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NUMERICAL ASSESSMENT TO HARVEST RAINWATER THROUGH CORE CUTS ON A FLAT ROOF

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ABSTRACT

An approach of rainwater harvesting (RWH) collected from the roof of a building provides the practical and effective utilization of rainwater which would ensure the availability and sustainable management of water. Instead of flat slabs, architects have designed attic and inverted slabs, which can serve the purpose of rainwater catchments and allow water to fall into dedicated catchment areas. Herein, the approach of rainwater collection through the core-cut method on a flat slab was analyzed on FLOW-3D based on the mean annual rainfall data of Karachi city, Pakistan. The results of the numerical simulation ensured that the developed harvesting system had the capability to capture and deliver the collected water into the storage tank. It has been noticed that between time 0 and 54 seconds, the value of the volume flow rate was 0, which indicated that the rainwater took time to accumulate prior to flowing into the cuts. After t = 54 seconds, a sudden increment in the volume flow rate was observed. This was due to the rainwater that accumulated on the roof and started to go through the cuts. However, after t = 70 seconds, the volume flow rate became steady and very minor fluctuations in the flow rate were noticed.

Keywords: Rainwater harvesting, RWH, Core cuts, Flat roof, Sustainability, SDG 6.

INTRODUCTION

Water always changes its state from liquid to vapor by means of evaporation and then returns to Earth in the form of precipitation and snowfall by means of condensation. This balanced water cycle describes the movement of water on, above and below the surface of the earth. Rainwater, being the purest form of water, is one of the weighty sources of living in different parts of the world but due to the depletion of the major water resources and the rise in global warming, an effective decrease in water resources has been witnessed (Kumar et al., 2021).

Alternatively, extreme rainfall events could lead to disasters and unwanted casualties. Thus, as engineers, one should respond to this by implementing methods to conserve rainwater through effective strategies that can be altered in the project life cycle and essential daily processes. One such economical technique would be rainwater harvesting (RWH), which would not only conserve rainwater but also mitigate the impact of floods. However, the acceptance of RWHs is limited and confined due to their high setup and initial costs. Apart from the initial and maintenance cost, RWH is an ideal way out of all water-related problems in this highly integrated and developing world (Shah et al., 2021). Furthermore, the contamination of roof-collected potable water is of major concern. A good quality water source within the low-risk category of the World Health Organization (WHO) can be ensured if a well-kept catchment system is implemented. In contrast, a poor collection basin and maintenance strategy will reduce this quality (Meera and Ahammed, 2006). Herein, the water quality parameters have not been taken into consideration and the focus was mainly on the roof behavior toward rainwater collection.

Subsurface artificial recharge and domestic roof-water harvesting approaches have been common practices for years. Herein, the numerical simulation was performed mainly focusing on the concept of core cuts in the flat slab roof-top. Since the study was conducted in the Karachi, city – Pakistan, the rainfall data of the city for the last 25 years from 1996 to 2020 were received from the Pakistan Meteorological Department.

LITERATURE REVIEW

Conventional rainwater harvesting approaches

Rainwater harvesting is a simple approach that gathers the run-off coming from rocky catchments, paved lands, rooftops, etc. and collects it in the storage tank for future use as shown in Fig. 1. The runoff coming out of an urban building is less polluted than other impermeable surfaces, such as roads and parking lots; thus, these structures are recommended as a potential source of utilizing rainwater for drinking and domestic purposes. Studies have shown that green roofs help stabilize the pH of rainwater almost to neutral: however, the concentration of ions, namely, Fe, Al, and Cu, increases as runoff is generated. It further filters the nutrients, namely, nitrates and phosphates, from the runoff water. Thus, it is not ideal to integrate green roofs, particularly when the source of water collection is the roof-top of an urban building (Hoseini et al., 2015).

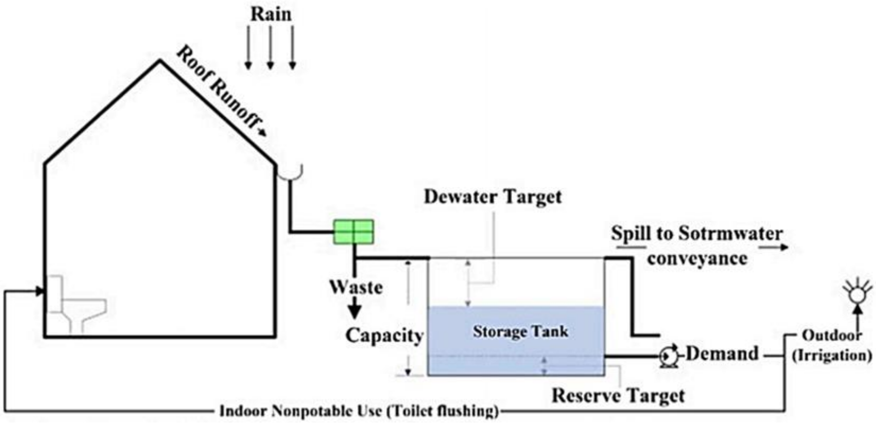


Figure 1: A typical rainwater harvesting system, adapted from Hoseini et al. (2015)

To select the most appropriate roof that could maximize rainwater harvesting on a roof-top, a one-way design with 4 levels of slope on different roof surfaces with different surroundings was performed as shown in Fig. 2. For each roof type, namely Clay Tile (Slope: 30°) – CT, Metal Sheet (Slope: 30°) – M, Polycarbonate Plastic (Slope: 30°) – P and Flat gravel (Slope: 1°) – F, it was determined that the surface runoff greatly depends on the rainfall height. However, the maximum abstraction of the rainfall was noticed from the F-type roof, whereas other sloping roofs showed minimal abstraction. Low levels of pollutants were noticed in the sloping roofs: on the other hand, the contaminants on the F-type roof were found at high levels mainly due to roof weathering, plant colonization, particles deposition, etc. Based on the above observations, it has been recommended that sloping roofs perform best (Farreny et al., 2011).

It has been reported that the quality of harvested water is greatly influenced by the type of roofing materials, as shown in Fig. 3. For instance, ceramic tile roofs have shown prominent outcomes in regard to assessing rainwater quality when compared to asphalt and concrete tile roofs. However, prior to consuming the harvested rainwater obtained from the ceramic tiles, it has been advised to treat it as the COD and TN values obtained from it exceeded the drinking water standards. Concerning green roofs, it has been reported as a source of ions, the release of TN from such roofs has been witnessed, and the COD concentration was found to be high. It is therefore advised not to use green roofs (Zhang et al., 2014).

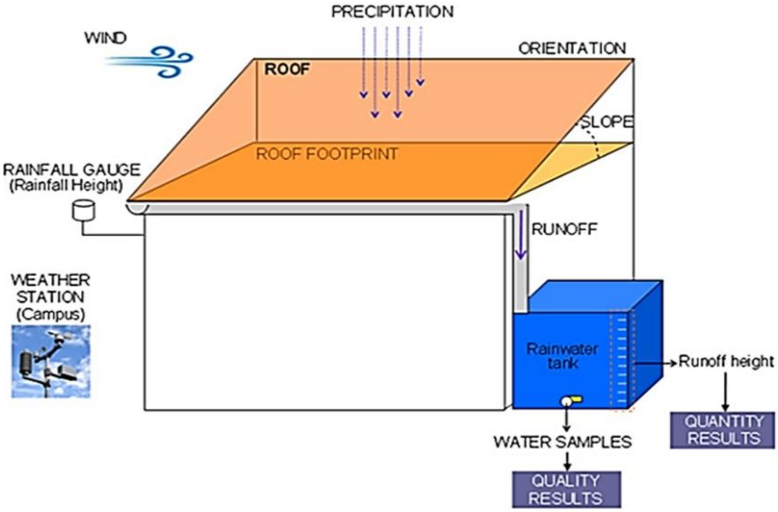


Figure 2: Experimental design setup, adapted from Farreny et al. (2011)

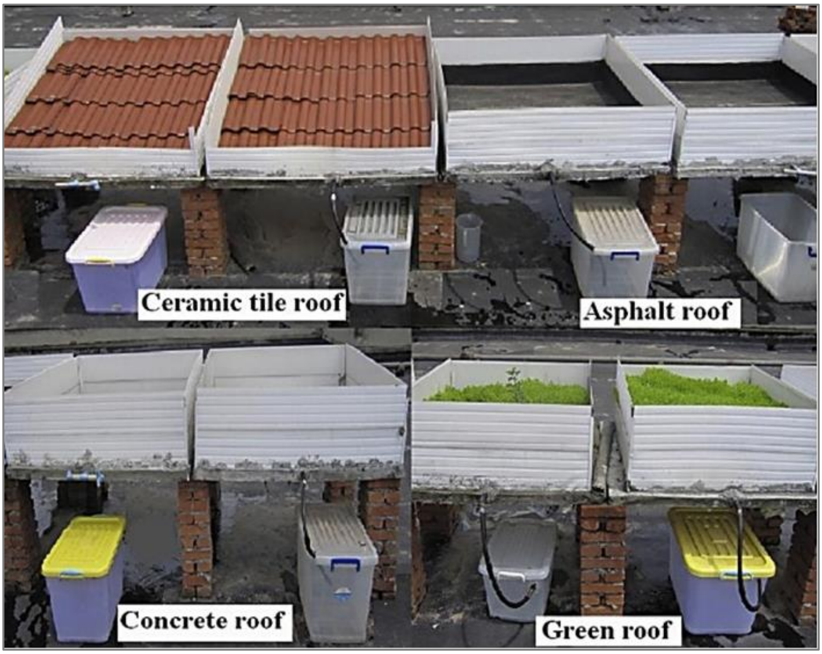


Figure 3: Conventional and green roofs, adapted from Zhang et al. (2014)

Harvested Rainwater Treatment

Rainwater treatment is of primary importance in regard to utilizing harvested rainwater. For developing countries, this criterion should be ensured only if the treatment procedure is inexpensive. As a very first measure, it is advised to cut off the very first flush of the rain event followed by disinfection, which is usually fulfilled through chlorination either by chlorine gas or chlorine tablets. The bacteriological quality of water can be obtained either by a rapid or slow sand filter. Slow sand filters are preferred mainly due to their filtration process, which relies on biological treatment. Another process for the elimination of particulate matter in water can be obtained by boiling. This can be achieved by means of radiation through a process called pasteurization. Pasteurization can be achieved in plastic bags or continuous flow reactors at 50°C. Finally, for the removal of hazardous substances from water, metal membrane filters are recommended. These filters appear suitable to clarify rainwater up to utilization quality (Helmreich and Horn, 2009).

Conventional rainwater harvesting approaches have been recognized as tools of low impact development (LID) solutions that aim at conserving the water cycle in the urban environment (Palla et al., 2017). In recent decades, many developing countries have undergone urbanization; thus, many construction activities are being carried out. Once constructed, a building structure is usually provided with a rooftop, which can be of several types, namely, flat, shed, gable, pyramid, etc. Since the focus of the study is Karachi city, where the rooftops are usually flat, an open-terraced structure was analyzed provided with core cuts for rainfall water collection, as shown in Fig. 4. To assess the rainfall data of Karachi, the statistics were provided by the Pakistan Meteorological Department (PMD) between 1996 and 2020.

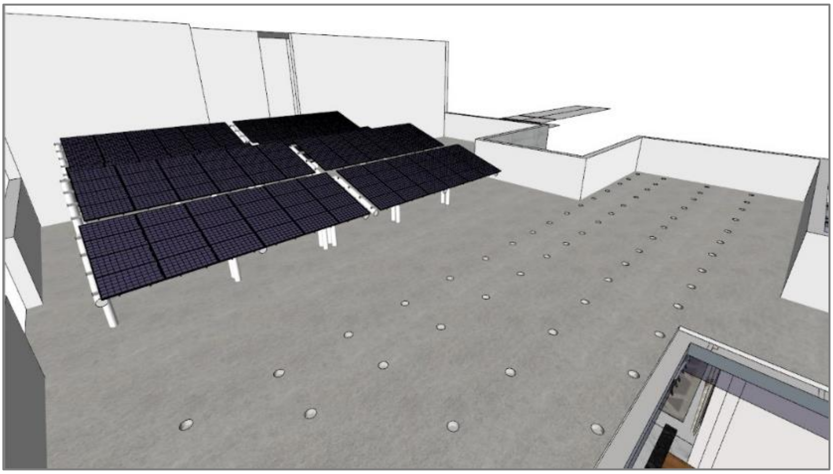
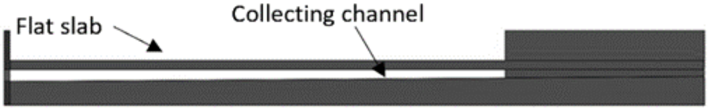


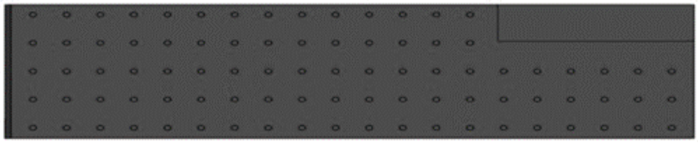
Figure 4: Core Cut for Rainwater Penetration

METHODOLOGY

In this study, a numerical study was performed through Flow3D to investigate the efficiency of the newly developed rainwater harvesting system which consists of two main parts, namely, the flat slab with a core cut and the collection tank, as shown in Fig.5.



a) Front View



b) Top View

Figure 5: Flat slab geometry

To solve the fluid flow in a 3D form, the governing equations were solved by software, including continuity and momentum equations. These equations can be written in the general form as in Eq. 1 and 2-4. On the other hand, the k- Ɛ model was used to solve the fluid turbulence which consists of two transport equations namely, turbulent kinetic energy k_T (Eq.5) and its dissipation $Ɛ_T$ (Eq. 6). The free surface flow was solved by implementing the volume of fluid (FOV) method, which was represented by the factor F, which ranges between 0 and 1. The case F = 0 refers to empty cells, F = 1 represents the case where the cells are full of fluid, and 0 < F < 1 refers to cells partially full of fluid.

$$V_F\frac{\partial P}{\partial t}+A_x\frac{\partial u}{\partial x}+A_y\frac{\partial v}{\partial y}+A_z\frac{\partial w}{\partial z}=\frac{R_{SOR}}{\rho} \tag{1}$$

$$\frac{\partial u}{\partial t}+\frac{1}{V_F}\left\{uA_x\frac{\partial u}{\partial x}+vA_y\frac{\partial u}{\partial y}+wA_z\frac{\partial u}{\partial z}\right\}=-\frac{1}{\rho}\cdot\frac{\partial P}{\partial x}+G_x+f_x \tag{2}$$

$$\frac{\partial v}{\partial t}+\frac{1}{V_F}\left\{uA_x\frac{\partial v}{\partial x}+vA_y\frac{\partial v}{\partial y}+wA_z\frac{\partial v}{\partial z}\right\}=-\frac{1}{\rho}\cdot\frac{\partial P}{\partial y}+G_y+f_y \tag{3}$$

$$\frac{\partial w}{\partial t}+\frac{1}{V_F}\left\{uA_x\frac{\partial w}{\partial x}+vA_y\frac{\partial w}{\partial y}+wA_z\frac{\partial w}{\partial z}\right\}=-\frac{1}{\rho}\cdot\frac{\partial P}{\partial z}+G_z+f_z \tag{4}$$

$$\frac{\partial K_T}{\partial t}+\frac{1}{V_F}\left\{uA_x\frac{\partial K_T}{\partial x}+vA_y\frac{\partial K_T}{\partial y}+wA_z\frac{\partial K_T}{\partial z}\right\}=P_T+G_T+Diff_{KT}-\varepsilon_T \tag{5}$$

$$\frac{\partial \varepsilon_T}{\partial t}+\frac{1}{V_F}\left\{uA_x\frac{\partial \varepsilon_T}{\partial x}+vA_y\frac{\partial \varepsilon_T}{\partial y}+wA_z\frac{\partial \varepsilon_T}{\partial z}\right\}=\frac{CDIS1.\varepsilon_T}{K_T}+(P_T+CDIS3.G_T)+ Diff_{\varepsilon}-CDIS2\frac{\varepsilon_T^2}{K_T} \tag{6}$$

To capture the 3D model geometry three uniform orthogonal mesh blocks with a Cartesian coordinate system were designed and generated as shown in Fig. 6. Mesh blocks 1 and 3 were generated to capture the rain column and the collecting channel, respectively with a mesh cell size of 0.05 m. On the other hand, mesh block 2 was designed to capture the flat slab and the core cuts with a cell size of 0.025 m. An additional mesh block with a cell size of 0.05 m was generated to capture the fluid flowing from the outlet and this mesh block acted as a tank to store the collected rainwater. Table 1 summarizes the designed mesh blokes and captured sections. To check the 3D geometry model captured by the designed mesh blocks, the FAVOR solver was used. Fig. 7 shows the geometry after applying the FAVOR solver, and it can be said that the cell sizes used were good and applicable.

Table 1: Cell sizes

Mesh Block	Cell Size (m)	Number of Cells	Captured Section	Aspect Ratio
1	0.050	110700	Rainwater column	1
2	0.025	442800	Flat slab and the core cuts	1
3	0.050	129150	Collecting channel	1
4	0.050	4800	Storage tank	1

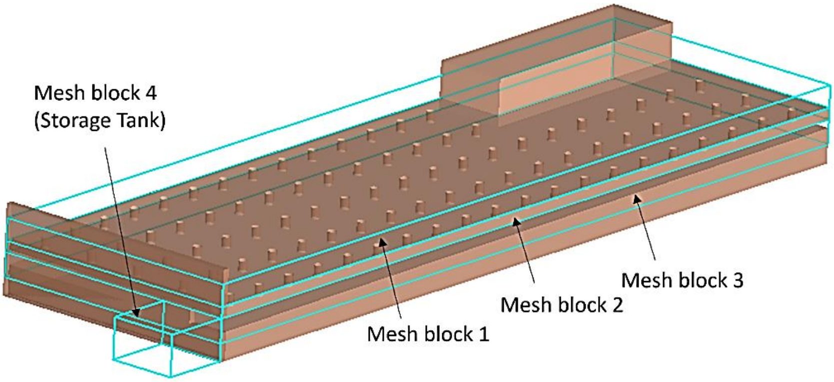


Figure 6: Mesh block arrangement

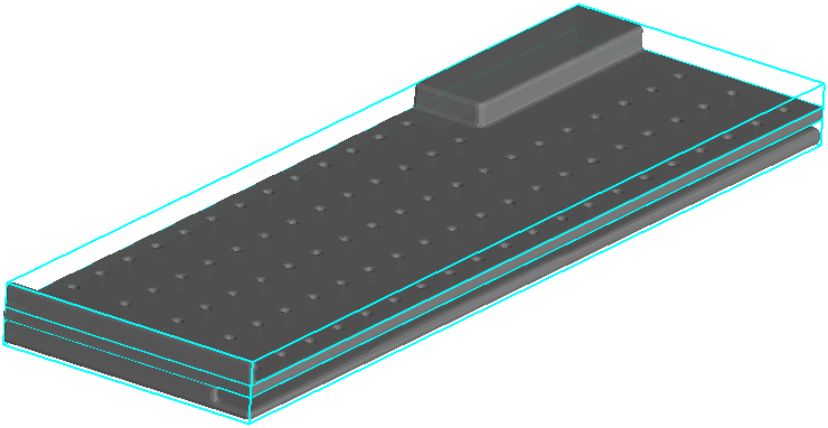


Figure 7: Model 3D geometry after running the FAVOR solver

To represent the real-life conditions, proper boundary conditions were selected to define each model side. The top face of mesh block 1 was considered the inlet, and it was defined with a flow discharge of $0.05m^3/s$ and a fluid fraction of 1. The outlet was defined as a free flow with atmospheric pressure and 0 fluid fractions. Other external sides of the mesh blocks were defined as walls with no slip, while the internal sides were defined with symmetry boundary conditions. To measure the magnitude of the collected water from all core cuts, a flux surface was placed in the middle of the flat slab. The flux surface is a horizontal plane probe that has the ability to detect and record the flow discharge that crosses it.

RESULTS AND DISCUSSION

According to the results of the numerical simulation, the developed rainwater harvesting system had the capability to capture rain and deliver the collected water into the storage tank, as shown in Fig. 8. Fig. 9 shows the volume flow rate Q variation with time which was recorded by the flux surface at each time step. It can be seen that between times 0 and 54 seconds, the value of Q was 0, which indicated that rain had not been started. After time (t =54 seconds), a sudden increment in the volume flow rate was observed. This was due to the rainwater that accumulated on the roof and started to go through the core cuts. However, after t = 70 seconds, the volume flow rate became steady and minor fluctuations were noticed. This was because the rainwater started to flow in a uniform manner. In this case, under the same rainfall intensity and roof area used in this study, the average volume flow rate was approximately $0.03m^3/s$.

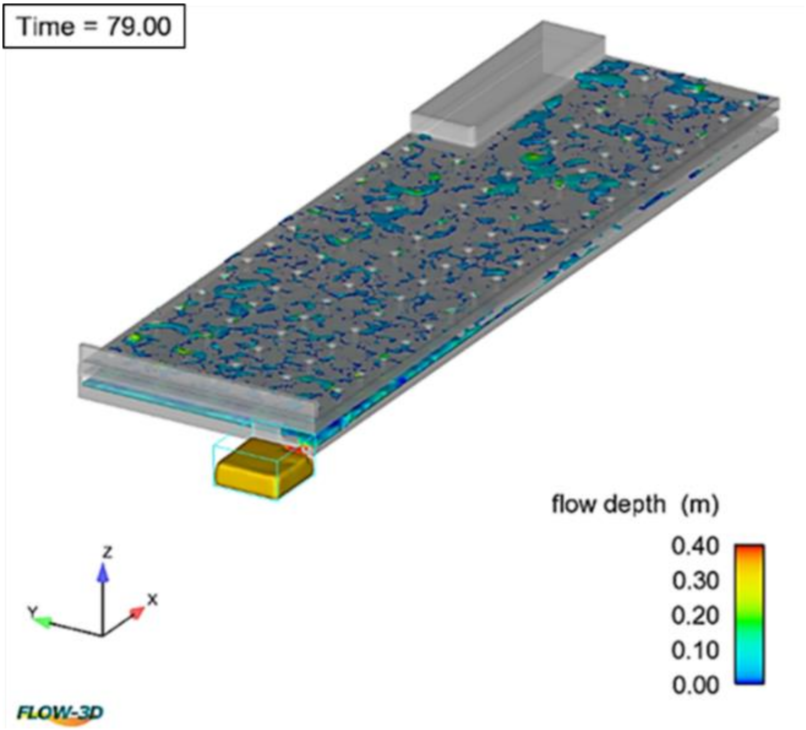


Figure 8: 3D plot illustrating the water depth distribution among the models

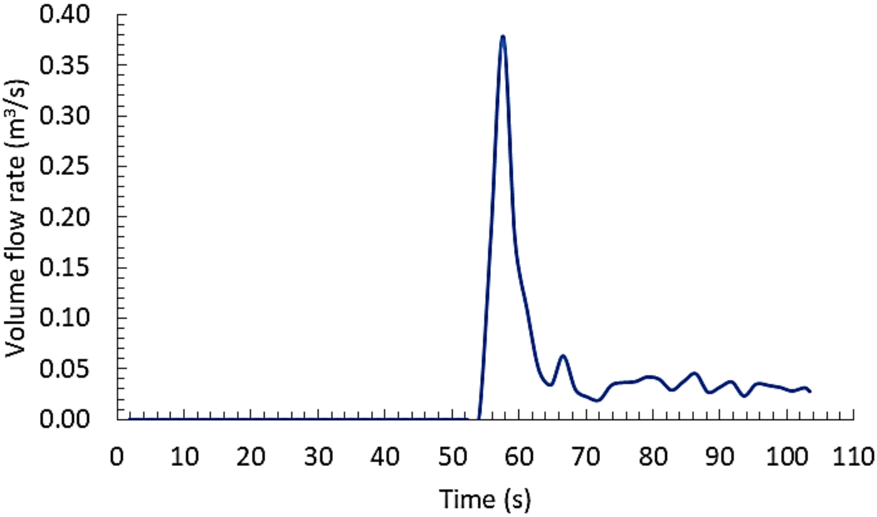


Figure 9: Volume flow rate variation with time

Fig. 10 shows the 2D plot of the flow velocity and water depth among the whole system at 80 seconds. The water moved gently into the storage tank through the collecting channel. However, some water accumulated inside the collecting channel, which required more investigation to enhance the system efficiency.

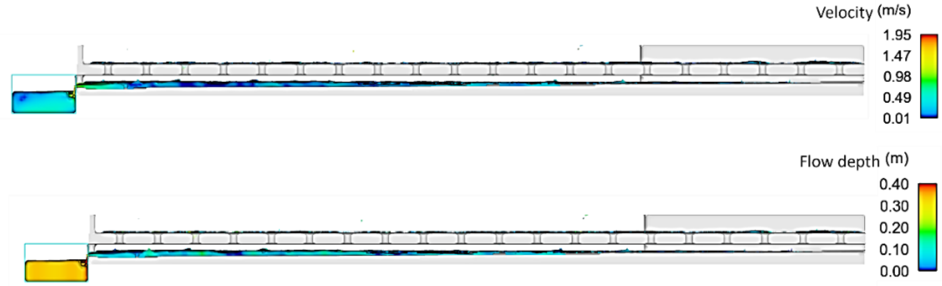


Figure 10: 2D plot illustrating the velocity and flow depth distributions

CONCLUSIONS

Considering the imperative need for sustainable engineered approaches, rainwater harvesting plays a crucial role in conserving rainwater. Rainwater Harvesting can be implemented in rain-fed areas across the globe. The developed rainwater harvesting system would be capable of capturing the rain and delivering the collected water into the storage tank, which has been further clarified by the volume flow rate Q variation with time recorded by the flux surface at each time step. Keeping in mind the seasonal climatic change in Karachi city, new developing schemes and projects should integrate such rainwater harvesting techniques. Rainwater harvesting is an essential element of green building matrices that upholds the imperative need to recycle or consume precipitation more effectively. However, more investigations on the proposed design would further enhance the system efficiency.

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