1})	Min. ER (mm ka^{-1})	Max. SSY (t km^{-2} yr^{-1})	Min. SSY (t km^{-2} yr^{-1})
15. 128th St 2	1989–1994	Grazing	Granitic	310 (40.4)	248 (28.0)	33.716550, −111.79117	0.31	2,200	69.0 ± 28.6	59.6 ± 7.8	109.5 ± 45.9	94.5 ± 12.4
	1995–2000	After wildfire							195.8 ± 56.2	175.6 ± 11.2	278.7 ± 94.4	250.0 ± 15.9
	2001–2008	Road construction							97.7 ± 29.9	88.9 ± 8.0	149.1 ± 48.4	135.7 ± 12.2
16. Asher Hills	1989–2001	Grazing	Granitic	310 (17.5)	248 (18.4)	33.731003, −111.703998	2.10	9,800	94.5 ± 18.1	84.7 ± 7.8	140.5 ± 27.6	125.9 ± 11.6
	2002–2007	House construction							123.7 ± 4.6	113.4 ± 4.9	199.1 ± 15.0	182.6 ± 7.9
17. Gold Cyn	1989–2009	Cattle grazing and house construction	Ignimbrite, granitic	254 (23.2)	209 (17.9)	33.367485, −111.515636	5.10	18,000	55.7 ± 11.6	44.0 ± 2.4	57.3 ± 13.1	45.3 ± 2.5
18. Peralta	1989–2000	Grazing	Ignimbrite, granitic, breccia	254 (23.2)	209 (17.9)	33.334978, −111.429506	0.78	2,800	42.2 ± 2.0	36.1 ± 2.4	52.2 ± 3.8	44.7 ± 3.0
	2001–2005	Subdivision construction							69.8 ± 5.1	55.4 ± 3.6	77.4 ± 6.8	61.5 ± 3.9
	2006–2009	Subdivision finished							8.2 ± 2.6	5.9 ± 0.4	8.7 ± 2.8	6.2 ± 0.4

Note. MAP: mean annual precipitation during the 10-year period of study periods; P1: Period 1 (1989–1999); P2: Period 2 (2000–2009); I_{30} is the total amount of peak 30-min rainfall exceeded 10 mm for 30 min; Ad: drainage area; At: tank area; Max. ER: maximum erosion rate; Min. ER: minimum erosion rate; Max. SSY: maximum area-specific sediment yield; Min. SSY: minimum area-specific sediment yield.

3 | RESULTS

3.1 | Overview

During the first 10-year period, both MAP and I_{30} were higher (Table 1). The average MAP of all stock pond sites in the first decade (258 mm) when grazing was more dominant lowered substantially (212 mm) in second 10-year period (2000–2009) dominated by urbanization. Table 1 also breaks down erosion rates and area-specific sediment yields for all study areas and all time slices studied. Despite decreases in MAP and I_{30} (with two site exceptions) in the second decade of study (Table 1), erosion associated with urbanization processes increased significantly. The following data present a ratio of soil erosion under the new land use compared with soil erosion during the period of just grazing. Exposure of bare ground from construction—whether road, housing, or commercial developments—accelerated erosion over the grazing period by 1.3×, 1.7×, 1.8×, 2.9×, 3.1×, and 3.1× for the Asher Hills, Peralta, Circle Tank, Anthem, Cline, and Bronco tanks, respectively. The first period after a wildfire erosion accelerated by 2.1×, 2.4×, 2.7×, 2.8×, 3.1×, and 3.7× for the Cave Creek, Anthem, 128th street, 128 street 2nd, Anthem, and Rock tanks, respectively. The second time slice after a wildfire saw a reduced effect of accelerated erosion over the prefire grazing condition of 1.4×, 1.4×, and 2.3× for the 128th street, 128 street 2nd, and Rock tanks, respectively. The next sections explore the statistical significance of different factors that could potentially impact soil erosion.

3.2 | Controls on erosion related to urbanization-related land-use changes

All but one of the study areas experienced cattle grazing at the start of this study. Thus, this results section explores how different factors (drainage area, average slope, relief, vegetation cover, and precipitation) impact sediment yield during the period of cattle grazing. A correlation matrix (Table 2) presents Pearson's correlation coefficients between sediment yield data (i.e., maximum erosion rate, sediment yield, and area-specific sediment yield) and climatic and morphometric properties of each catchment.

The metrics of soil erosion during cattle grazing did not show any statistically significant relationship with precipitation or vegetation cover. All of the correlations between maximum erosion rate or Emax, specific sediment yield, sediment yield, and the precipitation metrics of annual, summer, and most intense rainfall were not statistically significant. Vegetation density revealed the same story of no statistically significant correlations with soil erosion.

Only basin morphometry revealed statistically significant correlations with soil erosion metrics. Sediment yield was significantly and positively correlated with drainage area (Ad; $r = 0.97$, $p < 0.05$) and relief ($r = 0.68$, $p < 0.1$), but average slope (Savg) did not show a clear correlation.

The bulk density of the accumulated sediment did show a slight positive correlation with the maximum erosion rate ($r = 0.70$, $p < 0.1$), a statistically significant correlation with vegetation cover ($r = 0.81$, $p < 0.05$), and an even stronger relationship with specific

TABLE 2 Correlation matrix between the sediment yield and some stock tank catchment variables, Phoenix metropolitan area, Sonoran Desert, Arizona, USA

	Emax	Ad	Savg	Relief	BD	VC	MAP	MSP	I_{30}	SY	SSY
Emax	1										
Ad	0.42	1									
Savg	−0.16	−0.28	1								
Relief	0.45	0.59	0.40	1							
BD	0.70*	0.21	−0.47	−0.01	1						
VC	0.37	0.30	−0.28	0.14	0.81**	1					
MAP	0.13	0.25	−0.01	0.19	−0.17	−0.13	1				
MSP	−0.07	0.14	0.20	0.18	−0.35	−0.14	0.89**	1			
I30	0	0.26	0.02	0.15	−0.02	0.33	0.23	0.50	1		
SY	0.61	0.97**	−0.26	0.68*	0.32	0.34	0.27	0.12	0.25	1	
SSY	0.98**	0.37	−0.24	0.36	0.82**	0.51	0.05	−0.16	0	0.56	1

Note. Data S3 (in excel) provides supporting documentation for this table. Emax: maximum erosion rate (mm ka^{-1}); Ad: drainage area; Savg: average slope; Relief: maximum height difference in catchment; BD: bulk density; VC: percent vegetation cover; MAP: mean annual precipitation; MSP: mean summer seasonal precipitation; I_{30}: the total amount of peak 30-min rainfall exceeded 10 mm for 30 min; SY: sediment yield (t yr^{-1}); SSY: area-specific sediment yield (t km^{-2} yr^{-1}). *Significant at $p < 0.1$. **Significant at $p < 0.05$. ***Significant at $p < 0.01$.

sediment yield ($r = 0.82$, $p < 0.05$). These positive relationships suggest that there was a tendency for more sand and gravel deposition, as opposed to silt and clay, at sites with a higher sediment yield, more vegetation cover, and a higher erosion rate.

Because rock type can be an important factor influencing sediment yield, the stock tank periods experienced only grazing were grouped into granitic and other lithologies. Half of the stock tank watersheds are underlain by only granitic lithologies, ranging from granite to granodiorite with some diorite. Then, half of the stock tank watersheds are underlain by a mix of rock types, typically including rhyolitic tuff (ignimbrite), basalt, metavolcanic, and metasedimentary rocks. A *t* test comparing sediment yields of granitic versus other rock types influenced by only grazing reveals a difference but no statistically significant difference for granite ($M = 103.7$, $SD = 791.1$) versus other rock types ($M = 68.9$, $SD = 1001.0$) conditions, $t(12) = 2.14$, $p > 0.05$. However, there was a statistically significant difference for maximum erosion rates between granitic ($M = 71.83$, $SD = 256.97$) and other rock types ($M = 50.88$, $SD = 319.55$), $t(12) = 2.27$, $p \leq 0.05$. This difference is shown graphically in Figure 4a.

3.3 | Sediment yield increases from urbanization in a warm desert

Urban expansion in the Phoenix BWh Sonoran Desert setting resulted in a variety of substantive changes to the dominant land use. From the perspective of established sediment yield forcings reviewed in the introduction, three major land-use changes resulted in the exposure of bare ground in different studied periods.

Wildfires set by human abuses on the urban fringe, unfortunately, occurred in several stock tank watersheds. In two watersheds, it was possible to subdivide time slices after wildfires into 3- to 5-year intervals. The initial time slice after the fire is designated Fire1 in Figure 4b. The time slices that experienced vegetation recovery after Fire1 are grouped into Fire2 in Figure 4b.

Bare ground exposure also occurred in association with two sorts of construction-related activities. The building category in Figure 4b is from home and commercial real estate construction. The infrastructure category in Figure 4b is from road and pipeline construction.

Statistically significant differences of specific sediment yield in *T* tests occurred between grazing and all other dominant land uses associated with different periods of time, as revealed visually by box and whisker plots (Figure 4b). There was a significant difference in specific sediment yield for grazing ($M = 85.0$, $SD = 1103.3$) and infrastructure ($M = 143.6$, $SD = 140.6$) construction conditions, $t(18) = 1.73$, $p = 0.001$. There was a significant difference in specific sediment yield for grazing and building ($M = 150.9$, $SD = 6245.7$) conditions, $t(24) = 2.91$, $p = 0.004$. The largest difference occurred between grazing and all wildfire ($M = 246.8$, $SD = 7097.38$) conditions, both Fire1 and Fire2 grouped together, $t(23) = 6.75$, $p = 0.000$.

4 | DISCUSSION

4.1 | Natural controls on Sonoran Desert sediment yields

This study of sediment yields on the sprawling fringe of metropolitan Phoenix, USA, revealed very little clarity with regard to natural controls (Table 2). The list of no correlation with metrics of soil erosion (maximum erosion rate, sediment yield, or area-specific sediment yield) in the period of just cattle grazing is quite long: annual precipitation, summer convective precipitation, most intense rainfall, vegetation density, and average slope.

We offer no clear explanation for why our study did not conform to the first hypothesis of the paper and the expectation of research carried out elsewhere that variables such as precipitation and vegetation cover are important in a well-studied semiarid catchment in southern Arizona (Nichols, 2006), in microcatchments in Iran (Vaezi, Abbasi, Bussi, & Keesstra, 2017), and for regional studies of sediment

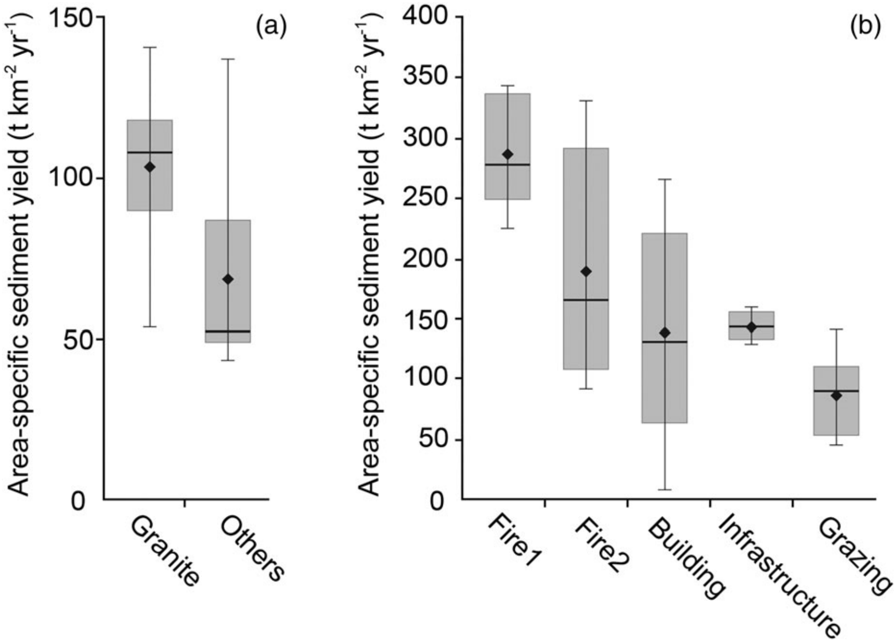

FIGURE 4 Box and whisker plots of specific sediment yield associated with variables are inappropriate for linear regression but appropriate for *T*-test comparisons. (a) A comparison of specific sediment yields for granitic and nongranitic stock tank watersheds influenced only by grazing land use. (b) A comparison of specific sediment yields for stock tank periods of time dominantly influenced by different land uses. Fire1 refers to the period of time immediately after a wildfire (typically 3–5 years). Fire2 refers to the period of time after Fire1 where some revegetation has occurred. Building refers to stock tanks experiencing the exposure of bare ground due to building homes and commercial real estate. Infrastructure refers to stock tanks experiencing the exposure of bare ground due to major infrastructural developments such as road and pipeline construction

yield in Europe (Vanmaercke, Poesen, Verstraeten, et al., 2011) and Africa (Vanmaercke et al., 2014).

Four speculative possibilities emerged to explain the lack of statistical clarity. First, pathways of sediment connectivity in the stock tank watersheds can be often highly irregular—similar to the findings of Marchamalo et al. (2016)—where pockets of sediment can rest behind vegetative dams that are suddenly released. Second, data are not available on rain drop size, and prior research (Marques et al., 2008; Nyssen et al., 2005) reveals its importance. Third, off-road vehicle use influences sediment yield (Villarreal et al., 2016), and it is possible that undetected vehicle use could have influenced observed correlations.

A fourth potential reason for the lack of correlation is that our analysis assumed that cattle grazing was a constant between the different stock ponds, despite being unable to find data on the number and frequency of cattle grazed. However, cattle grazing was on the decline on the periphery of Phoenix for decades prior to this study. The reason is that the cattle grazing in the late 19th and early 20th centuries ate palatable perennial forage grasses leaving mostly unpalatable forage. Thus, discussions with ranchers and land-use managers indicate that by the 1989–1995 period, cattle grazing was minimal in the study areas. However, because grazing intensity can be an important factor (Al-Awadhi et al., 2005; Vaezi et al., 2017; Vanmaercke et al., 2010), the lack of quantitative data on grazing intensity could have influenced our correlation analysis.

T tests, in contrast, did reveal a statistically significant finding. Rock type was an important control on erosion rate with granitic watersheds yielding more sediment than mixtures of metamorphic, basaltic, and rhyolite rock types. The importance of rock type is consistent with the findings in other research (Sadeghi, Najafi, & Bakhtiari, 2017; Vanmaercke, Poesen, Maetens, de Vente, & Verstraeten, 2011), including in an urbanizing catchment (Ferreira, Walsh, Blake, Kikuchi, & Ferreira, 2017).

4.2 | Urbanization influences on Sonoran Desert sediment yields

Rózsa and Novák (2011) mapped sensitivity to human factors globally from the perspective of different Köppen-Geiger climate types and predicted that arid regions with minimal relief (plains and hills) would be the least sensitive to anthropogenic influences. The various LULCC changes between 1989 and 2009 associated with the urban sprawling of Phoenix, USA (Fan et al., 2017), took place on alluvial and pediment surfaces with minimal relief (Jeong, Cheung, Walker, & Dorn, 2018). In contrast to prior expectation, our data for the Sonoran Desert reveal a great sensitivity of low-relief desert landforms to soil erosion. Figure 4b graphically portrays the findings for the urban fringe of Phoenix, USA. When each study site's data (Table 1) are treated as a separate data point, human-set wildfires can increase sediment yields typically 1.7- to 4.2-fold overgrazing; exposure of bare ground due to building homes and commercial real estate development can increase sediment yields typically by 0.2- to 3.4-fold over grazing; and exposure of bare ground due to infrastructural development from road and pipeline construction can increase sediment yields typically by 1.4- to 3.1-fold overgrazing. What is not known is the acceleration of soil erosion from grazing over natural background catchment-wide denudation rates. Thus, there is little doubt that urbanization processes significantly increased soil erosion well beyond even the impact of grazing, the prior land use, at the sprawling edge of a desert metropolis.

The acceleration of erosion from urbanization in this BWh climate was likely dampened due to the climatic conditions that occurred during the study period from 1989 to 2009. The first decade, dominated by grazing in the study sites, was wetter than the second decade more dominated by urbanization LULCC. Yet, despite less annual rainfall and less cumulative time of intense rainfall, sudden and aerially extensive (e.g., Figure 2) exposure of bare ground from urbanization processes significantly increased soil erosion and specific sediment yield.

Our findings are in contrast with the results of Nearing et al. (2005) who examined the response of seven soil erosion models to basic precipitation and vegetation-related parameters, because higher specific sediment yield occurred in the second decade of the study period due to urbanization processes, despite less annual rainfall and less cumulative intense rainfall. Still, these findings are consistent with prior research emphasizing the importance of human activity in general (Vanmaercke, Poesen, Govers, & Verstraeten, 2015; Vanmaercke et al, 2012), on human-caused wildfire (Martínez-Murillo & López-Vicente, 2018), on building new roads (Marchamalo et al., 2016; Nyssen et al., 2002), and on vehicle disturbance (Villarreal et al., 2016), and the importance of rock type in an urbanizing catchment (Ferreira et al., 2017).

The findings of this study have implications for conservation practices in the Sonoran Desert and similar urbanizing settings in other BWh climates. At the present time, there are no requirements to mitigate soil erosion on slopes associated with urbanizing processes. Conservation practices focus on impacts to channels. Discussions with land managers reveal an awareness of a paucity of research on the soil erosion impacts of urbanization in the Sonoran Desert. In constructing Figure 5, we compiled prior knowledge on the soil erosion rates in the Sonoran Desert; most of these data were associated with unpublished research associated with development projects (see Data S4). No prior effort had been made to compile or analyze available data. Thus, a broader implication of this research rests in tasking such local and national governmental agencies as the Maricopa County Flood Control District and the Army Corp of Engineers to develop appropriate conservation practices to mitigate the soil erosion impacts of urbanization in BWh climates. This is because sediment yield produced from arid urbanization impacts flood control structures that exist at all scales from streets to regional impoundment dams.

Figure 5 contextualizes the magnitude of the anthropogenic effect seen on the urban fringe of metropolitan Phoenix, USA, in the Sonoran Desert. The same data presented in Figure 4b are contrasted with all available data from BWh drainage areas globally in Figure 5. Data S4 presents all data used to construct Figure 5 in an excel format. Figure 5 reveals that the magnitude of area-specific sediment yields associated with different land uses in the Phoenix area rests within observations of BWh drainages experiencing agricultural and grazing land uses. This finding implies that other BWh drainages that undergo an LULCC conversion from grazing to urban could experience an even greater acceleration of soil erosion observed here, if precipitation amounts and intensity do not decrease—as occurred in the Phoenix area.

4.3 | Sediment yields in Köppen-Geiger warm desert (BWh) settings

Jansson's (1988) global survey of sediment yield compiled variations by Köppen-Geiger climate groups. At the time, the BWh climate type had an *n* of 3 drainage basins uniquely in warm deserts with very low

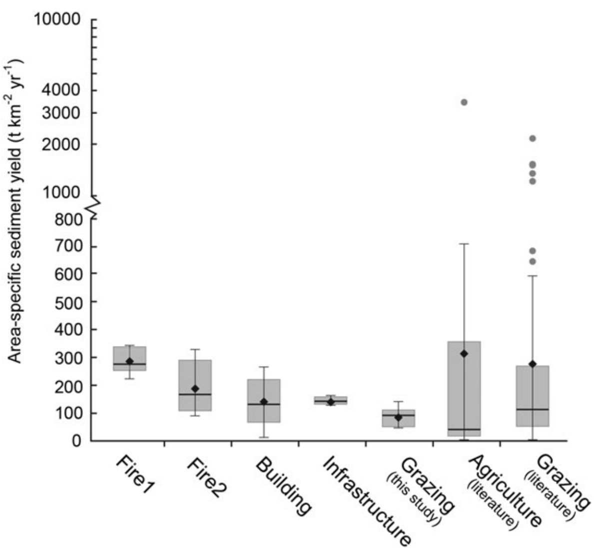

FIGURE 5 Box plot of the importance of different land uses surrounding metropolitan Phoenix (where Fire1, Fire2, building, and infrastructure are explained in the caption of Figure 4) is placed in comparison with a more global data set of agricultural and grazing land uses in the BWh warm desert setting. Note the break and shift in scale from linear to log in order to portray outliers in the global data set

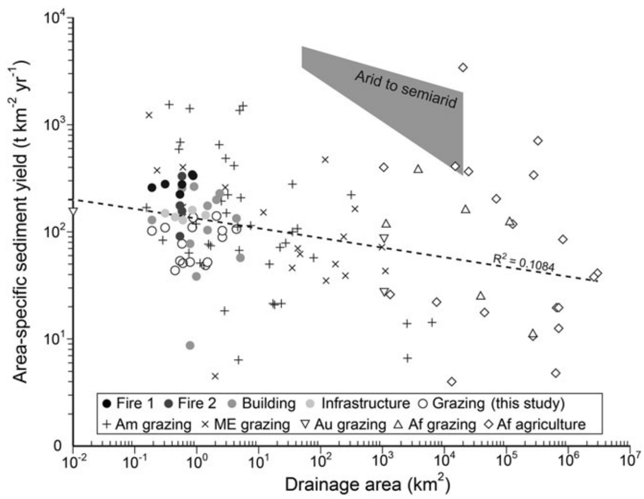

FIGURE 6 Log–log scatterplot and linear regression of all available specific sediment yield from the Köppen-Geiger BWh warm desert climate type. The gray shading indicates the sediment yield portrayal by Einsele and Hinderer (1997). Data from the literature are portrayed by symbols on the lower row of the legend, where Am refers to sites in the Americas, ME from the Middle East, Au from Australia, and Af from Africa. Circles in the top row of the legend were derived from Table 2 in this study; Fire1, Fire2, building, and infrastructure are explained in the caption of Figure 4. Data S4 provides data used to construct this figure

sediment yields with a median of 25 and a mean of 34 t km^{-2} yr^{-1} of sediment yield. Ultimately, in the global analysis, the BW "group has been excluded because of few data" (Jansson, 1988, p. 94). Einsele and Hinderer (1997) also conducted a global analysis of sediment yield focused on estimating the lifetimes of reservoirs and other depressions. In their analysis, they created a plot (Einsele & Hinderer, 1997, p. 295) placing arid to semiarid sediment yields among the highest for various climates. These global generalizations appear contradictory.

Thus, to place our Sonoran Desert BWh findings in a global context, we compiled all available BWh sediment yield data (Data S4). Most of the African BWh data were compiled by Vanmaercke et al. (2014). The other data were derived from published and also unpublished sources (e.g., theses and consulting reports). Figure 6 presents all available area-specific sediment yield data from BWh warm desert climate settings. Data from this study are identified by the circle with different land uses portrayed by different shadings. Data from the Americas, the Middle East, Australia, and Africa are differentiated by land use where such data were available. Taken altogether, this compilation of BWh warm desert sediment yield is consistent with the observation of Einsele and Hinderer (1997) basin size and sediment yield as a slight negative relationship. However, the magnitude of the sediment yield approximation by Einsele and Hinderer (1997), portrayed by the gray shading (arid to semiarid in Figure 6), is far greater than our compiled observations.

Compared with the analysis of Africa (Vanmaercke et al., 2014) and Europe (Vanmaercke, Poesen, Verstraeten, et al., 2011), the log–log scatterplot of sediment yield data points for BWh in Figure 6 rests in the middle of both the African and European log–log scatter plots. Although individual study sites may yield particularly high or low sediment yields, taken as a whole, the BWh warm desert climate does not seem to be particularly anomalous or unique, as is sometimes suggested.

Thus, Figure 6 is consistent with the third hypothesis that the early generalizations about the sediment yield in deserts being particularly anomalous cannot be confirmed by our Sonoran Desert research or by a compilation of available data from BWh catchments. Similarly, Figure 6 is consistent with the fourth hypothesis that the general trend of increasing specific sediment yield in smaller basins observed in Europe (Vanmaercke, Poesen, Verstraeten, et al., 2011), Africa (Vanmaercke et al., 2014), and global comparisons (Einsele & Hinderer, 1997) holds true for warm desert BWh settings.

5 | CONCLUSION

"Human activities (i.e. deforestation, ploughing, livestock grazing, removal of remnant vegetation, road building) led to an overall increase in erosion process intensity" in the Northern Ethiopian Highlands (Nyssen et al., 2008, p. 706). Although the setting and land use of this Sonoran Desert study were very different, our fundamental conclusion is quite similar. Monitoring sediment accumulation behind 18 earthen berms at each major land-use transition enabled calculations of soil erosion rates. Using a correlation matrix, we examined statistically significant correlations between catchment properties and erosion rates. Unpaired *t* tests revealed statistically significant differences between stock pond watersheds that were only granitic and those that were nongranitic.

Unpaired *t* tests also compare the specific sediment yield from basins experiencing grazing; construction of isolated houses, subdivisions, and commercial properties; infrastructure of road and pipeline building that exposes bare ground; and wildfires. Wildfires set by urbanites increased sediment yields by up to 4.2×, exposure of bare ground due to road and pipeline building increased sediment yields by up to 3.4×, and housing and commercial real estate developments all led to an overall increase in sediment yield of up to 3.4× above grazing on the urban fringe of metropolitan Phoenix, Sonoran Desert, western USA.

The broader significance of this research rests with the need for U.S. county and federal regulatory agencies to consider policies that mitigate soil erosion from exposed bare ground during urban expansion in BWh climates. Concomitantly, mitigation strategies might also be warranted for other warm desert settings experiencing urbanization (Garba, 2004; Liu, Zhang, Lei, & Zhu, 2010; Xian, Crane, & McMahon, 2008; Yagoub, 2004). Although each desert region is unique with respect to the geomorphology surrounding the city (Cooke, Brunsden, Doornkamp, & Jones, 1982), the magnitude of sediment yield observed in this study could be of use in urban planning in other warm desert settings. Barbero-Sierra et al. (2013, p. 95) made the case that urban sprawl "has become the most active desertification agent in Spain" by soil sealing. The soil erosion and sediment yield associated with two decades of sprawling urbanization of metropolitan Phoenix, USA, could be interpreted in the same way but in a two-stage process: first came the exposure of bare ground with enhanced soil erosion and then came the sealing of soil when the pavement and construction was completed.

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SUPPORTING INFORMATION

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