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Quantitative Assessment of Environmental Site Design vs. Traditional Storage-Based Stormwater Management: Impacts on Catchment Hydrology of Minebank Run, Baltimore, MD

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ABSTRACT

Environmental site design (ESD) is a stormwater management approach that prioritises the use of infiltration-based non-structural techniques to mimic the natural hydrologic cycle by reducing impervious surfaces, slowing runoff and increasing infiltration. Traditional storage-based stormwater management is designed for flood control by quickly diverting runoff from developed areas. This study compared the effect of ESD and only storage-based stormwater management practices on the hydrology of an urban watershed in Baltimore County, Maryland, USA. Minebank Run is an 8.47 km^2 flashy urban stream with a catchment largely developed without stormwater management. A calibrated SWMM model was used to simulate changes in catchment hydrology resulting from ESD and detention basins over a 54-year period, from the onset of urbanisation in 1948 to the state of urbanisation in 2001. This approach offers a novel, retrospective perspective by simulating how the watershed hydrology might have changed if ESD had been implemented from the beginning of urban development. The model results were analysed by quantifying and comparing different hydrologic metrics to evaluate runoff quantity and flow variability. Results indicated that although storage ponds performed similarly to ESD in reducing annual maximum peak flows (43% vs. 45% reduction, respectively), ESD reduced mean annual runoff coefficients significantly more than ponds (28% vs. 2.7%, $p < 0.0001$). The Richards–Baker Flashiness Index was reduced from 0.46 to 0.32 with the implementation of ESD, as compared to 0.36 with detention ponds. This study also tested the hypothesis that the impact of urbanisation on the hydrology of the Minebank Run watershed would have been reduced if it had been developed with ESD. The results indicated that the implementation of ESD would have reduced annual maximum peak flows by an average of 46%, annual mean runoff coefficients by 51% and the Richards–Baker Flashiness Index by 37%, as compared to the as-is condition. The study provides quantitative insights into the performance of traditional and innovative stormwater management techniques at the catchment scale, illustrating the benefits of a combination of both infiltration practices and detention storage in reducing the hydrologic impacts of urbanisation.

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1 | Introduction

Urbanisation causes an increase in impervious surface cover, which decreases infiltration, in turn increasing surface runoff. This increased runoff overwhelms urban drainage systems, leading to more frequent and severe urban flooding, which poses direct risks to public safety, property and infrastructure (Rainey et al. 2021). In smaller urban catchments, increases in runoff volume result in higher peak discharges per unit drainage area, contributing to flashiness (Smith and Smith 2015). Hydrologic alterations due to urbanisation not only affect channel stability (Plumb et al. 2017; Russell et al. 2020), but also the biological integrity of the stream (Lu et al. 2024; Martin 2020; Williams-Subiza et al. 2024). The United Nations estimates that the number of people living in cities and adjacent urban areas will increase from 55% in 2020 to 68% by 2050 (UN-Habitat 2022); therefore, the development of innovative and sustainable approaches to managing urban stormwater is a critical need.

The primary focus of traditional stormwater management (SWM) was rapid diversion of runoff from developed areas (Davis 2005), which resulted in downstream flooding. In response, detention ponds were constructed for flood control (Davis 2005) to redistribute runoff to the falling limb of the hydrograph (Miller et al. 2021). For example, in Maryland, the first state-wide SWM regulations were adopted in 1983 (MDE 1983). The goal of these initial regulations was to minimise downstream flooding by reducing peak flows for the 2-year to 10-year recurrence interval (RI) storm events. In 2000, these regulations were updated to include measures designed to protect water quality and channel stability (Schueler and Claytor 2000). The latest stormwater control method, known as environmental site design (ESD), was then instituted by Maryland in the Stormwater Management Act (SMA) of 2007 (Maryland General Assembly 2007).

ESD, also referred to as low-impact development (LID), includes source-control and spatially distributed green infrastructure (GI). The goal of ESD is to replicate the natural hydrologic cycle (Sparkman et al. 2017) by conserving natural features, minimising the use of impervious surfaces and slowing down runoff to increase lag time, infiltration and evapotranspiration. Stormwater controls include infiltration-based non-structural or micro-scale practices whose purpose is to capture a prescribed runoff volume. Unlike traditional SCMs, ESD does not target peak flows. Instead, the primary objective of ESD is to achieve runoff volume reduction by promoting infiltration, evapotranspiration and onsite storage of stormwater. ESD design guidelines require that the site runoff volume from a 1-year, 24-h RI storm event be equivalent to runoff from a forested site characterised as 'woods in good condition' (MDE 2009). These requirements are unique in that they require the full implementation of distributed, infiltration-based stormwater control measures (SCMs). Use of traditional detention structures is only permitted if the required volume storage cannot be achieved with the distributed practices.

Traditional storage-based systems alone are often insufficient for restoring watershed function, especially in highly urbanised areas. Therefore, effective SWM should integrate both ESD and detention/retention storage, normally in the form of a pond (Jefferson et al. 2017). Storage-based SWM can be effective in reducing peak flows, but in most cases, it does not reduce flow volumes (Booth and Jackson 2007). Studies have shown that implementation of infiltration-based SWM practices like ESD is effective in reducing runoff volume (Avellaneda et al. 2017; Feng et al. 2016; Jarden et al. 2015).

Several studies have utilised the Storm Water Management Model (SWMM) to simulate the implementation of LID or ESD practices, producing a time series of catchment runoff (Avellaneda et al. 2017; Ayoubi Ayoublu et al. 2024; Gao et al. 2021; Lammers et al. 2022). Using SWMM, Alamdari and Hogue (2022) evaluated the impact of various SCMs on annual infiltration in the semi-arid urban catchment of Ballona Creek in southern California; the authors predicted a maximum net infiltration increase of 67.8% through the implementation of vegetated swales and bioretention. Similarly, de Oliveira Sousa et al. (2024) used the SWMM model to simulate runoff reduction within an urban catchment in midwest Brazil, incorporating combinations of permeable pavement, rainwater harvesting and infiltration trenches. They observed a median runoff reduction of 30%, with a range of 10%–41% across different scenarios. Other modelling tools have also been applied to assess SCM and LID performance; for example, a study using the Long-Term Hydrologic Impact Assessment LID model (L-THIA-LID), which is based on the curve number method, simulated runoff volume reductions for various practices including dry detention ponds (33%), wet retention ponds (7%), wetland basins (5%), grass swales (42%) and grass strips (34%) (Liu et al. 2015). Distributed, physically based models such as the U.S. Army Corps of Engineers' Gridded Surface Subsurface Hydrologic Analysis (GSSHA) model require more extensive input data and greater computational resources (Fry and Maxwell 2017). Applying the GSSHA to a 0.26 km^2 urban subwatershed in Denver, Colorado, USA, Fry and Maxwell (2017) found that distributed SCMs had the greatest impact on peak flow reduction for smaller storm events, achieving 25%–41% reductions for the 2-year storm.

In addition to runoff quantity, stream flashiness is one indicator of hydrologic alteration. Stream flashiness is a parameter that synthesises event dynamics, such as precipitation intensity, duration and conditions prior to the event, with the features of the catchment, including slope, soil properties and land use/land cover (Gannon et al. 2022). Stream flashiness can impact the health and diversity of aquatic ecosystems through habitat and water quality degradation (USEPA 2024). Lockett et al. (2024) applied the Richards–Baker Flashiness Index (RBI), the coefficient of variation (CV) and a baseflow index (BFI) to quantify stream flow response to land–use change in southern Ontario. Urban catchments exhibited the highest levels of flashiness and lowest baseflow indices, indicating rapid surface runoff and low levels of groundwater recharge. Pennino et al. (2016) performed an analysis of variance (ANOVA) to assess the effect of different levels of ESD implementation on hydrologic flashiness metrics in 23 catchments in Baltimore County and Montgomery County, Maryland and Washington, DC, USA. Results of their study showed that catchments with at least 10% implementation of ESD practices exhibit a 26%–44% reduction in hydrologic flashiness metrics (volume-to-peak ratio) compared to those without ESD.

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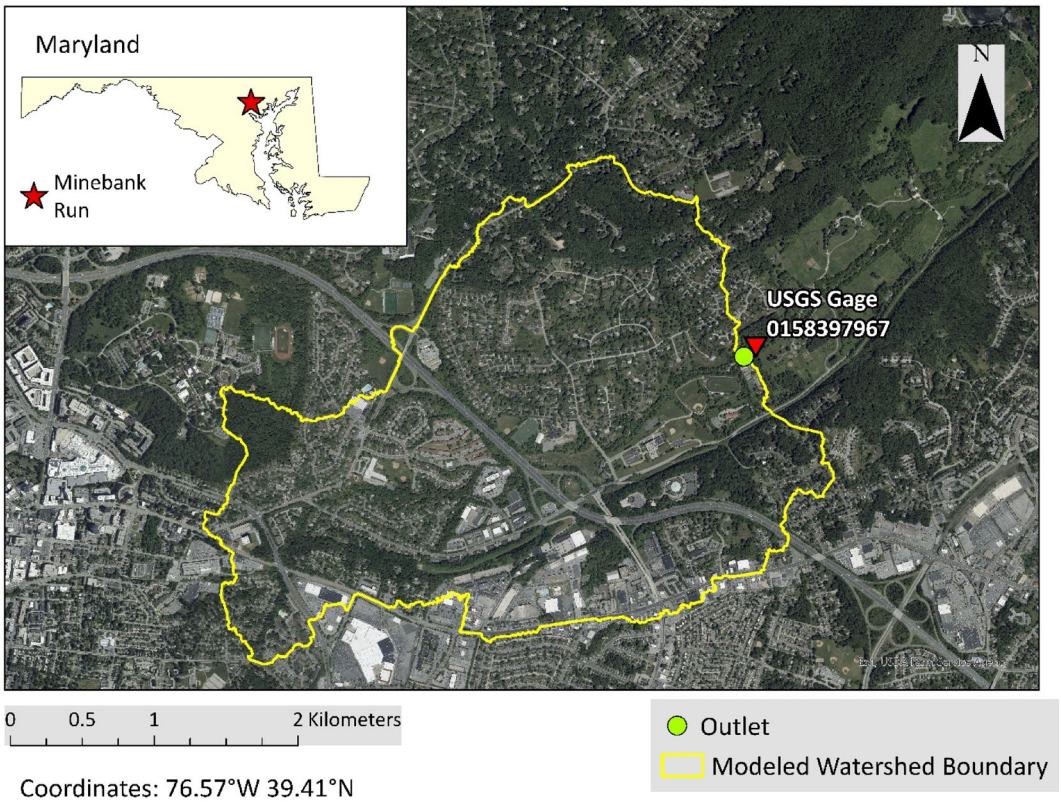

FIGURE 1 | Location of the Minebank Run study catchment in Maryland, USA.

While ESD is effective at reducing the hydrologic impact of urbanisation, Lammers et al. (2022) observed that the performance of infiltration practices differs significantly when analysed at the subbasin scale compared to the catchment scale. Their study demonstrated that bioretention cells achieving volume reduction at the subbasin scale may not provide equal reduction at the catchment scale. Given this complexity, evaluating the effectiveness of ESD at the catchment scale requires a model that can predict changes in catchment hydrology due to urbanisation and incorporate the effects of SWM practices.

The study site for this research is a flashy urban stream in Baltimore County, Maryland, USA named Minebank Run. This urban catchment was largely developed without SWM. The goal of this study was to evaluate the effectiveness of ESD in reducing the hydrologic impacts of urbanisation at the catchment scale. Specifically, the objectives were to:

1. Compare the catchment runoff response (peak flow, runoff volume and stream flashiness) under three SWM scenarios (as-is, storage ponds only and ESD implementation);
2. Assess the relative performance of traditional storage-based ponds and ESD, which is a combination of both infiltration-based and storage-based SWM; and
3. Explore a hypothetical scenario in which ESD had been implemented from the onset of urban development in the Minebank Run catchment and observe the hydrologic response of the catchment (1948–2001).

To achieve this, a calibrated and validated SWMM model was applied to simulate runoff under different SWM approaches for the period of 1948–2001. This study is unique, given the catchment-scale analysis over a multi-decadal period (Ashmore et al. 2023). The modelling framework incorporated land cover and precipitation data spanning decades of urbanisation, with the ESD scenario designed to meet current regulatory standards (to the maximum extent practicable) as outlined in Maryland's SMA of 2007 (Maryland General Assembly 2007). This reverse-engineered approach offers a novel perspective by simulating the long-term hydrologic consequences had modern ESD practices been in place historically. By quantifying these alternate outcomes, the study provides insight into the cumulative benefits of early and widespread ESD adoption.

2 | Study Site

Located in Baltimore County, Maryland, USA, Minebank Run has a drainage area of 8.47 km^2 (Figure 1) and is a tributary to Gunpowder Falls. Catchment elevations range from 121 to 152 m NAVD88 at the drainage boundary and from 46 to 122 m in the stream valley. The relief in most areas of the catchment varies between 30.5 and 91.5 m (Doheny et al. 2007) (Figure 2), and the mainstem channel slopes are generally around 1% (Doheny et al. 2007). The typical storm hydrograph is very flashy (Figure 3) due to the combination of relatively steep channel slopes, significant relief and large areas of impervious surfaces (Doheny et al. 2006).

The Minebank Run catchment is situated in the Piedmont physiographic province of Maryland and is bounded by two ridges running southwest to northeast, with a broad, gently

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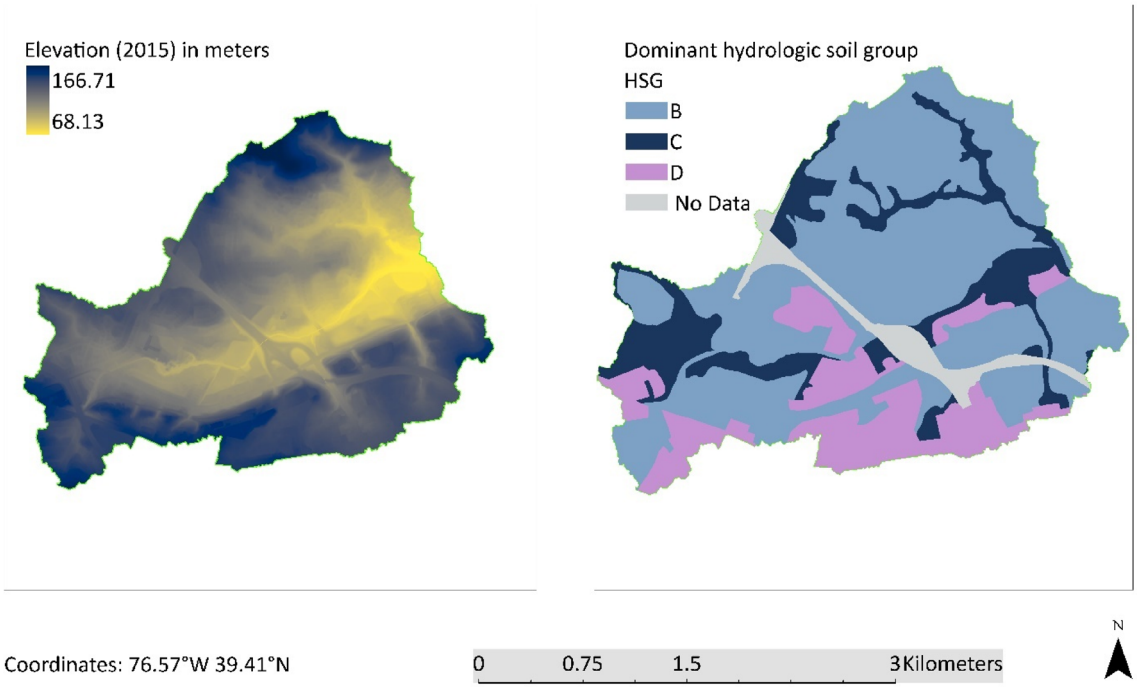

FIGURE 2 | Digital elevation model (DEM) and SSURGO Soil map of the hydrologic groups for the Minebank Run watershed.

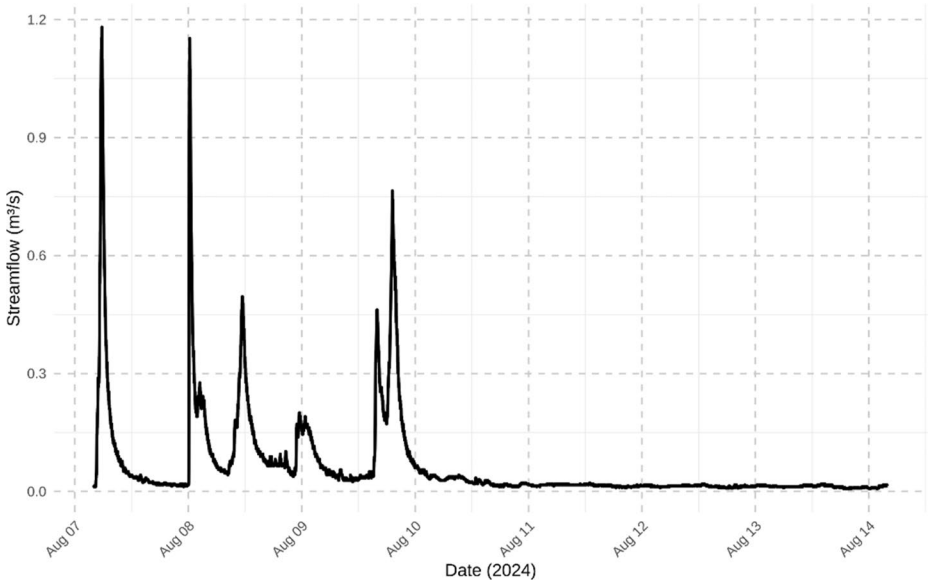

FIGURE 3 | Stream discharge in Minebank Run, illustrating the flashy hydrology (USGS gauge 0158397967: 7 August 2024 to 13 August 2024).

sloping valley in between. In the floodplains of the upper reaches, most of the soil is sand that has been carried and deposited by runoff. In the lower reaches of the catchment, silt loam (Lindside series) was deposited over most of the alluvial sediments (Doheny et al. 2006). According to the USDA NRCS web soil survey dataset, 61% of the total catchment area is classified as hydrologic soil Group B, followed by 23% as Groups C and D (Figure 2) (NRCS 2024). The Minebank Run catchment falls within the humid subtropical climate zone (Köppen classification Cfa), characterised by hot, humid summers and cool to mild winters (NOAA 2024). The climate normal provided by the National Centers for Environmental Information (NCEI) for the period 1991–2020 (Station USC00182308) indicate an annual temperature normal of 13.4°C (56.1°F). The average maximum temperature reaches 30.3°C (86.5°F) during the month of July, and the average minimum of −3°C (26.6°F) occurs in January.

The precipitation normal is approximately 1274 mm (50 in.) annually (NOAA's NCEI Station US1MDBL0016), which is distributed relatively evenly throughout the year. Precipitation falls mostly as rain with limited snowfall during the months of January and February (Figure 4). Thunderstorms are common, particularly in the summer, and intense storm events bring heavy rainfall that contributes to rapid runoff in the Minebank Run catchment.

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Development within the catchment was limited prior to the 1950s, but accelerated in the late 1950s through 1970 (Figure 5). Land cover based on the National Land Cover Database (NLCD) in 2019 was 76% developed (Classes 21–24), 21% forested (Classes 41–43 and 52) and 3% grass and pasture (Classes 71 and 81) (Dewitz 2021). Most of the developed area was built prior to the promulgation of SWM regulations. As such, only 7.4% of the catchment drains to SCMs, almost all of which were built before ESD was widely adopted.

The outlet of the study catchment is located 540 m upstream of Cromwell Valley Park Road (39.409248, −76.557873) in a reach that was previously studied by the U.S. Geological Survey for the purpose of assessing a stream restoration project (Figure 1) (Doheny et al. 2012). An active USGS stream gauge (#0158397967) is located approximately 180 m downstream of the study catchment outlet. The gauge has been in continuous operation since October 2001; limited water quality data are available from 2002 to 2008.

The mainstem Minebank Run channel flows through land owned by Baltimore County in Cromwell Valley Park, and the county has funded stream restoration efforts in phases covering much of the length of the main channel since 1999. These projects were designed to stabilise the channel, protect infrastructure and restore channel habitat by reconnecting the channel with the adjacent riparian zone. Continued flooding and excess sediment influx from upland sources have undermined the stability of some of the restored reaches.

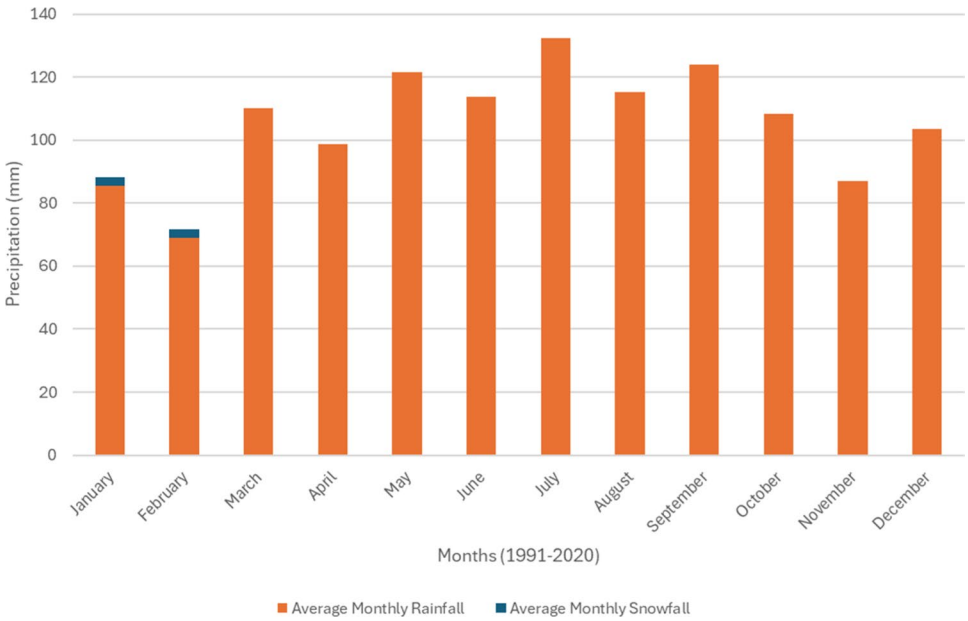

FIGURE 4 | Thirty-year average monthly rainfall and snow in NOAA/NCEI station US1MDBL0016.

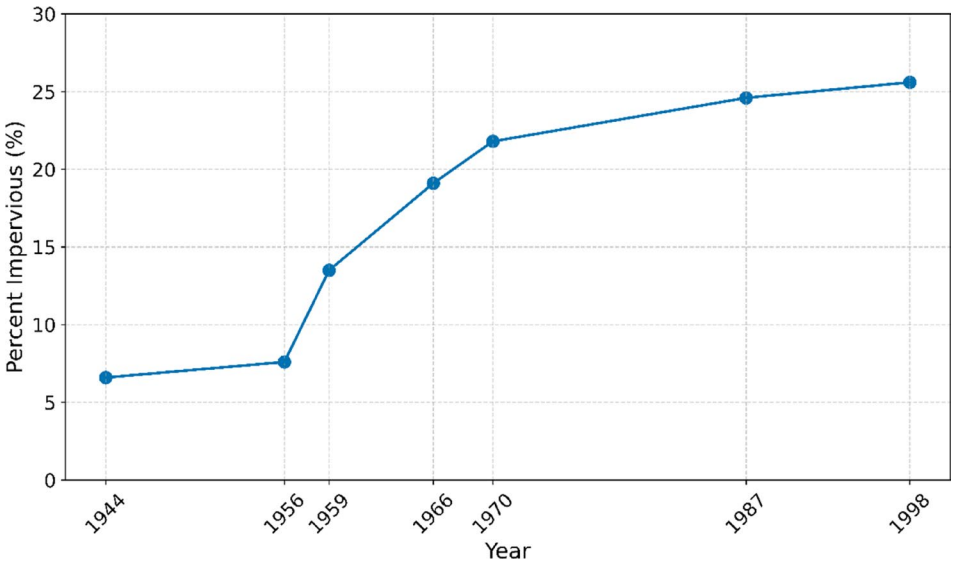

FIGURE 5 | Percent impervious cover within each development period in Minebank Run catchment obtained using historic aerial photographs and satellite imagery of the area and shapefiles of structures and roads provided by Baltimore County.

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3 | Methods and Analysis

3.1 | Hydrologic Modelling

3.1.1 | Subcatchment Delineation and Parameterisation

The Minebank Run catchment was subdivided into 100 subcatchments. Watershed partitioning was based on multiple parameters, including stream/conduit network connectivity, the existence of SCMs and locations where simulated flow outputs were needed for the calibration process. Topography within each subcatchment was based on a 1.83-m (6-ft) digital elevation model (DEM). The DEM was obtained from the Maryland iMAP Data Catalog (iMAP 2018) while digital soil information was collected from the Soil Survey Geographic Database (SSURGO) (NRCS 2019). The impervious percentage for each subcatchment was determined using county-provided shapefiles that detailed impervious structures, including roads, buildings, sidewalks, driveways and parking lots. Several temporally stable land cover periods were identified based on the percentage of impervious cover (Figure 5). Historic aerial images were used to eliminate structures from undeveloped areas, working backwards in time from the county GIS data to reflect conditions on the ground during each of these land cover periods. To predict flow within the subcatchment, the model utilised Manning's roughness coefficient, with appropriate values for both impervious and pervious surfaces assigned according to the guidelines provided in the SWMM 5.1 documentation (Rossman 2015).

The Green–Ampt equation was used to simulate infiltration. A shapefile representing the saturated hydraulic conductivity was extracted from the SSURGO soil database and intersected with the subcatchment shapefile to obtain the saturated hydraulic conductivity by subcatchment. Suction head was estimated for each subcatchment using published data (Rawls et al. 1982, 1983; Gowdish and Muñoz-Carpena 2009). Subcatchment groundwater parameters were determined through calibration utilising observed baseflow values.

3.1.2 | Existing SCM Representation

Most developments within the Minebank Run catchment took place prior to the adoption of the ESD approach to SWM. Existing management practices consist mainly of detention ponds. A shapefile of existing SCMs was obtained from Baltimore County, identifying seven detention ponds within the watershed. Five ponds were identified in the Minebank Run catchment that were large enough (drainage areas > 2.02 ha) to potentially impact peak flows at the catchment level. Two ponds with smaller drainage areas were omitted, as their inclusion did not influence model results. Pond data were derived from as-built plans and verified through field investigations. These detention ponds were represented in SWMM by developing the depth-surface area curve and determining the type, size and elevation of the outfalls.

3.1.3 | Calibration and Validation

To calibrate and validate the SWMM model, 5-min precipitation data were obtained from Baltimore County for several stations with close proximity to the Minebank Run catchment. Station HR19 was the closest to the catchment. For this station, precipitation data were available starting in 2009. Streamflow records were available from USGS Station 0158397967 on Minebank Run near Glen Arm, MD starting in water year 2001. The SWMM model was manually calibrated for water year 2018 and validated for water year 2012. These 2 years were selected for their relatively high maximum annual flow and because they contained fewer data gaps as compared to other years. Both years fell within the period of full development of the catchment, where land cover conditions were similar to current conditions. Model parameters adjusted during the hydrologic calibration process included subcatchment width, Manning's roughness coefficient for impervious and pervious land segments, depression storage for impervious and pervious land segments and groundwater equation coefficients and exponents. Table 1 provides a list of the adjusted parameters.

Based on parameter adjustments made during the hydrologic calibration process, good visual and statistical agreements were obtained between the observed storm flows at the USGS gauge and the simulated flow. Goodness-of-fit statistics for the calibration and validation periods for Minebank Run SWMM modelling are provided in Table 2. The calibration and validation statistics meet the evaluation criteria for goodness-of-fit in hydrologic modelling as defined by Moriasi et al. (2007). The corresponding performance categories (e.g., Good and Very Good) are indicated in Table 2 using lowercase letter notation. Observed and simulated streamflow plots for the calibration and validation periods are provided in Figures S1.1 and S1.2, respectively. Flow duration graphs for the calibration and validation comparison are also provided in Figures S1.3 and S1.4, respectively. Based on the goodness-of-fit criteria, model calibration varied from Good (PBIAS) to Very Good (NSE, R^2), while model validation ranged from Good (R^2) to Very Good (PBIAS, NSE).

While the model achieved good performance in matching peak flows, it tended to overestimate low flows, as seen in Supporting Information S1. This was a result of prioritising calibration towards peak flow metrics, given the study's focus on evaluating the effectiveness of SCMs in reducing flood peaks, storm runoff volumes and flashiness. These SCMs are primarily designed to manage storm events and have limited influence during baseflow conditions. Therefore, while the model does not simulate low flows with high accuracy, this limitation has minimal impact on the interpretation of study results, which centre on storm-driven hydrologic responses rather than baseflow dynamics. To provide an indication of uncertainty in the simulations, we calculated RMSE for peak flows in both the calibration and validation years (Table 2). While RMSE provides a measure of uncertainty in simulating peak flows, it does not directly translate to uncertainty in return period estimates, which require frequency analysis of peak flow records. However, the relatively low RMSE values indicate that the model provides a reliable representation of peak flow dynamics, with only limited error around extreme events.

3.1.4 | Stormwater Scenarios

The calibrated/validated SWMM model for the Minebank Run catchment was utilised to simulate multiple scenarios to assess

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TABLE 1 | SWMM parameters adjusted during the calibration process.

Parameter	Definition	Unit	Calibrated range
Characteristic width	Characteristic width of the overland flow path for sheet flow runoff and is a function of subcatchment area and longest flow path	m	19.80–867.16
Impervious Manning's roughness	Manning's *n* for overland flow over the impervious portion of the subcatchment	—	0.014–0.022
Pervious Manning's roughness	Manning's *n* for overland flow over the pervious portion of the subcatchment	—	0.23–0.60
Impervious depression storage	Depth of depression storage on the impervious portion of the subcatchment	cm	0.239
Pervious depression storage	Depth of depression storage on the pervious portion of the subcatchment	cm	0.61–1.14
Hydraulic conductivity	Soil saturated hydraulic conductivity	cm/h	0.081–1.420
A_1	Groundwater flow coefficient	—	0.01
A_2	Surface water flow coefficient	—	0.01
B_1	Groundwater flow exponent	—	1
B_2	Surface water flow exponent	—	0.01

TABLE 2 | Statistics describing the calibration and validation performance of the SWMM hydrologic modelling.

	Calibration (2018)		Validation (2012)	
	Observed	Simulated	Observed	Simulated
Maximum 5-min peak flow (m^3/s)	33.1 (1170 cfs)	45.8 (1617 cfs)	33.1 (1170 cfs)	32.9 (1163 cfs)
Mean flow (m^3/s)	0.088 (3.1 cfs)	0.091 (3.2 cfs)	0.068 (2.4 cfs)	0.076 (2.7 cfs)
RMSE (mean daily, m^3/s)	—	0.095	—	0.049
RMSE (peak flows, m^3/s)	—	2.56	—	1.96
NSE (mean daily flow)	—	0.76[b]	—	0.86[b]
R^2 (mean daily flow)	—	0.83[a]	—	0.92[b]
PBIAS (%) (mean daily flow)	—	−2.4%[b]	—	−11.4%[a]

Note: Performance criteria (Moriasi et al. 2007).
[a]Good: $0.75 \leq R^2 \leq 0.90$; $0.65 \leq \text{NSE} \leq 0.75$; $\pm 10 \leq \text{BBIAS} \leq \pm 15$.
[b]Very Good: $0.9 \leq R^2 \leq 1.00$; $0.75 \leq \text{NSE} \leq 1.00$; $\text{BBIAS} \leq \pm 10$.

the impacts of land cover changes and SWM strategies on stormwater runoff within the Minebank Run catchment. The following scenarios were developed:

1. Baseline scenarios: Two baseline scenarios were developed with the corresponding land cover data and the existing limited SWM. The first baseline scenario portrayed the modern conditions (2019) in a single model, while the second baseline scenario consisted of a series of seven models that reflected the historic changes in catchment land cover as it developed (1948–2001; Figure 5). The SWMM model parameters, including the percentage of impervious, were adjusted for each subcatchment in the calibrated/validated SWMM model to reflect conditions based on historic land cover for different time periods.
2. Hypothetical scenarios: Two hypothetical scenarios were evaluated, reflecting different approaches to SWM. These scenarios were developed with modern land cover data (2019). These scenarios are as follows:
   a. Implementation of storage ponds in the catchment.
   b. Implementation of ESD practices in the catchment.
3. Historic what-if scenario: This scenario explored the potential impact of implementing ESD practices with historic land cover data, providing insight into the catchment hydrology had ESD regulations been in place as the catchment developed. Model parameters were adjusted to reflect the hypothetical adjustments.

To simulate the current SCM requirements in the hypothetical scenarios and the historic what-if scenario, a procedure

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was developed in accordance with the State of Maryland's stormwater control regulations for SCM sizing (MDE 2009). This procedure targeted the channel protection volume (Cpv), which is based on the 1-year, 24-h storm event. The SCMs were sized to reduce runoff volume from the developed areas in each subcatchment to levels comparable to those from wooded areas in good condition, consistent with the design intent outlined in the Maryland Stormwater Design Manual (MDE 2009). For every subcatchment, a rainfall target depth (PE) that needed to be captured was obtained from Table 5.3 in the Maryland stormwater manual (MDE 2009), as a function of the hydrologic soil group and the percentage of imperviousness within the subcatchment. The runoff depth used to size the SCMs was then calculated based on the following equations:

$$\mathrm{QE} = \mathrm{PE} \times Rv \tag{1}$$

$$Rv = 0.05 + 0.009\,(I) \tag{2}$$

where QE is the runoff depth used to size stormwater practices and I is the percentage of imperviousness. Total runoff volume over the entire catchment area was calculated by multiplying the runoff depth from each subcatchment by the subcatchment area.

Detailed runoff volume calculations and design of ESD measures on a site-by-site basis for the fully developed catchment were beyond the scope of this project; therefore, a novel procedure was needed to represent the hypothetical implementation of ESD measures within the SWMM model. Rather than focusing on present-day feasibility or site-scale design, the goal of this study is to assess the watershed-scale hydrologic impacts that may have occurred if ESD principles had guided development from the start. Several modifications to the SWMM model were implemented to reflect the impact that different ESD approaches and/or SCMs could have. To evaluate the catchment-scale impact of these modifications, a sensitivity analysis was performed using the 1-year 24-h storm hydrograph and the SWMM model representing the fully developed land cover as existing in the year 2019. Multiple options for model parameter adjustments intended to represent ESD implementation within each subbasin were explored, including reducing impervious area, routing impervious area runoff onto pervious areas, increasing detention storage or soil hydraulic conductivity and adding stormwater detention ponds. The results of this sensitivity analysis are summarised in Supporting Information S2. The parameter-based representation of ESD within the model was intended to simulate the functional outcomes of full-scale ESD implementation across the landscape at the onset of development. This approach provides insight into the potential cumulative benefits of early, widespread adoption of ESD. It is important to note that the Maryland ESD guidelines primarily target runoff volume reduction, not peak flow attenuation. As a result, timing and routing are less critical since the regulatory focus is on reducing runoff through a linear, additive process. The Minebank Run watershed spans 8.47 km^2, which is relatively large for modelling multiple historical scenarios. Since the study involved six distinct time periods, each with unique land cover, developing individual models for each period introduced significant time and resource constraints. Thus, the modelling approach prioritised achieving the required volume reductions, consistent with the ESD design intent. Two of the options, one representing traditional stormwater controls and one representing ESD, were then extended to the entire simulation period using the 5-min precipitation from 1948 to 2001 to generate flow time series to compare the long-term impact of the hypothetical changes to catchment conditions on the flow regime. Hourly precipitation records were available starting in 1948 and were disaggregated using NETStorm version 19.10 to run the historic model series on a 5-min basis (CDM Smith Inc. 2019).

3.1.5 | Model Representation of the Stormwater Scenarios

To simulate the hypothetical scenario of the implementation of only storage ponds, the ponds were simulated as detention basins. Topographic analysis was performed within the catchment to identify potential locations for the added detention ponds. A total of 12 pond locations were identified. A DEM was used in the topographic analysis to identify potential pond locations along tributaries where sufficient volumetric storage could be provided to meet the targeted runoff volume reduction. The process involved starting at the mouth of each tributary and moving upstream to locate areas with adequate topographic depressions or storage capacity. Based on the topography of each location, the potential storage volume for the 12 locations ranged from 987 to 12 334 m^3 (0.8–9.9 acre-ft) with a combined storage volume of 67 200 m^3 (2.4 million ft^3), which is equal to the reduction volume needed to meet the state's channel protection requirements. The locations and sizes of these potential ponds within the Minebank Run catchment are shown in Figure 6.

Because the design of multiple infiltration-based SCMs was not feasible, the hydrologic impacts of distributed infiltration practices were represented in the SWMM model as changes in hydrologic model parameters. Several parameter changes were tested, including reducing impervious area, increasing depression storage and/or soil hydraulic conductivity and routing impervious areas to pervious land. The impact of these parameter changes on runoff peak flow rates and volume is summarised in Supporting Information S2. The final model modifications (option 9, Table S2.1) included increasing detention storage by 50% throughout the catchment and routing runoff from 50% of all impervious areas to pervious areas in subcatchments with less than 50% impervious area, if the elevation of the impervious surface was higher than that of adjacent pervious areas. These parameter adjustments represent the hydrologic impact of installing infiltration practices, such as bioretention cells and infiltration trenches, and disconnection of impervious surfaces from the stormwater system, as retrofits throughout the catchment. Ultimately, only 19 600 m^3 could be stored in infiltration practices. Therefore, as permitted in the Maryland ESD regulations (MDE 2009), the remainder of the required volume reduction was stored in five ponds, in addition to the existing five detention structures, bringing the total runoff storage to 67 200 m^3. These adjustments to the current condition model (2019) are representative of the

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potential hydrologic changes that could occur through the implementation of additional stormwater controls within the existing catchment.

3.1.6 | Model Representation of ESD in Historic Model Series

Three model parameters were selected for modification to represent the application of ESD based on the sensitivity analysis (Supporting Information S2): level of imperviousness, soil saturated hydraulic conductivity and depression storage. Adjustments to these parameters were made until the runoff volume for the 1-year, 24-h design storm was equivalent to the runoff under the condition of 'woods in good condition'. Although the sensitivity analysis also tested routing impervious runoff and adding detention ponds, these were not selected because routing was not feasible to represent consistently across multiple time periods, and ponds mainly reduced peak flows rather than runoff volume. The final model parameters for each simulated time period are provided in Table 3. The five existing stormwater detention ponds were included in this series of models, but the five retrofit ponds from the existing condition model were not added to reflect the ESD goal of minimising impervious surface areas and maximising infiltration.

3.2 | Rainfall Event Identification and Hydrologic Metrics

The model was run using 5-min interval continuous rainfall data from 1948 to 2001. The result of the model provided 5-min interval discharge rates under the different SWM scenarios. To extract hydrologic metrics for further analysis, discrete rainfall events were identified from the continuous precipitation data. A threshold of 2.54 mm was applied to filter out minor rainfall events that did not significantly contribute to runoff (Liu et al. 2013). A minimum inter-event time (MIT) of 6 h was used to distinguish separate rainfall events, ensuring that periods of

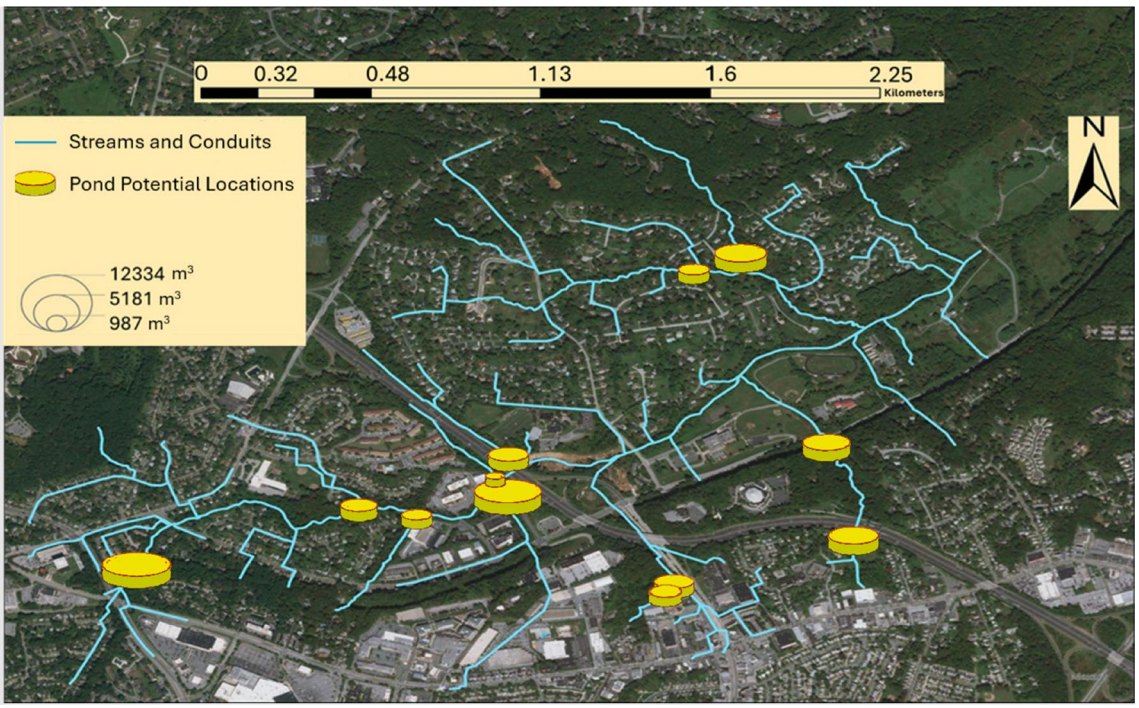

FIGURE 6 | Locations and size of potential detention ponds within the Minebank Run (MBR) catchment.

TABLE 3 | Changes in model parameters for each historic model to represent environmental site design.

Land cover period	Depression storage	Soil saturated hydraulic conductivity	Reduction in % imperviousness
1948–1955	Multiplied by 1.5	Multiplied by 1.5	16%
1956–1958	Multiplied by 1.5	Multiplied by 1.5	23%
1959–1965	Multiplied by 2	Multiplied by 2	30%
1966–1969	Multiplied by 3	Multiplied by 3	40%
1970–1986	Multiplied by 4	Multiplied by 4	50%
1987–1997	Multiplied by 5	Multiplied by 5	46%
1998–2001	Multiplied by 5	Multiplied by 5	46%

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rainfall separated by less than 6 h were merged into a single event (USEPA 1986).

The hydrologic metrics analysed in this study to compare different scenarios included peak flow, runoff depth per unit rainfall (runoff coefficient) and flashiness index. Peak flow for each identified rainfall event was extracted. Annual maximum peak flows (54 records for 1948–2001) were obtained for each scenario. Stormflow volume for each event was calculated after baseflow separation. The baseflow separation was conducted in R using the source code for the function for baseflow separation from the EcoHydRology package (Fuka et al. 2019). This function estimates baseflow iteratively based on the streamflow data. The separation process was refined using a filter parameter and the number of passes. Using the stormflow volume resulting from baseflow separation and catchment area, runoff depth per unit rainfall, also known as the runoff coefficient, was calculated for each event. Additionally, the annual maximum, mean and median runoff coefficients (for 1948–2001) were extracted for each scenario.

The RBI was used to assess the flashiness of the stream under the SWM scenarios. The index is calculated by dividing the sum of the absolute values of changes in discharge (q) over specific time intervals (i.e., hourly/daily/monthly) by the total discharge over the same time interval.

$$\mathrm{RBI} = \frac{\sum_{i=1}^{n} \left| q_i - q_{i-1} \right|}{\sum_{i=1}^{n} q_i} \tag{3}$$

For smaller catchments, it is preferable to use hourly data to avoid underestimation of the flow oscillations (Baker et al. 2007). Therefore, since Minebank Run is a small urban catchment, mean hourly streamflow data were used to calculate the flashiness index.

3.3 | Statistical Analysis

3.3.1 | Hypothetical Scenarios

To evaluate if the effects of the two different SWM strategies on annual maximum peak flows were statistically significant, a paired t-test and ranked ANOVA/Kruskal–Wallis tests were performed. First, the Kolmogorov–Smirnov (K–S) hypothesis test was conducted to identify the best-fitting distribution for the annual maximum peak flow, revealing that the data followed a log-normal distribution. Subsequently, equal variance tests were performed on the log-transformed annual maximum peak flow data. Across all cases, the true ratio of variances was equal to 1. Based on these preliminary analyses, a paired t-test was performed to compare the log-transformed peak flows of the SWM scenarios. The statistical significance of differences in peak flows between the scenarios was also evaluated using a ranked ANOVA (Kruskal–Wallis test, $\alpha = 0.05$) with scenarios as the independent variables and annual maximum peak flows as the dependent variables. A similar analysis was conducted for the annual mean runoff coefficients. Post hoc tests (Dunn's test) were performed for pairwise comparison of the scenarios. The ranked ANOVA test was chosen due to the fact that parametric ANOVA requires normality of residuals, and the datasets violated this assumption (Lockett et al. 2024).

3.3.2 | Historic What-If Scenario

Similar to the hypothetical scenarios, a paired t-test was performed on the log-transformed annual maximum peak flows. Various data transformations, including logarithmic, square root, gamma and exponential, were applied to the annual maximum peak flows and annual mean runoff coefficients from the historic what-if scenario to achieve normality of residuals. However, none of the transformations resulted in a distribution that met the assumptions of normality for the residuals, as assessed by the Shapiro–Wilk test and visual inspection of Q–Q plots. Therefore, a non-parametric Brunner–Dette–Munk (BDM) test was applied to the annual maximum peak flows and annual mean runoff coefficients for the historic what-if scenario to perform pairwise comparison with the as-is historic data (Helsel et al. 2020).

4 | Results and Discussion

The average annual peak flows simulated across the different historical land cover periods (1948–2001) reflect the combined effects of precipitation and urbanisation in the catchment (Figure 7). As the catchment urbanised with limited SWM, peak flows increased with the increase in impervious cover. However, although the percentage of imperviousness increased rapidly during the land cover periods of 1959–1965 and 1966–1969, peak flows did not show a corresponding increase due to the effects of one of the largest droughts on record in Maryland (NIDIS 2024).

4.1 | Comparison of Stormwater Scenarios With Existing Land Cover

4.1.1 | Peak Flows

To observe the effects of traditional SCM and ESD implementation, a second baseline scenario was simulated with modern land cover data (2019) and the 54 years of precipitation data (1948–2001). This approach kept the land cover constant across all time periods to reflect fully urbanised conditions. This model enabled the evaluation of catchment hydrology under traditional and ESD SWM techniques without the effects of varying impervious cover. The implementation of only storage ponds led to an average reduction in peak flows of 43.1%. The ESD scenario, which combined infiltration practices and storage ponds, achieved an average reduction of 45.4% (Figure 8). A similar modelling study of a suburban catchment in Columbia, Maryland, USA explored the effects of different levels of rain garden installation on peak discharge and runoff volumes over a three-year period. Study results showed peak flow and runoff volume reductions of only 14.3% and 11.4%, respectively, when 100% of the residential

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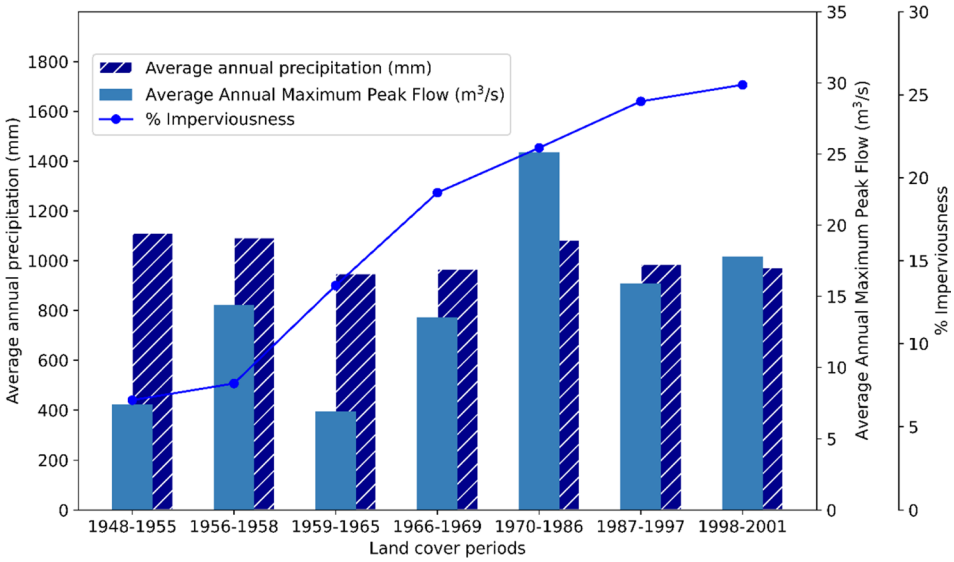

FIGURE 7 | Average annual peak flows, precipitation and percentage of imperviousness over different land cover periods for the baseline model with limited stormwater management.

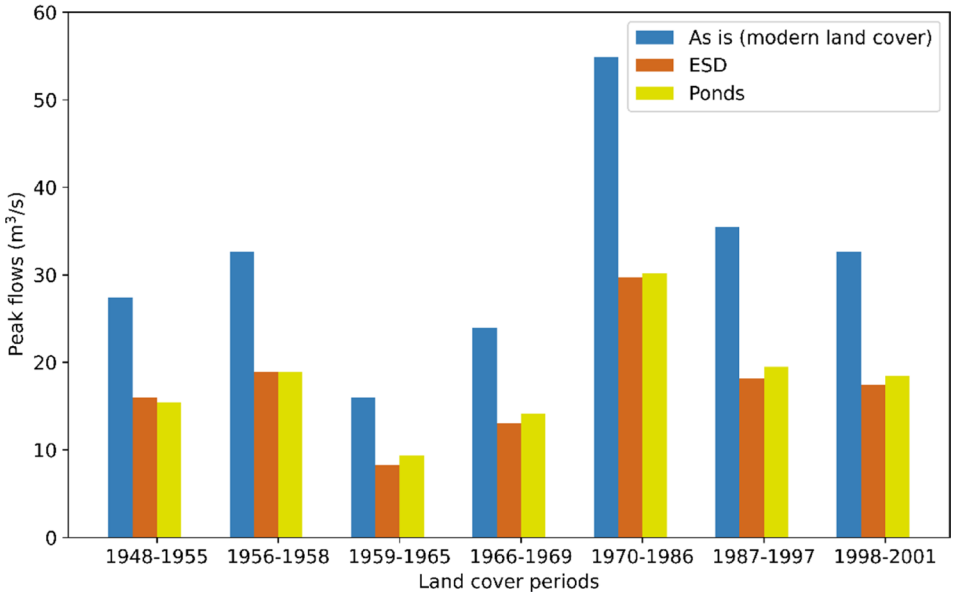

FIGURE 8 | Maximum peak flow during each time period, as simulated for different stormwater management scenarios with 2019 land cover: As-is condition with limited stormwater management, environmental site design (ESD) and storage ponds.

roofs were treated (Daniels and Yeakley 2024). This reduced treatment effect, as compared to this study, was likely the result of only 41% of the total impervious area (4% of the overall catchment) being treated. Additionally, the rain gardens were not designed to meet the ESD requirements. Their study focused on the cumulative performance of residential rain gardens, while this study assessed watershed-scale impacts under the current ESD stormwater regulations.

A hydrologic frequency analysis was conducted for the three different SWM scenarios with the 2019 land cover by fitting the annual maximum peak flow data to a log-normal distribution to determine the 2-year, 10-year and 100-year RI peak flows (Table 4). The goodness-of-fit was assessed using the K–S hypothesis test, which indicated *p*-values greater than 0.86, indicating a good fit to the data. The 95% confidence intervals for the discharge values were determined using bootstrapping (Efron and Tibshirani 1994). Results of this analysis show that ESD produced greater reductions in peak flows for the 2-year and 10-year RI floods than the storage ponds, while the storage ponds reduced the 100-year RI peak flow by 47.1%, as compared to 45.3% for ESD (Table 4). Infiltration-based practices have a limited capacity for retaining water and heavy rainfall can quickly lead to saturation, reducing their effectiveness in lowering peak flow during larger storm events (Samouei and Özger 2020). Storage ponds have higher retention capacity; therefore, the implementation of storage ponds results in higher reductions in peak flows for more extreme events. In a study conducted in suburban catchments in Maryland, Loperfido et al. (2014) found that distributed SCMs, such as

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TABLE 4 | The 2-year, 10-year and 100-year recurrence interval peak flows for three different stormwater management scenarios.

Recurrence interval	Existing	Ponds		Environmental site design	
	Peak flow (m^3/s)	Peak flow (m^3/s)	% Reduction over existing	Peak flow (m^3/s)	% Reduction over existing
2-year	17.1 (14.7–19.9)	10.5 (9.2–12.0)	38.6	9.5 (8.2–11.0)	44.4
10-year	36.2 (29.7–43.4)	20.5 (17.1–24.2)	43.4	19.9 (16.2–24.0)	45.0
100-year	66.5 (49.9–85.7)	35.2 (27.4–44.3)	47.1	36.4 (27.6–46.9)	45.3

Note: The 95% confidence interval for each flow is indicated in parentheses.

infiltration practices, were more effective at reducing flows from smaller storms (< 27 mm), while centralised SCMs, such as ponds, were better suited for lowering flows during larger storm events (> 27 mm). In a study performed in a 23 km^2 urban catchment in Tianjin, North China, different combinations of infiltration-based practices were simulated; peak flow reductions ranged from 5% to 9%, 13% to 25% and 20% to 32% for the 100-year, 10-year and 2-year RIs (Li et al. 2020). In this study, the differences in different RI flows between the two SCM scenarios were small. Considering the 95% confidence intervals for the three RI discharges in Table 4, the differences in design storm discharges between the storage ponds and the ESD practices are not significant, likely because the incorporation of five additional storage ponds was necessary in the ESD scenario to fully meet Maryland's ESD requirements.

Results from paired *t*-tests on annual maximum peak flows across the different SWM scenarios also indicate that the implementation of either storage ponds alone or ESD significantly reduces the mean annual peak flow, as compared to the limited stormwater controls in the existing condition ($p < 0.0001$). These statistical analyses were confirmed for the median annual peak flow using the Kruskal–Wallis tests (ranked ANOVA) and a post hoc analysis with Dunn's test. The ESD scenario, which combined infiltration practices and stormwater ponds, produced significantly lower average and median annual peak flows than the storage ponds alone over the 54-year study period, indicating that integrating infiltration practices with traditional storage-based SCMs is an effective strategy for mitigating peak flows in urban catchments. Specifically, the combined approach leverages the strengths of both methods: infiltration practices are effective in reducing the overall volume of runoff, while storage ponds attenuate peak flows by temporarily storing runoff and releasing it at a controlled rate. This difference was statistically significant following a paired t-test ($p < 0.0001$, mean); however, the significance of the difference was not supported by the non-parametric Dunn's test ($p = 1$, median). Examination of pairwise plots of the annual maximum peak flows for the different stormwater scenarios clearly shows the effectiveness of both traditional stormwater control and ESD in reducing peak flows, as compared to the existing limited stormwater control (Figure 9a,b). However, differences between the two stormwater approaches in controlling storm peak flows are slight (Figure 9c), likely because the ESD technique included five additional storage ponds.

4.1.2 | Runoff Volume

In this study, runoff specifically refers to storm runoff, excluding baseflow, to focus on the direct contributions of precipitation to surface flow within the catchment. ESD targets runoff volume reduction by promoting infiltration, while storage ponds are designed to simply attenuate peak flows by detaining runoff. Although storage ponds perform well in reducing peak flows (Figure 9), they do not enhance infiltration and, consequently, do not reduce the overall runoff volume. As a result, the receiving stream is exposed to elevated flows for longer durations (Colosimo and Wilcock 2007). To assess the impact of ESD and storage pond implementations on flow volume, the runoff depth per unit of rainfall, also known as the runoff coefficient, was compared across the three scenarios. This dimensionless parameter normalises the effects of catchment area and accounts for the amount of rainfall generating runoff.

Similar to the annual maximum peak flows, the annual maximum runoff coefficients for the three different SWM scenarios were analysed by fitting the annual maximum time series to a log-normal distribution to calculate the 2-year, 10-year and 100-year RI runoff coefficients (Table 5). The goodness-of-fit was assessed using the K–S hypothesis test ($p > 0.05$).

Adding the 12 storage ponds to the catchment is expected to reduce both the 2-year and 10-year runoff coefficients by 9% and the 100-year runoff coefficient by 11% (Table 5). In comparison, the implementation of ESD resulted in 21%, 18% and 16% lower runoff coefficients for the 2-year, 10-year and 100-year RIs, respectively, as compared to the existing condition with limited stormwater control. Simulating different levels of ESD implementation, Li et al. (2020) also observed higher reductions (11%–22%) in runoff coefficients for 2-year RI flows, as compared to the 100-year RI flood (4.7%–8.8%).

To assess the impact of ESD and storage pond implementation on flow volume, the mean runoff depth per unit of rainfall, also known as the mean runoff coefficient, was compared across different scenarios (Figure 10). Peak flows are associated with extreme rainfall events, while mean runoff coefficients are used to describe the overall hydrologic response of a catchment to all rainfall events, both extreme and moderate. Comparing the performances in reducing mean runoff depth per unit rainfall reveals that ESD implementation results in a

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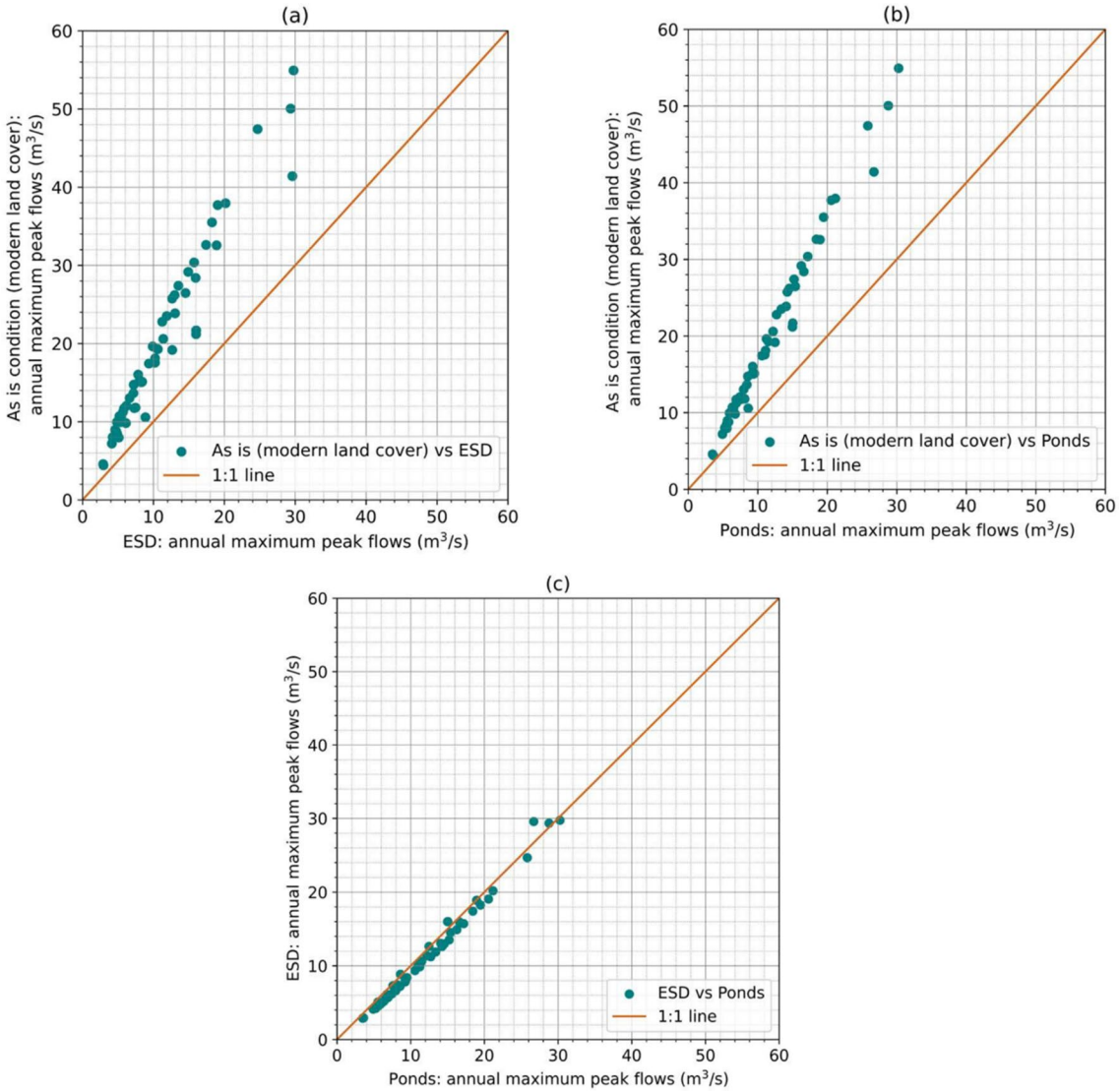

FIGURE 9 | Comparison of annual maximum peak flows: (a) As-is condition vs. environmental site design (ESD), (b) as-is condition vs. storage ponds and (c) ESD vs. storage ponds.

TABLE 5 | The 2-year, 10-year and 100-year recurrence interval runoff coefficients for three different stormwater management scenarios.

Recurrence interval	As-is	Ponds	ESD
2-year	0.33	0.30	0.26
10-year	0.44	0.40	0.36
100-year	0.56	0.50	0.47

greater reduction (28%) in the mean runoff coefficient compared to the implementation of ponds (2.7%), confirming that ESD is more effective in reducing runoff volumes through infiltration. Statistical assessment of these differences using paired *t*-tests revealed that both the ponds and ESD significantly reduced the mean runoff coefficients as compared to the existing condition ($p < 0.0001$), and that the reduction due to ESD was significantly greater than that produced by the ponds ($p < 0.0001$).

While the *t*-test of the means shows the storage ponds significantly reduced the mean runoff coefficient, as compared to the existing condition, the reduction was slight (Figure 11b). The Kruskal–Wallis post hoc analysis indicated that the ponds did not produce a statistically significant reduction in the median of the annual mean runoff coefficients ($p = 0.3817$). This finding suggests that ponds, while effective in reducing peak flows, are less effective in reducing runoff volume, which is more influenced by moderate rainfall events. In contrast, infiltration-based practices outperform storage ponds in reducing runoff from moderate storm events. This observation aligns with findings from other studies that have simulated various levels of ESD practices (Daniels and Yeakley 2024; Samouei and Özger 2020).

4.1.3 | RBI

The RBI is a metric used to quantify the frequency and rapidity of short-term changes in stream flow (Baker et al. 2007). Flashiness in small streams is difficult to quantify using daily

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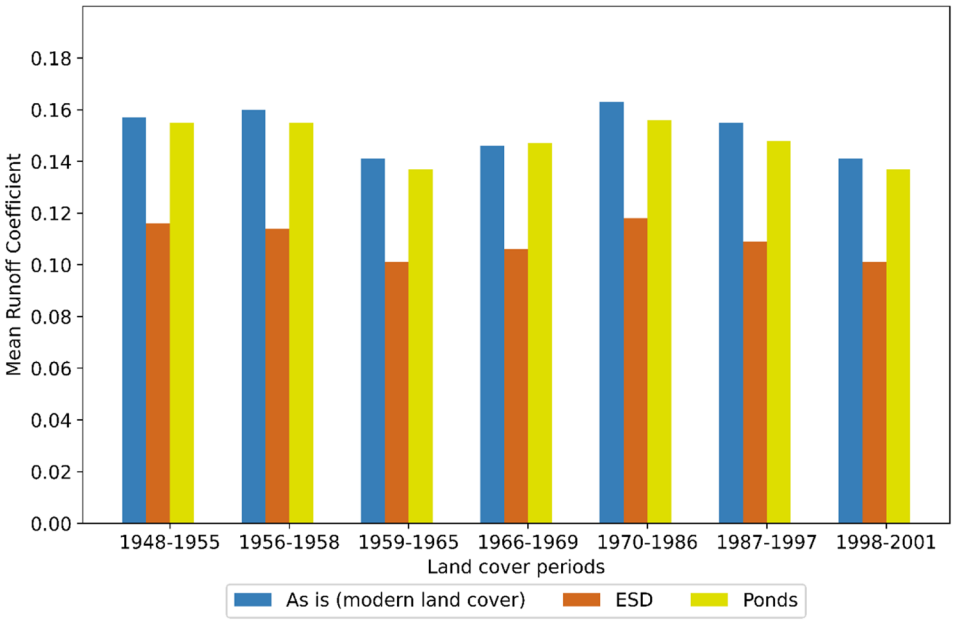

FIGURE 10 | Mean runoff coefficients for as-is condition with no stormwater management, environmental site design (ESD) and traditional storage ponds.

data, as their flow characteristics change rapidly over short timeframes (Johnson et al. 2022). Utilising sub-hourly data, Saharia et al. (2017) identified a strong correlation between increased flashiness and catchment area in smaller catchments (areas < 145 km^2).

Since Minebank Run is a small stream with a catchment area of 5.5 km^2 at the USGS gauge, the RBI in this study was calculated using hourly peak flows. For the as-is condition with limited SWM and the modern developed land cover of 2019, the RBI was 0.46 for the 54-year precipitation record. Although direct numeric comparisons should be made with caution due to differences in data resolution, prior studies using daily streamflow data calculated RBI values for urban catchments with drainage areas ranging from 12.2 to 259 km^2 between 0.29 and 0.54 (Keir 2003; OEHHA 2015; Rosburg et al. 2017). Gannon et al. (2022), also using daily streamflow data, observed that higher RBI values were associated with gauges in specific urban areas in the mid-Atlantic and northeastern US, as compared to other regions across the continental US. For catchments in Maryland, the RBI values reported by Gannon et al. (2022) ranged from 0.40 to 1.00. These studies provide useful context, although differences in data frequency may influence absolute RBI values.

When storage ponds were included in the SWMM model, RBI decreased 22% to 0.36, indicating that ponds dampen peak flows and reduce flashiness by capturing and slowly releasing stormwater. The most significant reduction in flashiness was observed when both infiltration measures and stormwater ponds were utilised; the RBI for the ESD scenario was reduced 30% to 0.32. Simulating the application of infiltration-based SWM practices in a catchment in Cincinnati, Ohio, Lammers et al. (2022) observed a median reduction of 19% in stream flashiness (RBI), with reductions ranging from 7% to 46% depending on the level of ESD implementation (low to high).

4.2 | Potential Change in Historic Flow Regime With ESD

The historic what-if model series sought to evaluate whether the implementation of ESD throughout the development of the Minebank Run catchment could have reduced the impacts of land development on catchment hydrology. This series of SWMM models was developed with historic land cover data, and ESD was implemented by adjusting model parameters to reflect the hydrological impact of infiltration practices (Table 5). The incorporation of land cover data specific to each period allowed the results to reflect the effects of progressive urbanisation.

4.2.1 | Peak Flows

Because the annual maximum peak flows from the historic what-if scenario did not comply with the assumption of normality of residuals, the non-parametric BDM test was conducted to assess the effects of % impervious cover on the peak flows, followed by a pairwise comparison (Helsel et al. 2020). The results indicate that impervious cover had a significant effect on peak flows ($p < 0.0001$). The pairwise comparison revealed that during the early periods of urbanisation (1948–1955 and 1956–1958), when the percentage of impervious cover was low (6.6%–7.6%), there were no significant differences between the existing condition and ESD peak flows ($p = 0.6116$ and $p = 0.5871$, respectively). As the percentage of impervious cover increased, there was a significant difference between the annual maximum peak flows under existing conditions and with ESD after 1970 ($p = 0.0235$ and $p = 0.0188$ for 1970–1986 and 1987–1997, respectively). No significant differences were determined for the time periods 1966–1969 or 1998–2001, likely because of the small data set for each time period. When evaluating the annual maximum peak flows in totality using a paired t-test on the log-transformed values

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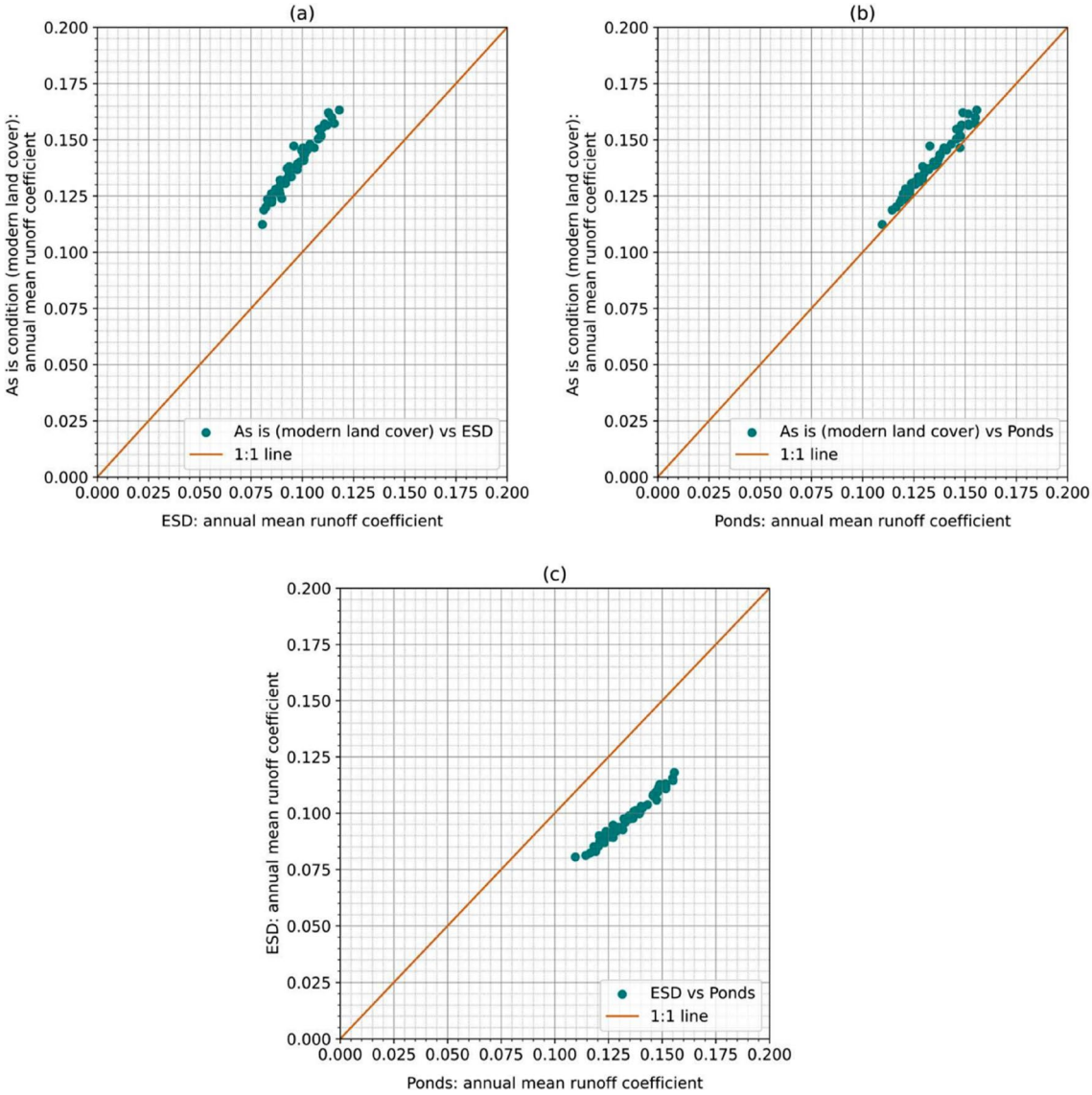

FIGURE 11 | Comparison of annual mean runoff depth per unit rainfall across different stormwater management scenarios: (a) As-is condition vs. environmental site design (ESD), (b) as-is condition vs. storage ponds and (c) ESD vs. storage ponds.

($n = 54$), the 46% decrease in annual maximum flow due to ESD was highly significant ($p < 0.0001$), with 20%–66% reductions in the annual maximum peak flows over the existing condition for the different time periods (Figure 12). These results suggest that incorporating ESD practices from the initial stages of development would have significantly reduced annual maximum peak flows through increased infiltration.

When comparing the peak flows simulated under constant modern land cover (Figure 8) and those under historical land cover conditions (Figure 12), notable differences were observed across time periods. In the models using modern land cover for all years, peak flows remained consistently higher, reflecting the influence of fully urbanised conditions. In contrast, when land cover corresponding to each development stage was used, peak flows were lower in the early time periods (1948–1955 and 1956–1958) and progressively increased as urbanisation advanced. The percentage reductions in peak flow achieved through ESD were also variable between the two approaches. Under the modern land cover, ESD produced consistent peak flow reductions (41.6%–48.7%) across all periods. Under historical land cover, the reductions were smaller in early periods (19.8%–30.1%) with limited development and increased to over 53% in later periods with higher imperviousness. This comparison indicates that as impervious cover increased over time, the relative benefit of implementing ESD practices in reducing peak flows also increased.

4.2.2 | Runoff Volume

To assess the impact of ESD on flow volume, the mean runoff depth per unit of rainfall, also known as the mean runoff coefficient, was compared across different scenarios. The annual mean runoff coefficients for the historic scenario with ESD were 51% lower on average than for the existing conditions (Figure 13). To compare the annual mean runoff coefficients from the historic as-is condition and with ESD, the non-parametric BDM test was conducted for each time period, considering the influence of impervious cover. Unlike the findings for the annual maximum peak flows, the runoff coefficients were significantly different

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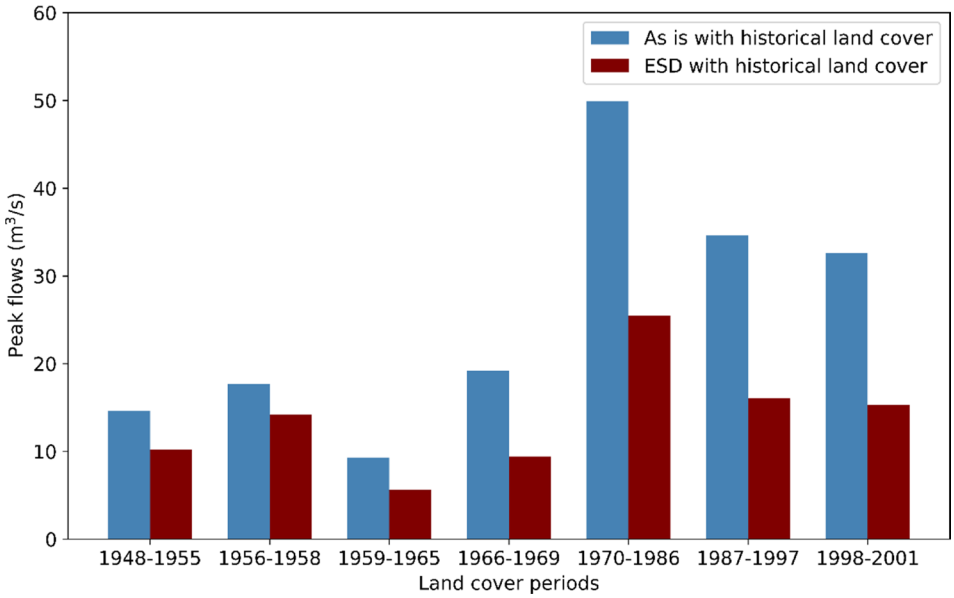

FIGURE 12 | Maximum peak flows for each time period for the existing land cover and with simulated environmental site design (ESD).

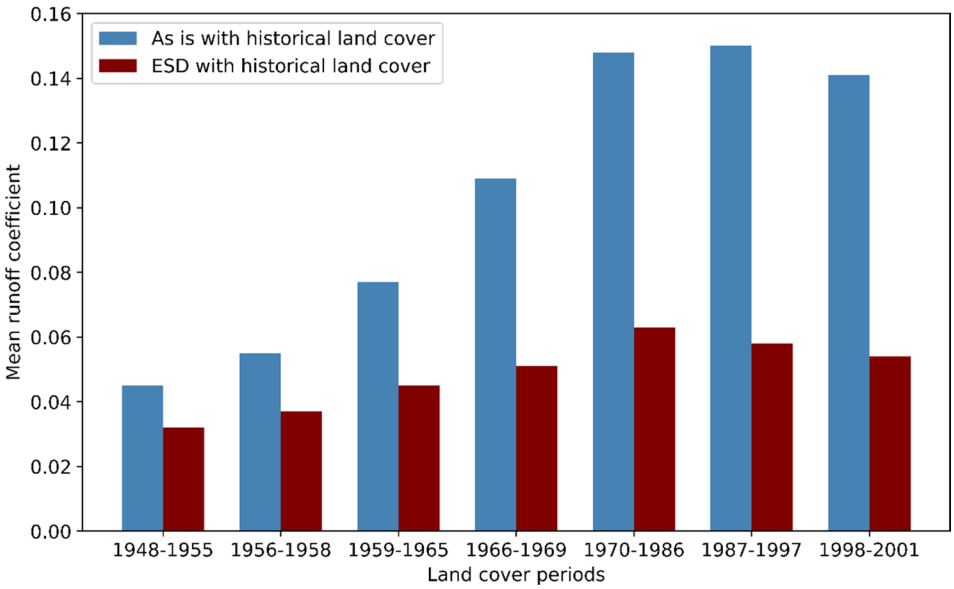

FIGURE 13 | Mean runoff coefficients for the existing land cover and with simulated environmental site design (ESD).

in almost all of the land cover periods, indicating that had the catchment been developed under the ESD regulation, the runoff volume would have been reduced as compared to the historic conditions. The only time period without a significant difference in runoff coefficient was the 1956–1958 period, likely due to the small sample size in this land cover period.

4.2.3 | RBI

To evaluate the potential change in flow flashiness had ESD been implemented as the catchment developed, the RBI was calculated using a series of models over the 54-year time span. With the historic land cover, RBI is 0.38; however, if ESD had been implemented, the RBI would have decreased 37% to 0.24. Improving infiltration through ESD from the onset of development would have dampened the sudden changes in flows in the stream. Reducing stream flashiness can lead to improved water quality, enhanced aquatic habitats, reduced erosion and mitigated flooding (Rosburg et al. 2017). Therefore, incorporating ESD practices from the outset of catchment development would have likely contributed to maintaining a more stable and sustainable catchment ecosystem.

5 | Study Limitations

All computer simulation models have limitations. Using a highly simplified synthetic catchment, Sytsma et al. (2022) demonstrated that semi-distributed models like SWMM can produce substantial prediction errors when calibrated parameters are applied to different land cover or climate scenarios.

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While our study used measured continuous data for calibration and validation, we recognise that some degree of calibration parameter transfer uncertainty is inherent in hydrologic modelling. Therefore, our predictions should be interpreted with this limitation in mind, consistent with the findings of Sytsma et al. (2022). Because this study was focused on the impact of urbanisation on peak flows, model calibration focused on matching flood peaks, at the sacrifice of matching low flows. As a result, baseflows were overestimated by the model (see Supporting Information S1). Additionally, explicitly representing individual infiltration SCMs throughout the catchment was not feasible for this study due to the time and resource constraints associated with developing multiple SWMM models for each historical time period. Instead, we followed Maryland's regulatory guidelines focused on runoff volume reduction to represent ESD implementation through parameter adjustments such as impervious area, depression storage and soil saturated hydraulic conductivity. These parameter changes were implemented without the consideration of cost or the land–use changes that could have been required to achieve this increased level of stormwater infiltration. For example, to meet the ESD requirements using infiltration practices as the development increased after 1970 (with the existing five detention ponds), would have required reductions in impervious area of up to 50% and increases in detention storage and soil saturated hydraulic conductivity by as much as five times existing values. Achieving these targets would have required changes in the density of development and/or extensive use of ESD practices, such as permeable pavement, green roofs and bioretention.

6 | Conclusions

The Minebank Run catchment was originally developed with limited SCMs, which led to increasingly high peak flows, increased flashiness and stream channel erosion. This study employed hydrologic modelling using 2019 land cover and a 54-year precipitation record (1948–2001) to assess the effects of two different approaches to SWM on catchment hydrology, traditional stormwater detention structures and ESD. Both storage ponds and ESD successfully reduced peak flows, resulting in 43% and 45% reductions in annual maximum peak flows, respectively. However, ESD was more effective in reducing runoff volume and flow flashiness. Implementation of ESD with the 2019 land cover reduced the mean annual runoff coefficients 28% over the existing conditions, compared to storage ponds, which produced only a 2.7% reduction, an order-of-magnitude difference. Flow flashiness was also reduced, with the RBI changing from 0.46 for the current conditions with limited stormwater control to 0.36 with the use of storage ponds and 0.32 using ESD. It should be noted that the ESD scenario employed both infiltration practices and storage ponds to meet the state of Maryland stormwater requirements that runoff from the 1-year, 24-h design storm should be equal to the runoff volume from a catchment with 'woods in good condition'. While ponds have higher retention capacity, these structures have limited ability to infiltrate runoff and thereby reduce overall runoff volume.

In addition to comparing two different approaches to SWM, this study evaluated the hypothesis that, had the Minebank Run catchment been developed under the current ESD regulations, the impacts of urbanisation on the catchment hydrology would have been reduced. Study results indicated that implementation of ESD during development would have improved the hydrologic response of Minebank Run, with a 46% average reduction in annual maximum peak flows, a 51% average reduction in annual mean runoff coefficients and a 37% reduction in flashiness index (RBI), as compared to the current conditions with limited SWM. These reductions would have significantly alleviated hydrologic stress on the channel resulting from urbanisation; however, meeting the ESD requirements would have required a reduction in the overall development density and widespread implementation of infiltration-based practices.

A 2009 report by the US National Research Council, Urban SWM in the United States (National Research Council 2009) determined that urbanisation has '... degraded water quality and habitat in virtually every urban stream system'. With the increasing population and size of urban and suburban areas globally, the development and implementation of innovative stormwater controls is critical to protecting limited water resources. Results of this unique, multi-decadal study indicate a combination of distributed infiltration-based controls and traditional detention structures is needed to minimise both peak flows and overall runoff volume from developed lands.

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Data Availability Statement

The data that support the findings of this study are openly available in HydroShare at https://www.hydroshare.org/, reference number https://doi.org/10.4211/hs.ce4acf45a05e435795c01c56eef08eda.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Data S1:** Supporting Information S1. SWMM model calibration and evaluation. **Data S2:** Supporting Information S2. Sensitivity analysis for representing infiltration practices in SWMM.

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