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Flood and drought mitigation using stormwater attenuation and enhanced infiltration systems

Atténuation des inondations et des sécheresses à l'aide de systèmes d'atténuation des eaux pluviales et d'infiltration améliorée

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ABSTRACT: Engineering systems are described for stormwater attenuation and enhanced infiltration, including the construction of trenches containing perforated attenuation pipes with a gravel surround, integrated with large numbers of drilled vertical infiltrators installed through the base of the trenches. Adding the pressure head of water in the attenuation trenches to the negative suction pressure in the unsaturated vadose zone, provides the differential pressure to force the water into the ground surrounding the infiltrators. The vertical infiltrators often encounter anisotropic ground strata where the horizontal permeability is much greater than the vertical permeability. Stormwater Attenuation and Enhanced Infiltration Systems have been used for many years in the United Kingdom to mitigate flooding and erosion, and to provide recharge to groundwater resources. With groundwater resources similarly in decline in Portugal, together with more frequent flooding conditions during intense rainfall, similar collection and enhanced infiltration systems could also be most beneficial to the hydrogeology and weather conditions of Portugal. Using this system, stormwater infiltrating into the vadose zone eventually find its way down to the water table, and so mitigate drought conditions by supplementing the aquifer water resources.

RÉSUMÉ: Des systèmes d'ingénierie sont décrits pour l'atténuation des eaux pluviales et l'infiltration accrue, y compris la construction de tranchées contenant des tuyaux d'atténuation perforés avec un entourage de gravier, intégrés à un grand nombre d'infiltrateurs verticaux forés installés à travers la base des tranchées. L'ajout de la pression de l'eau dans les tranchées d'atténuation à la pression d'aspiration négative dans la zone vadose non saturée, fournit la pression différentielle pour forcer l'eau dans le sol entourant les infiltrateurs. Les infiltrateurs verticaux rencontrent souvent des strates de sol anisotropes où la perméabilité horizontale est beaucoup plus grande que la perméabilité verticale. Les systèmes d'atténuation des eaux pluviales et d'infiltration améliorée sont utilisés depuis de nombreuses années au Royaume-Uni pour atténuer les inondations et l'érosion, et pour recharger les ressources en eaux souterraines. Les ressources en eaux souterraines étant également en déclin au Portugal, ainsi que des inondations plus fréquentes lors de pluies intenses, des systèmes similaires de collecte et d'infiltration améliorés pourraient également être très bénéfiques pour l'hydrogéologie et les conditions météorologiques du Portugal. Grâce à ce système, les eaux pluviales qui s'infiltrent dans la zone vadose finissent par se frayer un chemin jusqu'à la nappe phréatique, et atténuent ainsi les conditions de sécheresse en complétant les ressources en eau de l'aquifère.

Keywords: Stormwater attenuation; enhanced groundwater infiltration.

1 INTRODUCTION

Climate change and global warming are affecting all countries of the world, with more extreme weather events happening with greater frequency (Stott, 2016). In the United Kingdom (UK), one major impact of global warming has been the increase in hotter periods combined with an increasing frequency of high-intensity rainfall events (Kay et al., 2011, Schaller et al., 2016). With more of the UK being covered with urban developments, roads and industrial parks, the available open land to enable natural infiltration to the ground is receding (Charlesworth and Booth, 2016).

Over time this means less water is being recharged back into the ground and the major aquifers. As a consequence, the UK Government has enforced where possible the need for a developer to construct a Sustainable Drainage System (SuDS) to mitigate peak flooding that occurs from rapid runoff from hard impermeable surfaces such as roofs, roads, car parks or other paved areas (Fletcher et al., 2015).In 2010, the UK Government published Building Regulations with Part H (Building Regulations, 2015).

Within these Regulations, Part H3 (3) describes the design of systems to manage the drainage of rainwater with the following priority:

a) An adequate soakaway or some other adequate infiltration system; or where that is not reasonably practicable,
b) A watercourse; or where that is not reasonably practicable,
c) A stormwater sewer; or where that is not reasonably practicable,
d) A foul sewer.

The building regulations guidance presented above clearly states that the priority is to discharge collected groundwater to an adequate soakaway or some other adequate infiltration system. In response to these regulations a Stormwater Attenuation and Enhanced Infiltration System (SAEIS) has been developed to provide an efficient method to collect, attenuate and infiltrate stored water into soils of variable permeability at depth. This system has been designed to infiltrate water at greater depths (typically in the range of 3 m to 12 m deep) than conventional soakaways which means this system is more suitable in areas where low permeability anisotropic soils such as laminated sandy and silty clays are more prominent (Jarvis et al., 1984).

By enabling infiltration at depth into laminated silt or sand lenses within clay soils, an enhanced infiltration system helps to mitigate local surface water flooding by reducing the flow of water to watercourses and sewers. This in turn helps to lower the peak water levels in local rivers following storm events, as illustrated in Figure 1 for a non-attenuated and attenuated concept storm hydrograph.

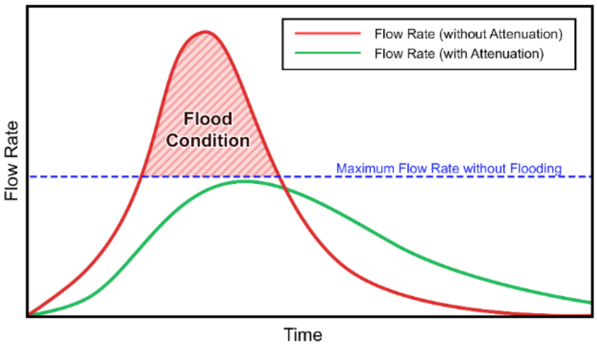

Figure 1. Illustration of two storm event hydrographs for non-attenuation and attenuation conditions respectively.

This paper describes the mathematical modelling applied to demonstrate the impact of attenuation and enhanced infiltration systems, by simulating the seepage of stormwater from the infiltrators into the surrounding anisotropic strata of mixed medium and low permeability, common in the United Kingdom.

With storm flood conditions also occurring more frequently in areas of Portugal over recent decades, enhanced infiltration techniques have the potential to mitigate the worst impact of such flooding events. Furthermore, the resulting enhanced infiltration of storm rainwater back to the unsaturated vadose zone will also serve to contribute to the mitigation of drought conditions, as the infiltrated rainwater will eventually find its way downwards to the water table.

2 STORMWATER ATTENUATION AND ENHANCED INFILTRATION SYSTEM

The enhanced infiltration system has been designed to attenuate and infiltrate large volumes of rainwater following storm events. The schematic in Figure 2 depicts how the system collects stormwater, and then how it is attenuated and infiltrated into the ground.

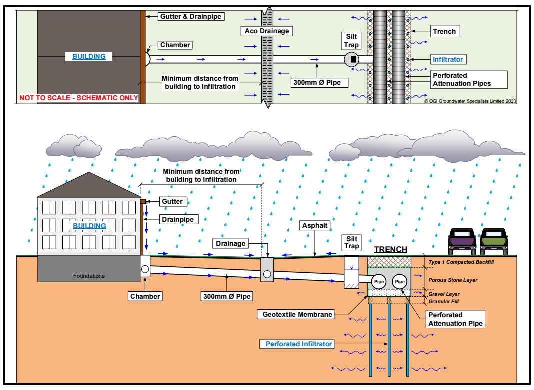

Figure 2. Attenuation and Enhanced Infiltration System.

Stormwater that lands on buildings and paved surfaces such as car parks, then enters the drainage system through a series of gutters and drains. Water then flows through a series of underground drains towards a silt trap where fine particles can settle out from the water to mitigate clogging of the infiltration system. Water then flows into a series of attenuation trenches set a minimum of 5.0 m away from any buildings. The trenches are typically in the order of 1.8 m wide and 1.7 m deep Figure 3).

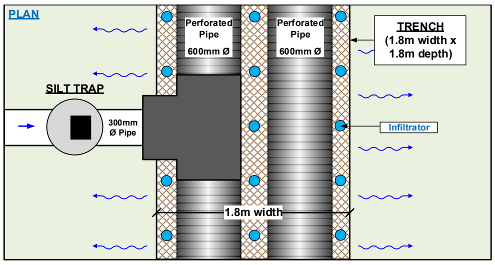

Figure 3. Schematic of the Attenuation and Enhanced Infiltration system in plan.

Each trench normally contains one or two large diameter perforated pipes, designed to provide a high storage volume to attenuate collected rainwater following a storm event. The trench is backfilled around the perforated pipes with gravel or angular stone. At the base of each trench, the pipes typically sit on a layer of 10 mm pea gravel. Gravel or stone is then backfilled around the pipes and typically to 300 mm above the crown of the pipes. Surrounding this gravel & pipe attenuation structure is a specialist nonwoven green geotextile developed to promote the growth of a microbic biofilm to absorb and digest any hydrocarbon. The nonwoven geotextile also provides stabilising of the sub-base construction. Above the attenuation structure is placed graded stone, which is compacted to provide greater bearing capacity.

Pre-drilled beneath the attenuation trenches are a series of specially designed vertical infiltrators (Figures 2 and 4), which aid the infiltration of water into the soil. Each infiltrator comprises a 90mm drilled borehole, then installed with a device that is designed to accelerate the transmission of water into the ground. The top of each infiltrator is set normally 300 mm below the base of the trench as depicted in Figure 4. The length of infiltrators normally varies between 3 m and 12 m, depending on the geology and volume rate of water that needs to be infiltrated.

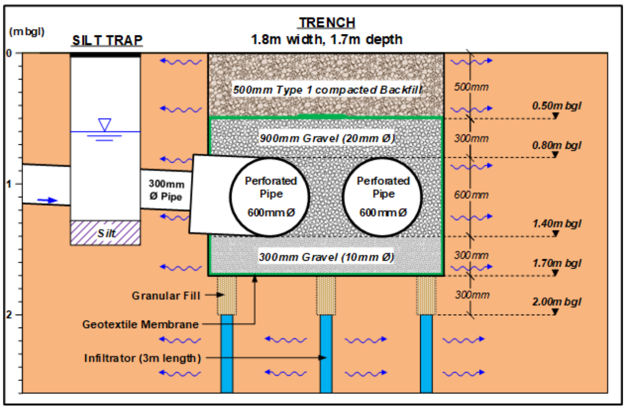

Figure 4. Attenuation and Enhanced Infiltration section.

The attenuation and enhanced infiltration system depicted above has been successfully implemented to discharge collected water at over 500 sites in the UK. The system provides an elegant and energy-efficient solution to the flooding challenges at each location.

The system has proved particularly successful in draining waterlogged sports fields, including rugby fields, cricket pitches and horse racing tracks. However, the main area of growth currently is for new-build housing and commercial construction, where city councils are legislating for 100% of the collected rainfall to be reintroduced back to ground.

To illustrate the application of this attenuation and enhanced infiltration system, Figures 5, 6 and 7 present the application at an industrial unit and car park in the northeast of England. The silty-clay ground was initially considered to be unsuitable to soakaway stormwater; but after installation, the 180m of trench, together with circa 500 infiltrators, was sufficient to manage the rainwater over a 4 Ha.

Figure 5. Perforated pipes within attenuation trenches.

Two horizontal perforated pipes are installed and then backfilled with gravel to 300 mm above the crown of the pipes. Nonwoven green geotextile wrapping of the gravel is then completed before a graded stone is infilled and compacted on top of the geotextile to provide greater bearing capacity before the construction of an asphalt finish for vehicle use.

To mitigate the potential of silts from entering the trench attenuation system, there are many silt traps and chambers constructed to intercept the silts. These structures are regularly cleaned as part of a planned maintenance program.

To degrade any possible hydrocarbon collected, the attenuation trench comprising pipes and gravel is wrapped with a specialist green nonwoven geotextile (Figure 6) before compaction of the grading layer.

Figure 6. Final backfilling of attenuation trench and wrapping with green nonwoven geotextile.

The combination of the nonwoven geotextile of a green fibre structure, with the pea gravel backfill, adds treatment for hydrocarbon contamination by promoting the growth of a microbic biofilm which absorbs and digests the hydrocarbon.

3 RAINWATER INFILTRATION THEORY INTO UNSATURATED GROUND

Rainwater infiltration into unsaturated ground above the water-table is complex to simulate. When water fills the attenuation volume within the trenches, this water also fills the infiltrators beneath. This results in a high differential pore water pressure between the water-filled infiltrator, and the natural suction pressure in the surrounding unsaturated ground.

(i) The pressure in the infiltrators will be governed by the elevation of the water head in the attenuation storage (Figure 7). For example, if the water level fills the trenches to 600 mm above the base of the trench, and the infiltrators are installed to 3.3 m below the base of the trench, there will be a pressure of circa 38 kPa at the tip of the infiltrator.

(ii) The initial negative pore water pressure in the unsaturated ground surrounding the infiltrator (i.e., less than atmospheric pressure), is also commonly referred to as soil suction. In fine-grained soils, suction pressure can be high-negative, with values of -50 kPa regularly produced.

(iii) Combining these two conditions can result in circa 88 kPa in differential pore-water pressure between the positive pressure at the infiltrator tip and the negative suction pressure in the surrounding unsaturated soil. This results in the pressure in the infiltrator "pushing" the water into the surrounding ground, and the unsaturated ground also effectively "pulling" the water from the water-filled infiltrator.

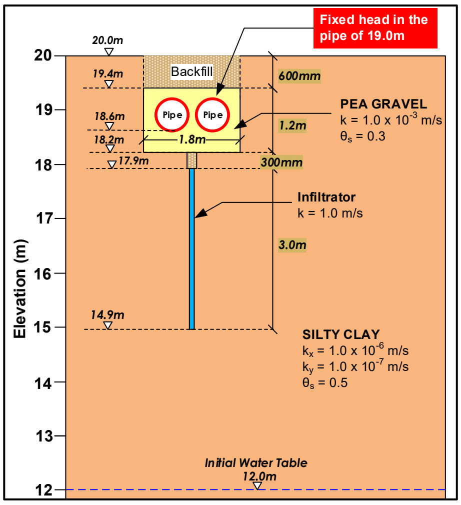

Figure 7. Conceptual model of a single infiltrator with ground properties used in the mathematical modelling.

Experience from the UK has demonstrated that the performance of a stormwater attenuation and enhanced infiltration system far exceeds the rate of infiltration from a normal and traditional soakaway trench, i.e. without the addition of drilled infiltrators.

This performance is regularly met with surprise by those who have traditionally viewed that a soakaway does not work sufficiently in silt or clay soils. However, when the concept of high anisotropy that occurs in a laminated soil, together with the fact that an unsaturated soil "pulls" the water from the infiltrator, especially when mathematical models are used to simulate and validate the performance, this innovative system is now becoming increasingly accepted in the construction industry.

Although over 500 enhanced infiltration systems have been installed in the UK, there is still always resistance to a new technique. The main opposition to the use of the system to dispose of stormwater is the view by some that this high water infiltration rate into low permeability ground is considered not feasible, despite the system having been tested and demonstrated to work in practice.

For this reason, more "science" has been required to demonstrate how it is indeed technically feasible to infiltrate high water flow rates into soils of low to medium permeability. To achieve this requirement, the authors built a non-linear finite element model to demonstrate that a carefully constructed and tested system can be proven to work scientifically.

4 FINITE ELEMENT MODELLING OF ENHANCED INFILTRATION

The movement of the collected stormwater through the infiltrator into the ground has been modelled by French and Thomas (Authors) using the GeoStudio finite element software SEEP/W (Geostudio, 2012).

The finite element model requires "discretisation" of the ground domain surrounding the infiltrators into tens of thousands of smaller zones called "elements" to geometrically simulate the groundwater behaviour using the radial version of the equation below:

$$\frac{\partial}{\partial x_i}\left(k_{rw}K_{ij}\frac{\partial h}{\partial x_j}\right) = \left(S_w S_s + \varphi\frac{\partial S_w}{\partial \psi}\right)\frac{\partial h}{\partial t} - Q_w (1)$$

where k_{rw} is relative permeability, K_{ij} is Hydraulic Conductivity Tensor, h is hydraulic head, φ is porosity, S_w is water saturation, S_s is Specific Storage, ψ is pressure head, and Q_w is a point water source.

The non-linear functions used in the modelling for (i) Volumetric Water Content, and (ii) Hydraulic Conductivity, which are dependent on soil suction, are presented in Figures 8a and 8b.

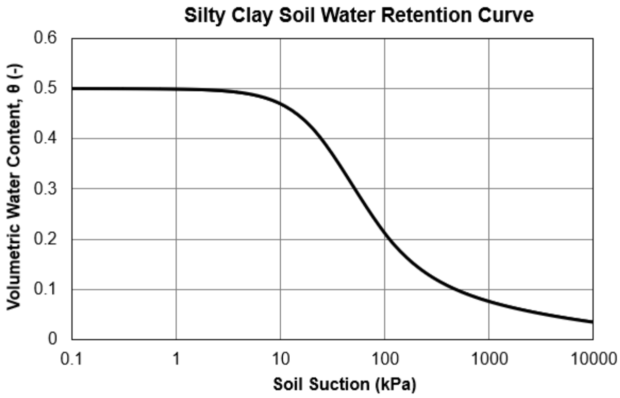

Figure 8a. Soil-water retention function curve.

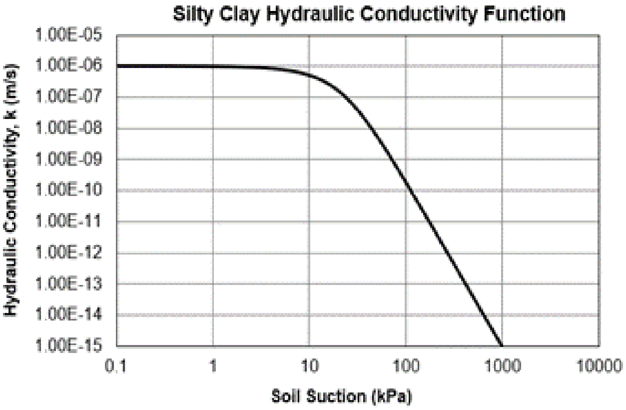

Figure 8b. Hydraulic conductivity function vs soil suction.

The finite element model then enables different properties and boundary conditions to be input in a range of locations for which the governing flow equation is solved, and heads output.

From these outputs, other information can be calculated such as pore pressure, degree of saturation and groundwater velocity.

An axisymmetric finite element computer model has been utilised to simulate two-dimensional radial steady-state flow of collected water into the vadose (unsaturated soil) zone surrounding an infiltrator.

For this scenario, a saturated sump and infiltrator have been simulated using SEEP/W. The simulated soil is based on a typical anisotropic silty clay, common to the northeast of England.

Input horizontal permeability is 1.0 x 10^{-6} m/s and vertical permeability 1.0 x 10^{-7} m/s. To simulate the unsaturated behaviour of the soil, SWRC (soil water retention curve) along with a hydraulic relative conductivity function have been selected based on typical functions for silty clays, (Figures 8a and 8b).

A fixed head boundary condition is applied to the sump, and a high permeability infiltrator is specified, to simulate the flooded sump and infiltrator.

Figure 9 presents simulated groundwater head contours (ranging from 18 m to 6 m) and the flow lines (shown by the green lines with arrows).

The dashed blue line represents the position of the water table (which is the position where pore water pressure equals 0.0 kPa and saturation equals 100%).

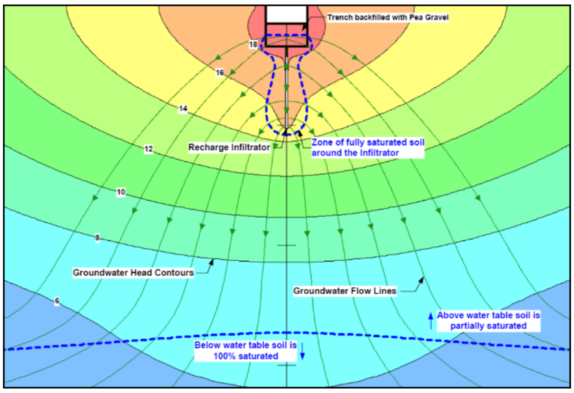

Figure 9. Simulated head contours and flow paths.

Groundwater flow velocity is driven by a gradient of hydraulic head (Darcy's Law); which explains the pattern of groundwater flow that can be seen in Figure 9. The head changes from 19.0 m at the sump to 15.0 m at the bottom of the infiltrator. This 4.0 m head differential drives the water down through the vertical infiltrator, as depicted by the green arrows.

Another driver is that the pore pressure in the unsaturated vadose zone above the water table will be negative, i.e. under suction. This means there is a greater differential head produced between the positive pressure in the infiltrators, and the negative pore-water pressure in the unsaturated vadose zone.

The collected and filtered water then enters the soil at depth, and then flows into the horizontal silt or sand layers of higher permeability. This horizontal flow into the soil results in a zone of fully saturated soil immediately surrounding the infiltrator within the upper blue water-table line in Figure 9.

Enhanced saturation enables greater groundwater flow into the surrounding soil as this increases the permeability. Radially from the infiltrator beyond the saturated zone, saturation decreases, increasing soil suction, but also reducing the effective permeability.

Whilst a reduction in the permeability of the soil occurs in the unsaturated zone, the soil suction pressure gradient, combined with the head gradient in the infiltrator, is sufficient to drive the collected water into the vadose zone surrounding the infiltrator.

The concept of transient stormwater attenuation and enhanced infiltration during and after a rainstorm event is depicted in Figure 10. Surface water during a storm event is directed to the drains and attenuation trenches. After cessation of the storm, this collected and attenuated stormwater will dissipate from the infiltrators into the surrounding unsaturated soil, and will then slowly percolate down to the water table, so ultimately restoring aquifer water resources.

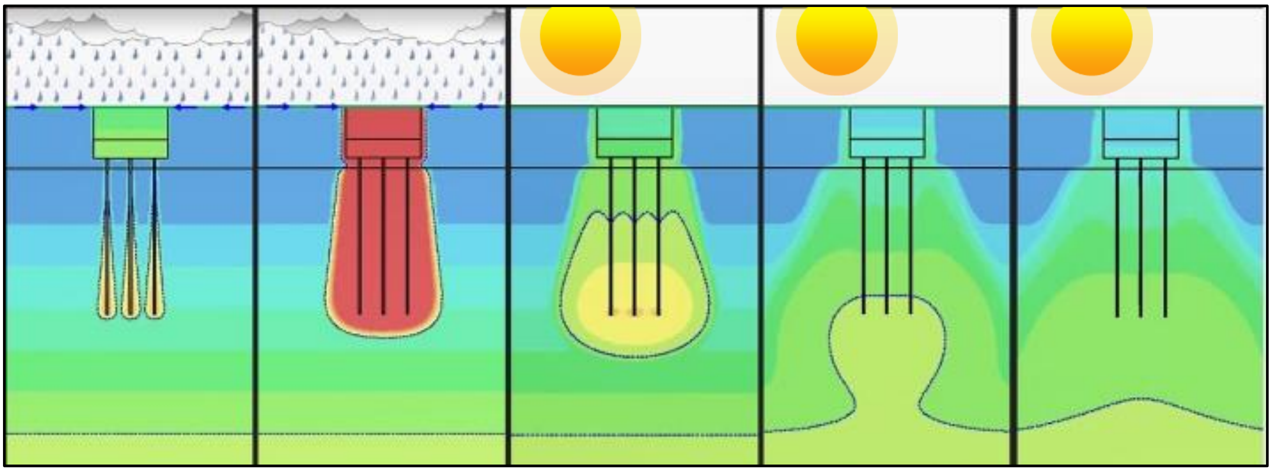

Figure 10. Various stages of attenuation and enhanced infiltration during and following a storm event.

5 CONCLUSIONS

A Stormwater Attenuation and Enhanced Infiltration System enables collection, attenuation and infiltration of stormwater back to the ground, thus mitigating surface flooding. This paper describes how this innovative attenuation and infiltration system functions in practice, and then demonstrates by mathematical modelling how water flows through the system and infiltrates water into the soil at a far greater rate than can be achieved using a conventional soakaway system. Soil characteristics used in this study are based on a typical laminated anisotropic silty clay.

Mathematical modelling conducted by the authors demonstrates that infiltration systems can be effective in both medium and low permeability ground, benefitting from the anisotropy of the ground where horizontal silt and sand bands exist within otherwise clay soil, as it enables the infiltration of stormwater at depth into more permeability soil layers.

Where stormwater has traditionally been sent to watercourses and sewers, the application of effective infiltration systems has a significant benefit by mitigating the risk of localised flooding, together with replenishing water resources. This opens the option of using enhanced infiltration systems anywhere in the world where shallow soakaway systems were once not originally thought suitable.

Stormwater attenuation and enhanced infiltration exemplify true low-carbon sustainability, contributing to the United Nations Department of Economic and Social Affairs for Sustainable Development Goal 6: ***Ensure availability and sustainable management of water and sanitation for all.***

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