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RESEARCH ARTICLE

HYDRODYNAMIC MODELLING OF ACTIVE DOMESTIC RAINWATER HARVESTING FOR FLOOD MITIGATION IN SEMI-ARID URBAN AREAS: CASE STUDY, ABHA CITY, SAUDI ARABIA.

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ABSTRACT

Unplanned urban expansion, which disregards urban runoff drainage, leads to flooding in urbanized catchments, making it one of the most dangerous disasters. The current study aims to evaluate the effect of implementing active rainwater harvesting (RWH) tanks at a domestic scale in controlling and managing urban floods in a semi-arid urban area. The study employed PCSWMM, the Personal Computer Storm Water Management Model, to run a 2D model for investigating the effect of implementing RWH tanks on peak runoff reduction. Simulations were conducted for various return periods (2y, 5y, 10y, 25y, 50y, and 100y) for both with and without RWH scenarios, utilizing varying tank sizes. The research found that domestic rainwater harvesting has a major effect on reducing surface runoff. The reduction values are dependent on the depth of the rainfall, the size of the tank, and the proportion of the roof ar-ea to the total area of the parcel. Moreover, the reduction values have maximum values which cannot be exceeded even with increasing tank size. The maximum peak reduction values are (42.37%, 40.43%, 39.65%, 38.65%, 38.2%, and 37.75%) for the return periods (2y, 5y, 10y, 25y, 50y, and 100y) by using tank sizes of (8, 12, 18, 24, 32, and 40) m^3 respectively. Gener-ally, the deduced results improve understanding of the active domestic rainwater harvesting effect on the runoff peak reduction in a semi-arid urban area and its ability to reduce urban flood depths and discharges.

KEYWORDS

Urbanization; urban runoff; stormwater; sustainable urban drainage systems (SUDS); PCSWMM.

1. INTRODUCTION

Urbanization induces abrupt changes in land use, and in general, the most forceful change for all land use changes that are potentially affecting the hydrology of catchment through stream degradation is urbanization (Akhter and Hewa, 2016; Qin, 2020; Zhou et al., 2019). Where natural landscapes trap rainwater to filter into the ground and reach water bodies gradually, however, impervious surfaces such as roads, parks, and buildings do not allow runoff to per-colate into the ground. This is why the loss of permeable catchments, and the growth of im-pervious areas have had a bad effect by raising runoff peak discharges and volumes. This makes it more likely that existing drainage networks will become flooded or waterlogged. In some areas, due to financial constraints or limited space, it is not always possible to implement conventional pipe drainage systems (Hassan et al., 2022; Kaykhosravi et al., 2020; Maksi-mović et al., 2009). Conversion of natural watersheds to urban lands has a major effect upon natural hydrological streams due to vegetation cover removal, modification of stream chan-nels, and increase in impervious surfaces (Taji and Regulwar, 2021; Leopold, 1968; Abdrabo et al., 2022). When these kinds of changes happen, the land's surfaces often have less hydrau-lic resistance. This makes the hydrograph flashier, with the storm event hydrograph rising and falling faster and higher and earlier peak flows (Arnone et al., 2018; Qiao et al., 2020; Bedan and Clausen, 2009).

While many factors influence runoff volume and discharge, one finding is that peak discharg-es in urbanized catchments are 30% to 100% higher than in non-urbanized or natural catch-ments (Jacobson, 2011). The natural hydrological processes of catchments receive water run-off from non-urbanized areas. The smooth surface and low percolation rates of impervious catchments lead to increased urban runoff. Consequently, the percentage of imperviousness is the most important environmental indicator for studying the effects of urbanization on the aquatic environment (Chithra et al., 2015). Figure 1 shows the impact of urbanization on hy-drological processes and hydrographs of stream flows. Erosion, water quality, the layout of hydraulic flood control and stormwater drainage systems, habitat quantity and quality, and other downstream consequences can be rather detrimental because of these effects. The post-developed catchment surfaces have high flow velocities, which reduces the lag time and makes the storm hydrograph more visible. Peak flows are bigger than they would be under natural surface conditions due to this more visually striking hydrograph (Price, 2011; Hung et al., 2018; Huang et al., 2008; Burns et al., 2005; Fletcher et al., 2013.

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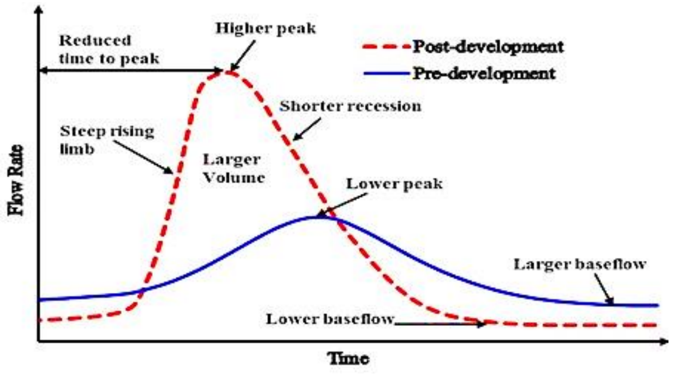


Figure 1: Pre- and post-development runoff hydrographs over an urban area (Rezaei et al., 2019).

Figure 1 shows how the hydrograph changes because of urbanization's influence on the catchment's hydrological system, namely how the time to peak, peak flow, and total discharge are all reduced and increased, respectively (Rezaei et al., 2019).

To minimize these negative effects of urbanization, some measures are employed that include the implementation of the concept of sustainable urban expansion with regard to spatial urban planning and stormwater flooding control (Woods-Ballard et al., 2007). Many stormwater management measures aim to control and mitigate urban stormwater runoff. These control measures and facilities differ from conventional stormwater drainage networks to more emerging sustainable decentralized systems to manage and control urban stormwater runoff (Stec, 2017). Such decentralized control measures help to make a source control of storm-water runoff in urban areas and provide additional advantages like domestic water harvesting and the greening of urbanized areas. Decentralized stormwater management measures include barrels of rainwater harvesting, rain gardens, green roofs, and porous pavements (National Research Council, 2009). The increased awareness of urbanization's effects on catchment hy-drology and the necessity of managing both the quality and quantity of urban stormwater runoff in the past two decades resulted in the concept of best management practices (BMPs).

There are two main objectives for BMPs: Firstly, it is to mitigate the risk of urban stormwater flooding during storm events. The second goal of BMPs is to reduce pollution in waterways. Some of the other things that should be thought about when choosing between one or more BMPs or a mix of them are the hydraulic analysis of how well it works, the social and envi-ronmental conditions, as well as the cost of construction, operation, and maintenance (Martin, 2007). Sustainable urban drainage systems (SUDs) techniques work in the same way as natu-ral processes. They make use of natural drainage processes (Rezaei et al., 2019). SUDS have gained significant importance as urban stormwater flood management measures because they aim to restore the natural drainage conditions of undeveloped catchments.

Rainwater harvesting (RWH) is one such control measure. Harvesting rainwater is the oldest technique that is used to support water supply for human needs (Campisano et al., 2017), and recently, domestic rainwater harvesting tanks have been considered stormwater management tools to reduce surface runoff volumes in urbanized catchments (Palla et al., 2017). Currently, because of climate change and the recently developed water treatment techniques, domestic rainwater harvesting tanks are recognized as an alternative source of water in many locations in the world. As shown by a recent assessment, rainwater harvesting tanks can be used to mit-igate urban runoff flooding and reduce the pressure and flooded points in existing stormwater drainage networks (Petit-Boix et al., 2018). More people are aware of the benefits of using RWH tanks to lower the risk of stormwater runoff in urbanized catchments, but not enough is known about how well domestic RWH tanks work to control and lower surface runoff vol-umes and peak discharges at different scales of urbanized catchments.

Many diverse goals around the world have stimulated the implementation of RWH tanks. For example, in the United Kingdom, RWH tanks in populated regions are constructed to support the use of non-potable water, like house garden irrigation and flushing toilets and laundries. In governmental and public buildings such as schools, universities, and supermarkets, large sizes of RWH tanks can sustain potable water supply because of their associated economic efficiency (Ward et al., 2012). In Japan, RWH tanks are implemented basically in large-scale buildings like commercial buildings and schools to reduce the stormwater flood risks in urban areas and are also used to help fill shortages in the potable water supply (Campisano et al., 2017). In Australia, by the end of 2013, one-third of households implemented RWH tanks, basically to support reducing the shortage of potable water supply in rural areas (Campisano et al., 2017).

In New Zealand, the installation of rainwater harvesting tanks is regulated by some councils in newly constructed private residential areas as an urban stormwater management control measure used to reduce stormwater runoff flooding and to minimize the negative environ-mental effects of such developments (Gabe et al., 2012). In Egypt, a study conducted found that ground tanks showed effectiveness in reducing urban stormwater flooding volumes in the most vulnerable areas, as the rainfall water was collected in the proposed groundwater tanks and could be reused after treatment by (Wahba et al., 2022).

Domestic rainwater harvesting research has received great attention in countries such as Aus-tralia, France, Italy, China, and the U.S. in the last decades (Campisano and Lupia, 2017; Freni and Liuzzo, 2019; Lawrence and Lopes, 2016; Steffen et al., 2013; Zhang et al., 2012. In a study conducted the results showed that using different RWH options helped to reduce stormwater flows and improve water quality characteristics back to the same as their prede-veloped conditions (Fletcher, T.D., Mitchell, V.G., Deletic, A., Ladson, T.R., Seven, A., 2007). Thus, RWH techniques as a retention system could be useful for the consequent con-trol of stormwater runoff volume (Coombes, P.J., Barry, M.E., 2008). However, only a few studies have assessed the effectiveness of using RWH in reducing urban stormwater runoff flooding (Farahati, 2021; (Burns et al., 2010; Burns et al., 2015). In Nanjing, China, a study was conducted, and it was observed that the use of implemented RWH from buildings' roof-tops has a significant effect in reducing urban waterlogging in sewage infrastructures, and it could be potentially mitigated by rainwater harvesting (Zhang et al., 2012).

Research done for seven cities in the U.S. examines the benefits of urban stormwater control and management at a neighborhood level (Coombes, P.J., Barry, M.E., 2008). results pro-posed that United States urban communities and individual residents can have benefits from using rainwater harvesting techniques as an alternative source of water and as a stormwater control measure. Researchers discovered that RWH can help lower the problems of urban flooding caused by stormwater runoff by lowering the amounts of runoff that happen during three types of rainfall: the heaviest daily rainfall, the heaviest daily rainfall on average each year, and the critical rainfall of rainwater storm events (Freni and Liuzzo, 2019). Pervious studies have investigated the multiple benefits associated with using RWH in different loca-tions around the globe, but there is a lack of studies in the Middle East and especially in the Arab world region, and there is no study carried out within Abha City, KSA. Moreover, pre-vious studies have focused on evaluating the use of passive rainwater harvesting system, which relies on the balance between demand and supply, and considers rainwater control to reduce flooding as a secondary objective. Furthermore, there is no clear assessment of the im-pact of active rainwater harvesting at the local level, and the factors affecting the efficiency of this system, such as rainfall depth, tank size, roof area. Therefore, this study focuses on the effect of using active domestic RWH tanks in controlling and managing urban flood runoff for a residential urban block located in a semi-arid urban environment in Abha city, KSA. The fundamental objective of the research presented is to find out the effect of implementing ac-tive RWH tanks on reducing depths, runoff volumes, and peak discharge of floods in a semi-arid urban environment. The research specifically aims to study and model the current base scenario, which does not include RWH tanks, as well as the proposed scenarios that incorpo-rate RWH tanks of varying sizes for varying rainfall depths.

2. Materials And Methods

2.1 Study Area

An urban residential block located in Abha city is selected, as shown in figure 2, to examine the benefits of implementing RWH tanks at the household scale. Abha city is the capital of the Asir region, which is characterized by a semiarid climate and located at a latitude of 18° 12' 59" N and a longitude of 42° 30' 19" E. It is situated on a high plateau in the southwest of the KSA with an elevation of more than 2200m above sea level and receives more precipita-tion than the other parts of the country. In Abha city, between 2002 and 2020, urban areas increased by 200%; the main urbanization occurred to the east and northeast of the old center (Ansar, and Naima, 2021). The Asir Region has an area of 81,000 km² and has a popula-tion of 1.6 million, which is nearly 3.5% of the total area of KSA and 8% of the country's population. The highlands in the Asir region have an annual average rainfall ranging from 300 mm to 500 mm, which is the highest rainfall in the country and results in 60% of the total sur-face water runoff in Saudi Arabia. It can be used for sustainable farming lands. Rainfall is to occur in any month of the year.

Generally, in the Asir region, the maximum rainfall is in spring and winter. The largest amount of rainfall occurs in spring, but the maximum number of rainy days is in winter. The selected study area is an urban residential portion that has a total area of 58.9 ha; it has various types of land uses like residential, gardens, roads, and public building areas. It has a total number of 699 buildings with an average house area of about 386 m². This residential urban block has a high level at the southwestern boundary, which has an elevation of 2277 m above mean sea level and goes lower in the direction to the northeastern part with an elevation of 2175 m (amsl). This makes the Alnaseem residential block one of the riskiest urban areas; according to analysis , 43.4% of the Alnaseem residential block built-up area is subjected to flood risk.

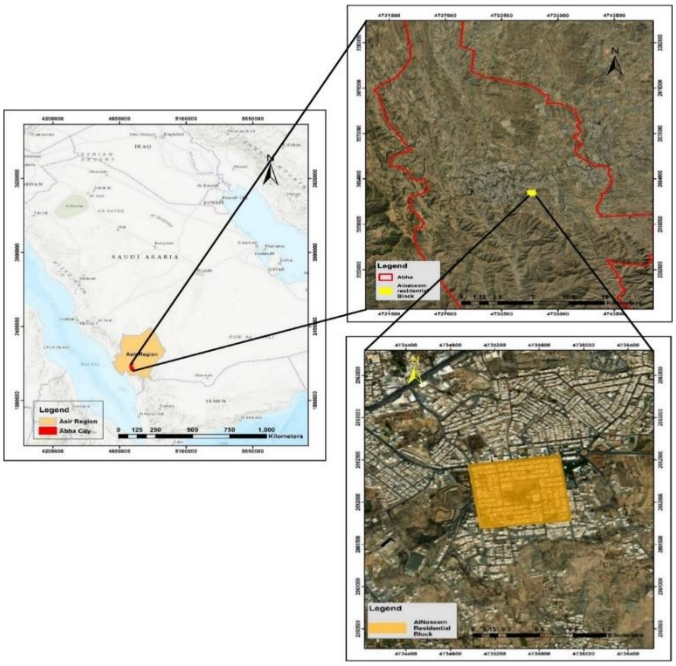
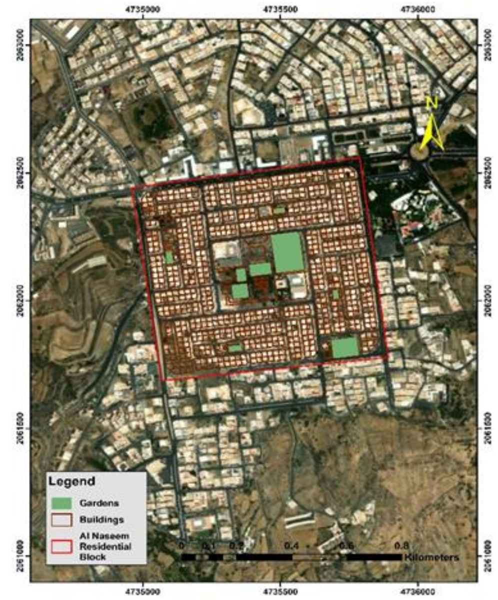


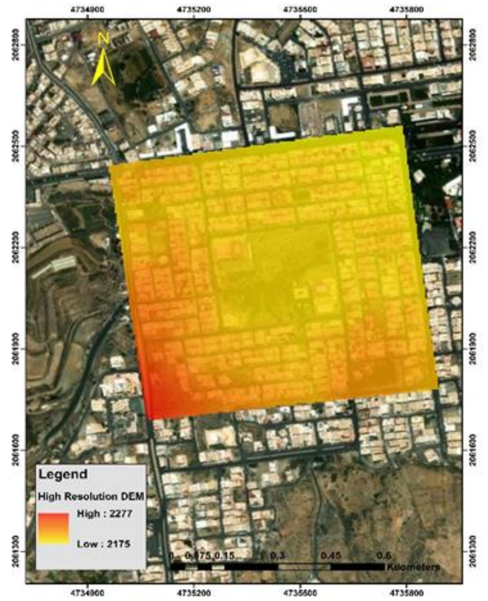
Figure 2: Location and topography of the selected area of study.

2.2 Data Sets

In the framework of this research, four distinct types of data sets were gathered and em-ployed: (a) land use base map, (b) high resolution digital elevation model (DEM) for Abha City, (c) the rainfall data from Abha station (A005), which is the nearest meteorological sta-tion, and (d) soil maps. The ArcGIS and Global Mapper were used for the processing and preparation of the data, as the data sets were gathered in various databases, photos, and re-ports. The land usage base maps, DEMs, and maps of soil were gathered from the local gov-ernmental agencies; moreover, the georeferencing of all maps was done using ArcGIS. The observed and measured rainfall data were provided by the General Authority of Meteorology and Environmental Protection in Saudi Arabia for the Asir region, where the study area is af-fected by Abha station (A005), located in Abha at 18° 12' 00" N and 42° 29' 00" E, as de-scribed in figure 3. The observed rainfall depths were provided for a total number of 46 years between 1969 and 2018, and they were provided in terms of the depth of daily rainfall, where the maximum depth of rainfall in a single day per year was used for analyzing rainfall data and obtaining the rainfall depths for each return period of 2, 5, 10, 25, 50, and 100 years. The Soil Conservation Services' (SCS) type II hypothetical storm profile was used because it is one of the most recommended distributions in the Middle East and Egypt and is also rec-ommended for use in the dry catchments of the United States (Shelan., S, Shabibi, I., Majeed, Z., 2014; Awadallah et al., 2017; Awadallah and Younan, 2012). Figure 4 shows the SCS 24-hour rainfall distributions.



(A)



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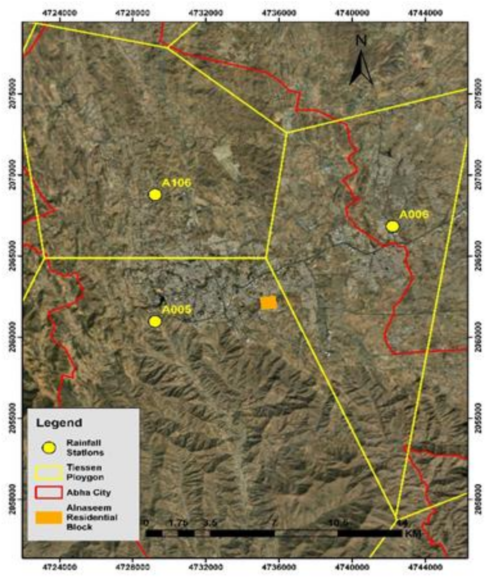

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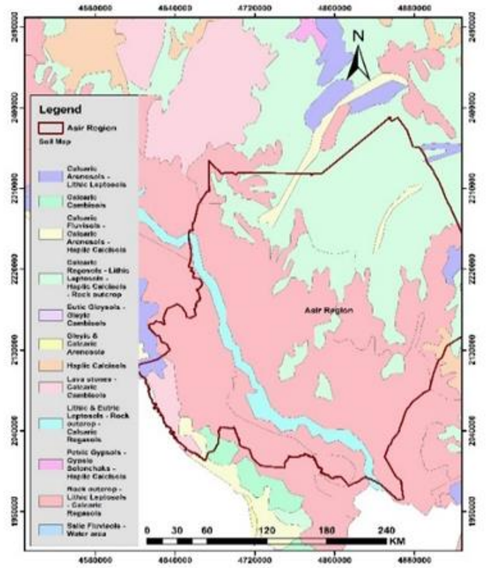


(D)

Figure 3: Collected data sets for the study area: (A) Land use base map, (B) Digital elevation model, (C) Rainfall stations in Asir region and (D) Soil type.

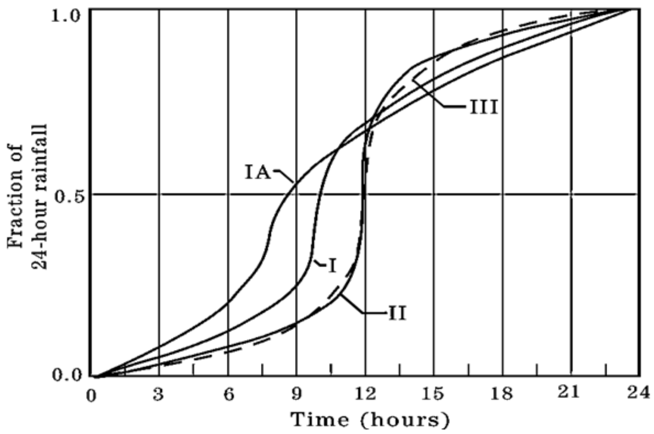


Figure 4: SCS 24-hrs rainfall distributions (Cronshey, 1986).

2.3 Modeling

The main non-structural control measure that has been used recently around the world for flood mitigation is flood forecasting; typically, the integrated hydraulic-hydrologic modeling approach is involved. The US Environmental Protection Agency (US EPA) launched the Storm Water Management Model (SWMM), a widely used tool for urban stormwater model-ling (Metcalf, 1971). It has many types of applications, including the modeling of hydrologic stormwater runoff quantity and quality, catchment discretization, urban flooding, and drain-age network modeling (Guan et al., 2015; Abdul-Aziz and Al-Amin, 2016; Sun et al., 2014; Rai et al., 2017). However, due to the complexity of urbanized catchment areas, the absence of a spatial interface poses significant challenges for SWMM models. Hence, the Personal Computer Stormwater Management Model (PCSWMM) is a commercial version of SWMM, in addition to a standalone Geographic Information System (GIS). The current study used PCSWMM to develop the urban rainfall-runoff in the form of a 2D model. In the PCSWMM program, the SWMM5 hydrological and hydraulic engine is used along with other decision support tools to help with strong and powerful simulation in cities, such as GIS technology.

The SWMM5 engine is a discrete-time simulation model with a physical foundation in which Manning's equation is used to find out surface runoff outflow, and Saint-Venant's continuity and conservation of momentum equations are obeyed to calculate flow routing within a con-duit (Rossman, 2010). Each subcatchment in the 1D domain is working as a nonlinear reser-voir. Inflow reaches the subcatchment in the form of direct precipitation or any upstream flow, and surface runoff happens when the reservoir's water depth is above the maximum de-pression (Leitao et al., 2010). On the other hand, the 2D domain has a 2D mesh with topogra-phy from the DEM. This mesh is made up of nodes (2D junctions) and open conduits without walls (2D conduits). We use the 1D Saint-Venant flow equations to solve the water flow be-tween the 2D junctions and the 2D conduits. Moreover, according to the connectivity of the link-node system, a coincident transition between the 1D and 2D domains is possible (Ortega Sandoval et al., 2023).

For this study, PCSWMM was used to simulate two sets of situations. The first set is the base scenario without RWH tanks for each return period of 2, 5, 10, 25, 50, and 100 years. The second set is the scenarios with RWH tanks (as a low-impact development technique) in-stalled with different sizes for each return period of 2, 5, 10, 25, 50, and 100 years. The goal was to find the highest level of runoff reduction that could be reached for each rainfall depth. This framework applied Computation Hydraulics International (CHI)'s PCSWMM model version (7.2.2785) with the SWMM version (5.1.013). The 1-D Saint-Venant equations pro-vide the basis for the hydrological and hydraulics engine, as described below:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0 \quad (1)$$

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right) + gA\frac{\partial H}{\partial x} + gAS_f + gAh_L = 0 \quad (2)$$

where g is the acceleration of gravity, Sf is the slope of friction, hL is the loss per unit length of local energy, and Q, H, and A are the flow rate, hydraulic head, and area of the cross-section, respectively.

We applied integrated hydrological and hydraulic models to simulate all urban surface runoff inundation scenarios in the selected urban area. We used two modules in PCSWMM for hy-drological and hydraulic simulations, which included process models for rainfall-runoff and flow routing. Table 1 defines various properties used to describe catchment characteristics in the PCSWMM model. Sub-catchments, junctions, conduits, and outfalls are the four input aspects. The hydrological input parameters, such as area, slope, flow route length, and imper-vious percentage, were assigned to each sub-catchment in accordance with the type of land use. In this framework, the SCS curve number infiltration method was selected for runoff computations using equations (3), (4) and (5).

where: Q is the exceeding rainfall, P is the depth of rainfall, Ia is the initial abstraction, S is the greatest soil retention after the beginning of storm event. Table 1. shows the catchment`s characteristic parameters.

$$Q = \frac{(P-Ia)^2}{P-Ia+S} \quad (3)$$

$$Ia = 0.2S \quad (4)$$

$$S = \frac{100}{CN} - 10 \quad (5)$$

Table 1: Catchment properties in PCSWMM model.

Parameter	Definition
Area	The catchment area, including any LID controls.
Width	the overland flow path for sheet flow runoff (m).
% Slope	Average slope percentage of the catchment.
% Imperv.	The Percentage of impervious land area (excluding the area used for LID controls)
N-Imperv.	Manning's n for overland flow on the impermeable part of the catchment.
N-Perv.	Manning's n for overland flow on the permeable part of the catchment.
Dstore-Imperv	Depth of depression storage on the impervious part of the subcatchment (mm).
Dstore-Perv	Depth of depression storage on the pervious part of the subcatchment (mm).

Figure 5 illustrates the conceptual model of surface runoff utilized in SWMM. The subcatch-ment surface functions as a nonlinear reservoir. The flow originates from direct precipitation and the upstream catchment regions. The flow departs the catchment via many processes, in-cluding runoff, percolation, and evaporation. Depression storage, defined as the maximum surface storage associated with ponding, surface wetting, and interception, represents the res-ervoir's capacity. W Surface runoff per unit area (Q) occurs when the depth of runoff exceeds the depression storage (dp). Manning's equation determines the outflow in this scenario. How the balancing equation for the subcatchment is solved numerically changes the amount of sur-face runoff (d) over time (t) (Rossman, 2010). We utilize dynamic wave theory to ascertain the flow's route. We resolve the Saint-Venant flow equations as comprehensive one-dimensional equations, producing the most theoretically precise findings (Butler et al., 2018). Figure 6 illustrates a schematic diagram depicting the evolution of the 1D model and the con-nected 1D–2D model.

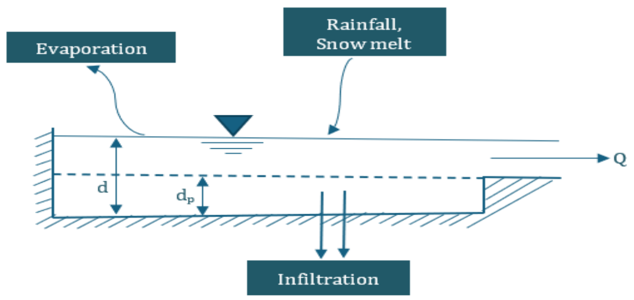


Figure 5: Conceptual view of surface runoff in swmm5 (Rossman, 2010).

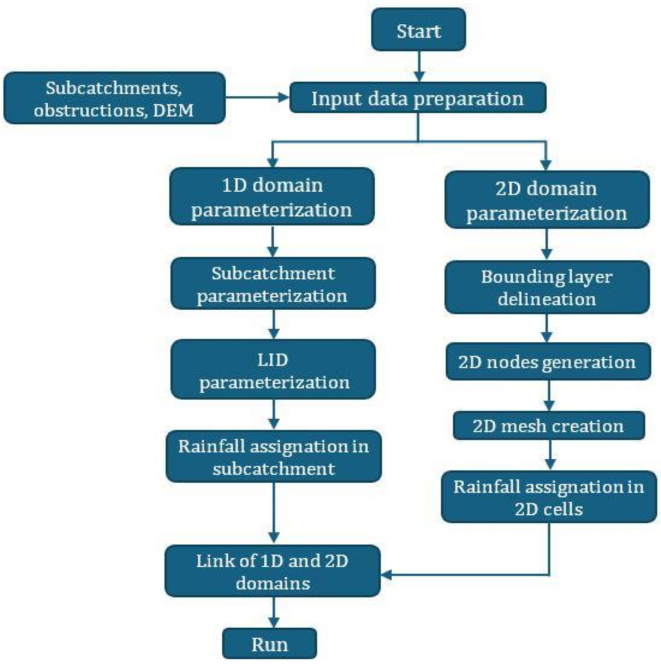


Figure 6: The setup of PCSWMM model considering LID in the 1D–2D model (Sidek et al., 2021).

We define LID measures using five vertical layers: surface, pavement, soil, storage, and un-derdrainage. The definition of these layers is per unit area. This approach makes it simple to position LIDs with the same design. The moisture balance simulation calculates the volume of water transferred or stored in each LID layer (Szeląg et al., 2022). This study applies the LID technique to the RWH tank (rain barrel), which includes a storage layer.

2.4 Methodology

The employed methodology comprises three principal steps: first, it simulates urban runoff in baseline scenarios devoid of RWH tanks; second, it simulates urban runoff with the RWH technique implemented across all buildings in the study area; and third, it evaluates the effi-cacy of RWH tanks by quantifying the maximum reduction in system runoff. The effect of domestic rainwater harvesting (RWH) on mitigating surface urban runoff was evaluated by modeling urban floods for return periods of 2, 5, 10, 25, 50, and 100 years, utilizing various tank sizes until the peak flow reduction rate attained its maximum potential. Table 2 deline-ates the implementation of these procedures across 59 scenarios, comprising 6 base scenarios and 53 RWH scenarios, throughout diverse return periods.

Table 2: Number of simulation scenarios for each return period.

Return Period	2	5	10	25	50	100	Total
No. of Scenarios	6	7	10	9	11	16	59

The nearest ground meteorological station to the research region, Abha Station (A005), is uti-lized to get the maximum annual daily rainfall data. The data undergoes statistical analysis for return periods of 2, 5, 10, 20, 50, and 100 years. Figure 7 illustrates the highest daily precipi-tation depth for each year, while Table 3 presents the analytical results for each return period. The hypothetical storm profiles of type II from the Soil Conservation Services technique (SCS-24hrs) were utilized, as this distribution is widely employed and endorsed in Saudi Arabia.

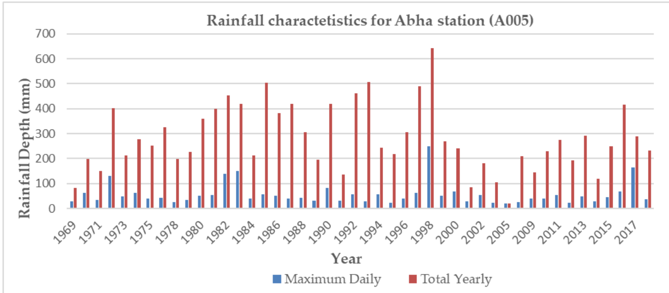


Figure 7: Rainfall characteristics of Abha station (A005), (1969-2018).

Table 3: Rainfall depths for each return period used in the study.

Return Period	Rainfall (mm/day)	Confidence Interval
2	43.8	36.6–50.9
5	73.5	56.7–90.4
10	100	71–130
25	143	88.6–198
50	182	100–263
100	226	111–342

2.4.1 Urban surface runoff modelling without RWH

Modeling urban surface runoff in the current scenario without the use of rainwater harvesting. The establishment of a 2D domain in PCSWMM primarily involves three steps: delineating the boundary layer, generating 2D nodes, and constructing the 2D mesh. The scope of the 2D model is determined by the boundary layer and may encompass numerous polygons to reflect the infiltration and roughness parameters of subcatchments. The present study's enclosing lay-er encompassed houses, roads, and gardens. Table 4 delineates the sub-catchment characteris-tics utilized in this research, determined on an average basis. This research used the SCS curve number infiltration approach, with curve numbers of 90, 80, and 60 assigned to roads, build-ings, and gardens, respectively.

Table 4: Input Parameters of sub-catchments used in PCSWMM for the study,							
Subcatchment type	**Total area (m²)**	**(Width)ᵃ (m)**	**(N)ᵇ Imperv.**	**(N)ᵇ Perv.**	**(Dstore-Imperv) ᶜ (mm)**	**(Dstore-Perv) ᶜ (mm)**	**% Imperv.**
Roads &Parking	262936.47 (44.65%)	6	0.014	0.2	2.5	3.5	70
Buildings	295671.23 (50.20%)	27.7	0.012	0.2	2.5	3.5	70
Gardens	30338.49 (5.15%)	78.37	0.014	0.2	2.5	3.5	30

[a](Szeląg et al., 2022). (W=α·A0.50, α=1.35). [b](Mays, 2010), [c](Water Environment Federa-tion, 2022).

According to the Saudi code of buildings, each building's roof area accounted for 70% of its parcel area. In PCSWMM, the mesh types are hexagonal, rectangular, directional, and adap-tive. Hexagonal mesh type is used in this study with a resolution of 5 m, which generates ho-mogeneous cells that are specified by its resolution, providing a better simulation of road. Additionally, the 2D user interface of the PCSWMM allows for the addition of a layer of ob-structions, specifically buildings, in the current study. Once the boundary layer has been pa-rameterized, 2D nodes are made. This lets the DEM be used to describe the 2D cells' approx-imate locations and heights. The 2D mesh is then produced, and 2D conduits are used to con-nect the 2D nodes. 13055 2D junctions, 33618 2D conduits, and 13055 2D cells comprise the current 2D model.

2.4.2 Urban runoff modelling with implementing RWH

The second procedure entails the simulation of urban surface discharge in a proposed scenar-io in which RWH Tanks are implemented. The RWH containers are implemented as low-impact development (LID, rain barrels), and the same procedures as in the default scenario are followed. The SWMM engine, version 5.1.013, was employed in this investigation, which en-abled the implementation of low-impact development (LID) strategies in each subcatchment (USEPA,2024). The model incorporates domestic rainwater harvesting, which is depicted as rain containers that allow for the storage and utilization of collected water. The model depicts rain containers as a layer of stowage that includes an exhaust valve at the base. The runoff from the roof is directed to each tank by the model. equation (6). When the volume of water entering the tank surpasses its capacity, the excess water is discharged through the upper ori-fice as overflow.

The inflow retained by the tank is denoted as Q1, while the overflow is represented as Q2, and the underdrainage is indicated as Q3 (Arnone et al., 2018). SWMM permits the closure of the

$$Q_{out} = Q_1 - Q_2 - Q_3 \quad (6)$$

drain valve before a rainfall event, with the option to reopen it at any point following the conclusion of the storm event. When the drain valve is closed, Q3 is equal to 0. Equation (7) is employed to calculate the volume of the underdrainage flow. The coefficient (C), derived from equation (8), regulates the duration of the drained outflow.

$$Q_3 = C(h - H)^n \quad (7)$$

where h is the rain barrel's height, C is the drainage factor, n is the drainage exponent, and H

$$C = 0.6(A_3/A_1) * 2gl/2 \quad (8)$$

where A_1 is the tank surface area, A3 is the area of bottom drainage opening and g is gravita-tional acceleration. There is an important parameter in SWMM when simulating the rainwater harvesting, which is drained delay time, which means the time to start emptying the tank after the storm event stops.

SWMM provides three options for directing tank outflows: bottom, top, and a combination of both. Drainage can be directed to the drainage network, permeable catchments, or alternative LID control measures. This study posits that the emergency overflow will discharge the sur-plus water volume to the prior area. Figure 8 presents a schematic that illustrates the function-ality of the RWH tank within SWMM. In this study, the drain valve of the rain barrel is as-sumed to be closed during the simulation, resulting in Q3 being equal to zero. When the in-flow volume to the rain barrel exceeds its capacity, the surplus is discharged through the up-per overflow. This overflow volume is then directed to the subcatchment outlet. The number of tanks required for each parcel is calculated by dividing the parcel area by the average par-cel area. A total of 53 scenarios of urban surface runoff were modeled, incorporating rain bar-rels of various tank sizes across different return periods, until the maximum flow reduction was attained. Table 5 presents the tank sizes utilized in the modeling for various return peri-ods. This study assumes active tank management, meaning that tank sizes are determined by surface water management goals rather than actual supply and demand. In the case that the system is operated in such a way that no runoff occurs for any event up to the design rainfall depth. There are two methods that ensure there is always enough volume available for the de-signed rainfall depth. The first involves predicting a significant event and releasing the water storage in preparation for it, and the second involves releasing a portion of the water storage up to a specific level once a certain threshold is exceeded. The connection to information re-garding rainstorm predictions is necessary for the first mechanism to work. The second one employ a timing delay to ensure that water is released out at certain times following the com-pletion of the event.

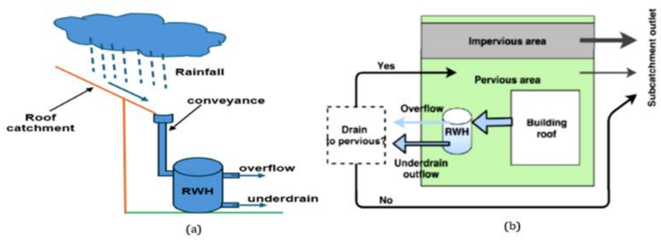


Figure 8: Simplified diagram of rain barrels functioning (Stec, A. (2018)): (a) Cross Section, (b) Plan.

Table 5: Tank sizes used for simulation for various return periods.						
Return Period	**2**	**5**	**10**	**25**	**50**	**100**
Tank sizes (m³)	4, 6, 8, 10 and 12	4, 6, 8, 10,12 and 14	4, 6, 8, 10,12, 14, 16, 18 and 20	4, 8, 12, 16, 20, 24, 28, and 30	4, 8, 12, 16, 20, 24, 28, 30, 32 and 34	4, 8, ,12, 16, 20, 24, 28, 30, 32, 34, 36, 38, 40, 42 and 44

In the absence of real urban runoff outflow records for calibrating and validating the baseline scenarios, the subsequent approaches were employed to ascertain the corresponding reduc-tions in peak flow rates and urban runoff volumes[28]. Initially, real characteristics were uti-lized to characterize all SWMM models, including rooftop areas, geographical locations, slopes, and altitudes. Secondly, in each SWMM model, the indications for runoff and flow continuity errors were kept below 1%. The SWMM Runoff Error, calculated as the percent-age discrepancy between total precipitation and surface runoff, final storage, and total losses in each subcatchment, models the continuity of runoff throughout the framework. The conti-nuity of flow in the simulation is represented by the Flow Error in SWMM, calculated as the percentage difference between total input and total outflow (e.g., floods) for each model component throughout the simulation.

2.4.3 RWH tanks performance evaluation

We evaluated the performance of rainwater harvesting tanks in reducing urban surface runoff for each return period. We applied the peak flow reduction indicator to assess the perfor-mance of RWH tanks [27]. The following equation was used to calculate the peak and vol-ume runoff reduction values.

3. Results And Discussion

$$Peak\ Reduction(PR\%) = \frac{System\ Peak\ Runoff\ (without\ RWH) - System\ Peak\ Runoff\ (with\ RWH))}{System\ Peak\ Runoff\ (without\ RWH)} * 100 \quad (9)$$

3.1 Results of system peak runoff reductions for different return periods

The study area employs the three primary processes outlined in the methodology section across 59 simulation runs. The simulation tests conducted for rainfall depths across various return periods indicated that the implementation of rainwater harvesting tanks in the simulat-ed urban catchment would decrease the runoff peak. Simulations were performed for each return period (2, 5, 10, 25, 50, and 100 years) using various tank sizes until the maximum peak reduction was attained. Figure 9 depicts the correlation between tank size and peak reduc-tions across various return periods. Table 6 presents the tank size and the associated runoff peak reduction for each return period.

Figures 10 and 11 demonstrate the effect of Rainwater Harvesting (RWH) implementation on flood depth reduction across different return periods, specifically under the maximum peak reduction scenario. Simulations indicate that for return periods of 2, 5, 10, 25, 50, and 100 years, with corresponding rainfall amounts of 43.8, 73.5, 100, 143, 182, and 226 mm, the largest reductions are 42.37%, 40.43%, 39.56%, 38.86%, 38.20%, and 37.75%, respectively. The reduction can be accomplished by employing tank sizes of 8 m^3 for the 2-year return peri-od, 12 m^3 for the 5-year return period, 18 m^3 for the 10-year return period, 24 m^3 for the 25-year return period, 32 m^3 for the 50 year return period, and 40 m^3 for the 100-year return peri-od. Moreover, maintaining a fixed roof area of 70% relative to the parcel area, along with an increase in tank size, will not alter the maximum peak reduction.

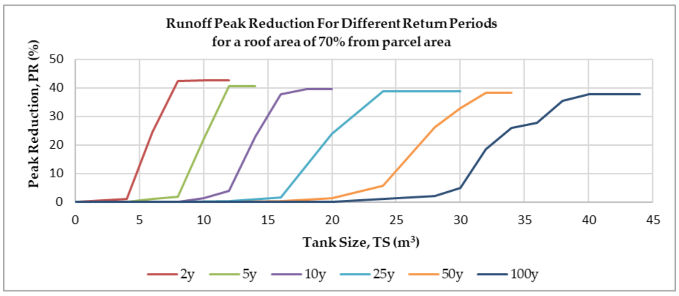


Figure 9: Relation between tank size and peak reduction for different return periods.

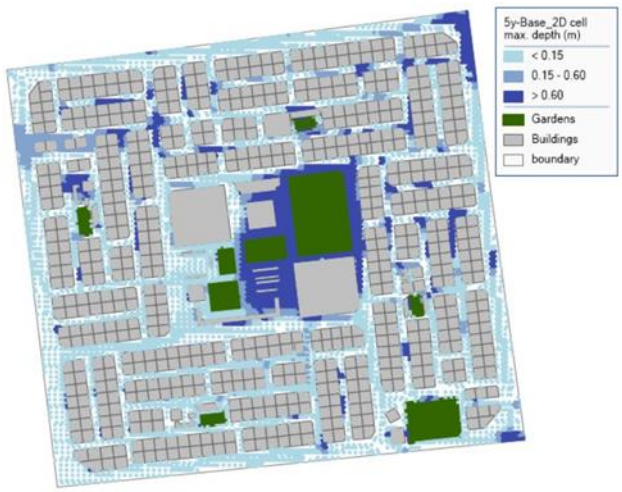
Table 6: Summary of system peak runoff results for different return periods.

Return Period	2y		5y		10y		25y		50y		100y	
Tank Size (m^3)	Peak Runoff (m^3/s)	Peak Reduction (%)	Peak Runoff (m^3/s)	Peak Reduction (%)	Peak Runoff (m^3/s)	Peak Reduction (%)	Tank Size (m^3)	Peak Runoff (m^3/s)	Peak Reduction (%)	Peak Runoff (m^3/s)	Peak Reduction (%)	Peak Runoff (m^3/s)
0	6.6	0	12.22	0	17.44	0	26.18	0	34.24	0	43.4	0
4	6.52	1.17	12.22	0	17.44	0	26.18	0	34.24	0	43.4	0
6	4.98	24.49	12.1	0.98	17.44	0	--	--	--	--	--	--
8	3.85	42.37	11.99	1.88	17.42	0.114	26.15	0.115	34.23	0	43.4	0
10	3.80	42.46	9.553	21.82	17.23	1.204	--	--	--	--	--	--
12	3.80	42.46	7.279	40.43	16.78	3.78	26.11	0.267	34.2	0.117	43.4	0
14			7.270	40.51	13.46	22.82	--	--	--	--	--	--
16					10.86	37.73	25.77	1.57	34.14	0.29	43.4	0
18					10.54	39.56	--	--	--	--	--	--
20					10.53	39.62	19.93	23.87	33.77	1.37	43.39	0.11
22							--	--	--	--	--	--
24							16.06	38.66	32.33	5.58	42.95	1.1
26							--	--	--	--	--	--

Table 6 (Cont.): Summary of system peak runoff results for different return periods.

28							16.02	38.81	25.24	26.28	42.46	2.2
30							16.02	38.81	22.97	32.91	41.29	4.9
32									21.16	38.2	35.36	18.6
34									21.16	38.2	32.13	26
36											31.36	27.8
38											28.03	35.4
40											27.04	37.75
42											27.04	37.75
44											27.03	37.77

(A)

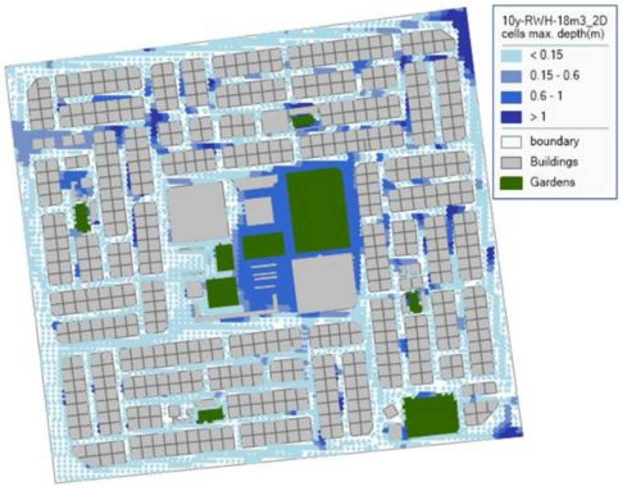


(C)

(B)

(D)

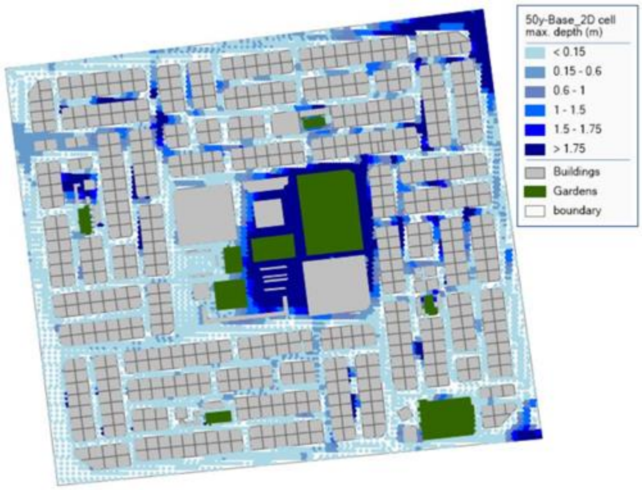
(E)



(F)

Figure 10: Flood depths for (2, 5 and 10) return periods: (A) 2y flood depths without RWH tanks, (B) 2y flood depths with 8 m3 RWH, (C) 5y flood depths without RWH tanks, (D) 5y flood depths with 12 m^3 RWH, (E) 10y flood depths without RWH tanks, (F) 10y flood depths with 18 m^3 RWH.

(A)



(C)

(B)

(D)

(E)

(F)

Figure 11: Flood depths for (25, 50 and 100) return periods: (A) 25y flood depths without RWH tanks, (B) 25y flood depths with 24 m³ RWH, (C) 50y flood depths without RWH tanks, (D) 50y flood depths with 32 m³ RWH, (E) 100y flood depths without RWH tanks, (F) 100y flood depths with 40 m³ RWH.

3.2 Relation between rainfall depth, the maximum peak reduction and tank size

Figure 12 illustrates the analysis of simulation results for various return periods, highlighting the relationships between rainfall depth, maximum peak reduction, and tank size. These rela-tionships are necessary to determine the tank size, rainfall depth, and maximum peak reduc-tion for a roof area that is 70% of the parcel area:

where RD is the rainfall depth, MPR is the maximum peak reduction and TS is the tank size

$$MPR = 55.045\ (RD)^{-0.071} \quad (10)$$

$$TS\ = 0.1768\ (RD) - 0.3015 \quad (11)$$

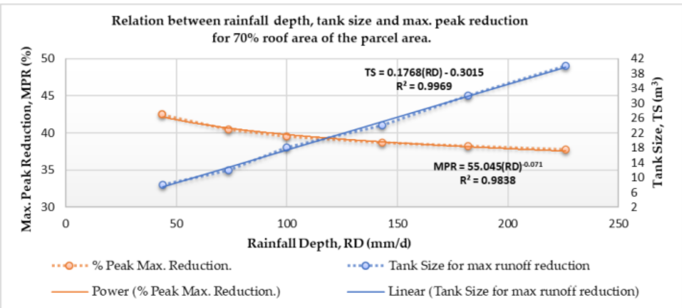


Figure 12: Relation between rainfall depth, tank size and maximum peak reduction.

Numerous studies have already examined the impact of domestic rainwater collection on re-ducing urban runoff. For instance, in Poland, a study conducted examined the impact of rainwater collection on runoff in the Zasanie district (Stec, 2018). They found that peak flow dropped by 9.7% to 19.8% when RWH was used in 25%, 50%, and 100% of the buildings compared to the base scenario without RWH. In San Diego, in the United States, a study conducted found that simulating the effect of RWH in homes reduced runoff by 2.5% to 10.4% by (Walsh et al., 2014). Another study carried out in 23 cities in the United States es-timated that the reduction in peak flow due to the use of RWH in buildings is up to 20% by (Steffen et al., 2013). A study estimates that the implementation of RWH in southern Italy reduced peak flow by 12.5% (Campisano et al., 2014). A more recent study simulated how rainwater harvesting would lower surface runoff during a one-hour storm with an intensity of 39.9 mm/h and a return period of 20 years (Snir et al.,2022). They found that rainwater har-vesting would lower stormwater runoff by 18.1%. The difference in results between the above-mentioned studies and our study arises because those studies calculated tank capacity based on water demand and supply, whereas our study focuses on using tank capacity primar-ily for runoff reduction and surface water management which is actively management for this goal. The current study aims to find the tank size that gives the maximum peak reduction and to develop a relation between the rainfall depth, tank size, and maximum peak reduction. The roof area percentage is an additional reason, as it is significantly affecting the percentage re-duction in peak runoff. Another factor contributing to this difference is the proportion of buildings equipped with rainwater harvesting tanks.

3.3 Sensitivity Analysis Of Maximum Peak Reduction To The Roof Area Percentage

To explore the effect of the roof area percentage on the decrease value of peak discharge, roof areas of 50% and 90% of the parcel area were used for the 2-year return period. We ran ten scenarios for tanks with varied capacity. Maximum discharge values fell when 70% roof area values dropped. Table 7 compares the reduction values of 50% and 90% of the roof area to the 70% employed in this study for a two-year return period with a rainfall depth of 43.8 mm/d.

Table 7: Max. peak reduction for different roof area percentages for 2y return period.

Tank Size (m³)	0	4	6	8	10	12
Peak Runoff	6.60	6.52	4.98	3.80	3.80	3.80
peak Reduction 70% roof area	0.00	1.17	24.49	42.37	42.46	42.46
peak Reduction 50% roof area	0.00	20.72	35.63	35.77	35.77	35.77
peak Reduction 90% roof area	0.00	0.93	13.00	47.15	47.43	47.46

Figure 13 illustrates the impact of roof area percentage on the attenuation of peak runoff for 50%, 70%, and 90% roof area relative to the parcel area. The maximum decrease of runoff peak correlates directly with the percentage of roof area. Figure 14 illustrates the correlation between roof area % and the highest peak reduction attainable. By investigating the influence of roof area on maximum peak reduction, we establish the subsequent correlation between roof area and maximum peak reduction:

$$MPR = 20.101\ln(RA\%) - 43.201 \tag{12}$$

where MPR is the maximum peak reduction and RA% is the roof area percentage from the parcel area.

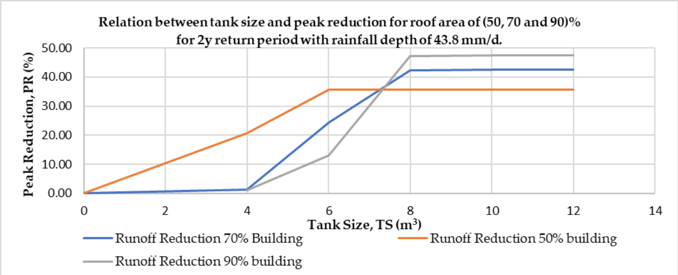


Figure 13: Comparison between maximum peak reduction for different roof area for 2yr re-turn period.

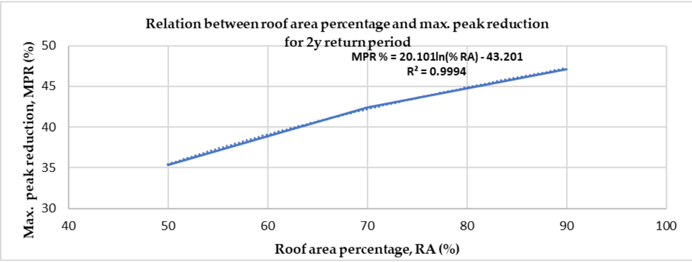


Figure 14: The relation between roof area percentage and maximum peak reduction for 2y return period.

4. Conclusion

In this paper the potential for using active domestic rainwater harvesting technologies as a sustainable control measure to control and manage runoff floods in a semi-arid urbanized catchment was examined. The investigations were performed using PCSWMM single events simulations modelling of Alnaseem urban residential block catchment, located in Abha city in Saudi Arabia, as a case study in the base scenario without RWH and in the proposed scenari-os with implementing RWH technique for different return periods with different tank sizes. The study's findings are as follows:

- Active rainwater harvesting system is an effective low impact development technique that can efficiently be used in managing floods in semi-arid urban areas as it can re-duce urban runoff flood depths and peak flows.
- By analyzing the simulation results for different return periods, the relations between rainfall depth, maximum peak reduction and tank size required to achieve this maxi-mum reduction are developed for a roof area of 70% from the parcel area.
- A sensitivity analysis has been carried out to study the effect of roof area percentage from the parcel area on the maximum reduction in peak runoff and the findings show that the maximum peak reduction value can be increased with increased roof area.
- The results in general enhance understanding about the impact of active domestic rainwater harvesting in the reduction of peak runoff and flood depths in a semi-arid urban area and its performance depends on rainfall depth, tank size and roof area per-centage as site conditions. To overcome data insufficient quantity, a comprehensive framework was conducted that can be recognized as innovative for this catchment will be beneficial for evaluating other ungauged catchments under comparable circum-stances.
- Finally, this study has substantial consequences for a lot of semi-arid urbanized catchments which are vulnerable to flash floods. Consequently, the study provides in-sight into the effect of using active domestic rainwater harvesting as one of the low impact developments on reducing urban flash floods and the main factors that are af-fecting the reduction values such as tank size, rainfall depth, and percentage of roof area.

The urban runoff flood risk highlights the need for sustainable urban planning methods as well as improving the drainage facilities design policy to incorporate sustainable urban drain-age systems to make it more resilient to the stressors of increased urbanization and climate change, which is predicted to worsen the situation. Due to the assumptions of the model input parameters, land cover curve number values and data limitation, the results may have uncer-tainties. Despite this, the study emphasizes the significance of domestic rainwater harvesting in reducing urban runoff flood depths and runoff peak discharge.

Author Contributions

Conceptualization, I.M.A.M., E.F.M.E. and D.A.; methodology, I.M.A.M., E.F.M.E and M.A.R.E.; formal analysis, I.M.A.M., E.F.M.E. and D.A.; investiga-tion, I.M.A.M., E.F.M.E., and M.A.R.E.; data curation, I.M.A.M, D.A and E.F.M.E.; writ-ing—original draft preparation, I.M.A.M., D.A., and E.F.M.E.; writing—review and editing, I.M.A.M., and D.A. All authors have read and agreed to the published version of the manu-script.

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Data Availability Statement

The data are available from the first author upon reasonable request.

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Conflicts Of Interest

The authors have declared that no competing interests exist.

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