Gravel Bed Stormwater Detention System for Growing Trees in Extra-urban Areas

A Cooperative demonstration project with the City of Knoxville, University of Tennessee Departments of Civil and Environmental Engineering and Forestry, Wildlife, and Fisheries, and the USDA Forest Service

Prepared by:
Eric Kuehler
Eric.Kuehler@usda.gov
Science Delivery/Technology Specialist
Urban Forestry South
320 Green St., Athens, GA
706-559-4268

Development has been shown to increase stormwater runoff especially in highly-developed, extra-urban areas like downtown cores. Forest systems (tree canopy, ground cover, and soil) retain significantly more stormwater runoff than developed, urban areas primarily due to better soil conditions. Uncompacted soils in forests allow for greater water infiltration and storage belowground for tree roots to use unlike in urban areas where soils are typically compacted. Access to more abundant ground water and soil nutrients allows trees to maximize leaf surface area which drives environmental benefits such as shade in parking lots and improved air quality.

Because of the need for belowground stability in developed areas like parking lots and pedestrian areas, soils are typically compacted. This restricts water storage and movement within the soil leading to increased water runoff by overland flow. As such, stormwater retention/detention systems are built to attenuate stromwater runoff. In highly developed parts of town, parking lots and pedestrian areas are typically uninviting to people because of the lack of trees to provide shade for comfort. Trees that are planted in small parking lot islands or tree boxes typically do not grow well because of the lack of belowground volume needed for root growth.

Products have been developed, such as suspended pavement systems or structural soil, to provide needed soil volume for tree root growth while providing stability for impervious surfaces. However, they can be quite expensive, and smaller communities with limited budgets may not be able to afford them. A potential alternative to these products is to store runoff in gravel beds beneath paved surfaces and give tree roots access to that water resource.

Gravel is relatively inexpensive. By constructing parking lots, sidewalks, pedestrian plazas, etc. on gravel beds, we could achieve the stability needed for construction and allow for increased stormwater storage and movement similar to pre-development soils. Planting trees in smaller soil beds adjacent to these belowground gravel systems will allow roots to exploit the stored water (and nutrients) and could help return the environmental benefits that forest systems provide for less money than other engineered practices.

The purpose of this demonstration project is to investigate the feasibility of growing trees in parking lots where gravel is used as the base on which the structure is built. This method could allow municipalities to maximize stormwater storage below-ground and grow trees in highly developed parts of town thus reducing stormwater runoff, urban heat island effects, and ambient air pollution while increasing property values and general standard of living at a much reduced cost compared to currently available suspended pavement technologies.

Gravel Bed Stormwater Detention System Structure and Function Overview

For this demonstration project a 6’ x 6’ x 3’ mineral soil bed was surrounded by an 18’ x 18’ x 3’ gravel bed (Fig. 1) adjacent to an asphalt-paved parking lot into which stormwater runoff from the parking lot flowed. A 4” perforated PVC under-drain with an up-turned PVC elbow at the outfall was used to regulate the volume of water stored in the system and allow excess water to drain.

The mineral bed provided 108 ft^3 of soil volume and the gravel bed had 864 ft^3 of storage volume. Assuming that gravel allows for 40% volume storage capacity[1], this system can store approximately 486 ft^3 of water (3650 gallons).

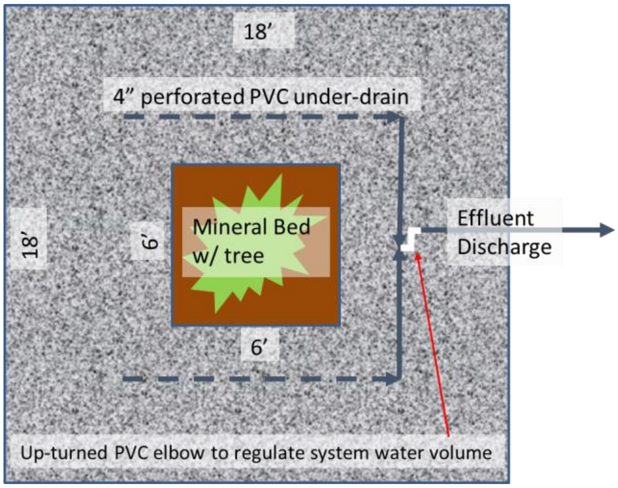

Figure 1 Gravel bed stormwater storage system diagram showing position of mineral soil bed within the gravel bed and the PVC underdrain location

Primarily, this system is a belowground stormwater detention structure that temporarily holds stormwater runoff from a large paved area. Water fills the large pore space between the rocks and is stored. Excess water is released from the system via an underdrain system to prevent extended periods of inundation and allows space for oxygen for tree root respiration and growth (Fig. 2). Although pore space is extremely large in the gravel layer, stored water in the system increases humidity deeper in the gravel profile giving roots adequate moisture for growth. Between rainfall events water level in the gravel system is slowly released by infiltration into the existing soil layer, conductance and evaporation through the mineral soil bed, and by transpiration of the tree(s) planted in the mineral bed.

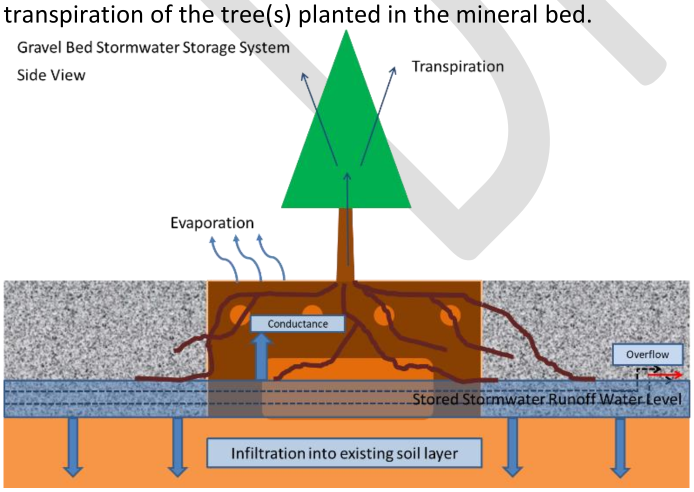

Figure 2 Stormwater stored in this system exits as overflow, infiltration, and evapotranspiration. Tree roots are able to explore the gravel layer for additional nutrients and moisture.

[1] http://www.deeproot.com/blog/blog-entries/the-pros-and-cons-of-using-aggregate-to-store-stormwater

Stormwater Catchment Area

The City of Knoxville was not willing to tear up a paved parking lot for this demonstration project, so the gravel bed system was placed on the downhill end of a city-maintained parking lot (Fig. 3). The total catchment area for this stormwater system was approximately 16,000 ft^2. It included 4,215 ft^2 of directly connected impervious area (DCIA) draining directly to the gravel bed. The remainder of the catchment consisted of permeable surfaces. The total catchment to gravel bed area ratio was 49:1. The ratio of DCIA to gravel bed was 13:1.

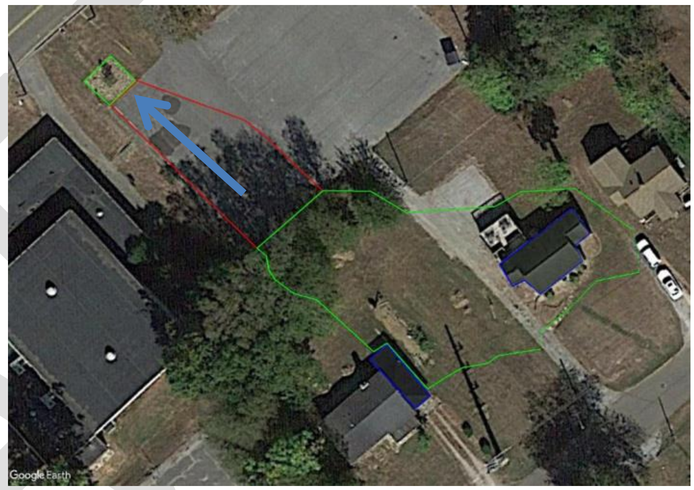

Figure 3 Gravel bed stormwater storage system located at the northwest corner of the parking lot. The system is adjacent to the paved parking lot to allow stormwater runoff (blue arrow) from the parking lot to drain into system.

Mineral Soil Bed Construction

A box constructed of untreated Oriented Strand Board (7/16” OSB sheathing) was used to keep the mineral soil separated from the gravel layer (Fig. 4). OSB was chosen as a temporary form because it is inexpensive and quickly decomposes when continually exposed to moisture. Holes were cut into the OSB to allow for tree roots to migrate from the mineral soil layer into the gravel layer. Five 3” circular holes were cut every 12” on center at 9” below the top of the form. A larger 18” x 36” hole was centered and cut from the bottom of the OSB sheathing to allow for root migration deeper in the soil/gravel profile. The form was joined at the corners by driving 1.25” wood screws into a 3’ section of untreated 2x4. The mineral bed form was covered with an 8 ounce, non-woven geotextile fabric to provide continued separation of soil and gravel after the OSB form disintegrated (Fig. 5). Because it was not certain that roots could penetrate the geotextile, slits were cut into the fabric at each hole in the form. Non-woven geotextile fabric was also placed at the bottom of the form to prevent erosion of mineral soil from the mineral bed into the gravel layer below the form. Originally, soil excavated from the gravel bed was to be used in the mineral bed form, however, because the quality of the existing soil was suspect, a higher quality top soil from another site was used for the mineral bed.

Figure 4 A wooden form constructed of 7/16" Oriented Strand Board (OSB) was used to keep the mineral soil separate from the gravel layer.

Figure 5 Mineral soil bed form was covered with an 8 ounce non-woven geotextile fabric to provide additional separation support of mineral soil and gravel after the OSB form disintegrates. Slits were cut into the fabric to allow roots to migrate from the mineral soil into the gravel layer.

Gravel Bed Construction

An 18' x 18' hole was excavated to a depth of approximately three feet adjacent to the low end of the parking lot, and a 4" PVC drain line was installed into the side of the bed closest to the street to allow excess stormwater to exit the system (Fig. 6). The bed was lined with a non-woven geotextile fabric to help keep the sides of the existing mineral soil from eroding into the gravel bed. Four layers of 6 mil vapor barrier lined the gravel bed to help prevent stormwater runoff from infiltrating into the surrounding soil. For this project, we wanted to quantify the evapotranspiration properties of the tree/mineral soil in the system, and thus needed to eliminate the infiltration effects of the stored stormwater into the surrounding soil. If infiltration into the surrounding soil is desired, then do not line the gravel bed.

Because the excavated hole was slightly deeper than needed, several inches of #57 sandstone gravel was placed in the bottom of the pit and leveled so that the mineral bed form would be at the proper depth for adequate stormwater drainage at the outfall. After placing the mineral bed form in the center of the pit, gravel was loaded around the form. A perforated, PVC under-drain with a 10" upturned elbow was also installed in the gravel bed around the mineral bed form. See Under-drain Construction section below for more details. To prevent the mineral bed form from being crushed by the weight of the gravel around it, we filled the gravel bed to half the height of the form, and then filled the mineral bed form with soil before finishing filling the gravel bed.

Figure 6 18'x18'x3' excavated pit next to parking lot lined with non-woven geotextile fabric. A 4" PVC drain line was installed to allow excess stormwater to drain from the system.

Gravel Material

Forty-six tons (approximately 33 cubic yards) of ¾" crushed, quartzitic sandstone was used to fill the gravel bed. The larger stone provides larger macropores to store more stormwater, and will not adversely affect tree root exploration within the system. Larger river rock on the upper 4 inches of the gravel bed was used to keep vehicles from parking on the bedding area, however, if prepared properly, this system could be parked upon without damaging its functionality. Caution should be taken when choosing gravel material so as not to change the pH of the water stored in the system. This could have an adverse effect to tree growth and health. Do not use limestone or any other material that could raise or lower the belowground pH.

Under-drain Construction

To prevent inundation of the tree roots in the system, a 4" perforated PVC under-drain was placed in the gravel bed to allow for excess stormwater to exit the system (Fig. 7). An upturned elbow was installed at the outfall at a depth to allow the system to store approximately 18" of water. The elbow was connected to the previously installed drain line mentioned in the Gravel Bed Construction section. A filter fabric encased the perforated PVC to help prevent fines from accumulating in the pipe.

Figure 7 Under-drain constructed of 4" perforated PVC pipes, wrapped with black filter fabric, and connected to the previously installed drain line. An upturned elbow was used to regulate the amount of stored water in the system. The angled, white PVC pipes were not part of the drainage system.

Monitoring Equipment

To monitor the volume of water being stored in the system a pressure transducer (HOBO Onset Water Level Logger) was placed in a 4”, perforated PVC well set in the Northwest corner of the gravel bed. This was the lowest point in the gravel system. The well was encased by filter fabric to prevent fine particles from entering the well. The pressure transducer recorded water pressure every minute and stored the data until downloaded bi-monthly. A V notched weir box was also installed outside the system at the outfall. A pressure transducer was placed in the weir box to record stormwater effluent discharge every minute from the system. Rainfall data were collected every minute at the gravel bed site using a tipping-bucket rain gauge.

A 2” caliper baldcypress tree was planted in the mineral soil bed of the system and one was planted in the lawn next to the gravel bed to compare growth rates. Clear, plastic mini-rhizotron tubes were installed to observe root growth in the mineral bed and in the gravel profile. Four clear, plastic tubes were placed at various locations around the mineral soil bed (Fig. 8); two completely in the mineral bed and two in the interface between the mineral and gravel layer.

Figure 8 Location of monitoring equipment (left) and finished project (right). Perforated PVC gravel bed monitoring well (1); mini-rhizotrons in the mineral bed (2); mini-rhizotrons in the mineral/gravel interface (3).

Material Costs

The cost of this system was relatively inexpensive for the area covered. The major expense was the gravel (Table 1). Labor and equipment costs were not considered because the project was installed using municipal employees and equipment. Monitoring equipment costs were included.

Table 1 Cost of gravel bed construction not including labor and equipment.

Mineral Soil Bed Form Materials			
Item Description	Unit Price	# Units Needed	Total
Oriented Strand Board Sheathing 7/16”	$8.65	4	$34.60
#2 Kiln-dried whitewood lumber 2x4 12’	$4.68	1	$4.68
#8 x 1.25” Wood screw – 110 count	$6.28	1 box	$6.28
3” Bi-metal arbored hole saw	$19.98	1	$19.98
8 oz. Non-woven geotextile fabric (15 ft. wide)	$2.35	6 ft	$14.10
Under-Drain System Materials			
Perforated PVC Sewer Drain Pipe – 4” x 10’	$8.65	4	$34.60
Solid PVC Sewer Drain Pipe – 4” x 10’	$8.65	4	$34.60
PVC Cap Fitting – 4”	$1.98	2	$3.96
PVC Sewer Drain Elbow 90 degrees – 4”	$3.45	2	$6.90
PVC Sewer Drain Street Elbow 90 degrees – 4”	$5.38	2	$10.76
PVC Sewer Drain Sanitary Tee – 4”	$5.98	1	$5.98
PVC Cement and Primer	$8.48	1	$8.48
Drain Sleeve – 4” 100 feet	$21.98	1 box	$21.98
6 mil clear plastic sheeting – 20’ x 100’	$98.00	1 box	$98.00
Gravel			
Quartzitic Sandstone – 0.75” Crushed Stone	$30.00	46 Yd^3	$1380.00
Trees			
15# baldcypress	$90.00	2	$180.00
Monitoring Equipment			
HOBO Water Level Data Logger (0-13 ft.) – Part# U20L-04	$299.00	3	$597.00
Weir box (built to fit site)	$450.00	1	$450.00
TOTAL			**$2861.90**

Observed Results

Hydrology

Rainfall and hydrology data were collected from 21 storm events in 2016 and early 2017. Rainfall totals ranged from 0.1 to 1.23 inches with an average depth of 0.45 inches. The gravel bed system was shown to generally retain stormwater runoff for rainfall less than 0.75 inches with few exceptions (Fig. 9).

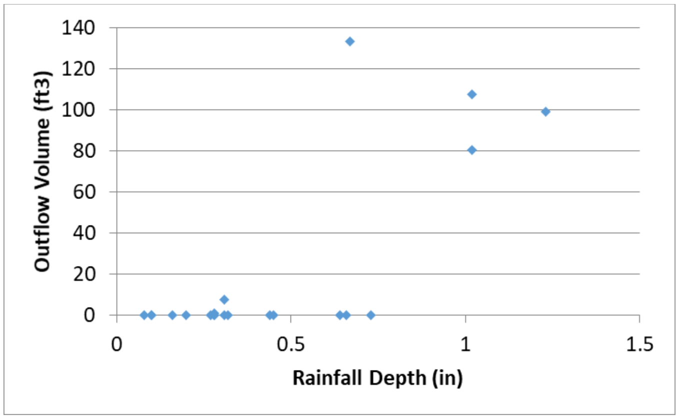

Figure 9 Gravel bed effluent discharge volume by rainfall depth. Significant discharge volume was generally not evident until the rainfall depth exceeded about 0.75 inches.

The gravel bed captured 100% of the runoff in 15 of the 21 recorded storm events, mostly from storms less than 0.75 inches (Fig. 10). The average capture percentage of the six storms having effluent discharge was 68%.

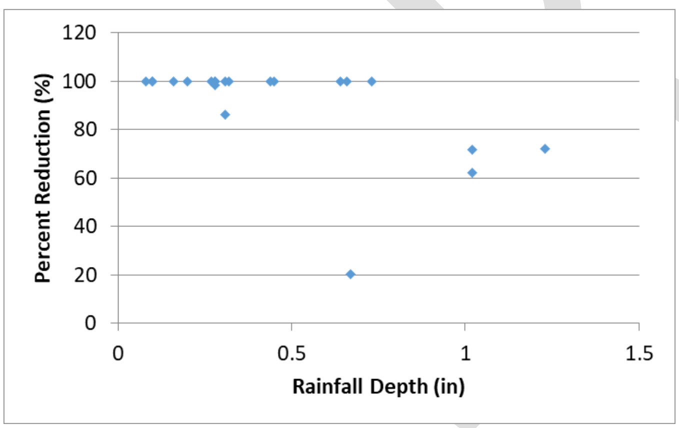

Figure 10 Capture rate of the gravel bed system from 21 recorded storm events.

From the monitoring data in the gravel bed and the weir box, water levels seemed to rise soon after rainfall began and water flowed from the parking lot into the gravel system indicating that the system functioned as expected (Fig. 11).

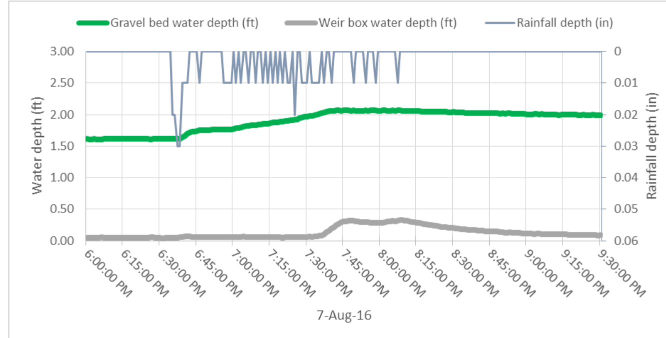

Figure 11 Gravel bed stormwater detention system functionality during a relatively light, steady rainfall event. As rain begins to fall water depth in the gravel system rises. Eventually, excess water from the gravel bed is discharged as observed by the weir box water depth.

For larger storms stormwater runoff was shown to be detained and delayed (Fig. 12), however, this delay may be dependent on the water level in the gravel system at the time of rainfall. For example, on July 26, 2016 a 1.22 inch rain fell on the parking lot and gravel system. The rainfall began at 7:52 p.m. and effluent discharge from the system was observed at 8:26 p.m., some 34 minutes later. For this rain event over 72% of the stormwater runoff was retained. Of the estimated 3200 gallons of rain falling on the parking lot, 741 gallons were recorded as discharge out of the gravel system.

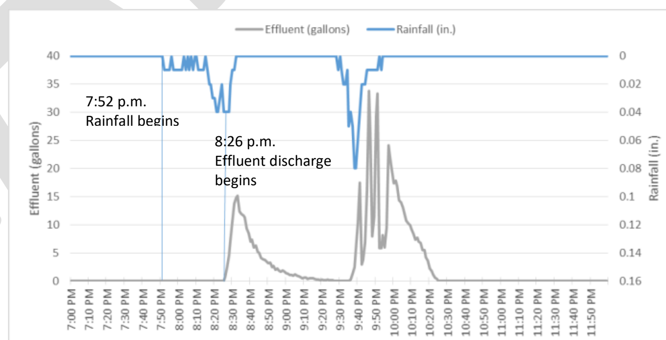

Figure 12 Rainfall (in inches) and stormwater effluent (in gallons) from the gravel retention system. For this rain event, effluent from the gravel system was observed approximately 30 minutes after the initial rain began to fall.

Data collected from this demonstration project showed that gravel-based stormwater detention systems have the potential for reducing runoff volume especially if the size of the underdrain system is adjusted such that the gravel bed is able to maximize its water holding capacity during a storm and release the stored water slowly. We used a four inch perforated PVC underdrain for this project, but perhaps using a smaller diameter pipe would reduce effluent volume and extend the flow over a greater period of time. Effluent discharge volume from this system was dependent on the stored water level at the beginning of a storm. Our system was lined thus inhibiting exfiltration into the surrounding soil profile. Allowing the stored water to infiltrate into surrounding soil would help to increase volume capacity between storm events.

Tree Growth

Two, 2" caliper baldcypress trees were planted in April 2016; one inside the gravel system and one outside the system. The tree planted in the lawn outside the gravel bed was planted downhill of the system but was not given supplemental water after being planted. The tree did not survive the hot, dry summer and was dead by September 2016. The tree planted in the gravel system also was not given supplemental water but used the stored runoff in the gravel bed, and it survived. In May 2018, caliper diameter was 5.5" and in June 2019 it was 8.7". After three and a half growing seasons the tree in the gravel bed had increased diameter by 6.7". The crown spread by 2019 was 16', and the dripline was nearing the extent of the gravel bed (Fig. 13).

Figure 13 Baldcypress tree growing in gravel bed stormwater retention system from 2016 to 2019

Large, healthy trees need abundant, healthy roots. Root growth was observed in September 2016 and again in May 2018 using a lighted periscope with a camera inserted into the mini-rhizotron tubes. Toward the end of the 2016 growing season abundant root growth was observed in both the mineral soil bed and in the gravel profile (Fig. 14). Again in 2018, roots were evident in the gravel layer of the system. It was not possible to quantify the number of roots growing in the gravel profile of the system, but visual observations showed that roots were growing in the highly porous gravel layer.

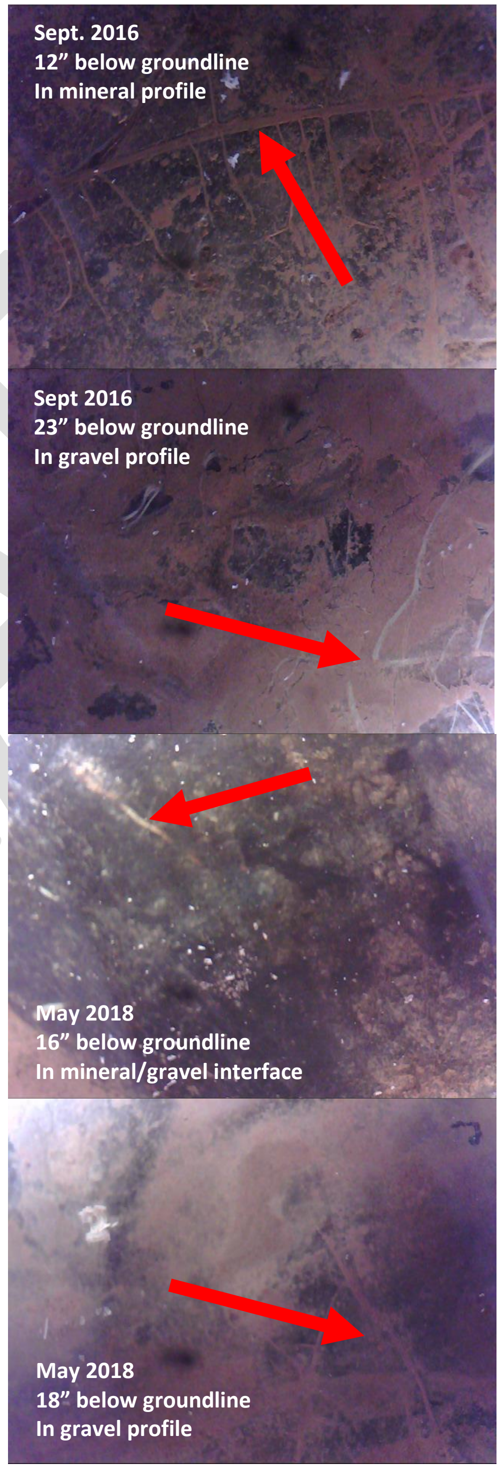

Figure 14 Root growth observed from mini-rhizotrons in mineral and gravel profile.

The abundant stem growth of the tree in the gravel bed system and the observation of root growth in the gravel profile is encouraging and indicate that this type of system may be feasible in ultra-urban areas to sustain tree growth. Using non-engineered top soil in the mineral soil bed did not seem to impede above-ground growth for the tree in this project. Jim Urban and DeepRoot recommend a minimum soil volume for urban trees[2]. Although this project has only four growing seasons of growth data, canopy diameter for this tree exceeds the projected mature tree size for the soil volume provided (108 ft^3). It is suspected that trees in this gravel-based system may not reach their potential mature size, but smaller trees in ultra-urban areas provide more benefits than no trees at all.

A complimentary greenhouse demonstration project using trees growing in perforated, mineral soil columns surrounded by gravel was conducted in 2019 to quantify root growth in the gravel profile over a growing season[3]. The trees showed abundant root growth into the gravel layer. This gravel system may provide a path for root growth to an area of higher mineral soil volume if available near the practice. Giving roots access to mineral soil could help trees in this practice reach their full growth potential.

Potential Uses

This type of system may be useful in large parking lots with gravel parking bays surrounding narrow mineral soil beds instead of raised planting islands to provide greater belowground volume for root growth (Fig. 15). Sidewalks and pedestrian plazas under which water could be stored would also be a good use for this system. Planting trees in long, narrow mineral beds surrounded by gravel provides shared mineral soil to maximize canopy growth.

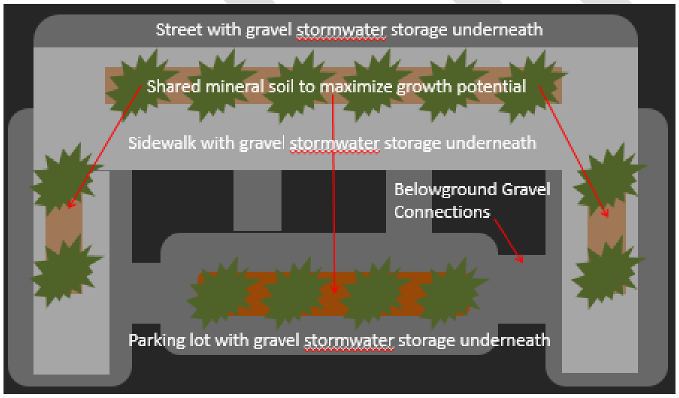

Figure 15 Potential uses of a gravel-based stormwater detention system

Conclusion

Typically in smaller communities parking lots take priority over tree canopy cover. Reduced tree canopy cover increases stormwater runoff and may not be very attractive to visitors. Providing adequate soil volume for tree growth can be expensive in highly impervious areas. The purpose of this demonstration project was to show the potential of an inexpensive, gravel-based stormwater detention system to store water for use by trees in ultra-urban areas without sacrificing needed parking space. This Green Stormwater Infrastructure system can maximize water-storage capacity by using gravel, which has greater pore space than soil (compacted or non-compacted), while providing increased belowground rooting volume for trees. Storing water in this way allows for greater infiltration into the existing soil layer helping to improve water quality downstream and has the potential for creating a more natural hydrologic runoff pattern in extra-urban areas.

Larger trees have greater leaf area which drives environmental services (i.e. energy conservation, reduced urban heat island, air pollution removal, stormwater runoff mitigation, etc.). Trees need an adequate volume of mineral soil to reach their full growth potential. Tree roots grow where there is water, oxygen, and nutrients. Stormwater runoff typically has essential nutrients in it for trees to utilize (i.e. N and P). It has yet to be determined how this gravel system impacts tree growth. Even if trees planted in this type of system are smaller than trees growing in a larger mineral soil bed, having some canopy cover is better than nothing to provide environmental benefits and attract potential visitors for the local economy.

Contributors

Jon Hathaway, PhD, PE
Department of Civil and Environmental Engineering, University of Tennessee, Knoxville, TN

Jennifer Franklin, PhD, Plant Physiologist, Department of Forestry, Wildlife and Fisheries, University of Tennessee, Knoxville, TN

Andrew Tirpak, PhD, Postdoctoral Researcher, Department of Food, Agriculture and Biological Engineering, Ohio State University, Columbus, OH

Kasey Krouse, Urban Forester, City of Knoxville, TN

[2] https://www.deeproot.com/blog/blog-entries/our-recommended-soil-volume-for-urban-trees

[3] https://www.urbanforestrysouth.org/resources/library/ttresources/gravel-bed-stormwater-retention-system-greenhouse-demonstration-project/at_download/file