An experimental and numerical model for performance evaluation of the new galley design filter bucket for storm networks.

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Abstract. Storm networks are a major item of civil infrastructure and a significant element of community life. One of the most significant problems facing storm networks is the blockage of pipes, frequently caused by sediments in the sewage system. This study was undertaken to offer a performance evaluation of a new design of gravel filter bucket for storm networks that offers the separation of sediments at different intensities of rainfall and street slopes based on the development of an experimental model. Stormwater with different sediment loads was simulated and samples of filtrate examined with regard to removal efficiency for these particles. A flow-3D numerical model was also developed to investigate the removal efficiency of the gravel filter. The predicted removal efficiency was then validated using experimental data. Assuming proper model validation, numerical models of this type can yield evaluation data with respect to filter removal efficiency for other dimensions and particle sizes of sediment. The results in this case indicated that the efficiency of the gravel filter increased with increases in slope, intensity, and duration. The gravel filter efficiency was 61% at a low intensity of rainfall and 90% at a high intensity of rainfall, while the results also showed 88% and 63% efficiency for the maximum and minimum diameter sediments, respectively. In terms of validation, the numerical model was compared with a statistical equation to calculate the filter efficiency (\(E_f\)), with the use of an SPSS model to estimate the \(R^2\) value, which was 0.88.

Keywords: Filter, Flow-3D, Efficiency, CFD

1. Introduction

Storm networks, as key parts of urban infrastructure, are critical elements of life in modern society, and they have designed to meet a range of increasingly diverse challenges to offer protection against floods and discharge limitations in the natural environment, where aging underground infrastructure presents a risk. The burden on municipal agencies to prioritise and maintain rapidly deteriorating sewer pipelines is thus increasing [1]. Water drainage networks are also one of the most important segments in the construction of infrastructure projects such as streets, highways, residential housing developments, commercial developments, schools, and airports. Any storm drainage system built for such developments typically includes underground sewage pipes, collection basins, culverts, and drop inlets; the latter form a connection between the storm water drainage system and finished street-side curb-and-grate inlets. As the construction of a development continues, government regulations and building codes generally require that the storm water drainage system be kept substantially free of silt and sediment that might enter through the curb-and-grate inlet, which can be difficult, given that construction on site
can significantly dislodge or disturb silt and sediment. If silt and sediment are washed into collection basins and other parts of the sewage system, or otherwise collected, the collection basins can become clogged, making it necessary to send workers down into the collection boxes to clean them manually in order to comply with clean water regulations. These cleaning operations are difficult, however, as the pipes are fairly tight, making it difficult for workers to manoeuvre[2].

In order to simulate natural rainfall precisely and accurately, a rainfall simulator must be developed that can offer naturalistic duration and intensity. The literature shows that a number of researchers have studied rainfall simulators previously [3 - 9]. Rainfall simulation can be divided into types by area and the factors that affect both rainfall intensity and regularity of rain. For areas up to about 10 meters per side, there are two standard options for rainfall simulators; these are rows or nozzle arrays and sweeping sprinklers. [10] performed one of the first nozzle type simulations, and recommended them for standard small areas or laboratory scales (1m² or smaller). [11] studied a 0.24 m² rainfall simulator at 55 mmh⁻¹ with a spatial uniformity coefficient of 93 %; the rainfall intensity and distribution were found to depend on the type and number of nozzles used. The standard design for large areas scale is the rotating precipitation simulator, initially developed by Swanson, as mentioned in [12]. In addition, many studies [13- 21] have introduced different forms of catch basin filters to filter storm water runoff when rainwater reaches a catch basin.

[22] studied a street curb discharge filter consisting of U-shaped brackets installed on the inner wall of street drainage, adjacent to the entrance. Other researchers have studied soil corrosion processes and looked for ways to improve process-based corrosion prediction models [23]. The implementation of a new system generally improves the rain network, and the objective of the current study is thus to enhance the efficiency of storm networks by introducing and using a new filter after testing with experimental and numerical models.

FLOW-3D software was developed to deal with fluid behaviour by solving partial differential equations based on the conservation of mass and conservation of energy, and it has been used in many previous studies [24-28]. FLOW-3D uses sophisticated digital techniques to solve the motion equations of liquids to produce 3D transient solutions for multi-physics flow problems. A range of physical and numerical options also allows users to apply FLOW-3D to a wide range of fluid flow and heat transfer phenomena. For example, [29], [30] studied the numerical simulation of 3D leakage flows with fractional derivatives in a porous medium in two special cases: the discontinuous leakage flow in the uniform media and the continuous leakage flow in the non-uniform media, while [31] developed a finite difference method to simulate stable fluid flow in the case of pores in the porous medium.

In this research, the numerical results were calibrated and evaluated against the laboratory results [32] in order to study the effects of both duration of intensity and diameter of sediments on filter efficiency. The filtration efficiency was calculated by using the formula:

\[ E_f = 100 \times \left[ 1 - \frac{M_o}{M_i} \right] \]  

... (1)

where \( E_f \) is the filtration efficiency (%); \( M_o \) is the sediment mass of the filter outlet (g); and \( M_i \) sediment mass of filter inlet (g).

2 Methodology

2.1 Experimental Model

The laboratory model representation of the rain phenomenon and the transfer of sediments from the street to the outlets of the drainage system consisted of several parts connected to each other to form a complete system. This system included a structure to support all details of the model and the rain system in terms of pipes, as well as the layout of the street and its filters and drainage outlets. The first part of the model was thus the steel structure holding the rain pipe network, with the street represented by a sandwich panel. The dimensions of the model were 2 x 2.2 x 4.1 m. The second part was the rain system, consisting of two plastic pipes with length 4.1 m and diameter 0.127 m. Each pipe had 12 nozzles, spaced 33 cm apart, as shown in figure 1. The directions of nozzles openings were set by making the angles between the horizontal axis and the top of each nozzle (48° to 54°) alternate angles to the
horizontal. The laboratory model also contained the gully with a gravel filter in one side of the street, while the other side had a gully without a filter, to allow comparisons between systems with and without such filters and thus investigation of the actual performance of the filter [33]. The dimensions of the filter were 0.05 m depth and 0.1 m width, while the length varied according to the experiments required. Several variables were studied during this experimental work, including intensity of rainfall, length of filter, and bed slope. At the end of each run, the weight of the passing sediments in both sides of the pavement were calculated in order to obtain the sediment mass values for filter inlet $M_i$ and filter outlet $M_o$. Figure 2 shows the gravel used as a porous media for the filter in the gully, which contained a mixture of gravel types, including circular and angular particles. The gravel particles were 1.25 mm to 2.5 mm in diameter, and the gravel was placed inside the filter container without compaction.

![Figure 1. Outline of the laboratory model used.](image1)

![Figure 2. Gully with gravel filter (1.25 to 2.5 mm).](image2)
2.1.1 Uniformity and intensity of rainfall
Several tests are available to assess rain simulations. These tests examine the uniformity and the intensity of rain, thus assessing the level of distribution. The test developed by Christiansen, as mentioned in [33] and used in this study, depends on statistical equivalence, and the process utilises a collection of containers with fixed diameter set at equal distances in the form of a mathematical matrix, with the distance between the centre of each container and the next being 0.5 m. There are three lines of containers, and each line contains eight containers, for 24 in total, as shown in Figure 3. After the completion of the distribution process, the rain is run for a set period of time, and the height of the water is calculated in each container. The equation for coefficient of uniformity (CuC) as shown in equation (2) is then applied:

\[(CuC) = \left(1 - \frac{\sum_{i=1}^{N}|X_i - \bar{X}|}{N \bar{X}}\right) \times 100 \quad \ldots (2)\]

where \(X_i\) is amount of rainfall at location i, \(N\) is the point number that indicates where the measuring container was placed on the ground to collect rain, and \(\bar{X}\) is the average amount of precipitation. The CuC is a useful indicator of spatial uniformity of precipitation, showing adequate uniformity of rainfall when it reaches 70%, as mentioned in [12].

![Figure 3. Distribution of containers according to Christiansen theory](image)

2.1.2 Sieve analysis
A sandy soil was used in this study, with local materials from the Karbala governorate adopted; soil samples were then sieved, according to ASTM [34]. After initial analysis, the sand was transferred from a #8 sieve and that remaining in a #16 sieve was used as a filter. The sand used to represent the street was that remaining in a #100 sieve.

2.1.3 Testing procedure
The variables for practical investigation were rainfall intensity, duration of intensity, the slope of the street, and the length of the filter. The remaining variables were fixed. In each experiment, a fixed amount of sediment was put on the street and the rain showers run; after the end of the experiment, the amount of sediment passing the gully with filter was compared with the amount of sediment passing the gully without a filter. The diameter of the gravel filter, diameter of sediments, and initial mass of sediments were thus the same for all experiments. Table 1 illustrates each experiment and its variable values:
Table 1. Variables used in experimental work.

| Run | Slope | Intensity $m mh^{-1}$ | Length filter (mm) | Duration (min) |
|-----|-------|------------------------|-------------------|---------------|
| 1   | 1     | 30                     | 100               | 5             |
| 2   | 1.5   | 37                     | 150               | 10            |
| 3   | 2     | 44                     | 200               | 15            |
| 4   | 2.5   | 51                     | 250               | 20            |
| 5   | 3     | 58                     | 300               | 25            |

2.2. Numerical Method Description

To simulate rainfall numerically, the inlet is treated as runoff; using rational methods, [35] calculated the discharge of rainfall for all intensities, and here, the Manning formula was used in order to calculate the velocity and depth of the surface water used as an inlet flow in the numerical simulation. The calibrated numerical model was used to analyse the performance of the new gravel filter with additional parameters that could not be simulated in the experimental model, such as varying particle sizes of sediment and duration of intensities.

2.2.1. Governing Equations

The Navier-Stokes equations show that the governing equations for incompressible viscous fluids are continuity and momentum [35]. These equations can be expressed mathematically with regard to conservation of momentum and mass. [36] derived an improved $k-\varepsilon$ turbulence model known as the RNG (renormalisation group) $k-\varepsilon$ model, in which the coefficients are obtained from theoretical analysis rather than experimental data. The RNG $k-\varepsilon$ model is thus more adaptable than the standard $k-\varepsilon$ model. In this work, RNG $k-\varepsilon$ was used to simulate the turbulence flow of a rain network, adopting the standard wall function method for dealing with a nearby wall.

\[
\begin{align*}
\frac{\partial p}{\partial t} + \frac{\partial \rho u_i}{\partial x_i} &= 0 \\
\frac{\partial \rho u_i}{\partial t} + \frac{\partial (\rho u_i u_j)}{\partial x_j} &= \frac{\partial}{\partial x_i} \left( \mu + \mu_t \right) \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) + \frac{\partial P}{\partial x_i} + \frac{\partial G}{\partial x_i} + \frac{\partial \rho \varepsilon}{\partial x_i} \quad \text{(3)} \\
\frac{\partial \rho u_i}{\partial t} + \frac{\partial (\rho u_i k)}{\partial x_i} &= \frac{\partial}{\partial x_i} \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_i} + G + \rho \varepsilon \quad \text{(4)} \\
\frac{\partial (\rho \varepsilon)}{\partial t} + \frac{\partial (\rho u_i \varepsilon)}{\partial x_i} &= \frac{\partial}{\partial x_i} \left( \mu + \frac{\mu_t}{\sigma_{\varepsilon}} \right) \frac{\partial \varepsilon}{\partial x_i} + C_{1\varepsilon} \frac{\varepsilon}{k} G - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k} \quad \text{(5)}
\end{align*}
\]

where $t$=time, $u_i$= the speed component; $\mu$=molecular viscosity; $\rho$= density; and $P + \frac{2\rho k}{3} = \bar{P}$

Disturbed kinetic energy ($G$) generation due to average speed gradients is given as

\[
G = \mu_t \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \frac{\partial u_i}{\partial x_j} \quad \text{(7)}
\]
Each $P$ and $\overline{P}$ represent the relevant pressure and modified pressure, respectively. Based on the turbulent dissipation rate ($\varepsilon$) and turbulence kinetic energy ($k$), the parameter $\mu_i = \text{turbulence viscosity}$ can be calculated as

$$\mu_i = \rho c_\mu \frac{k^2}{\varepsilon}$$

... (8)

where $C_{1c}$, $C_{2c}$, $C_{\mu}$, $\sigma_\varepsilon$, and $\sigma_k$ are all dimensionless user-adjustable parameters, which in this work took values of 0.7179, 0.7178, 1.39, 1.42, and 0.085, respectively [36]. The renormalised group (RNG) model was selected as the stronger and most accurate model available in the software, based on data from the FLOW3D user’s manual, which also mentioned that the model may offer better performance for scour simulations [36].

The open volume divided by the total volume gives the porosity [36].

Porosity = $Vf$  ... (9)

The usual conservation equations are obtained by building a solid model of porous materials and applying the averaging for each control volume. The mass conservation is representing by the formula [36]:

$$\frac{\partial \rho_f}{\partial t} + \nabla \cdot (\rho_f U) = 0$$

... (10)

where $U$ is the microscopic flow velocity. According to French engineer Henry Darcy (1856), a momentum equation in porous media can be created dependent on the observation that the unidirectional flow rate through porous media is proportional to the applied pressure difference; thus

$$V_f U = \kappa \frac{\partial p}{\mu \partial \chi}$$

... (11)

2.2.2 Geometry

The geometry is structured in FLOW-3D through the use of solid geometric objects to define the flow region for a simulation. The geometry in any simulation may be defined by using one or more components, ith each component composed of one or more subcomponents added and subtracted in sequence to define a more complex shape. Several parts used in the construction of the model representing the street in this work had characteristics of solid bodies with opening to represent manholes; the other side then contains a porous object to represent the filter; the parts used define all necessary characteristics for an element.

2.2.3 Initial and Boundary Conditions

Determining suitable boundary conditions is a very significant phase in numerical flow analysis. These boundary conditions must correspond with the physical conditions of the problem correctly [37-48]. Three-dimensional flow domain is defined in FLOW-3D through the use of orthogonal hexahedral meshes in Cartesian coordinates, with six boundaries defined on rectangular mesh prisms. The boundary conditions must thus be carefully defined. As shown in Figure 4, for this work, the Upstream boundary (X-min) was the velocity condition (v), the Downstream boundary (X-max) was an outflow condition (O); the Top boundary(Z-max) was a symmetry condition (P); the Bottom boundary(Z-min) was an outflow condition (O); and the Side boundary (Y-min, Y-max) was a wall condition (W).
The starting conditions for the simulation define the initial conditions, and the initial state is important for transi t fluid flow problems in order to allow discovery of a solution. In a manner similar to that of border conditions, the initial conditions are assumed, and the real state defined, at a time equal to zero.

2.2.4 Meshing Generation

Grid builds in Flow-3D are necessary for an accurate solution, and the development of a good quality mesh is necessary to obtain reliable results from the numerical model. The decisive component of any numerical model simulation is thus the selection of a suitable grid domain along with an appropriate mesh cell size. Cell size and grid can affect both the simulation time and the accuracy of results; it is important to reduce the cells size while calculating a sufficient resolution to preserve significant features of the geometry and important flow detail. Beginning with a comparatively large mesh of cells and thereafter gradually decreasing the mesh size is an effective approach to determining critical cell size; this is done until the output data no longer changes notably with any further reductions. Various cell sizes were thus tested to determine the best cell size to meet the conditions of the phenomenon under investigation, and a minimum cell size of 5 mm, as shown in Figure 5, was finally adopted.

3 Results and Discussion

3.1 Experimental results

The filter efficiency was examined in terms of various different parameters such as rainfall intensity and duration, filter dimensions, and the road slope. Five different intensities of rainfall were used in the
experimental model (30, 37, 44, 51 and 58 mm h\(^{-1}\)). Each intensity was runoff on five slopes (1, 1.5, 2, 2.5 and 3). The duration for all intensities was 15 min, the average diameter of sediments was 0.2 mm and the length of filter was 200 mm. The filter efficiency for different intensities is shown in Figure 6. As the intensity of the rainfall increased, the filter efficiency also increased. The reason for this change in efficiency was that the increase in rainfall intensity increases the velocity of water on the road, causing the amount of sediments transported to be greater. The increase in the efficiency for different intensities with all slopes is non-uniform, however. There are many reasons for this non-uniformity: the first is that the intensity of the rainfall is not ideal; thus, the drag force for each sediment is different from that of others. The second reason is related to the distribution of sediments on the surface of the road being irregular. The experimental results indicate that increasing the slope of the road increases the filter efficiency due to an increase in velocity effects.

The amount of sediment passing the filter is also greatly affected by the length of the filter. The length of the filter was thus varied to study the behaviours of passing sediments. Five lengths of filter were used: 100, 150, 200, 250, and 300 mm. For each length of filter, a run was done with intensity of rainfall equal to 44 mm h\(^{-1}\); the diameter of sediments was retained at 0.2 mm, and the duration of intensity remained 15 min. Figure 7 shows the filter efficiency for different filter lengths with various road slopes. It is clear from the results that length of filter has a crucial effect on filter efficiency. The efficiency observed increased with increases in the length of filter, due to increased surface area being available to catch sediments, as well as increases in the length of the path in the filter causing sediments to need higher velocity and energy to pass through the filter. The difference in the filter efficiency at slope 3 for each length of filter was smallest; this increased with the decrease of slope due to the difference in the velocity of the runoff being increased at increased slopes. The results generally show that that the efficiency of the filter increases on increasing the length of the filter, however, with longer filters catching the largest amount of sediments at all slopes.

![Figure 6](image)

**Figure 6.** Relationship between intensity and filter efficiency for difference slopes.
3.2 Verification of Numerical and Experimental Models

To verify the numerical results, conditions similar to those used in the laboratory model were applied. The results showed that the maximum percentage error between the numerical and laboratory model was 16% and the value of $R^2$ was 0.93, indicating that the results are acceptable, as shown in Figure 8. The main reason for the differences in measured and computed passing ratios the size of cell used in the model.

![Figure 8](image)

**Figure 8.** Comparison between filter efficiency results for numerical and experimental work.

3.3 Effects of the diameter of sediments on filtration efficiency

Diameter of sediments is one of the important variables in this study, as streets naturally have different diameters of sediments. Five different diameters of sediments were tested (0.1, 0.15, 0.2, 0.25, and 0.3 mm), and each diameter of sediment on the ground was run with five slopes (1, 1.5, 2, 2.5, and 3). The duration of intensity was 15 min in all cases, with a rainfall intensity of $44 \text{mmh}^{-1}$ and a filter length
of 200mm. The filtration efficiency for each sediment diameter is shown in Figure 9. Increases in the diameter of the sediments is thus seen to increase filter efficiency. The results suggest that sediment diameter 0.1 mm shows the greatest rate of increase in filter efficiency with increases in pavement slope. For slope 1, the filter efficiency was 62% with sediment diameter 0.1mm, while for slope 3 the filter efficiency was increased to 82%. The main causes of this increase in filter efficiency at 0.1 mm diameter is that this size is relatively small in compression as compared with the other diameters studied, making it easy to move, thus increasing erosion with runoff for the same rainfall intensity and duration. At a diameter of 0.3 mm and slope 1 the filter efficiency was 88%, while at slope 3 it reached 81%. This difference is less than seen with a smaller diameter of sediment because the increase of the diameter makes it difficult for the sediments to pass through the filter in any case, thus decrease the differences in efficiency ratios.

![Figure 9. Effect of diameters of sediment on filter efficiency.](image)

3.4 Effect of duration of intensity on filtration efficiency

The duration of rainfall intensity significantly affects the amount of sediment transported. In order to examine the effect of duration on filter efficiency, five different durations of rainfall intensities were used (5, 10, 15, 20 and 25 min), and each duration was runoff on the pavement layer for five slopes (1, 1.5, 2, 2.5, and 3). The rainfall intensity used was 44 $\text{mm h}^{-1}$, with the diameter of sediments set to 0.2 mm and the length of filter to 200 mm. The results of the simulations are shown in Figure 10, which offers the filter efficiency for each duration of intensity for each slope. The results show that the value of filter efficiency increases with the increase of duration. In the case of slope 3, the difference in filter efficiency between durations did not exceed 6%, however, while for slope 1, the differences in efficiency between durations reached as high as 15%. It was observed from the results that the filter efficiency is near uniform, due to constant rainfall intensity, where the runoff has a stable velocity; at such points, the volume of sediments transported increases uniformly with the increase of duration of intensity.
4. Development of a filter efficiency formula

Dimensional analysis is a mathematical instrument that shapes the form of any relationship used to describe a natural phenomenon (Buckingham method), and it can be used to solve the physical mechanisms of system operation. The variables that characterise fluids include the density of water ($\rho$), while the variables that characterise the flow include the duration of intensity ($T$), rainfall intensity ($I$), the bed slope ($S_0$), and acceleration due to gravity ($g$). The variables that characterise the filter include the length of the filter ($L_f$), the diameter of sediments ($D_s$), and the mass of sediments ($M_s$), with the variables that characterise the mass of sediments being the mass of sediments passing through the filter ($M_o$) and the mass of sediments passing through the manhole ($M_i$).

$$f(M_i, M_o, M_s, I, T, D_s, g, S_0, L_f, \rho) = 0 \quad \text{... (12)}$$

$$E_f = \frac{M_i - M_o}{M_i} = f \left( S_0, \frac{I \cdot T \cdot L_f}{L_f}, \frac{D_s}{L_f} \right) \quad \text{... (13)}$$

IBM SPSS was used to analyse the data and build the required model. Figure 11 presents a comparison between the numerical data and the estimated values for filter efficiency. The value of the coefficient of determination for the equation was $R^2 = 0.88$.

$$E_f = 0.38 + 210 \left( \frac{D_s}{L_f} \right) + 0.13S_0 + 1.68S_0 \left( \frac{I \cdot T}{L_f} \right) - 51.4S_0 \left( \frac{D_s}{L_f} \right) - 0.51 \left( \frac{I \cdot T}{L_f} \right) (S_0)^2 \quad \text{... (14)}$$
Figure 11. Comparison between numerical and predicted efficiency $E_f$.

5. Conclusions
This study investigated the efficiency of a new gravel filter inside gullies on the sides of roads by applying experiment and numerical models with different rainfall intensities. The aim was to increase the efficiency of rainfall networks by suggesting a new gravel filter, and the results showed that the maximum percentage error between the numerical and laboratory model was 16%, with a value of $R^2$ of 0.93, suggesting that the results are acceptable. Road slope had significant effects on filter efficiency, with filter efficiency being 73% for the minimum slope (1%) of road and 86% for the maximum slope (3%) with median intensity. The length of filter, intensity, duration of intensity, and sediment particle sizes were also seen to play vital roles in gravel filter efficiency, however, with increases in all of these parameters increasing filter efficiency. The diameter of sediments was the most significant factor with regard to responses to duration of intensity, with correlation coefficients of 0.3 and 0.21 emerging for the diameter of sediments and the duration of intensity, respectively. The advantage of using a numerical model was the ability to develop a statistical equation to calculate the passing ($M_f/M_g$) ration, with an SPSS model developed to estimate the passing ratio developed such that $R^2 = 0.88$. This suggests that the experimental work can be extended to study the effect of new variables such as the type of gravel used in the filter and tested against such models.
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