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Detention basins as best management practices for water quality control in an arid region

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Abstract: Flood control detention basins (DBs) can act as water quality control structures or best management practices (BMPs). A key pollutant that DBs serve to settle out is particulate phosphorus, which adsorbs onto sediment. This study examines the sediment phosphorus concentration and its relationship with the particle size of sediment microcosms from pre- and post-rain event samples obtained from six DBs located in Clark County, Nevada. DBs were allotted a land use classification to determine if there was a correlation between the sediment phosphorus concentration and surrounding land use. The curve number method was used to calculate the runoff and subsequent phosphorus carried into the DB by the runoff. Our data show sediment phosphorus concentrations to be highest in soils from undeveloped areas. Runoff amount also plays a substantial role in determining the amount of phosphorus brought into the DB by sediment. This research has implications for improvement of water quality in arid regions.

Key words: *detention basin; soil contamination; runoff calculation; water quality control; phosphorus; Las Vegas Valley Watershed*

1 Introduction

Population growth has led to intense urbanization, which is characterized by commercial, industrial, and residential land grading; removal of vegetation; and soil compaction. Such landscape alterations increase impervious surface area and drastically affect the quality and quantity of stormwater runoff (Foley et al. 2005; Hatt et al. 2004; Walsh 2000). In particular, hydrologic consequences of urbanization include decreases in base flow and infiltration, and increases in floodplain area, peak flow rate, and runoff volume, with flooding being the most damaging consequence (Niemczynowicz 1999). Urbanization in arid regions requires the use of stormwater runoff quantity control structures because of the high-intensity, short-duration rain spells in these regions. In combination with the low drainage capacity of desert soils, these high-intensity storms can result in flooding, property damage, and loss of life. Hence, to manage flooding in arid regions, stormwater detention structures were introduced in the 1960s (Baxter et al. 1985).

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Detention basins (DBs) are a type of flood control structure that is most commonly used in the Western U.S. region (Shammaa and Zhu 2001). DBs are excavated areas or enhanced natural depressions in the earth that temporarily capture stormwater runoff and release it slowly back into the environment via evaporation, infiltration, and more commonly, surface flow. DBs are designed to mitigate peak flow by releasing water over a span of several hours to a few days (Fortunato et al. 2005). Although DBs may adjust flow patterns back to predevelopment characteristics, this cannot be achieved for the total runoff volume (USEPA 2002; Malcom 1980).

Being medially placed between a receiving water body and an urban or undeveloped area, DBs have the potential to act as an end-of-the-pipe best management practice (BMP) for water quality control. Sedimentation is the primary pollutant removal mechanism employed by DBs. Total suspended solids (TSS) and associated pollutants such as phosphorus settle out within a DB during the retention time. Sedimentation, if enhanced, can allow DBs to act as an efficient BMP for phosphorus and sediment removal from stormwater (NRC 1993). Research has been conducted on the efficiency of DBs in acting as a BMP for removal of phosphorus and sediment as non-point source pollution in stormwater, but much of this research is inconsistent and provides contradictory results. In Fairfax County, Virginia, Hogan and Walbridge (2007) concluded that the phosphorus sorption capacity in DBs with water quality control infrastructure was similar to that in natural riparian wetlands and higher than that in DBs designed only for flood control. Modeling studies of DB response to the non-point source pollution in stormwater indicates that there are several components that play a role in determining the effect of DBs acting as BMPs. The two main components are retention time (Weiss et al. 2006) and influent concentration (Barrett 2008). Some scientists have argued that DBs only redistribute and concentrate pollutants in a different area of the environment, doing little for pollution mitigation (Bäckström et al. 2002). Others state that the extended runoff rate and increased volume within DBs exacerbate stream bank erosion and raise TSS values (USEPA 2002; McCuen 1980). However, up to this time, all of the studies conducted on DB pollutant mitigation either have a theoretical basis or were done in wet climates. There are no studies of DB function in arid regions, particularly with regard to the amount of phosphorus that can be trapped by a DB during a rain event for a certain land use type.

Phosphorus exists in nature almost exclusively as phosphate (McKelvey 1973). Its release is facilitated by rain events, which promote weathering of rocks and decay of organic material. Sometimes, phosphorus tends to either leach away in water or settle out by adsorption onto sediment, where it becomes tightly bound and immobile. It then enters the biosphere through erosion and release of minerals and soils (Daniel et al. 1994; Sharpley et al. 1994). In natural ecosystems, phosphorus tends to be a limiting nutrient that allows biodiversity to flourish (Wassen et al. 2005). Naturally occurring phosphorus is usually released in low and constant quantities. However, anthropogenic activities can result in an unnatural and periodically excessive influx of nutrients from runoff. Copious phosphorus can result in decreases in dissolved oxygen and eutrophication, and, ultimately, in losses in biodiversity for a receiving water body (Bennett et al. 2001).

The purpose of this study was to determine whether DBs in arid regions can act as BMPs by (1) understanding how much phosphorus and sediments can accumulate in DBs for a single rain event, and (2) determining if phosphorus concentrations in DBs after a rain event relate to surrounding land use.

2 Materials and methods

2.1 Study sites

All study sites were located in Clark County in the Las Vegas Valley Watershed (with the longitude from 114°51'00"W to 115°33'00"W and the latitude from 35°49'12"N to 36°18'36"N), varying in different levels of development, as indicated by surrounding land use classifications for DBs. The watershed drains into the Las Vegas Wash and ultimately into Mead Lake. The levels of development were classified into three categories: low, medium, and high development. If a DB was surrounded by a natural environment with paved or built surface of less than 10%, the DB was classified as low. If the area surrounding a DB was mixed, with natural and built environments and with paved or built surface up to 50%, the DB was classified as medium. If the DB was surrounded by an environment with paved or built surface of more than 50%, the DB was classified as high (Table 1). The surrounding development and land use data in the drainage area of each DB was constructed from a map using the Clark County Regional Flood Control District Geographic Information Systems (GIS) database analyzed on January, 2010. A total of six DBs were chosen on the basis of surrounding land use classification, location within the watershed, and accessibility. Each of the six DBs was assessed for its main structural and non-structural characteristics, including surrounding land use, inlets, outlets, and low-flow channels.

Table 1 Size, drainage area, location in watershed, characteristics, and representative surrounding land use type for six selected DB sites in Clark County, Nevada

DB	Storage capacity (10^5 m^3)	Drainage area (km^2)	Location in watershed	Specific characteristics	Development and surrounding land use
Black Mountain	4. 51	9.76	Middle part of watershed	Defined outlet, upper and lower stages, and no defined inlet	Medium: dense residences on one side, and no development on other side
Upper Duck Creek	32. 61	76.72	Upper part of watershed	Defined outlet	Low: no development
Equestrian	6. 71	17.87	Lower part of watershed	Low flow channel, two inlets, and one defined outlet	High: residences, trails, roads, and schools
Mission Hills	5. 92	24.09	Lower part of watershed	Two outlets and no inlet	Medium: some residences
Pioneer	4. 65	19.84	Middle part of watershed	Low flow channel, no inlet, and defined outlet	High: freeways, colleges, railway stations, and industrialized construction zones
Red Rock	2 4.76	141.78	Upper part of watershed	Defined outlet and inlet	Low: no development

The Equestrian and the Pioneer DBs are located in a well-developed part of the watershed, while the Mission Hills and the Black Mountain DBs are located in a medium-developed region, and the Red Rock and the Upper Duck Creek DBs are located in a less-developed area. The Red Rock and the Upper Duck Creek DBs are located in the upper part of the watershed, the Black Mountain and the Pioneer DBs are in the middle, and the Equestrian and the Mission Hills DBs are in the lowest part of the watershed. The Red Rock and the Upper Duck Creek DBs have the largest contributing drainage area (141.78 km^2 and 76.72 km^2, respectively), followed by the Mission Hills (24.09 km^2), Pioneer (19.84 km^2), Equestrian (17.87 km^2), and Black Mountain (9.76 km^2) DBs. Study site descriptions are given in Table 1, and a map of DB locations in Clark County, created from the Clark County Regional Flood Control District GIS database, is shown in Fig. 1.

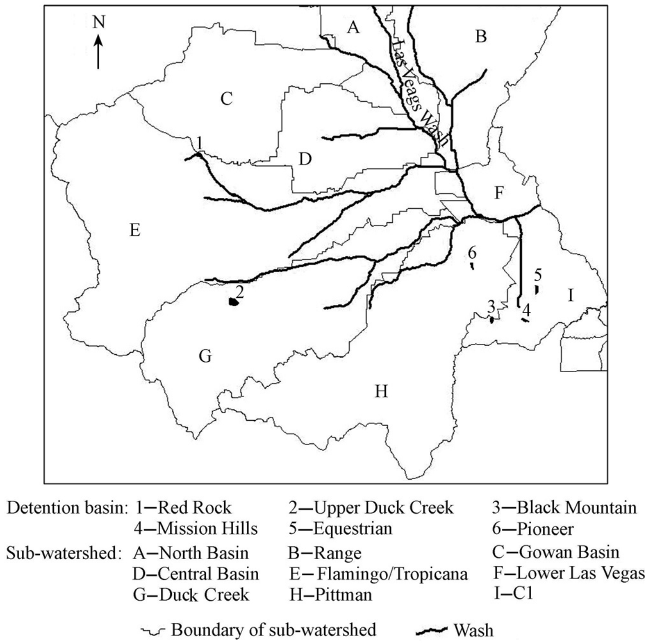

Fig. 1 Map of Las Vegas Valley Watershed with washes, sub-watersheds, and detention basin sites

2.2 Sample collection

Sediment samples were collected from the DBs following the *Soil Sampling Quality Assurance User's Guide* (Barth et al. 1989). To collect the sediment, first, litter and organic material (if any) were brushed from the surface. Then, sediment down to approximately 25 mm depth was removed with a shovel and placed in polyethylene bags. Five subsamples from each outlet were composited. The bags with the sediment samples were stored at 4ºC in a cooler until arrival at the lab. The composited samples were transferred to a plastic tub and homogenized using a shovel. Preparation and extraction of phosphorus was done within 48 hours after collection.

Sediment samples were collected before and after a rain event occurring in December 2010, which were registered on the DB rain gauges monitored by the Clark County Regional Flood Control District. Average annual rainfall in the Las Vegas Valley is about 10 cm. On a typical year, most rainfall occurs during the winter from December to February and the rest of the year remains dry, with very low relative humidity (less than 10% in the summer). The amounts of rainfall for the 24-hour period prior to our sampling were 5.8 mm for the Red Rock DB, 15 mm for the Mission Hills DB, 13.2 mm for the Pioneer DB, 18.3 mm for the Equestrian DB, 13.2 mm for the Black Mountain DB, and 18.3 mm for the Upper Duck Creek DB. Average rainfall for the entire region was calculated at 13.97 mm, with an intensity of 0.58 mm/h.

2.3 Particle size distribution

The particle size distribution of each sample was determined by following the *Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates (C136-06)* (ASTM 2005). Samples from the polyethylene bags were poured into large tin plates and dried in a convection oven at 110 ± 5°C for 24 hours. Dried samples were weighed prior to sieving. Seven 20-cm round sieves with opening sizes of 2 mm, 1 mm, 500 μm, 250 μm, 125 μm, 75 μm, and 53 μm, and a pan that captured particles with sizes less than 53 μm were pre-weighed, and the samples were then sieved. Sieved samples were weighed for calculating the percentage of particles with different sizes. This was done by taking the new weight of any sieve plus corresponding samples and subtracting the weight of just the sieve before the test. Sieves were cleaned with deionized water and a small brush after sample preparation was completed.

Sieved particles were also analyzed by laser diffraction (particle size analyzer) to determine how well the sieving method worked to separate out particle sizes. This is important because the sieving method may not prevent particles from adhering to each other.

2.4 Sediment phosphorus measurement

Phosphorus measurements were conducted for all the six DBs to determine the variation due to land use differences. DBs were allotted a land use classification, and samples from each DB were sieved prior to phosphorus measurements. To prepare for sediment phosphorus measurement, samples of between 20 and 50 mg were removed with a metal spoon from each sieve and placed into a glass test tube. Three subsamples were collected from each sieve. The prepared samples in the test tubes were analyzed using a modified phosphomolybdate colorimetric test on a spectrophotometer (UV-160, Shimadzu, Columbia, Maryland). This test was based on the formation of a phosphoantimonylmolybdenum blue species using ascorbic acid as a base and hydrogen peroxide as an acidifier. Upon acidification, the mixture was heated for 20 minutes and then neutralized. The antimonylmolybdenum reagent was added and the phosphorus in the soil turned blue so that it could be read by the spectrophotometer. The sediment was allowed to settle out, so that the liquid solution could be pipetted into cuvettes (Murphy and Riley 1962).

2.5 Runoff calculations

The runoff curve number method developed by the Natural Resources Conservation Service of the United States Department of Agriculture (NRCS-USDA) has been widely used by hydrologists to calculate runoff from rainfall. Its popularity is rooted in its four graspable and simple variables: soil type, land use treatment, surface condition, and antecedent conditions. Essentially, the curve number is a coefficient that reflects the reduction of discharge from the total amount of rainfall after considering potential for evaporation, absorption, transpiration, and surface storage. Curve number tables for land use are readily available in various references (e.g., NRCS-USDA 2004). The land use determined by the surrounding land's development characterizes the discharge potential of each DB. Soil properties affect the rate of infiltration, causing changes in discharge potential. Therefore, curve numbers are assigned mainly based on soil conditions and land use. The curve number for each DB was calculated based on the *Hydraulic Design Manual* (TXDOT 2011). The state soil geographic (STATSGO) model of the USDA was used for soil characterization (based on fractions of sand, clay, and silt) for each of the drainage areas that corresponded to the DBs (USDA 2010). The STATSGO model uses an average of the area-weighted textural classification for the DB drainage areas. Once the curve number for each DB was assigned, discharge was calculated using Eq. (1), as follows:

$$Q = \frac{\left(P - I_{\mathrm{a}}\right)^2}{P - I_{\mathrm{a}} + S} \tag{1}$$

where Q is the runoff (cm); P is the rainfall (cm); S is the potential maximum soil moisture retention after runoff generation (cm), where $S = 1000/CN - 10$, with CN defined as the curve number; and I_{a} is the initial abstraction or the amount of water retained by the surface before runoff generation (cm), such as by infiltration or by rainfall interception by vegetation, where $I_{\mathrm{a}} = 0.2S$. The curve number has a range from 30 to 100, with lower numbers indicating lower runoff potentials, and larger numbers indicating higher runoff potentials.

Precipitation data for calculation were gathered for a 24-hour period on the day before sample collection from the following gauges: station 4344 for the Red Rock DB, station 4654 for the Upper Duck Creek DB, station 5634 for the Black Mountain DB, station 4764 for the Mission Hills DB, station 4769 for the Pioneer DB, and station 4754 for the Equestrian DB. Rain gauges within each DB are monitored by the Clark County Regional Flood Control District (http://www.ccrfcd.org/raingauges.htm).

2.6 Statistical analysis

Significant differences in sediment phosphorus concentration variation and particle size distribution were determined by analysis of variance. Analyses were performed using JMP and Microsoft Excel software. Significant differences were considered at the p-value less than 0.05 ($p < 0.05$) as indicated in the text.

3 Results and discussion

3.1 Change in particulate phosphorus concentration

The dry sieving analysis used to separate particle sizes provides an indication of the availability of phosphorus at the surface and potential water pollutants, because water that passes over sand can pick up and carry particles and subsequent phosphorus to water bodies such as Mead Lake (Vaze and Chiew 2004). The average pre- and post-rain sediment phosphorus concentrations for all particle size fractions of each DB were significantly different ($p < 0.05$) with post-rain samples having higher phosphorus concentrations than pre-rain samples. On average, pre-rain samples contained about 600 μg/g of phosphorus, while post-rain samples contained about 750 μg/g of phosphorus, with an increase of about 150 μg/g. The increase in the phosphorus concentration of post-rain samples may be due to an influx of high nutrient loads carried by runoff, which settled into the DBs during the rain event. Dry spells are long in the Las Vegas Valley due to infrequent rain occurrence. The buildup of pollutants during the dry period influences initial loads of pollutants that are transported into a DB during a rain event. Furthermore, the pre-rain phosphorus concentration of a DB is important because it is diluted or mixed with the influent and carried by outflow into receiving environmental systems (Kim et al. 2006; Vaze and Chiew 2002).

Changes in phosphorus concentrations within a DB after a rain event reveal the efficiency of the DB in settling out sediment and associated pollutants, and the amount of phosphorus accumulated in the DB after a single rain event. If increases in phosphorus concentrations are observed in post-rain samples for even a small rain event, removal of phosphorus and associated pollutants from the water via sedimentation can be deduced. This deduction is important especially with respect to phosphorus removal from stormwater because of the negative environmental impacts associated with high phosphorus concentrations in a water body.

3.2 Precipitation and runoff effects on phosphorus concentrations

Based on the curve number method, we calculated the amount of runoff into each DB and then the amount of phosphorus carried by the runoff. The runoff amount into each DB was fairly low, ranging from approximately 2.2 to 12.4 cm (Table 2). Despite the amount of rainfall, runoff can account for some of the changes in phosphorus concentrations for the DBs. We calculated that for the Red Rock DB about 350 μg/g of phosphorus was brought in by the runoff. The Red Rock DB had a significantly higher ($p < 0.05$) post-rain phosphorus concentration. This is likely due to the fact that this DB is located in a less- developed area, so sediment and associated phosphorus can more easily be carried to the DB. The phosphorus level is high in the undeveloped part of the Red Rock DB due to the geological history of the area. Accumulation of phosphorus is heaviest on ocean floors (Delane 1998), and this area was part of a deep ocean basin for over 600 million years (RRG 2007). Furthermore, eroded and weathered material (and subsequently arriving phosphorus), which is abundant in unpaved areas, can easily be carried by water and deposited into the DB, since there is little land cover (e.g., plants). The Upper Duck Creek DB is also in a less- developed part of the watershed and showed a high level of phosphorus flowing into the basin (about 250 μg/g). The Mission Hills DB and the Black Mountain DB showed about 40 μg/g and 35 μg/g of phosphorus discharged into the basin, respectively. Both are located in medium-developed areas. The Equestrian and Pioneer DBs are located in well-developed parts of the watershed and received 70 μg/g and 20 μg/g of phosphorus, respectively. Excluding the Equestrian DB, most of the phosphorus discharged into the DBs that were located in less-developed parts of the watershed. The higher level of phosphorus discharged into the Equestrian DB could be due to the fact that there are horse trails surrounding this DB. Fecal matter from horses, which is high in phosphorus content, could accumulate and be carried into the DB through the trails. Other possible sources of phosphorus in sediment samples from well-developed areas are roads or highways, including adjacent right-of-ways, landscaped areas, and parking lots (Reginato et al. 2004).

Table 2 Runoff calculations for all DBs using curve number method

DB	P (mm)	CN	S (cm)	I_a (mm)	Q (cm)
Red Rock	5.8	68	12.0	23.9	10.1
Mission Hills	15.0	65	13.7	27.4	12.4
Pioneer	13.2	88	3.5	6.9	4.1
Equestrian	18.3	98	0.5	1.0	2.2
Black Mountain	13.2	68	12.0	23.9	10.9
Upper Duck Creek	18.3	68	12.0	23.9	11.4

The pre- and post-rain phosphorus concentrations were calculated by taking the average pre- and post-rain phosphorus concentrations from the sieved sediment of each DB. For four out of the six DBs, post-rain phosphorus concentrations were significantly different ($p < 0.05$) from pre-rain phosphorus concentrations. These four DBs include the Pioneer DB (514 vs. 634 μg/g), the Mission Hills DB (472 vs. 651 μg/g), the Upper Duck Creek DB (1 836 vs. 2 977 μg/g), and the Red Rock DB (2 976 vs. 4 366 μg/g), as shown in Fig. 2. Sediment characteristics, and hence the phosphorus concentration are functions of catchment characteristics (Goonetilleke et al. 2004). Therefore, when we determine the particulate phosphorus concentration of a DB, surrounding land use and catchment characteristics should be considered.

It should be noted that the pre-rain samples may not be completely free from sediment phosphorus deposited by the previous rainfall. However, the Las Vegas Valley gets an average of 10 cm of annual rainfall and most of that occurs in one or two intense rain events, which also produce large amounts of sediments in DBs during the winter months (December to February). In 2010, there was no rain from October until our sampling in late December. October rain was a smaller event (less than 2 mm on average) and, prior to October, there was no rain for seven months. The relative humidity in the Las Vegas Valley in summer months is usually less than 10%. The pre-rain sediments in the DBs accumulating in the previous rain events are mixed with windblown particles, but contribute only a small part of the total post-rain sediment of the current rain event. We believe that the fresh sediments that are brought immediately after a rain event are substantially larger and therefore allow for characterizing and comparing phosphorus concentrations of different DBs based on land use types.

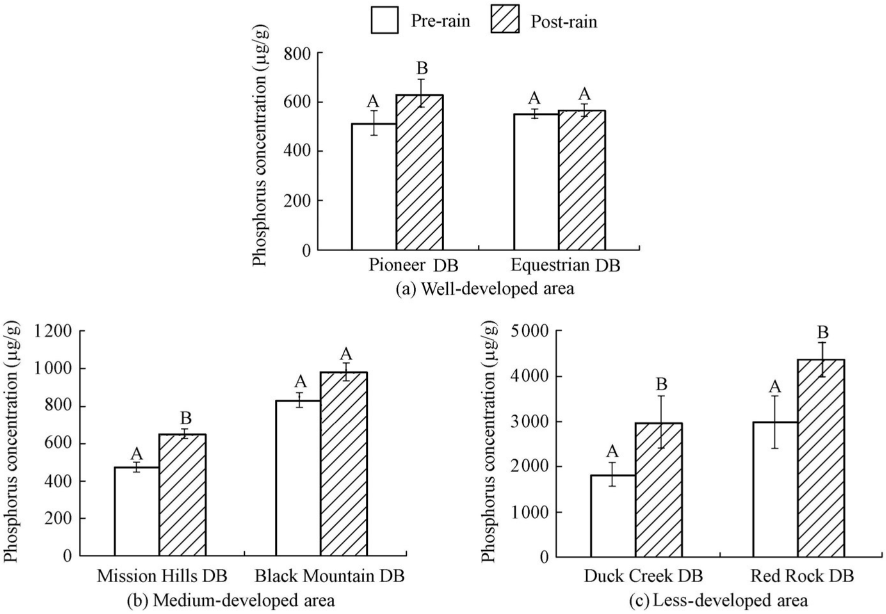

Fig. 2 Average pre- and post-rain particulate phosphorus concentrations for six DBs (error bars represent standard errors; letters above bars represent comparison between the pre- and post-rain phosphorus concentrations within a DB: different letters indicate statistical significance, and identical letters indicate statistical non significance.)

3.3 Particle size distribution and sediment phosphorus load

When analyzing land use type and particulate phosphorus contribution, 69% of the phosphorus came from DBs located in the less-developed regions of the watershed, and 15% and 16% of the phosphorus analyzed came from the medium- and well-developed surrounding land use areas, respectively. Phosphorus concentrations from the less-developed surrounding land use areas were significantly higher ($p < 0.05$) than those from the medium- and well-developed areas. There are a couple of reasons for the possible high levels of phosphorus in less-developed regions. First, the less-developed regions of the Las Vegas Valley Watershed have higher levels of sediment and subsequent erosion during rain events. Second, the watershed areas contributing to these DBs in less-developed regions are larger than the areas contributing to the DBs located in the medium- and well-developed regions.

In a modeling study, Reginato and Piechota (2004) found that less than half of the sediment and nutrient loading to the Las Vegas Wash came from undeveloped areas. Reginato and Piechota (2004) broke down land use by designating areas with parks, golf courses, roads, and highways according to land use classifications. They also identified the percentage of each land use type in the watershed. Approximately 70% of the general valley area was considered undeveloped in this study. The DBs in the undeveloped parts of the valley are much larger in drainage area than DBs in the medium-to-well developed land use classifications. This is possibly one of the reasons why the less-developed land use classification in this study accounted for over half of the phosphorus concentration.

A log linear correlation (R^2 = 0.74) was found between the particle size and mean phosphorus concentration of all six DBs in a pooled analysis (Fig. 3). This correlation was highly significant, with a *p*-value of 0.013. Our results are consistent with other studies, which also conclude that the finest particles have the highest concentration of pollutants (Li et al. 2006; Roger et al. 1998; Andral et al. 1999; Morquecho and Pitt 2003; Sansalone and Buchberger 1997). In particular, the phosphorus concentration is highly associated with particles less than 0.02 mm in diameter. Hence, the high phosphorus concentration occurs in the set of particle sizes less than 0.05 mm (Bavor et al. 2001; Vaze and Chiew 2004).

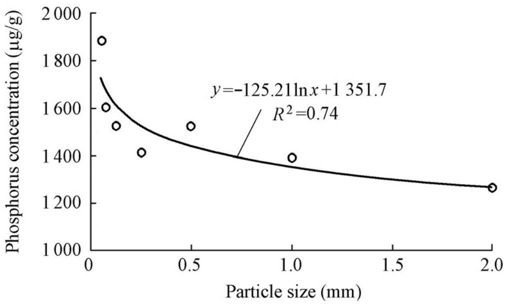

Fig. 3 A log linear correlation of particle size vs. mean particulate phosphorus concentration in DBs in Clark County, Nevada

Although the average phosphorus concentration increases as the particle size decreases, the percentage of phosphorus carried by sand-sized particles (particle sizes > 0.13 mm) was 65% in our total sample, while the phosphorus carried by silt and clay made up the other 35%. This was due to the fact that sand made up the bulk of the total sediment obtained from each DB. It is important to understand that fine particles have a larger surface area (with respect to the same volume). Therefore, the total pollutant (phosphorus) load would be smaller in larger particles as compared to the load carried by the same volume of smaller-sized particles (Goonetilleke et al. 2005).

4 Conclusions

We found that the phosphorus concentration was higher in post-rain fresh sediment of DBs when compared with that in pre-rain samples. Also, average sediment phosphorus concentration was higher for smaller particle size fractions for all the DBs in the study. Despite finer particles having higher phosphorus concentrations, larger particles carried nearly 70% of all the phosphorus analyzed due to the fact that sand made up the bulk of the sediment composition. With respect to land use, phosphorus was highest in the less-developed areas.

Based on our results, DBs can be used as BMPs not only to control stormwater runoff quantity (by holding peak discharge) but also to improve quality by allowing suspended particles that might carry contaminants such as phosphorus to settle out. DBs work especially well for water quality control when they are surrounded by undeveloped areas, since DBs easily trap sediments that can be removed from the basins.

This research establishes a guideline for DB- and BMP-related research in arid regions, especially since these areas are characterized by infrequent rain events, which makes it difficult to monitor infrastructural water quality outcomes. Our research shows that DBs appear to work well in such areas. Furthermore, water quality control remains an unexplored and important aspect of DB utility, particularly in arid regions, and this paper therefore provides a step in that direction. Future work needs to address how much phosphorus might go through the DB without being deposited.

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