METHODS TO REDUCE URBAN STORMWATER IMPACTS IN WATER BODIES QUALITY

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ABSTRACT

Despite the urban drainage systems in Portugal being mostly combined or mixed, a transition is starting towards separate drainage systems which can already be seen in the newest urban areas. While in combined systems the first-flush of an urban watershed would be treated by a WWTP, in a separate system, the polluted stormwater will discharge directly to streams or rivers and the urban watershed wash off may contain several contaminants harmful to the water bodies. This pollution consists mainly on total suspended solids, nutrients, bacteria, heavy metals and hydrocarbons. Many countries with separate drainage systems were taken into finding solutions to this stormwater problem. The main objectives of this dissertation are to warn about the lack of stormwater discharge legislation to the water bodies, disclose the management being made on these countries and set forth the main solutions adopted for stormwater management. Therefore, United States of America, New Zealand, Malaysia and United Kingdom legislations and best management practices on the stormwater subject will be presented, as well as sizing procedures and efficiencies against the main pollutants of treatment systems displayed on those documents.

Keywords: Urban drainage, separate systems, Sustainable drainage systems, Water quality design storm.

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1. INTRODUCTION

One of the biggest current challenges faced are stormwater management, in terms of quantity preventing floods from rare events, as well as in terms of quality where the wash of urban catchments by frequent events carry loads of pollutants to the water bodies. In these pollutants we find total suspended solids, nutrients, heavy metals such as copper, zinc and lead, bacteria, organic matter and hydrocarbons.

With the constant increase of watershed impermeabilization, the lack of infiltration which on pre-developed conditions would happen, will lead to an increase of stormwater plus the treat of climate change may cause the downstream stormwater drainage system to become undersized. The obvious solution would be to replace the undersized drainage system, although another solution may present itself.

According to Digman *et al*, 2012, countries like Sweden, Netherlands, United Kingdom and Australia have been investing in sustainable drainage systems to manage stormwater which also allows the stormwater to be treated prior to the discharge to the water bodies. Also, in the United States of America, studies have been made for cities like Philadelphia, Portland and New York as these cities pretended to invest in traditional pipe based below ground systems to reduce their combined system overflows. After the publish of these studies that solution was put aside as they embraced a new approach using sustainable drainage systems to reduce the intake of stormwater into their combined drainage systems (Foster *et al*, 2011).

2. LEGISLATION AND BEST MANAGEMENT PRACTICES

In Portugal the law states that the peak flow control needs to be compatible with the water bodies it drains to and can't be demanded peak flows lower than the predeveloped peak flows. Also, can't be demanded a lower volume of sediments than the volume carried on the predeveloped flows. Decreto Regulamentar n.º 23/95 also provides the sizing procedure of a retention basin to manage peak flows to the predeveloped conditions.

In terms of quality, the law states the pollutant concentration necessary to discharge to the water bodies for combined systems and the effluent quality necessary from Wastewater Treatment Plants (WWTP). Also, if the water body is listed as a sensitive water body, nutrient restrictions need to be applied (Decreto Lei n.º 152/97 e Decreto Lei n.º 236/98).

Although the law doesn't impose pollutant concentrations for stormwater discharges, which lead us to the combined values for discharges in water bodies. The only statement regarding stormwater comes from Lei n.º 58/2005, and it requires the treatment of stormwater in cases of diffuse pollution.

In the United States of America, the urban stormwater falls under the remit of National Pollutant Discharge Elimination System (NPDES) which provides the licenses that allow stormwater discharges to the water bodies. The process was divided into two steps, first in 1990 and the second in 1999 which still stands nowadays (EPA, 2010). This program under EPA requires the licensing for stormwater discharges for:

- Regulated Small MS4 (EPA, 2000);
- Construction sites above 4000m^2.

And, according to Clar *et al*, 2004, several states demand the treatment of the first flush in urban areas ranging from 12,7 to 25,4mm of precipitation.

In New Zealand, in accordance with the regulations provided by RMA, 1991, the district of Auckland created a stormwater management plan for their watersheds (ARC, 2012). This plans purpose is to regulate new impervious areas on two main subjects, peak flow control and total suspended solids concentration. In some cases, it requires the two- and ten-year event peak flow control to predeveloped values and the reduction of total suspended solids by 75% annually. In order to achieve a this last one, 80% of runoff volume of all storms should be captured and treated. From hydrologic analysis, it was concluded that retaining a third of the 24 hour 2-year rainfall would enable the necessary treatment to achieve the goal (ARC, 2003).

Woods Ballard *et al*, 2015, presents some good practices in stormwater management for the United Kingdom. For water quantity control, a good management should:

- Infiltrate all events up to 5 mm, to mimic the predeveloped response to these events;
- Storage the difference between pre and post developed volumes for the 6 hour 100-year event;
- Control the peak flow of the 1- to 2-year event to predeveloped values;
- Control the peak flow the 100-year event in, at least, 30%, comparing to the predeveloped value;
- The urban drainage system should not allow flooding, unless the area is designed to do so, up to the 30-year event;
- For flooding events, the drainage system should be evaluated so that minimum risks are taken on the flood management.

As water quality standards, a good management should:

- Infiltrate all events up to 5 mm, to mimic the predeveloped response to these events;
- Allow the treatment of frequent events (up to 15 minute 1-year event) following the Simple Index Approach;
- In cases of stormwater discharges to groundwater, a risk screening must be taken to determine whether the consultation of the environmental regulator is necessary.

Finally, and despite Malaysia being a developing country, a stormwater good practices manual was created, supported by Australian studies. As a tropical climate, Malaysia has a very high annual precipitation, compared to the other countries studied, with monsoons being a problem. The stormwater management approach relies on two superficial systems: a minor system which transports up to the 10-year event, and a major system which transports up to the 100-year event. Basically, the major system can be called a flood plain. Regarding the quality of the discharges to the water bodies, the events up to 3 months Average Recurrence Interval should be captured and treated (DID, 2000). According to The *et al*, 2015 and a study of the Australian precipitation it's safe to say that the 3 month ARI match the volume present by New Zealand (a third of the 24 hour 2-year rainfall). Regarding pollutants, they present different reduction objectives depending if we are talking about new impervious areas, urban rehabilitation or an upgrade to drainage system.

3. SUSTAINABLE DRAINAGE SYSTEMS

As pointed earlier, the stormwater treatment is a requirement for some countries. To achieve this treatment sustainable drainage system are now introduced. These systems tend to approximate the urban watershed to a predeveloped state in terms of peak flow and reduce pollutants acquired by washing the impervious areas. The solutions are as follows (ARC, 2003):

- Rainwater Harvesting;
- Green Roofs;
- Infiltration systems;
- Filter strips;
- Swales;
- Bioretention systems and sand filters;
- Pervious pavements;
- Ponds;
- Wetlands.

3.1. Rainwater Harvesting

This type of solution allows the roof stormwater to be captured and reused for non-potable water demand of the household. This provides minor water quality benefits but may provide peak flow attenuation if designed to do so. It can also be used in commercial and industrial developments. Their sizing method depends on the water demand of the household and, in case of peak flow attenuation the roof area. In New Zealand when discharging to drainage systems the 10-year event should be controlled, unless the water body, the drainage system discharges to, does not have peak flow restrictions and in this case, only the 2-year event control is necessary. If the discharge of the rainwater harvest goes straight to a water body only the 2-year event needs to be controlled.

3.2. Green Roofs

The green roofs allow to diminish the impervious areas inside a urban catchment, creates habitats, helps retaining higher levels humidity inside urban areas and has structural benefits, minimizing the expansion and contraction of roof membranes and protects from extreme temperatures.

Usually consists of:

- Waterproof membrane;
- Root barrier;
- An insulation layer (opcional);

- A drainage layer;
- Filter fabric;
- The engineered growing medium soil substrate;
- The plant material;
- Erosion protection.

This type of solutions must always take in account the structural needs for a total saturated state. It can be applied to roofs slopes up to 30%. If the slope is above 20%, it will require steps to prevent soil slippage and erosion. Wind precautions must be taken if there’s a historical record of strong winds.

3.3. Infiltration systems

Infiltration systems purposes are groundwater recharge and reducing the runoff going downstream. These systems are only usable when the soil has enough infiltration rate. The minimum allowable infiltration rate is about 3 mm/h. These systems can be:

- Infiltration trenches;
- Soakaways;
- Pervious pavements;
- Occasionally, bioretention, swales and filter strips may also provide groundwater recharge if designed to do so.

They possess a layer filled with aggregate, as the voids are used as storage for the water quality volume. Bioretention, swales and filter strips give pre-treatment as the water flows through a soil layer before reaching the aggregate layer. Clogging is the main concern on these type of systems as a pre-treatment system should be provided prior to entering the aggregate layer. To guarantee their good performance:

- The seasonal high-water table, bedrock or relatively impermeable soil layer must be, at least, one meter away from the bottom of the infiltration system;
- The soil shouldn’t have more than 30% clay, or more than 40% clay and silt combined;
- Must not be constructed on fill material;
- Slopes may not exceed 15%;
- Drainage area must not exceed four hectares, and preferably not more than two hectares;
- If the infiltration rates are higher that the one given for sand, caution must be taken, as primary treatment must be given prior to infiltration.

The sizing procedure of these types of systems are based on Darcy’s Law as the water quality volume must be infiltrated within 48 hours.

3.4. Filter strips

Filter strips consist on vegetated strips of land where a sheet flow will pass through. Usually they will need level spreaders upstream to guarantee a well distributed flow along the filter strip. These systems need a shallow depth flow to achieve their full potential as the flow must not be higher that the vegetation, so it can function as a natural filter. The retention time within the filter strip is another requirement for a good performance. If designed to infiltrate the stormwater, a sand layer will provide extra treatment before entering the aggregate layer. A perforated pipe must be within the aggregate layer in to drain excess water and anticipate a possible infiltration degradation or even failure. For a good performance, these systems need:

- Retention time of 9 minutes minimum for the water quality event;
- 0.4 m/s maximum velocity for the water quality event;
- 25 mm maximum depth for the water quality event;
- 1% to 5% slope.

The sizing procedure of these systems is made through the Gauckler-Manning-Strickler equation as the Gauckler-Manning-Strickler coefficient is a function of the water depth and vegetation height.

3.5. Swales

Swales are very similar to filter strips as both use vegetation as the main treatment for stormwater, require shallow depth and retention times to achieve their full potential. The main difference is that the swales accept concentrated flow as filter strips require distributed flow and may be sized to transport larger events downstream. There are three types of swales:

- Pure transport swale;
- Dry swales;
- Wet swales.

In pure transport swales the water will flow at the surface getting treatment from the vegetation, dry swales have a sand layer below the soil where the vegetation lies and the water is collected at the bottom, in case infiltration isn't allowed. Wet swales have a permanent pool and wetland plants but need flat sites, poorly drained soils and constant inflow.

For a good performance, these systems require:

- Retention time of 9 or 18 minutes minimum depending if lateral inflow is allowed;
- 0.8 m/s maximum velocity for the water quality event;
- 100 mm maximum depth for the water quality event;
- Maximum bottom width of 2 meters;
- Maximum side slopes 3:1 (H:V);
- Minimum length of 30 meters.

For swales, the slope can be higher than 5% if level spreaders or check dams are applied within 15 meters of each other to prevent flow concentration. If the slope is lower than 2%, the design should contemplate a sand layer, an aggregate layer and a perforated pipe even in non-infiltration cases. The sizing procedure of these systems is also made through the Gauckler-Manning-Strickler equation.

3.6. Bioretention systems and sand filters

Bioretention systems and sand filters are very similar as both treat the inflow by passing it through a soil/sand layer. Essentially these are water quality systems as they provide little flow peak attenuation. Sand filters usually have a sedimentation chamber prior to the sand filter itself to avoid clogging by removing TSS. The bioretention systems are rain gardens that accumulate and then infiltrate the stormwater into their soils which is collected at the bottom or may offer groundwater recharge. A sand layer may improve the performance of a bioretention system. Compared to the sand filters, the performance of the bioretention may be improved due to the presence of plants and their potential to remove certain pollutants.

3.7. Ponds

These systems are usually used for peak flow attenuation as well as treatment. They can be dry ponds which drain all the inflow to downstream and tend to have less effective treatment compared to wet ponds which have a permanent pool providing longer retention times. They can also be extended detention ponds in which case above the permanent pool is provided volume to store the event of 34.5 mm of precipitation (in New Zealand case) and slowly allow this volume to find its way downstream (usually sized so this event is drained along 24 hours). Upstream to the pond usually lies a sedimentation basin to reduce the amount of TSS accumulated on the bottom of the pond to reduce the need of maintenance on the pond. In wet ponds an emptying valve must be implemented for maintenance.

3.8. Wetlands

These shallow water systems use hydrophytic vegetation in the shallower zones which provide treatment to the inflow, also they usually don't provide peak flow attenuation. These systems should:

- Tend to a drainage area of, at least, one hectare;
- Be constructed above soils silty to clayey;
- Not have steep slopes or slope stability issues;
- Have constant inflow to ensure the long-term viability.

For a good performance, wetlands should have depth variations along its length, changing between 0-0.5m depths and 0.5-1.0m depths. The plants should be on the shallower zones, while the deeper areas allow to storage a higher amount of stormwater and the depth must be the same perpendicularly to the flow direction to avoid short circuiting. A well-designed wetland should have 60% of shallower areas, to 40% of deeper waters. Along with the ponds, a sedimentation basin must also be put upstream of a wetland.

3.9. SuDS efficiency

As it was already stated the sustainable drainage systems offer stormwater treatment but how much treat is the real question. According to ARC, 2003, the theoretical effectiveness of the sustainable drainage systems is given in Table 3.1 and Table 3.2. To verify these values, Clary *et al*, 2017 presented a summary of sustainable drainage system performance recorded in the United States of America. Comparing both we can assume that, apart from the swales, results fell in the theoretical spectrum.

Table 3.1 – Theoretical pollutant reductions of sustainable drainage systems (1/2).

SuDS / Pollutant	Peak flow control dry pond	Ext. Det. Dry pond	Wet Pond	Wetlands*
TSS	20-60%	30-80%	50-90%	44.90%
Total phosphorus	10-30%	15-40%	30-80%	-
Total nitrogen	10-20%	10-40%	30-60%	32.70%
COD	20-40%	20-50%	30-70%	26.40%
BOD	-	-	-	-
Total lead	20-60%	20-70%	30-90%	97.50%
Total zinc	10-50%	10-60%	30-90%	85.70%
Total cooper	10-40%	10-50%	20-80%	79.30%
Bacteria	20-40%	20-60%	20-80%	-
Hydrocarbons	-	-	-	-

*- Valores médios registados em 5 diferentes eventos pluviosos na Nova Zelândia.

Table 3.2 - Theoretical pollutant reductions of sustainable drainage systems (2/2).

SuDS / Pollutant	Bioretention and sand filters	Infiltration systems	Swales	Green Roofs
TSS	>75%	90%	73-94%	75%
Total phosphorus	-	60-70%	-	-
Total nitrogen	-	55-60%	-	-
COD	-	-	-	-
BOD	-	80%	-	-
Total lead	>75%	-	90%	-
Total zinc	>75%	-	80%	-
Total cooper	>75%	-	60%	-
Bacteria	-	90%	-	-
Hydrocarbons	>75%	-	-	-

4. CONCLUSION

If we compare some of the legislation presented with the Portuguese, the legislation regarding quantity control may affect later constructions since you don't require a peak flow control if the water body has capacity for it, but once capacity is reached, then constructions at that point will need require peak flow control, not to mention the unpredictability that climate change presents. But if we analyse the quality control in separate drainage systems, the studied countries have much more advanced legislation regarding the stormwater management in urban areas as Portuguese law allows these systems to fully discharge to their water bodies if no negative effects are detected. Their objective is to manage frequent events as these events usually are the ones washing the urban watershed. These frequent events controlled range from a third of the 24 hour 2-year event to a 15 minutes 1-year event (event with 63% annual exceedance probability). In order to manage these events, they present sustainable drainage systems which will treat the stormwater inflow. Clary *et al*, 2017 verifies that, overall, these drainage systems really have a good performance in dealing with the main urban pollutants Although, some of these systems may not perform so well under Portuguese climate, as some of them may require a constant inflow to maintain their full performance, such is the case of wetlands. Others might require additional maintenance in low precipitation seasons in order to keep the vegetation alive.

As for Portugal, I would recommend a study of the annual rain events and check the event that matches the New Zealand approach by trying to capture 80% of runoff volume for all annual events and compare it given the climate difference.

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