Presented at the regional conference on:
Experience with Best Management Practices in Colorado
April, 2003

EFFECTIVENESS OF URBAN STORMWATER BMPs IN SEMI-ARID CLIMATES

Ben R. Urbonas, P.E.
Chief, Master Planning and South Platte River Programs
Urban Drainage and Flood Control District
2480 W. 26th Avenue, Suite 156-B, Denver, CO, 80209

ABSTRACT

The phenomena of land-use changes, including urbanization, impacting the physical and biologic integrity of the receiving waters are discussed in this paper. The observed and reported impacts are tied to the types of structural stormwater best management practices (BMPs) that have the greatest potential in mitigating them in the semi-arid climates as experienced in Colorado and other states and regions that have similar climatic conditions. In addition, topics related to clogging of filtering and infiltrating systems, underground vs. above ground facilities, water quality capture volume vs. flow-through facilities, details of what makes extended detention basins function best and the basis for comparing "effectiveness" of BMPs are addressed in this paper.

INTRODUCTION

Virtually no one argues anymore that land use changes that increase site imperviousness or reduce rainfall-infiltration/interception capacity have an impact on receiving gulches, streams, rivers and lakes of the nation. The degree of these impacts appears to be related to the intensity of the land use change, local climate, site geology and the nature of the receiving water. When a tract of rangeland changes to a single-family residential land use, we estimate that the receiving waters in the Colorado's high plains region see the following changes:

Annual:	Before	After	Increase
Runoff Volume	0.52	3.61	700%
Number of Runoff Events	< 1.0	29+	>3000%
Load of TSS, & TP			>500%

What this table does not reveal is that most of the 29+ runoff events represent an increase from zero to some measurable values in peak and volume, namely an infinite ratio since the starting value is zero. The most obvious and immediate impacts that we visually observe are the geomorphic changes in the receiving gulches, streams and rivers (see Figure 1).

Figure 1. Channel degradation at Marcy Gulch.

At the August 2002 gathering of experts from around the world in Snowmass Village, Colorado the topic of "Linking Stormwater BMP Designs and Performance to Receiving Water Impact Mitigation" (Urbonas, 2002) was addressed and debated in much detail. The general themes (virtually a consensus) that emerged from this gathering support the above-stated observations for the Colorado's high plains region. The consensus is that land use changes that reduce rainfall abstractions and increase surface runoff increase the rates and volumes of storm runoff, increase the numbers of runoff events, increase the annual pollutant loads and modify the physical and biologic nature of the receiving waters. The physical changes that occur to our receiving waters also result in changes to aquatic and adjacent terrestrial habitat and in their biologic integrity (See Figure 2).

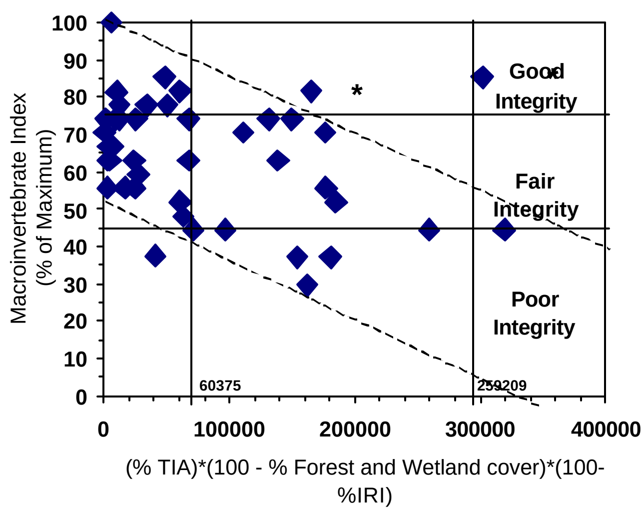

Figure 2. Changes in Macroinvertebrate Index in Austin, Texas with increasing degree of urbanization in a watershed. (Horner, 2001)

Of most interest to the professionals that manage our water resources and local waterways, were the following three observations that emerged from this conference:

1. Regardless of the location on earth, changes in biology and physical nature of receiving waters are virtually inevitable as land uses change.

2. Watershed-wide use of BMPs to control runoff rates and/or volumes <u>can reduce</u> the degree of these impacts. (See Figure 3)

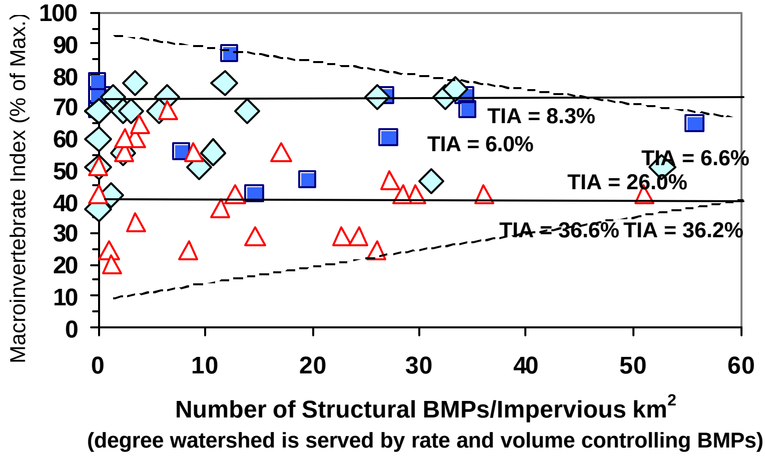

Figure 3. Biologic Index vs. Structural BMP Density. (Horner, 2001)

3. Stabilizing of receiving streams as lands begin to urbanize is essential in limiting stream bank and bed erosion and loss of aquatic habitat. (See Figure 4)

Figure 4. Grade control and soil-riprap stabilized bank - Rock Creek, Superior, Colorado.

WHAT SHOULD "EFFECTIVE" BMPs DO?

Assuming the reason we use BMPs is to help mitigate the impacts of urbanization on our receiving waters, the BMPs we select will need, as a minimum, to do the following:

1. Control rates of runoff from the large numbers of new, smaller runoff events seen in urban areas to very low rates of flow. This reduces, but does not eliminate, the erosive energies experience by the receiving streams and the erosion they cause.

2. Reduce runoff volumes from the new population of small runoff events, thus reducing the pollutant loads delivered by stormwater to receiving waters.

3. Remove from the water column, as much as practicable, Total Suspended Sediment (TSS) particles smaller than 60 µm found in the stormwater column.

4. Integrate structural BMPs into the fabric of the community by providing multi-use opportunities, minimizing nuisances associated with them (e.g., mosquitoes) and making sure they are readily maintainable when visual evidence indicates a need for such maintenance.

The criteria recommended in the Urban Drainage and Flood Control District's (District) *Volume 3 of the Urban Storm Drainage Criteria Manual* (*Manual*) (UDFCD, 1999) have been developed with all of these principles in mind. In addition, looking further down the road, should the Total Maximum Daily Load (TMDL) process mandate that numeric water quality limits be met, the BMPs recommended in the *Manual* will provide the space to modify these BMPs so as to address these mandates and, hopefully, meet them.

The various post-development BMPs recommended in the *Manual* are based on the following fundaments principles:

1. Reduce the accumulation of pollutants on the urban landscape through public education and other practices that encourage
   a. proper disposal of household waste and pollutants
   b. proper use of pesticides, herbicides, fertilizers, etc.
   c. control of pet waste
   d. aggressive erosion and sediment control during construction
2. Reduce surface runoff volumes as much as practicable
3. Fully capture and treat 80% of all stormwater runoff events (annual average) and the "first flush" of larger storms
4. Remove small TSS particles and associated pollutants from the stormwater column before discharging to the receiving waters
5. Appropriate industrial site management to keep rainfall and runoff from coming into contact with products and chemicals that may pollute the runoff
6. Be accessible and visible for easy inspection and maintenance.

Lets examine items 2, 3 and 4 further.

Reducing Stormwater Runoff Volume

The literature is full of terms such as "Smart Growth", "Low Impact Development", "Sustainable Development", etc. All of these terms refer to a family of stormwater management practices that promote the reduction of runoff volume from urban areas. The first step in stormwater quality management in the *Manual* recommends reducing runoff volumes through the use of "Minimized Directly Connected Impervious Areas" (MDCIA). This set of practices in nothing less than what is being recommended by the terms described above. The District's *Manual* has been advocating these practices since before 1994 and has specific design recommendations for the following runoff volume reducing BMPs:

1. Grass Swale (GS)
2. Grass Buffer (GB)
3. Modular Block Porous Pavement (MBP)
4. Porous Landscape Detention (PLD)
5. Porous Pavement Detention (PPD)
6. Sand Filter Basin (SFB)

The first three BMPs require that follow-up facility that has a Water Quality Capture Volume (WQCV) be provided downstream. They reduce runoff volumes, but do not eliminate runoff entirely from the smallest 80% of the runoff events. As a result, facilities that have a WQCV that is reduced in accordance with the recommendations given in the *Manual* need to be installed to capture and treat the residual runoff from these events.

The final three BMPs have their own WQCV and are actually designed to infiltrate water into the ground if the local geology permits. Even where the underlying soils have very low hydraulic conductivities, such as clays, some of the volume captured will not return to the receiving waters as surface runoff. It will return slowly as interflow or be evapotranspired, a similar manner as pre-developed soils and vegetation would do.

All of these can be integrated into the fabric of the development on site, very close to where the rainfall first reaches the ground. "Rain Gardens" (see Figure 5) used in the eastern United States are an example of what we call PLDs. They have the look of slightly depressed grass areas, flower gardens or shrub patches; yet can serve the needs of a commercial and residential sites very well. MBP or PPD can be made to be part of parking lots, private drives, roadside parking strips or shoulders, etc. GS and GB can be substituted for curb-and gutter in most developments, including residential and commercial areas as part of the often-required open space dedications for new developments (see Figure 6).

Figure 5. A "Rain Garden" in Prince George County, MD (same as a PLD in the *Manual*).

Figure 6. Use of GSs and GBs in a residential neighbourhood, Boulder, CO.

What does that mean in terms of runoff reduction benefits? We have not yet been able to complete data acquisition and analysis yet ourselves, but data collected in Scotland (Macdonald and Jefferies, 2002) show the following for the events when runoff actually occurred at the porous paved parking lot:

- Average Runoff Volume: 75% less than at asphalt paved parking lot.
- Lag time: Between 30 and 600 minutes at the porous paved parking lot, but almost instantaneous at the asphalt-paved lot.
- Average Peak Flow Rate: On the average reduced by 77%

In addition, these data also show that swales do produce a measurable benefit in reducing the runoff rates and volumes, but the result is not as dramatic as with porous pavement.

SUCCESSFUL ("EFFECTIVE") PERFORMANCE OF BMPs IS IN THE DETAILS

Like any technology, it is the details that make the difference between a product that works well and one that does not function well, requires undue amount of maintenance and operation, and is a general pain to own and to get to perform consistently. Let's examine some of the more common issues, problems and misconceptions that we encounter throughout the District and other locations in United States, namely:

1. Clogging potential of sand filters and infiltrating facilities
2. Extended Detention Basins – need for micro-pools and effective trash tacks.

Clogging Potential of Sand Filters and Infiltrations Facilities

There exists a perception that a SFB can impose a large maintenance burden on its owner. This concern is justified and has been addressed by the design parameters recommended in the *Manual.* The design criteria were developed to minimize maintenance and it is estimated that over an extended number of years an SFB should cost about the same to maintain as an EDB or a RP, and less than a Constructed Wetland Basin (CWB). This will not be the case if there is construction erosion occurring upstream that is washed down into the SFB. Regardless of this possibility, the removal of the accumulated sediment and the removal and replacement of the top two to three inches of the sand will return it to full operation. Under normal urban runoff conditions, it is estimated that a SFB will operate well, namely empty out the full WQCV within two days or less, for about five years. When the emptying time becomes longer than that, simple removal and replacement of the top 2- to 3-inch layer of sand will return it to full operation.

Similar, but less frequent maintenance costs are estimated for PPDs and PLDs. In the former, one must use a vacuum to remove the top 2- to 3-inches of sand from the annular spaces in the MBP blocks and replace it with fresh sand. For the latter, plant root activity will keep the top surface area open for a longer period of time than for bare soils, thus extending the period between maintenance.

It is important to recognize that all BMPs will require maintenance and some of them will be more difficult to maintain than others. For example, the micro-pool in an EDB will need to be drained, the bottom dried out and deposits removed. In addition, the forebay will need regular cleaning. The entire basin's bottom will eventually need to have a layer of deposits removed and revegetated, and the structural elements such as inflows, rundowns and outlets fixed as they deteriorate over time. A SFB does not have a forebay or an outlet (see Figure 7). Unless the underdrain pipes are crushed, something that can be avoided with the use of lighter tracked equipment, there are few structural elements to consider. In addition, the sediments on top of the sand media typically dry out quickly and can be removed at almost any time of the year.

Figure 7. Example of a SFB that functioned well for 10-years in Littleton, CO; was removed by RTD in 1999 to make way for park-and-ride lot expansion.

Extended Detention Basin

Two of the most important elements of an EDB that are often misunderstood and improperly implemented are:

1. Micro-pools
2. Trash racks.

<u>*Micro Pool.*</u> Despite that the fact that the latest version of the *Manual* has been in circulation since 1999, quite a few EDB facilities designed and constructed since then have outlets that work well and/or micro-pools. It appears that some designers and their clients continue to leave out micro-pools and do not use the details for the outlet recommended in the *Manual* in their designs. Much research and thought went into developing the recommended design details, especially in selecting the materials and the type of trash rack to be used at the outlet. When the recommended trash rack is used, its operation can be compromised if no micro-pool is installed. These two work in tandem to provide a well functioning EDB that will dry out the basin's bottom within a relatively short period of time, thus preventing ideal breeding conditions for mosquitoes. Yes, a micro-pool significantly reduces, and keeps in check, the mosquito populations associated with many BMPs. It does that by:

1. Providing an active surcharge storage volume for nuisance dry-weather flows and most frequently occurring runoff from very small storms
2. Having a relatively deep permanent pool with steep sideslopes that is poor habitat for mosquito breeding
3. Providing habitat for predator species (e.g., dragonfly) that eat mosquito larvae
4. Limiting the area where shallow waters will be present for extended periods of time
5. Providing a reservoir where mosquito larvae control agents (i.e., DIMP) can be added if the need arises.

Mosquitoes breed best in stagnant shallow waters. Without a micro-pool and the currently recommended details for EDB & RP outlets, the lowermost small orifices in the outlet plate, or riser if one is used, clog with sediment, along with the lower portions of the trash rack. When that happens, stormwater does not empty out fully, leaving behind large areas of the basin's bottom covered with a stagnant shallow layer of water and soggy soils that stay wet for weeks, a perfect mosquito breeding habitat. Typically, mosquito larvae need 72-hours to hatch, mature and emerge as the blood-sucking insects that we hate so much. When the EDB is constructed using the recommended details, the main body of the basin is emptied out in 40-hours or less, depending on the size of the storm, leaving only the 2.5-feet deep micro-pool area wet (see Figures 8 and 9).

Figure 8. A properly designed EDB in Jefferson County, CO. Note the small wet area (micro-pool) at the outlet during in 2002.

Trash Rack. Many EDBs and PRs today have an ineffective trash rack at the outlet or none at all. Water quality outlets, by their nature, require very small openings. As a result, they are prone to clogging by floating and neutrally buoyant trash such as paper, plastic bags, sticks, leaves, grass clippings, etc. A properly sized and designed trash rack is the best defense against such clogging. In addition, trash racks at all detention basin outlets are an essential element for public safety to keep persons from being lodged against the outlet by hydraulic pressure as the basins fill. The details recommended in the *Manual* are the result of many observations throughout the United States and suggestions by the practitioners in the Denver area. They come as close as possible to being optimum in configuration and sizing using the knowledge we possess today. The only configuration for the removal of suspended solids that would perform better is a floating outlet that rises and falls with the water level, but the technology for its continued long-term performance has not yet been perfected.

Figure 9. An EDB without a micro-pool. Note the large saturated wet area during a dry weather period in 2002, a drought year, that provides good habitat for mosquito breeding.

OTHER IMPORTANT BMP-RELATED ISSUES

Lets examine three other issues that are the topic of most questions we receive from practitioners, namely:

1. Use of BMPs with a WQCV vs. flow-through devices
2. Above-ground vs. underground BMPs
3. Basis for comparing BMP "effectiveness"

Use of BMPs with Water Quality Capture Volume vs. flow-through devices

Starting on page 3 of this paper we listed several points in answering the question of "What should effective BMPs do?" One of these is the ability of a BMP to control the rates of runoff from large numbers of smaller runoff events to very low rates of flow. This is needed to reduce the erosive energies experience by the receiving streams, thus also reducing the impacts of urbanization on aquatic habitat. Another was to remove the smallest TSS particles from stormwater (i.e., less than 60 µm) in order to reduce the deleterious effects of these particles on macroinvertebrates and fish in the receiving streams in Colorado.

The capture of the WQCV recommended in the *Manual* and its release over 12 to 40 hours, depending on the type of BMP used, goes a long way towards meeting those goals. It provides for complete capture and treatment, on an average annual basis, of 80% of all stormwater runoff events and of the "first flush" of the remaining 20%. In fact, doubling the capture volume increases the complete capture ratio by only 5%. When it comes to the removal of the small TSS particles, and associated pollutants, the release of the full WQCV over a 40-hour period by an EDB or 12-hour period by a RP provides the residence time needed to settle out these particles from the water column. The difference in the residence time is possible by the fact that the permanent pool of a RP provides a much more efficient treatment facility for the removal of TSS particles than an EDB without one. Another feature of the slow release of the WQCV is that it will retard even the smallest runoff events, thus not allowing them to short-circuit through the outlet without some treatment. For the smallest of these runoff events, the micro-pool provides a similar function to the permanent pool of the RP, extending TSS removal efficiency to runoff events not receiving much treatment without it.

Devices that do not have a WQCV, namely the flow-through devices, do not mitigate flow rates. As a result, the full energy of the large numbers of new runoff events in urban areas reach the receiving stream without any attenuation. In addition, the very short residence time, on the order of seconds, does not permit the removal of the smaller TSS particle. Some of these devices, however, can be effective in removing larger sediment, bed load and trash, namely, the "gross pollutants." For this reason the District has clarified its policy on their use in retrofit situations for small tributary areas (i.e., "not significant redevelopment"). When faced with the prospect of having one of these devices retrofitted into the existing urban landscape or not having any treatment, their use needs to be looked at on a case-by-case basis.

Aboveground vs. underground BMPs

Under most normal circumstances, there is no justifiable reason to use underground facilities in areas of new urban development or significant redevelopment. With the expectation of PLD and PPD which require about 4% of the total impervious area of the development, all of the above-ground BMPs recommended in the *Manual* require less than 2% of the total impervious area of the development to provide a WQCV. The surface area required by BMPs with a WQCV can further be reduced if PP, PPD, PLD, GS and/or GB are used. Since virtually all zoning ordinances require at least 5% of the total land area to be open and landscaped, BMPs can easily be integrated into the site landscape plan. All it takes is creativity and the services of a landscape architect to integrate the two functions, namely site landscaping and stormwater management.

Aboveground BMPs are visible to the owners and the public, while underground facilities are out-of-sight and, as a result, often become out-of-mind. As we discussed earlier, effective BMPs need to be accessible and visible for easy inspection and maintenance in order to keep operating as designed. An inspection program can be designed to visit each BMP site on a regular basis, open the access manholes, inspect its condition and to measure the floating debris and deposit layers on the bottom. It is also possible to schedule a regular maintenance cycle to clean them out. However, both approaches need a clear commitment on behalf of the original and subsequent owners, good record keeping and some form of institutional reporting to "assure" they are being maintained.

The author had an opportunity to inventory underground grease and oil traps at an industrial district. What became obvious is that despite the best of intentions and past agreements to maintain them, virtually all of the traps were not maintained for years and some had their manhole covers overlaid with asphalt paving sometime in the past. It took a jackhammer to break out the hardened grease in one of the traps that had its manholes under a 2-inch layer of asphalt and was not serviced for more than five years. This was a clear case of out-of-sight and out-of-mind.

A simple visual inspection, often not much more than a drive-by of aboveground facilities, will reveal significant problems. In addition, when the aboveground facility is not operating properly, becomes silted in, there is structural damage to the outlets, etc., the owner or the responsible municipality will see it and be compelled to take rehabilitative maintenance action to keep the site "clean" nuisance free and operating.

Basis for Comparing BMP "Effectiveness."

Two significant new thoughts have emerged in recent years about "effectiveness" of structural BMPs. First is the notion that a truly effective BMP will have an ability to mitigate many of the impacts of urbanization on receiving waters, including the modifications in hydrology that accompany land-use changes. The second is the questioning of the hypothesis that "percent removal" of pollutants is an appropriate metric in comparing the performance of different BMPs. The first one was already addressed earlier in this paper.

The Urban Water Resources Research Council (UWRRC) of the American Society of Civil Engineers (ASCE), under a grant from EPA, developed a BMP performance database based on scientific and engineering principles. At this time the database contains data from over 200 BMP field evaluation sites in United States, Canada and Europe.

After studying this data, it was concluded that there is no scientifically grounded basis for using "percent removal" of pollutants as the basis for comparing the performance of various structural BMPs (Clary, *et. al.*, 2001). Such comparisons may be valid if BMP performance were compared in a specific city to service similar land-use conditions. As the geography and land uses change, the runoff quality and quantity change as well. The result being that the "percent removed" numbers change as well.

What the investigative team found was that comparing the effluent quality vs. influent quality, and the volume of stormwater treated in relation to the average runoff volume in the area, provided more stable and scientifically sound basis for comparing performance or "effectiveness" of BMPs in their ability to affect the water quality reaching the receiving waters of the nation (for more information visit www.bmpdatabase.org web site). This is a very important finding if the performance data are to be used in TMDL studies and to make eventual commitments to the regulatory agencies. After all, the total maximum daily, seasonal or annual load will depend entirely on the effluent quality that leaves and bypassed the BMP and not on the percent removal of a constituent. The latter can show high percent removals when the concentrations in runoff are high and low removals when they are low, even when the runoff itself is very clean.

Figure 10 shows the results of a statistical analysis of several BMP types in terms of "percent removals" and effluent concentrations for TSS. The percent removal box and whisker plots show very wide bands of confidence that imply that almost all of the BMPs have similar performance when the 95% confidence test is applied. That is not the case when the effluent concentrations are compared. When interpreting this graph it is important to understand that most of these BMP groups (i.e., bioswales, hydrodynamic devices, retention basins and wetlands) have very few data sets and their results are prone to statistical anomalies and need to be viewed with some scepticism. Nevertheless, the trends so far show that, with the exception of hydrodynamic devices, all BMP groups reported here produce less than 30 mg/l TSS in the effluent, a concentration comparable to secondary treatment of wastewater.

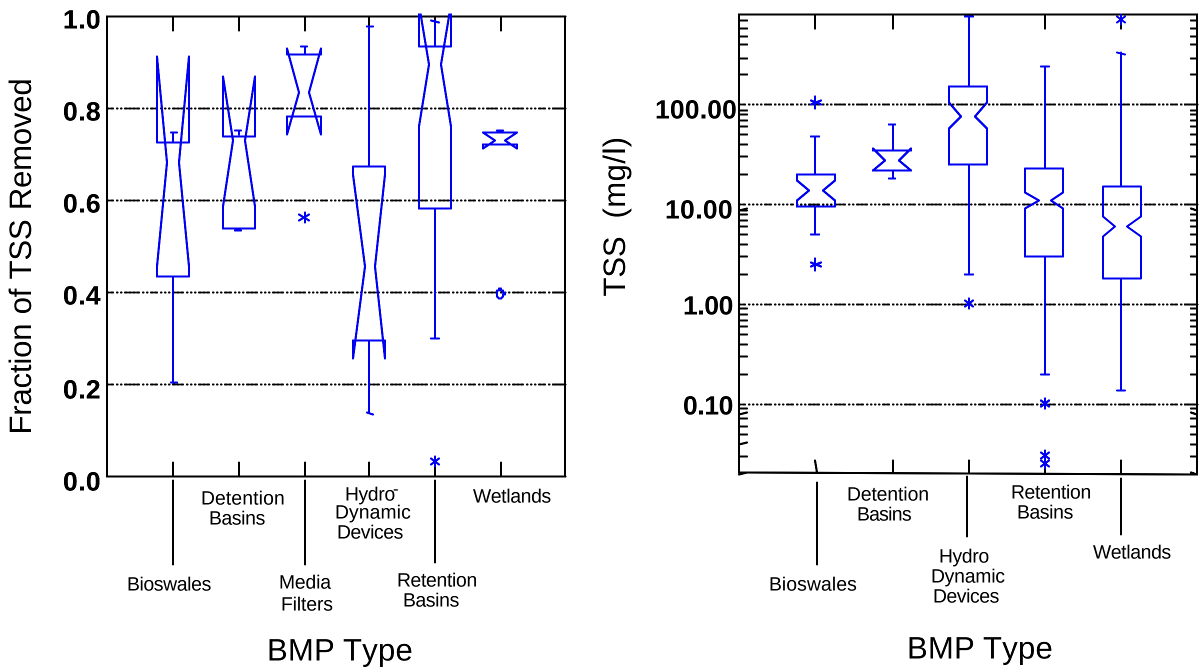

Figure 10. Box and Whisker Plot of influent and effluent *Event Mean Concentration* for TSS data for several BMPs in the National BMP Database (Ref.: www.bmpdatabase.org)

SUMMARY OF ISSUES DISCUSSED

The key issues discussed and points made in this paper can be summarized as follows:

- Urbanization and other land use changes can have a profound impact on the receiving waterways of Colorado's high plains that are driven by changes in hydrology, water quality and human activities.
- Watershed-wide use of BMPs that significantly reduce runoff rates and control runoff volumes from the majority of most frequently occurring smaller storms (i.e., 80% of runoff events) can reduce these impact on receiving waters and their biota.
- Effective BMPs, in addition to controlling runoff volumes and rates of runoff, need to remove TSS particles less than 60 µm in size from stormwater runoff to the maximum extent practicable, should be integrated into the urban landscape to the maximum extent possible and be readily accessible and visible for maintenance.

- The District's *Manual* provides good guidance for the selection, sizing and design of a number of BMPs, including those that can reduce runoff volumes.
- BMP effectiveness should be based on comparing their ability to mitigate the impacts of modified hydrology as well as the quality of the effluent they can produce. Use of "percent removals" for comparing BMP performance is not recommended by the National BMP Database project.
- Filter-type BMPs can clog quickly if not properly sized and maintained. The criteria in the *Manual* for sand filters take these issues into account.
- It is critical to provide a micro-pool and the trash rack details recommended in the *Manual* to have an extended detention basin that has fewest operational and mosquito problems.
- Aboveground facilities are recommended for all new development and significant redevelopment, reserving underground facilities for retrofit in dense urban areas.
- In order to mitigate hydrologic impacts of land use changes and to reduce small TSS particle concentrations in stormwater, BMPs with a water quality capture volume are needed.

REFERENCES

Clary, J., Kelly, J., Jones, J., Quigley M. and O'Brien, J. (2001). "National Stormwater Best Management Practices Database; a Key Tool to Help Communities Meet Phase II Stormwater Requirements," p. 44-48, *The Journal for Surface Water Quality Professional Stormwater*, March-April, Forester Press, Santa Barbara, CA.

Horner, R. (2002). "Structural and Non-Structural Best Management Practices (BMPs) for Protecting Streams," *Linking Stormwater BMP Designs and Performance to Receiving Water Impact Mitigation,* B.R. Urbonas, Editor, p. 60-77, ISBN 0-7844-0602-2, American Society of Civil Engineers, Reston, VA, USA.

MacDonald, K.C.B. and Jefferies, C. (2002). "Performance of BMPs in Scotland." *Linking Stormwater BMP Designs and Performance to Receiving Water Impact Mitigation,* B.R. Urbonas, Editor, p. 519-523, ISBN 0-7844-0602-2, American Society of Civil Engineers, Reston, VA, USA.

UDFCD (1999). *Urban Storm Drainage Criteria Manual - Volume 3, Best Management Practices*, Urban Drainage and Flood Control District, Denver, CO, USA.

Urbonas, B.R., Editor (2002). *Linking Stormwater BMP Designs and Performance to Receiving Water Impact Mitigation,* p.p. 572, ISBN 0-7844-0602-2, American Society of Civil Engineers, Reston, VA, USA.