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Evaluating The Functionality of the Existing Natural Wetland as A Nature-Based Solution in Runoff Control in Hai District

Benedict Daniel[1*], Dr. Tulinave Mwamila[2], Dr. Catherine Mushi[3]
Department of Water Supply and Sanitation Engineering
Water Institute Main Campus P.O. BOX 35059, Ubungo, Dar Es Salaam, Tanzania

Abstract - Urban flooding has become an increasing challenge in rapidly developing areas where conventional drainage systems are unable to cope with high-intensity rainfall and rising surface runoff. This study evaluated the functionality of Boroti natural wetland in Hai District, Kilimanjaro Region, Tanzania, as a nature-based solution for urban stormwater runoff control. Increasing urbanization, steep topography, and high-intensity rainfall have caused frequent flooding and failure of conventional drainage systems in the area. The study applied EPA-SWMM 5.2 to assess the hydrological performance of the wetland under two scenarios: with the wetland represented as a storage unit and without the storage function, where it was replaced by a junction. Catchment characteristics including sub-catchment area, slope, land use, hydrologic soil groups, curve numbers, and infiltration parameters were generated using ArcGIS 10.4 and standard hydrological methods. Results showed that both scenarios had low runoff continuity error (-0.03%), but the storage unit scenario produced a lower flow routing error (-8.16%) compared to the junction scenario (-16.90%). The findings confirm that natural wetlands significantly improve runoff attenuation and flood mitigation.

Keywords: ***Nature-based solutions, Natural wetland, Stormwater management, Runoff control, EPA-SWMM 5.2, Urban flooding, Hai District, Boroti Wetland.***

1. INTRODUCTION

Urban stormwater management has shifted worldwide away from conventional "grey" infrastructure pipes, concrete channels, pumps toward hybrid and nature-based approaches. This is because hard engineering alone can't handle the more intense rain and rapid urbanization that come with climate change. In the US, cities like Philadelphia, New York, and Portland have poured billions into green stormwater infrastructure since the early 2000s. Rain gardens, green roofs, and permeable pavements have cut runoff volumes by 50–85% (Hobbie and Grimm, 2020).

China's national "Sponge City" program launched in 2014 and now covers over 30 pilot cities. It's shown that well-designed NBS can reduce peak runoff by 70–90% while also cooling cities and boosting biodiversity (Qi et al., 2020). In Europe, the UK, Netherlands, and Germany have written Sustainable Drainage Systems into planning law, resulting in fewer combined sewer overflows and less downstream flooding (Martín Muñoz et al., 2024; Palermo et al., 2023). The global takeaway: NBS are technically mature, cost-effective over their lifespan, and deliver multiple ecosystem services (Huang et al., 2020; Moazzem et al., 2024).

But transferring NBS to the Global South isn't straightforward. Climates, landscapes, economies, and governance systems are different. In sub-Saharan Africa, urban population is expected to triple by 2050, and most cities sit in areas prone to both pluvial and fluvial flooding (Enu et al., 2023). Studies from Johannesburg, Cape Town, Nairobi, Kisumu, Kampala, and Ghana all show that conventional drainage systems are overwhelmed, poorly maintained, and often clogged with trash (van der Merwe et al., 2025; Long'or Lokidor et al., 2024; Muwafu et al., 2024).

That said, emerging African evidence shows NBS can perform well under tropical conditions. Constructed wetlands and retention ponds in Kampala and Mwanza remove over 80% of nutrients and cut peak flows by 60–90% at a fraction of the cost of grey infrastructure (Byekwaso et al., 2025; Lossindilo et al., 2025). And slow adoption is driven by weak municipal budgets, a lack of local data, unclear maintenance responsibilities, and poor integration into urban planning (Thorn et al., 2021; Acreman et al., 2021).

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In East Africa Tanzania specifically urban flooding has become a recurring headache. Dar es Salaam loses an estimated US$236 million every year to flood damage. Secondary cities such as Mwanza, Arusha, Tanga, and Morogoro also report flooding of homes, markets, and roads after short, intense rains (Cortes, 2020). Up in the northern highlands, Moshi and Hai District face a unique mix of steep slopes, intense convective storms, and rapid peri-urban growth on Mount Kilimanjaro's volcanic slopes. There is existing drainage which mostly narrow concrete channels and culverts built decades ago for much lower runoff. They're routinely overwhelmed now, causing flash floods, erosion, gullies, and sediment buildup in downstream rivers like Kikafu and Weru Weru (local government reports and community accounts, 2023–2025).

Tanzania's National Environmental Policy (2021) and the draft Urban Resilience Strategy do encourage nature-based approaches. But in practice, implementation has been almost entirely limited to coastal mangrove restoration in Dar es Salaam and Rufiji Delta. For inland and highland urban areas there is no systematic assessment, pilot, or monitoring of NBS for stormwater management has been published (Muwafu, 2024). That's a real knowledge and practice gap. Even though NBS like bioretention systems, vegetated swales, riparian buffers, and detention ponds have proven highly effective elsewhere in Africa reducing runoff volume by 50–85% and peak flows by 60–90% in comparable tropical and steep-slope environments (Lossindilo et al., 2025; Byekwaso et al., 2025; Long'or Lokidor et al., 2024) no empirical assessment or pilot has been done in Tanzania's highland urban areas.

Boroti Wetland. It's in Hai District, Kilimanjaro Region, northern Tanzania. Its history reflects both natural processes and human interaction. The wetland's origin is mostly natural it formed as part of the hydrological system coming off Mount Kilimanjaro. The mountain gets a lot of rain, feeding numerous rivers, streams, and underground sources. As water flows downhill, it collects in low areas, creating wetlands like Boroti. Over time, that process built a stable ecosystem with marshy land, waterlogged soils, and plants adapted to wet conditions. So Boroti emerged from long-term geological and climatic processes, not human construction. Lately, there's growing recognition of how important wetlands are for conservation and sustainable development. Wetlands like Boroti are now valued for water storage, flood control, and providing habitat for plants and animals (Swilla et al., 2024).

Also, Swilla et al. (2024) quantified the effectiveness of LID practices in mitigating runoff floods, reporting substantial peak flow reductions using selected NBS. But those coastal lowland studies provide valuable Tanzanian evidence on decentralized NBS performance while revealing a critical gap for highland volcanic terrains like Hai District. In these areas, steeper slopes, higher infiltration potential, and more intense convective storms may alter how well infiltration trenches, permeable pavements, wetlands, and other measures work. So the present study aims to fill that gap by assessing the functionality of Boroti Natural Wetland for urban stormwater management in Hai District.

2. METHODOLOGY

2.1 Study Area

This study took place at Boroti Natural Wetland in Hai District, Kilimanjaro Region, Tanzania. The wetland acts as a natural drainage and runoff retention area within a catchment that's urbanizing quickly. The area has steep slopes, high-intensity rainfall, and ever-increasing surface runoff. Flash flooding happens here because the conventional drainage systems aren't up to the task and land use pressures keep growing. Boroti wetland was chosen because it's an existing natural wetland that has the potential to serve as a nature-based solutions for urban stormwater management.

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Figure 1: Area of the study

2.2 Research Design

The study used a quantitative modeling approach to assess how well the existing Boroti natural wetland controls runoff hydrologically. The assessment compared runoff volume and peak discharge under two simulation scenarios using EPA-SWMM version 5.2. The first scenario represented current conditions, with the wetland modeled as a storage unit. The second scenario represented a modified setup where the wetland's storage function was removed and replaced with a junction node. Comparing the two made it possible to evaluate how effective the wetland is at attenuating stormwater runoff and reducing peak flow.

2.3 Data Collection and Preparation

The data needed for model development included topographic characteristics, land use - land cover, hydrologic soil groups, rainfall-runoff parameters, and hydraulic characteristics of the catchment. Spatial data were processed in ArcGIS 10.4 using the hydrology toolbox to delineate the catchment and generate the physical characteristics of the sub-catchments.

The Boroti wetland catchment was classified into four sub-catchments: C1, C2, C3, and C4. Parameters extracted for each sub-catchment included area, average width, average slope, drainage length, percentage impervious surface, and curve number (CN). The total modelled catchment area was 1893.15 hectares, while the wetland storage area was estimated at 911,892.773 m².

Land use analysis showed that the entire catchment consisted of pervious surfaces dominated by forest and grassland, resulting in 0% imperviousness and 100% perviousness. Soil classification identified two hydrologic soil groups: Group B and Group C. Group B soils were mainly found in sub-catchments C3 and C4, while Group C soils dominated C1, C2, and parts of C3 and C4. These classifications were used to determine SCS Curve Numbers for runoff estimation.

2.4 Determination of Hydrological Parameters

The Soil Conservation Service (SCS) Curve Number method was applied to estimate infiltration and runoff potential. Curve Numbers were assigned based on land use-land cover and hydrologic soil group relationships according to TR-55 guidelines. The CN values obtained were 70 for C1 and C2, 69.3 for C3, and 62 for C4.

Soil hydraulic properties including saturated hydraulic conductivity, suction head, porosity, field capacity, and wilting point were obtained from the EPA-SWMM 5.2 User Manual based on soil texture classes identified as silt loam and sandy clay loam. Manning’s roughness coefficient for pervious surfaces (N-Perv) was assigned an average value of 0.12 for all sub-catchments based on standard values for grass-covered and cultivated surfaces.

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2.5 EPA-SWMM Model Development

The hydrological performance of the wetland was simulated using EPA-SWMM version 5.2. Each sub-catchment was represented using its physical and hydrological parameters, and runoff was routed through the drainage network toward the wetland and downstream outfall.

Two scenarios were developed:

Scenario 1**:** The existing Boroti wetland was modelled as a storage unit representing its natural detention and retention capacity.

Scenario 2: The same model was developed without the storage unit, where the wetland was replaced by a simple junction, allowing direct runoff conveyance without temporary storage.

Both scenarios were subjected to identical rainfall and catchment conditions to ensure reliable comparison of runoff generation and flow routing performance.

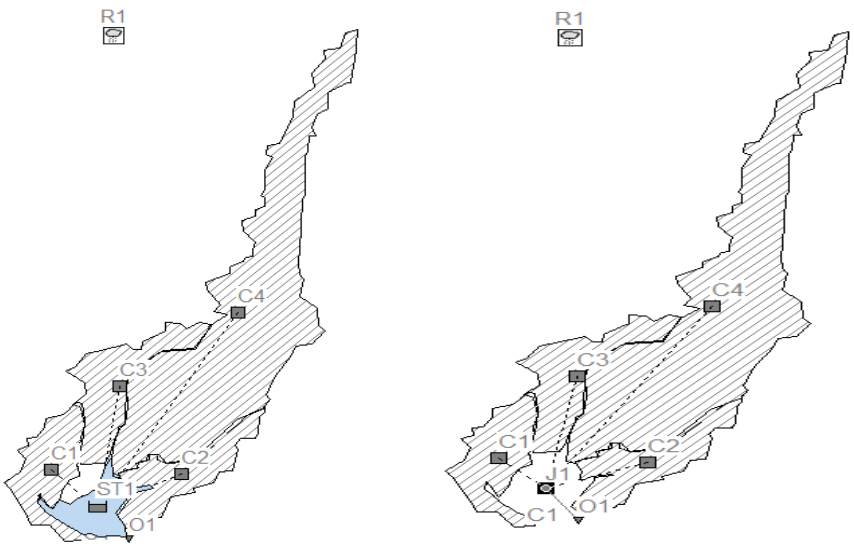

Figure 2: EPA SWMM 5.2 catchment models development with and without a storage unit

2.6 Model Performance Evaluation

Models performance were assessed using runoff continuity error, flow routing continuity error, runoff volume, and peak discharge. Continuity error helped evaluate how numerically reliable and stable the simulations were. Lower routing continuity error and reduced peak discharge were taken as signs of better hydraulic performance and effective stormwater attenuation.

Comparing the two scenarios made it possible to determine whether the natural wetland significantly improves runoff control and downstream flow regulation. That in turn confirmed its functionality as a nature-based solution for stormwater management in Hai District.

3. Results and Discussion

3.1 Development of EPA-SWMM 5.2 Model for Boroti Natural Wetland Catchment Performance Assessment

The functionality and hydrological performance of the existing Boroti natural wetland were assessed using EPA-SWMM 5.2 to estimate rainfall-runoff, by comparing two different scenarios. In the first scenario, the model includes the Boroti wetland as a storage unit, and runoff and peak flow are predicted. In the second scenario, the model uses the same characteristics but without a storage unit, and runoff and peak flow are predicted again. The data needed to set up the model's physical characteristics of the Boroti sub-catchments: sub-catchment areas, average width, average slope, percentage of impervious, and infiltration data in the form of Curve Numbers. These were developed by using ArcGIS 10.4 under the hydrology system.

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3.2 Physical Characteristics of Boroti Natural Existing Wetland Sub Catchment

The Boroti natural existing catchment was classified into 4 sub-catchments, namely C1, C2, C3 and C4 (Figure 3) in ArcGIS 10.4 software under the hydrology system, and the physical characteristics of each sub-catchment were developed, and the sub-catchment areas ranged from 233.53 to 1123.54 hectares. The total modeled area of all sub catchments is 1893.15 hectares, and the storage unit (Boroti natural existing wetland) area was estimated to 911892.773m^2.

These delineated units are important for runoff modelling in EPA-SWMM 5.2, as they allow rainfall-runoff response, peak flow and wetland flood mitigation performance.

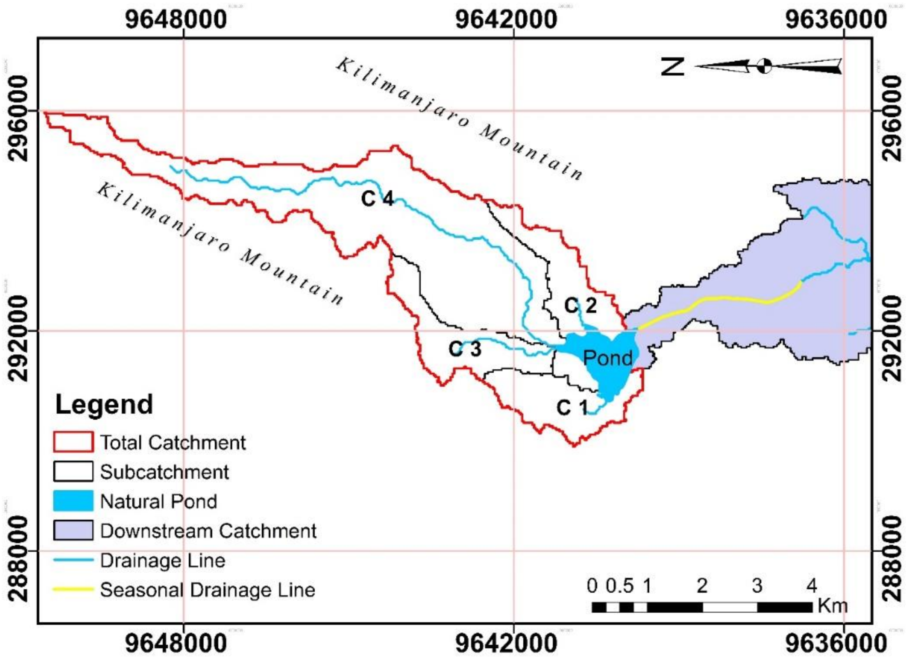

Figure 3: Shows the delineation of Boroti wetland sub-catchment (ArcGIS 10.4)

The sub-catchment C4 has the longest flow path of about 11509.75 m while C2 has the shortest flow path of about 1305.94 m within the catchment. Based on the delineated map, the stormwater runoff is mainly developed in all sub-catchments C1, C2, C3 and C4 and is conveyed through pond, then to outfall and finally into the downstream catchment. The Boroti natural existing wetland sub-catchments have estimated the slopes classified into four groups different values for each sub catchment (Figure 4) where by at sub catchment C1 the slopes range between 0.083% to 16% with an average slope of 6.54%, sub catchment C2 the slopes range between 0.016% up to 18% with an average slope of 7.752%, sub catchment C3 the slopes range between 0.16% up to 33% with an average slope of 14.2825% and sub catchment C4 the slopes range between 0% up to 49% with an average slope of 18.5125%. The study show that the sub-catchment C1 has the lowest estimated average slope of about 6.54% while C4 has the highest estimated average slope of about 18,5125% within the catchment.

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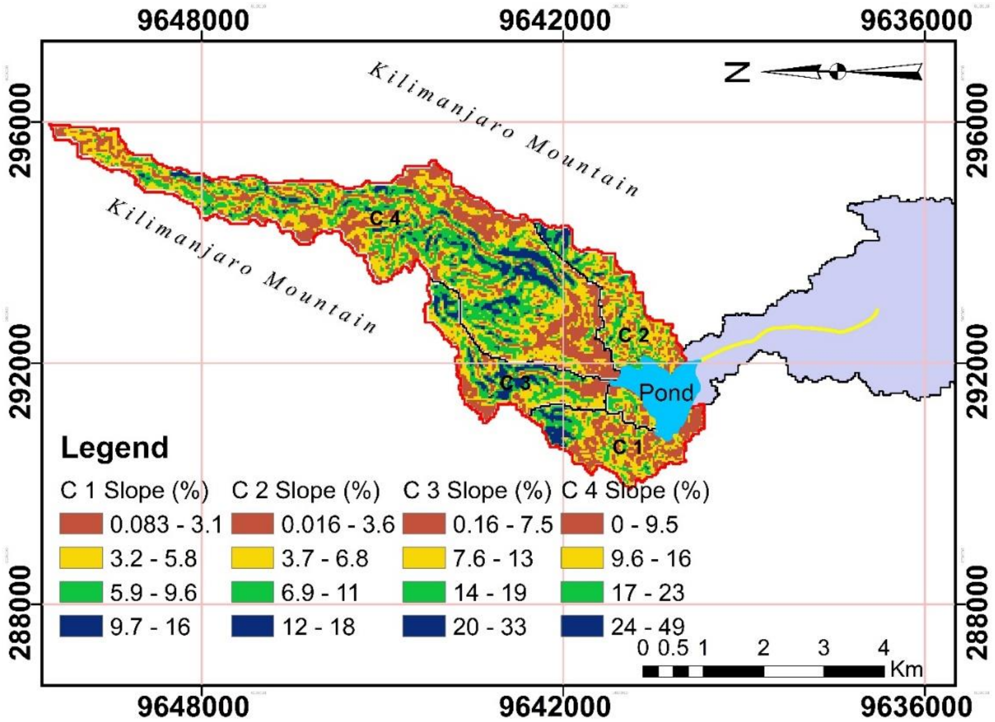

Figure 4: Shows the average slopes of Boroti wetland sub-catchment (ArcGIS 10.4)

The whole catchment of Boroti natural existing wetland involve only pervious area which is classified into two land use group of forest and grasses (Figure 5). This implies that the percentage of imperviousness is 0% while the percentage of perviousness is 100%.

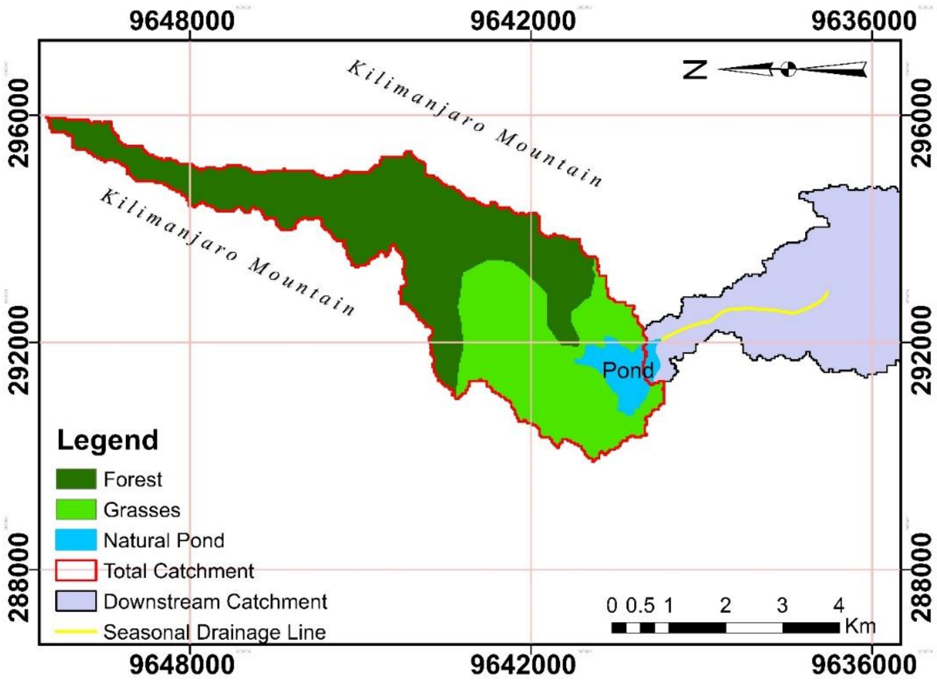

Figure 5: Shows the Land use/land cover map for Boroti wetland catchment (ArcGIS 10.4)

The relationship between curve number (CN) and NRCS hydrologic soil group shown on the hydrologic soil group map (Figure 6) is based on the infiltration capacity, runoff potential, and hydrological behavior of each soil group. The curve number is a hydrological parameter developed by the Soil Conservation Service (SCS) to estimate how much rainfall becomes surface runoff. It ranges from low values, indicating high infiltration and low runoff, to high values, indicating low infiltration and high runoff. There are four Hydrologic Soil Groups. A, B, C and D. These groups are based on how the soil can soak up water. Group A soils are

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really good at soaking up water, resulting in low runoff. Group D soils are not very good at soaking up water, resulting in high runoff.

In Boroti natural existing wetland, two hydrologic soil group were classified which are group B and group C. Group B soils covers 6,210,000 m^2 of the total catchment area where sub catchment C4 cover 6,100,000 m^2 and sub catchment C3 covers 110,000 m^2 and typically have a clay between 10% and 20% and have sand between 50% to 90% and have loamy sand or Sandy loamy textures which are usually have lower curve numbers because they contain larger sand particles that allow faster infiltration and better drainage, resulting in less runoff. Group C soils cover 12,721,503.53 m^2 where by sub catchment C1 covers the whole area of about 2,335,300 m^2, sub catchment C2 covers the whole area of about 2,995,900 m^2, sub catchment C3 covers 2,254,897.22 m^2 and sub catchment C4 covers 5,135,406.31 m^2 and this group C soils, typically have clay between 20% and 40% and have a sand less than 50% and have loam soils which have a moderate curve number because they possess balanced properties of sand, silt and clay, allowing moderate infiltration and moderate runoff generation. Therefore, the curve number in sub catchment varies directly with soil texture and water absorption capacity, making soil type an important factor in watershed management, drainage planning and flood risk assessment.

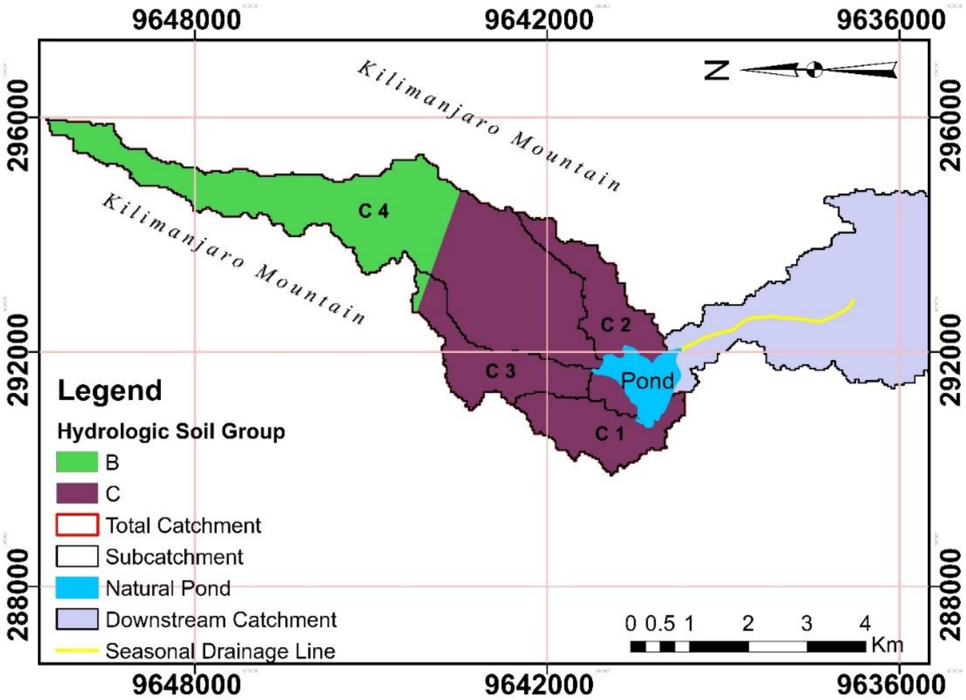

Figure 6: Shows the hydrologic soil group map for Boroti wetland catchment (ArcGIS 10.4)

Land use, Hydrologic Soil Group and the SCS Curve Number are really important when we talk about hydrology and figuring out how much water runs off the surface of the earth when it rains.

The SCS Curve Number is a number that combines what the land is used for the type of soil and how the land is treated. This number is usually between 30 and 100. It helps us understand how much water might run off.

If the curve number is low, that means the soil soaks up a lot of water and not much runs off. This is what happens in forests with Group A soils. If the curve number is high, that means a lot of water runs off. This is what happens in cities with pavement or farms with Group D soils (See Table 1).

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Table 1: Shows the relationship between Land use and hydrologic soil group

Land Use Description	Hydrologic Soil Group			
	A	B	C	D
Cultivated land				
Without conservation treatment	72	81	88	91
With conservation treatment	62	71	78	81
Pasture or range land				
Poor condition	68	79	86	89
Good condition	39	61	74	80
Meadow				
Good condition	30	58	71	78
Wood or forest land				
Thin stand, poor cover, no mulch	45	66	77	83
Good cover[2]	25	55	70	77
Open spaces, lawns, parks, golf courses, cemeteries, etc.				
Good condition: grass cover on 75% or more of the area	39	61	74	80
Fair condition: grass cover on 50-75% of the area	49	69	79	84
Commercial and business areas (85% impervious)	89	92	94	95
Industrial districts (72% impervious)	81	88	91	93
Residential[3]				
Average lot size (% Impervious[4])				
1/8 ac or less (65)	77	85	90	92
1/4 ac (38)	61	75	83	87
1/3 ac (30)	57	72	81	86
1/2 ac (25)	54	70	80	85
1 ac (20)	51	68	79	84
Paved parking lots, roofs, driveways, etc.[5]	98	98	98	98
Streets and roads				
Paved with curbs and storm sewers[5]	98	98	98	98
Gravel	76	85	89	91
Dirt	72	82	87	89

(Source: SCS Urban Hydrology for Small Watersheds, 2nd Ed., (TR-55), June 1986)

According to the stormwater management model user manual version 5.2, the soil characteristics, which include saturated hydraulic conductivity, suction head, porosity, field capacity and wilting point, were obtained from Table 1.2 corresponding with the soil texture class, where in this study we have Silt loam and sandy clay loam. And the Manning's Coefficient of surface of each sub catchment which flows overland, including fallow soil, cultivated soil and grasses, has an average of 0.12 (N-Perv) (See Table 1.3)

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Table 2: Shows the soil characteristics that entered into EPA SWMM 5.2

Soil Texture Class	K	Ψ	ϕ	FC	WP
Sand	4.74	1.93	0.437	0.062	0.024
Loamy Sand	1.18	2.40	0.437	0.105	0.047
Sandy Loam	0.43	4.33	0.453	0.190	0.085
Loam	0.13	3.50	0.463	0.232	0.116
Silt Loam	0.26	6.69	0.501	0.284	0.135
Sandy Clay Loam	0.06	8.66	0.398	0.244	0.136
Clay Loam	0.04	8.27	0.464	0.310	0.187
Silty Clay Loam	0.04	10.63	0.471	0.342	0.210
Sandy Clay	0.02	9.45	0.430	0.321	0.221
Silty Clay	0.02	11.42	0.479	0.371	0.251
Clay	0.01	12.60	0.475	0.378	0.265

The relation between Ψ and K can be obtained from $\Psi = 3.23\ K^{-0.328}$

Whereby; Ψ = Suction head (in)

K = Saturated hydraulic conductivity (in/hr)

φ = porosity, fraction

FC = field capacity, fraction

WP = wilting point, fraction

(Source: Rawls, W.J. et al., (1983). J. Hyd. Engr., 109:1316 through stormwater management model user manual version 5.2)

Table 3: Shows Manning's Coefficient (n) for overland flow surface under pervious area

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Surface	n
Smooth asphalt	0.011
Smooth concrete	0.012
Ordinary concrete lining	0.013
Good wood	0.014
Brick with cement mortar	0.014
Vitrified clay	0.015
Cast iron	0.015
Corrugated metal pipes	0.024
Cement rubble surface	0.024
Fallow soils (no residue)	0.05
Cultivated soils	
Residue cover < 20%	0.06
Residue cover > 20%	0.17
Range (natural)	0.13
Grass	
Short, prairie	0.15
Dense	0.24
Bermuda grass	0.41
Woods	
Light underbrush	0.40
Dense underbrush	0.80

(Source: McCuen, R. et al. (1996), Hydrology, FHWA-SA 96-067, Federal Highway Administration, Washington, DC, through Stormwater management model user manual version 5.2)

Table 4: Shows Boroti natural existing wetland sub catchment characteristics

Sub Catchment	Curve Number	Average Width (m)	Average Slope (%)	Area (ha)	% Imperviousness	N-Perv.	Drainage Length (n)
C1	70	11299.88	6.54	233.53	0	0.8	1636.06
C2	70	14263.78	7.752	299.59	0	0.8	1305.94
C3	69.3	13152.32	14.2825	236.49	0	0.8	2657.09
C4	62	32479.44	18.5125	1123.54	0	0.8	11509.75

(Source: ArcGIS 10.4)

The simulation results from the EPA SWMM 5.2 model show that both scenarios were executed successfully, indicating that the model setup, input data, and hydraulic network configuration were acceptable for analysis. In both cases, the continuity error for surface runoff was recorded as -0.03%, which is extremely low and demonstrates that the rainfall-runoff computations were reliable and numerically stable. This suggests that the runoff generated from the sub catchments was accurately balanced within the model,

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with negligible loss or gain of water during the runoff calculation process. Therefore, the hydrologic component of the model can be considered highly dependable for both scenarios.

However, differences were observed in the flow routing continuity error between the two scenarios. The scenario with a storage unit recorded a routing error of -8.16%, while the scenario with a junction (without a storage unit) produced a higher routing error of -16.90%. Although both scenarios completed successfully, the lower routing error in the storage unit scenario indicates better hydraulic performance and more stable flow routing conditions. The storage unit likely helped attenuate peak flows by temporarily storing runoff before releasing it downstream, thereby reducing instability in the conveyance system. In contrast, the junction scenario allowed runoff to pass directly through the system without detention, leading to more abrupt flow changes and a larger routing imbalance.

4. CONCLUSION AND RECOMMENDATION

Based on the simulation results obtained from the EPA SWMM 5.2 model, both scenarios were successfully executed and provided useful insight into the hydraulic performance of the drainage system under different design conditions. The continuity error for surface runoff was very low in both cases (-0.03%), indicating that the hydrologic computations were accurate and reliable. However, noticeable differences were observed in the flow routing results. The scenario with a storage unit recorded a lower routing continuity error (-8.16%) compared to the scenario with a junction without storage (-16.90%), demonstrating that the storage unit improved hydraulic stability and system efficiency.

Generally, the study concludes that using a storage unit works better for stormwater management than relying on a junction alone. Storage facilities boost the capacity and resilience of urban drainage systems by controlling runoff discharge and improving downstream hydraulic performance. So, integrating storage units into stormwater infrastructure can go a long way toward flood mitigation, sustainable drainage management, and better system reliability.

Based on the findings, it's recommended that storage unit detention or retention structures be included in urban drainage systems, especially in areas prone to flooding or rapid runoff generation. These facilities can effectively cut peak discharge, reduce surcharge in conduits, and improve overall hydraulic performance. Engineers and planners should consider storage-based designs as a preferred option when upgrading or developing drainage infrastructure.

Further studies should also be carried out using different storm return periods, rainfall intensities, and storage unit dimensions to evaluate system performance under varying hydrological conditions. That would help determine the optimum storage capacity for specific catchments and improve the reliability of drainage designs. Future research might also look at combining green infrastructure measures permeable pavements, infiltration trenches, bioretention systems with storage units for more sustainable stormwater management.

For better performance of the Boroti wetland in runoff and flood control, it's recommended to increase the pond depth to at least 6.6 meters. This could be done by building a buffer wall to hold enough stormwater, deepening the wetland bed, or using both options together.

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