An integrated technique for assessing flow parameters through subsurface drainage module systems

A S Abdurrasheed1,2, K W Yusof†, H Takaijudin1, E H H Al-Qadami1, A A Ghani1,4, M M Muhammad1, A T Sholagberu1,5, V Kumar1 and S M Patel1

1 Department of Civil and Environmental Engineering, Universiti Teknologi Petronas, 32610, Perak, Malaysia
2 Department of Civil Engineering, Ahmadu Bello University, Zaria, Nigeria
3 Department of Water Resources and Environmental Engineering, Ahmadu Bello University, Zaria, Nigeria
4 River Engineering and Urban Drainage Research Centre (REDAc), Engineering Campus, Universiti Sains Malaysia, Nibong Tebal, Pulau Pinang, Malaysia
5 Department of Water Resources and Environmental Engineering, University of Ilorin, Ilorin, Nigeria

E-mail: asa00@ymail.com

Abstract. Drainage modules are storage units for rainwater harvesting and are used to promote groundwater recharge, storage, quality and quantity control as well as reuse of surface runoff. Different assessment methods were applied in the past to assess the efficiency and performance of subsurface drainage modules including laboratory experiments, field and numerical. However, very few methods had been identified to use computational fluid dynamics (CFD) techniques to assess the performance numerically. In this paper, CFD was applied to study the flow parameters of Rainsmart modules. Among the findings of this study is that the module used alters the pattern and creates flow resistance with a higher Manning’s roughness coefficient of 0.10 at the US and a lower one of 0.02 at the DS which signifies the effect of the module. The modules pattern had been observed to be the major cause of the variation with the retardation occurring at the blocked parts and the increase across the porous openings. The study, however, recommends the application of numerical techniques to study the effect of the module under different slope and gate opening and closing conditions.

1. Introduction

Among the major causes of high surface runoff in our environment today is the issue of rapid urbanization which leads to more impervious surfaces due to the presence of more rooftops, car parks, paved surfaces, etc. Drainage modules are storage units at the subsurface of a drainage channel for rainwater harvesting used to promote groundwater recharge, storage, reuse, quantity and quality control of surface runoff [5, 9]. In Malaysia, these modules can be found in the Bio Ecological Drainage System (BIOECODS) of River Engineering and Urban Drainage Research Centre (REDAc) at Universiti Sains Malaysia (USM) as part of a pilot project to mitigate flooding and its detrimental impacts [6, 7]. In addition, due to their body pattern and roughness, drainage modules had been reported to provide flow attenuation especially in the BIOECODS. They usually come in different shapes and pattern with the main purpose of lag time increase in the flow or creating attenuation and
utilizing storage and ground water recharge as means of reducing volume of the surface runoff [2].

![Figure 1. Rainsmart module in the swale system](image)

Rainsmart module (RS) as shown in Figure 1 had been reported to have the potential to be highly applicable in the BIOECODS system as the module is designed for storage, provide infiltration through the soil pores and ensure controlled release to the stormwater in the drains [6]. A review of the advances in the technology can be found in [2]. Different assessment methods were applied in the past to evaluate the efficiency and performance of subsurface drainage modules including laboratory experiments, field and numerical. However, very few methods had been identified to use Computational Fluid Dynamics (CFD) technique to assess the performance of these modules numerically. Due to the latest developments in numerical techniques, this study therefore, applied the commercial general-purpose software (FLOW-3D) due to its robustness and accuracy in reproducing experimental results in other similar flow cases [3].

2. Materials and Methods

2.1. The experimental method of assessment

The experimental results of [1] were adopted in this study. The study already validated the application of FLOW-3D in the assessment of the REDAC module. This paper equally adopts a similar methodology in assessing the Rainsmart module performance parameters especially in terms of flow resistance.

2.2. Numerical model development

2.2.1 Geometry development and simulation setup. For the purpose of this study, Figure 2 shows the geometry of the RS module developed using the SOLIDWORKS CAD software. The dimensions and all the details are detailed in the figure. The geometries were then imported into the software using the stereolithography (.STL) file format. The simulation units were set to be centimeter gram second (CGS) system of units. Also, the gravity and non-inertial reference frame were selected in the Physics setup. In the viscosity and turbulence tab, and the viscous RNG model were selected with no-slip as the wall shear boundary conditions. Due to the symmetrical nature of the module, half of it was selected in order to reduce the number of cells as well as the computational time as highlighted by [3].
2.2.2. Meshing and Boundary conditions. Two mesh blocks were used in the meshing setup tab including the nested (with a size of 0.32 cm) and the containing mesh block (with a size of 0.64 cm). The Fractional Area-Volume Obstacle Representation (FAVOR) was used in the mesh independence studies. Figure 4 shows the boundary and initial conditions setup. An inlet velocity of 38 cm/s with an initial flow elevation of 8.3 cm was specified as the inlet conditions. The top and bottom were set to atmospheric pressure (with fluid fraction set to zero) and wall respectively. The left side was set to symmetry due to the nature of the geometry as highlighted earlier. The outlet condition was set to pressure outlet with a flow elevation of 2 cm.
3. Results and discussion

3.1. Numerical model validation with experimental results

In this study, to assess the validity and accuracy of the FLOW-3D modelling software, it was verified with the experimental results. The verification in the research by [1] on the use of the REDAC module was adopted in this study. The validation in this paper was achieved by measuring velocities at two points before and after the module. The two points were at 40 cm at upstream (US) and downstream (DS) of the module. Table 1 shows the validation of the numerical with experimental results. From the table, it can clearly be observed that, with a percentage error of less than 5%, there is a strong agreement between the numerical and experimental findings. The difference can be ascribed to mesh quality resolution. This value is acceptable according to [4].
3.2. Rainsmart module performance assessment

After the validation of the numerical results with the experimental, the CFD software FLOW-3D was applied to assess the performance of Rainsmart module in terms of flow parameters and resistance. The assessment was done using two cases of free flow without module (FFWM) for control purposes and flow with a module (FWM). The two cases were compared, and the effects of the module were observed and recorded.

| Working conditions | FFWM | FWM |
|-------------------|------|-----|
| Flow Parameter    | Exp. | Num. | % Error | Exp. | Num. | % Error |
| Flow Velocity (cm/s) | 51.6 | 50.40 | 2.38 | 42.00 | 43.50 | 3.45 |
| Flow Depth (cm)    | 52.5 | 53.18 | 1.28 | 44.50 | 46.50 | 4.30 |
| US                 | 7.6  | 7.71 | 1.43 | 7.65 | 7.75 | 1.29 |
| DS                 | 6.38 | 6.52 | 2.15 | 6.30 | 6.50 | 3.08 |

3.2.1. FFWM and FWM

Figure 5 shows the flow parameters plots of the FFWM case from upstream (US) to downstream (DS). Five probe points were used to assess the performance parameters. From the Figure, the flow resistance can be observed to remain constant in the flow path. In the flow with module, the most noticeable change is in the flow depth which varies from US (with a value of 9.12 cm) to DS (with a value of 3.78 cm), an increase in the velocity of flow from US (a value of 34.87 cm/s) to DS (a value of 88.74 cm/s). Moreover, while the flow depth signifies attenuation or delay in the flow, the velocity increase signifies the direct effect of the module in the flow path.

![Figure 5](image_url)

**Figure 5.** Flow parameters on FFWM case (a) US Flow depth at the probes (b) DS depth-averaged
velocity at the probes (c) DS Flow depth at the probes (d) US depth-averaged velocity at the probes

Figure 6 depicts the variations of the flow parameters in the flow with module plates. From the Figure, the lower value at probe 1 in both cases (30.01 in case a and 75.73 cm/s in case b).

**Figure 6.** Flow parameters on FWM case (a) US depth-averaged velocity at the probes (b) DS depth-averaged velocity at the probes

**Figure 7.** Flow parameters on FWM case (a) US flow depth at the probes (b) DS flow depth at the probes are as a result of the wall friction in the flow path
Figure 7 shows the flow depth variation from the US to DS under the case of FWM. From the Figure, the flow can be observed to show a decrease in-depth as highlighted earlier. This is evidence of flow attenuation due to the presence of the module. Table 2 shows the summary of the flow parameters computation for the two cases of flow with and without modules. From the table, the flow resistance can be observed to remain constant in the flow without module and decrease in the flow with the module from a value of 0.10 at the upstream to about 0.02 at the downstream. Manning’s coefficient variation signifies flow resistance due to the presence of the module.

| Flow parameters computations | Flow conditions | Y (cm) | A (cm$^2$) | V (cm/s) | Q (cm$^3$/s) | n |
|------------------------------|----------------|--------|------------|----------|--------------|---|
| FFWM                         | US             | 5.24   | 209.60     | 61.50    | 12890.40     | 0.04 |
| DS                           |                | 5.06   | 202.40     | 63.36    | 12824.06     | 0.04 |
| FWM                          | US             | 9.12   | 364.80     | 34.87    | 12720.58     | 0.10 |
| DS                           |                | 3.78   | 151.20     | 88.74    | 13417.49     | 0.02 |

4. Conclusion and Recommendation
This paper applies the numerical technique to study the flow parameters variation through the popular Rainsmart module with consideration of numerical validation from the work of [1]. The following conclusions were drawn based on the results and discussion:
1. Flow 3D was able to model flow parameters in the module with greater certainty. This can be ascribed to minimal percentage error of observed which is less than 5%. By the application of the software on this type of module, it means that other laboratory parameters can be studied, 2D and 3D views can be visualized with high degree of confidence and accuracy with this model. Therefore, it is suggested that FLOW-3D can be a useful and supplementary tool for module design and analysis.
2. The Rainsmart module was able to alter the pattern and creates flow resistance with a higher Manning’s roughness coefficient of 0.10 at the US and a lower one of 0.02 at the DS which signifies the effect of the module. The modules pattern had been observed to be the major cause of the variation with the retardation occurring at the blocked parts and the increase across the porous openings.
3. This technique can be highly applicable in the BIOECODS to study the behavior of larger number of modules and can be used to eliminate the frequent repetition of the laboratory experiment which is expensive and time consuming. The study, however, recommends the application of numerical techniques to study the effect of the module under different slope and gate opening conditions.

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