PAPER 4

A new look on attenuating stormwater runoff…

Do we really need to store all this water?

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ABSTRACT

Attenuation facilities have been the popular solution for redirecting stormwater runoff for many years. Stormwater, which would originally infiltrate into the natural ground, would need to be accounted for when hardened surfaces are increased during development within the catchment area. The development industry generally alleviates this issue using attenuation tanks. These can vary in size but usually take up a lot of space.

Infiltration rates can become extremely important in reducing the amount of water to be attenuated. Depending on the soil type underneath the surface, infiltration rates of that particular soil can become very useful when determining how much storage is actually required; for instance areas behind a primary dune near the coast. By combining the design of a soakaway and an attenuation tank, we can utilize the "soaking away" nature of the underground soil, and use the attenuation tank to provide adequate hydraulic head to sufficiently drive the water into the tanks surrounding soil.

A typical example of using this analysis can be seen in using attenuation crates, which allows for both infiltration and attenuation. By using similar systems such as these, we can reduce the need for such extensive attenuation tanks and redirect the surface flow into an area where it would have gone before development had occurred, the natural ground. This takes into account land usage, providing a solution for where there is inadequate space for attenuation tanks and will change the way we tackle stormwater issues as a whole. These systems can also be used underneath traffic areas, which allows development above the system as opposed to the general soakaway which undermines the stability of its surrounding soil.

Infiltration tests were done to determine the permeability rate of beach sand located in Forest Drive, La Lucia. The results of these tests allowed for the reduction of more than 80% of the attenuation volume required in that specific catchment. This allowed for the replenishment of groundwater reserves in the area as well as the prevention of flooding from the backflow of a seasonally blocked stormwater outfall located on the adjacent beach.

INTRODUCTION

The consequences of rapid urbanisation, such as an increase in impermeable surface areas, has resulted in many problems of flooding over the years (Andoh et al., 1997). This also causes groundwater depletion and threatens natural water resources. Alternative drainage strategies that mimic the way nature slows down runoff (attenuation) can be implemented to provide sustainable drainage schemes (Andoh et al., 1997). Conventional methods such as piping systems generally seem more cost-effective and convenient than sustainable urban drainage systems (SUDS). However, by using soil characteristics to our advantage, we can drastically reduce the costs associated with these schemes.

Before urbanisation, water naturally infiltrated into the ground. Rain travelled into the soil and rejuvenated groundwater supplies or it eventually ran into rivers, lakes and ultimately the coast as shown in Figure 1 (Epa.sa.gov.au, 2019).

Urban development reduces the permeability of the surface of the land and instead replaces the natural ground with impermeable surfaces such as roofs and roads. This increases the surface runoff and reduces the recharge of groundwater (Epa.sa.gov.au, 2019).

Attenuating further upstream can reduce the velocity of water running through this process in an urbanised environment. However, attenuation is expensive and requires a lot of land usage. Another conventional method is a soakaway, however, this restricts land usage above the installation of this application. Soakaways may undermine the soil around them preventing the land above to be built on or used. Both soakaways and attenuation

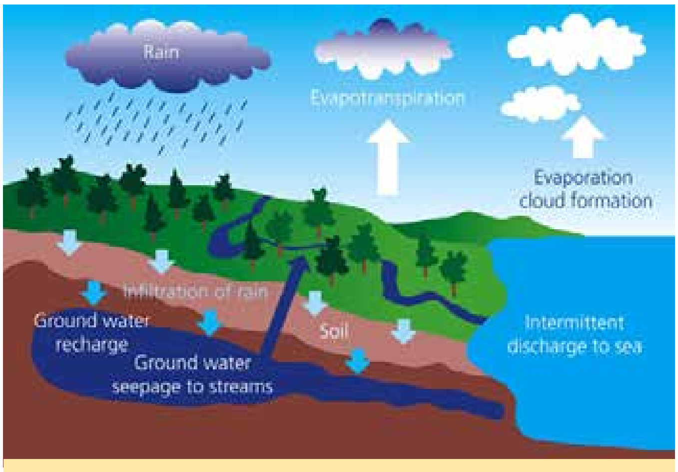

FIGURE 1: Natural water cycle at coast (Epa.sa.gov.au, 2019)

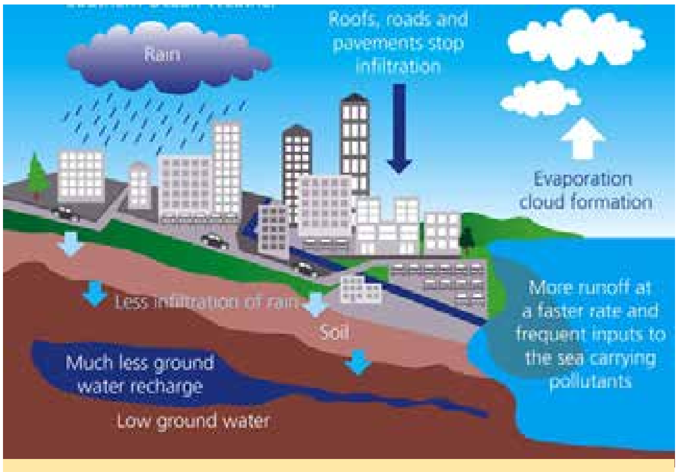

FIGURE 2: Urbanisation water cycle at coast (Epa.sa.gov.au, 2019)

FIGURE 3A: Typical example of an Attenuation Crate (Water Management Solutions: Modular Cell Systems, 2011)

FIGURE 3B: Attenuation crate underneath road with a traffic load (Water Management Solutions: Modular Cell Systems, 2011)

tanks have land usage implications and this is not ideal in an urban environment. Therefore maximising an area for both land use and stormwater management is crucial in a developed city.

Attenuation crates need to be designed to minimize flood risks. The crates can retain large volumes of water and fit together to create an underground tank. The tank can be used for attenuation, soakaways or even both. These particular cells have a 95% void ratio (figure 3a) and can be built according to the void volume required to store run-off volumes (Water Management Solutions: Modular Cell Systems, 2011).

Structurally capable of withstanding vertical loads in excess of 200 kN/ m^2, it is easy to handle and install and is light-weight (figure 3b). The cells come in different ranges which can cater for non-trafficked, trafficked or heavy trafficked areas. The material of the cells is made up of 100% recycled material (Water Management Solutions: Modular Cell Systems, 2011).

Using this system in conjunction with stormwater pipes can reduce the required capacity of stormwater outfalls that extend into the ocean.

Determining the number of cells required by a particular area, will not solely be established by the volume of water to be stored when using this system, but also by its surrounding soil characteristics. Infiltration takes into account the type of soil in contact with the cell, as well as the number of faces of the cell that can infiltrate water into the soil. An increased surface area that can allow infiltration, increases the overall infiltration of that cell.

BACKGROUND

Forest Drive, La Lucia has been an area of concern for the past 20 years. The test area is positioned behind a primary dune in the catchments low point, where water would naturally collect and seep into the ground and travel underneath the surface into the ocean. Due to development in this region, this natural process was replaced by stormwater pipes and an outfall into the ocean. Although the test area is situated in a small catchment (0.0326 km^2) residents have continuously been affected by flooding. Anecdotal accounts of the October 2017 floods describe water levels reaching 1.5 m above ground level, floating cars and flooding businesses.

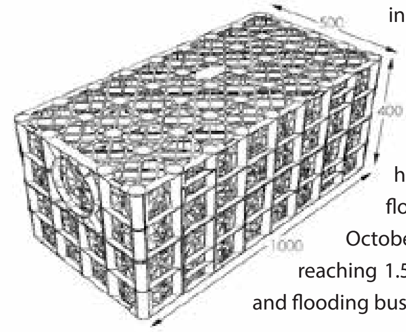

FIGURE 4: Dimensions of Attenuation Crate Used (Water Management Solutions: Modular Cell Systems, 2011)

The stormwater network drains directly to a coastal stormwater outfall that is situated at the adjacent beach. The outfall gets blocked due to fluctuating beach sand levels and extension of the outfall is not economically viable. This prompted the Municipality to investigate alternative solutions.

The soil was examined visually and represented slightly finer particles similar to that of beach sand. This meant that the soil characteristics potentially favoured high infiltration capabilities. It was also identified by our Geotechnical team that the water table was greater than 2 m below ground level, and no shallow bedrock was found.

These factors bolstered the potential application of the attenuation crate system, but required further investigation.

METHODOLOGY

We need to ascertain whether the attenuation crate system could provide the required infiltration and attenuation combination we needed to estimate the infiltration potential of the in-situ soils. There are many ways to determine the infiltration capacity of a specific soil. Laboratory tests may not depict true field conditions, but for this particular design, it was adequate to determine a conservative result. Southeast Michigan Council of Governments (SEMCOG) (2009) provide the following guidelines for the testing of soil infiltration:

1. Infiltration tests should not be conducted in the rain or after a major storm event.
2. On-site tests should be conducted at the same level as the proposed soakaway.
3. A minimum of two tests should be done to provide compaction of the soil which one would ordinarily see on site.

Our testing only took into account flow through the bottom of the soil and not horizontal or side flow; this will be calculated.

Laboratory Testing

Laboratory tests were undertaken to determine the flow of water through a sample of soil in one direction only; through the soil out of the base of the infiltration structure. The sample of the soil was taken from between 1.5 m to 2 m below the surface in the proposed position of the attenuation facility.

Equipment:

- 1 m high, 150 mm diameter clear Perspex cylindrical tube with both ends open
- 2 pieces of geofabric to cover open ends of the cylinder (A2 geofabric at 150 ℓ/s/m^2 @ 50mm head and 9.5 kN/m tensile strength)
- Sample of soil from the focus area
- Marker
- Measuring tape
- Water supply
- Timer/ Stopwatch
- 1 clamp
- Cable ties
- 2 buckets

Procedure:

- Place cylinder vertically and use a clamp to secure the cylinder above the ground.
- Use a marker to demarcate every 50 mm height on the cylinder.
- Wrap a sheet of geofabric around the bottom of the tube and secure well using cable ties.
- Take soil from a sample that was removed prior to the test from the area of concern.

- Place a layer of 100mm of soil into the tube, with the geofabric holding up the soil.
- Place another piece of geofabric on top of the soil to prevent disturbances from the force of water.
- Fill one bucket with sufficient water to pour into the cylinder and leave the other bucket underneath the cylinder for water to fall into.
- Pour water as quickly as possible into the cylinder
- Wait for the water to settle and reach a steady level of head and then start recording time
- Measure the time taken to drop in water level for each 50mm of head and record results
- Repeat experiment 2 more times

On-site Testing

Using most of the equipment listed above, a similar test was undertaken at the test area. A test pit was excavated to the invert level of the proposed infiltration structure. The Perspex tube was again used to conduct the test on site. No soil was placed into the tube and a sheet of geofabric was placed between the bottom of the cylinder and the soil. The drop in water level for different increments of head was recorded similar to that of the laboratory test.

Flow Analysis and Infiltration

Storage (m^3):

The storage for a single row of cells was calculated for the different head increments. Each level of head has a different storage volume according to the capacity of the cell. The total storage for a row of cells at 0.4m head (height of the cell) is 7.6m^3.

Once the maximum capacity of the cells is reached, storage may also occur within the connecting manholes. Therefore, the storage in the manholes on either side of the cells was calculated for head above 0.4m up to a head of 0.75 m (Maximum height of manhole from invert of cells). The dimensions of the manhole (1.5m by 1.5m) were used to determine volumes of storage for increments of head past the height of the cell. This was then added as additional storage from 0.4m and above.

Hydraulic Head (h):

It is unrealistic that the maximum head of an experiment will ever be achieved. Therefore, the average head between two increments is the commonly used head for hydraulic calculation purposes. Therefore to calculate the infiltration rate for the cells, a median head value was used for each increment.

Infiltration Rates (IR):

The infiltration rate is the outflow rate of water into the soil per square metre of area. Soil characteristics play a vital role in the permeability of the soil. Permeability is defined as the ability to allow liquids or gases to pass through the soil. The following equation was used to calculate the infiltration rate for each experiment for each increment of head:

(1)

$$IR = \frac{\Delta H \text{ x } A}{T} \div A$$

Where: IR = Infiltration Rate for a specific level of head (m³/s per m²)
ΔH = Increment of head (m)
A = Area of the bottom of the cylinder (m²)
T = Time at head (s)

The average infiltration rate of all three experiments was then calculated for each interval of head.

Base (Vertical) Flow:

Using the average infiltration rates calculated above, the base flow was determined by multiplying the area of the cells and the infiltration rate for each increment.

(2)

$$BF = IR \times L \times W$$

Where: BF = Base Flow (m³/s)
L = Length of row
W = Width of cell

This provided the infiltration rate in the vertical direction of the cells only.

Horizontal (Side) Flow:

In reality, the flow of water does not occur in one direction only. Therefore, the horizontal or side infiltration will need to be determined to provide an accurate representation of real-life scenarios.

When calculating horizontal infiltration, it is important to determine the surface area that the water can contact the soil around the cells. Horizontal infiltration for each increment of head is calculated as follows:

(3)

$$HF = IR \times P \times \Delta H$$

Where: P = Perimeter of one row that allows for infiltration (m)

To determine the total infiltration rate of horizontal flow, the accumulative horizontal infiltration rate must be calculated for every increment of head up to the maximum level of head for that specific instance. Accumulative horizontal flow is calculated as follows:

(4)

$$CHF_h = \sum_{k=0}^{h} HF_k \qquad \text{For } k = 0, 0.05, 0.01 \ldots h$$

Where: CHF$_h$ = Cumulative Horizontal Flow for a specific head (h)
HF$_k$ = Horizontal Flow for a specific level of head "k"
k = index of increments.

This result gives us the horizontal infiltration from all sides of the cell for the total level of head for a specific instance. The infiltration for horizontal flow was calculated in increments as the increase in head allows for different infiltration rates for that increment i.e.: a drop in head from 400mm to 300mm will have a higher infiltration rate for a drop in head for 100mm to 0 mm; even though it is the same amount of water loss. Therefore it is crucial to determine infiltration rates in segments as opposed to calculating one final value for one specific level of head.

Total Flow for 1 row of Attenuation crates:

To get the total infiltration rate in all directions, both the base flow and the accumulative horizontal flow must be added together.

(5)

$$\text{Total Flow} = \text{BF} + \text{CHF}_h \text{ for every increment of } h$$

The total infiltration rate will provide a conservative figure for the possible flow of water through the soil for both directions for every increment of head. We can then analyse the flow of water coming into the infiltration chamber versus the amount of water flowing out into the surrounding soil.

Reservoir Routing Analysis:

If we treat the attenuation crate system as a reservoir, we can analyse an

TABLE 1: Time required for a drop in head measured at 50 mm intervals and accumulative time taken for each laboratory test

Head (mm)	Test 1		Test 2		Test 3		Average Acc Time (s)
	Interval (s)	Acc (s)	Interval (s)	Acc (s)	Interval (s)	Acc (s)	
400	0	0	0	0	0	0	0
350	13	13	14	14	21	21	16
300	16	29	16	30	24.	45	35
250	17	46	19	49	28	73	56
200	22	68	26	75	37	110	84
150	29	97.00	31	106	50	160	121
100	32	129	36	142	63	223	165
50	35	164	41	183	76	299	215
0	38	202	46	229	89	388	273

inflow versus outflow hydrograph by means of flood routing. Usually, the outflow rate is never as large as the peak flow rate as much of the flow is temporarily stored in the reservoir (Roberson et al, 1998). However, by analysing these hydrographs we can determine exactly how many rows of the attenuation crate system is required to match the inflow graph with the soils infiltration rates as well as the storage available in the cells.

For uncontrolled reservoirs (where gates do not control the outflow) both storage (S) and outflow (O) are a function of water surface elevation in the reservoir (Roberson et al, 1998). In this instance, O is our infiltration of stormwater into the soil and S is the storage within the attenuation crates.

Using the Rational Method we can determine an inflow hydrograph by calculating the peak surface runoff for the catchment area.

Rational Method: (6)

$$Q = \frac{CIA}{360}$$

Where: Q = maximum rate of runoff (m^3/s)
C = run-off coefficient
I = rainfall intensity (mm/hr)
A = area of catchment (ha)

The system should be designed for a 1 in 10 year period storm (as per municipal guidelines), so the rainfall intensity should be derived accordingly. The minimum value for the time of concentration (T_c) should be 15 minutes. (Please see Ethekwini Design Manual for guidelines on how to proceed with calculations) (eThekwini Municipality, 2008).

Once the inflow, outflow, storage and time step parameters are determined, we can then proceed with reservoir routing. After reservoir routing is done, we then have both the inflow and outflow from the proposed reservoir scenario.

RESULTS

Having conducted both the on-site and laboratory testing we were now able to start interrogating the information gathered. Table 1 presents the time intervals taken for every 50mm drop in water level. This was easily seen due to the clear Perspex cylinder and no obstacles around the tube.

The first two tests on site were done similar to the tests in Table 1: Time required for a drop in head measured at 50 mm intervals and accumulative time taken for each laboratory test. Although the same clear Perspex cylinder was used for the in-situ test, it was difficult to see the markings for every 50mm as was observed in the laboratory. The surrounding soil of the test pit prevented clear views of the demarcated levels. The water infiltrated at such high rates that it was difficult to observe different time intervals for different levels of head.

Therefore, the total time taken for a known volume of water was used to calculate the results for tests 3 and 4 seen in Table 2. The equation for the volume of a cylinder was used to calculate the maximum head reached for these two tests after a recorded time and volume was established.

TABLE 2: Accumulated time for a drop in head measured on-site

Test No.	Head (mm)	Acc Time (s)
1	100	23
2	300	64
3	566	97
4	566	115

DISCUSSION

In-situ Test 1: For a drop in water level of 100 mm, it took a total time of 23 seconds. The same loss of head in the laboratory took an average of 35 seconds (From 400mm to 300mm).

In-situ Test 2: For a drop in water level of 300mm, it took a total time of 64 seconds. The same loss of head in the laboratory took an average of 215 seconds (From 400mm to 50mm).

In-situ Test 3 and 4: Interpolating the results for the laboratory tests for 550mm head gave an accumulative time of 211 seconds and for a 600mm head gave a total time of 295 seconds. Both these values are greater than the accumulative times seen in test 3 and 4 on site.

It is evident that the in-situ results showed higher infiltration capabilities than the laboratory results as it took longer in the laboratory test for the same levels of water to drop. Therefore, the average observed results for the laboratory tests were used to determine the infiltration rates for the proposed design. This will provide a conservative design, allowing for any errors during testing for both instances.

Several calculations were done from the laboratory results mentioned above. The calculations were based on a single row of attenuation crates with a length of 40m (40 cells). This utilized the entire length of the car park area as well as allowed for maximum use of the surface area of the cells (as opposed to placing cells next to each other in a square layout).

As depicted in Figure 5: Infiltration Rates (m3/s) vs Head (m) for one row of Attenuation Crates at Forest Drive, La Lucia, an increase in head shows an increase in infiltration. Due to the characteristics of the soil found on site, as well as the high infiltration results, the outflow of water into the soil is quite high. This means that infiltration will vastly decrease the amount of attenuation required. Reservoir Routing will be used to analyse inflow versus outflow.

The respective hydrographs can be seen in figure 6. It can be identified that the outflow is just as great as the inflow, resulting in an overlap of the graphs. This suggests that the storage provided by the attenuation crates is sufficient when used in conjunction with this specific soil type.

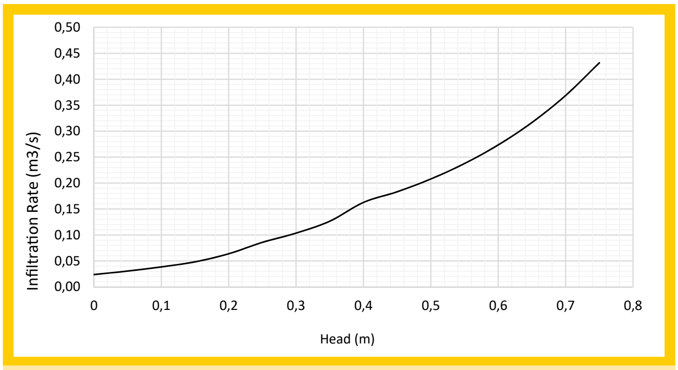

FIGURE 5: Infiltration Rates (m^3/s) vs Head (m) for one row of Attenuation Crates at Forest Drive, La Lucia

The inflow graph (red) was based on a 1:2 ratio from T_c to T_{max} as this was a small catchment area.

Both hydrographs reached a peak flow of $0.4m^3/s$. This suggests that at T_c, the inflow rate was equal to the outflow rate. This suggests that minimal storage is required, which is provided by the cells.

Working backwards using the outflow values from the routing above, we can calculate the hydraulic head reached in the reservoir. Steps were repeated for 3 rows of cells. The head reached for 1 row of attenuation crates is the same height as the cover of the connecting manhole. The head reached using 3 rows of crates is just below the height of the infiltration chamber.

CONCLUSIONS:

Figure 6 suggests that the outflow rate (infiltration into the soil) as well as the small storage capacity of only 1 row of attenuation crates, is sufficient in dealing with the inflow rate of the surface runoff. For 1 row of cells of 40m length, the maximum head of the reservoir can reach the same level as the surface of the ground (Figure 7). Although this is still acceptable, as the water would only accumulate within the manhole, if we wanted to avoid this we would simply need to increase the number of rows installed (See Figure 7: Head for 3 rows). The rows will have to be more than half a meter away from each other, to ensure maximum infiltration through the sides of the system. Rows will have to be the same size and length and level at the same depth to ensure that even dispersion of water occurs when flowing into the system.

The originally estimated attenuation for the same scenario without infiltration, assuming that only half of the runoff would be attenuated, was calculated at a volume of $120m^3$, which is approximately 632 attenuation crates (placed in a tank layout). Only 80 cells were used (2 rows), and this was an exaggerated design based on the maximum surface runoff, although 1 row would have sufficed. This reduced the size of the infiltration facility by over 85% from the original design.

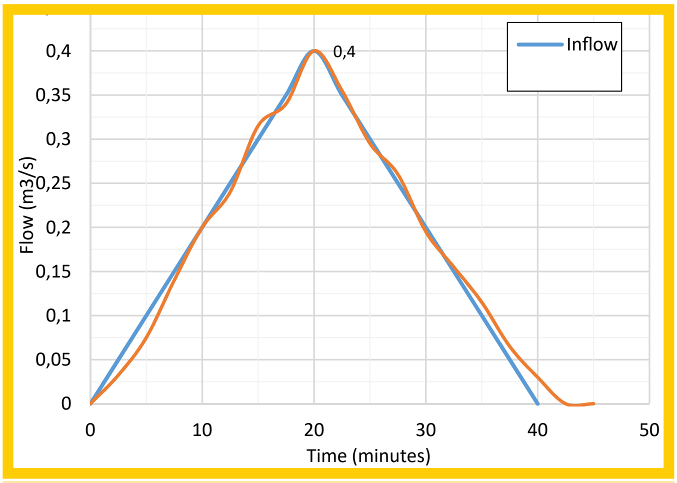

FIGURE 6: Flow vs. Time for an Attenuation Crate System for Forest Drive

RECOMMENDATIONS:

Further analyses into the flow patterns of water percolating into various soil sample need to be done. Different soils act differently. Coarse material, similar to beach sand, will infiltrate better than finer soil such as clay.

Application of this concept will need to be based on the specific location in question. Calculations need to be done according to the soil of the area to be designed. Detailed analyses of where the water table is, bedrock and other surrounding features need to be done before applying this technique.

This application is best used behind primary dunes (near the coast), as beach sand is highly permeable.

Further investigations should be done to replace stormwater outfalls, dispersing into the ocean, with attenuation crates to replenish groundwater supplies and mimic natural pre-historic processes before development occurred.

Siltation is a disadvantage of using this process. It is recommended to construct a siltation trap before the infiltration facility. Further investigations on maintenance of this system can be done.

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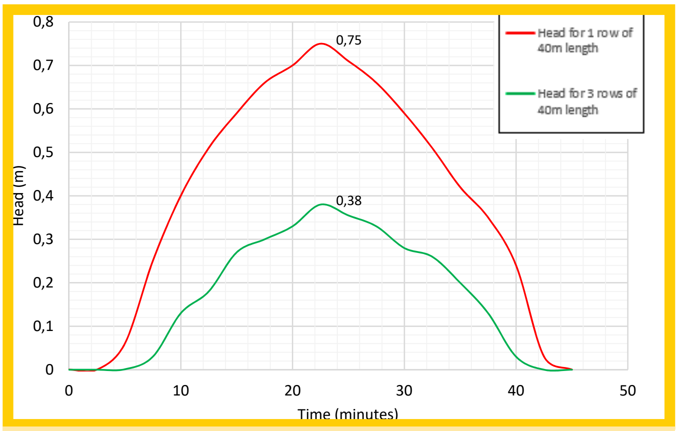

FIGURE 7: Head (m) Vs. Time (s) for an Attenuation Crate System for Forest Drive