

Research

GIS-based spatial approaches to refining urban catchment delineation that integrate stormwater network infrastructure

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Abstract

Rapid urbanization and escalating climate change impacts have heightened stormwater-related concerns (e.g., pluvial flooding) in cities. Understanding catchment dynamics and characteristics, including precise catchment mapping, is essential to accurate surface water monitoring and management. Traditionally, topography is the primary data set used to model surface water flow dynamics in undisturbed natural landscapes. However, urban systems also contain stormwater drainage infrastructure, which can alter catchment boundaries and runoff behavior. Acknowledging both natural and built environmental influences, this study introduces three GIS-based approaches to enhance urban catchment mapping: (1) Modifying DEM elevations at inlet locations; (2) Adjusting DEM elevations along pipeline paths; (3) Applying the QGRASS plug-in to systematically incorporate infrastructure data. Our evaluation using the geographical Friedman test ($p > 0.05$) and Dice Similarity Coefficient ($DSC = 0.80$) confirms the statistical and spatial consistency among the studying methods. Coupled with onsite flow direction validation, these results support the feasibility and reliability of integrating elements of nature and built infrastructure in urban catchment mapping. The refined mapping approaches explored in this study offer improved and more accurate and efficient urban drainage catchment zoning, beyond using elevation and topographic data alone. Likewise, these methods bolster predictive stormwater management at catchment scales, ultimately strengthening urban stormwater and flooding resilience.

Keywords Spatial planning · Built environment · Urban stormwater drainage · Catchment delineation · Stormwater infrastructure

1 Introduction

The swift pace of urbanization, coupled with the escalating impacts of climate change, has greatly intensified stormwater-related concerns in urban areas [1]. Urbanization leads to the expansion of impervious surfaces, disrupting natural hydrological processes by converting precipitation to surface runoff and exacerbating stormwater-related hazards, such as flooding, surface water pollution, and water supply shortage [2–6]. This context intensifies with climate change that triggers more frequent and intense precipitation events, placing additional strain on existing

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stormwater management systems [7–10]. In response to these challenges, the implementation of resilient stormwater management strategies becomes imperative, calling for a better understanding of urban hydrology, drainage and sewage network systems, and surface runoff behaviors [11–16].

In the context of stormwater management, a catchment—also termed as drainage area or watershed— is defined as a geographical region where all precipitation, surface water, and the collected sediment and dissolved materials drain to a common outlet, which is referred to as the drainage outfall [17, 18]. Determining accurate catchment boundaries with high spatial resolution is of critical importance, enabling targeted stormwater management by comprehending the flow paths and origins of stormwater, and precise mapping of areas susceptible to flooding and pollution [19–23]. Traditionally, topography has been the primary factor in determining surface water flow direction and delineating watershed boundaries in undisturbed natural landscapes [24–27]. However, applying the conventional DEM-only approaches becomes challenging in dynamic urban areas. This is due to the presence of stormwater pipeline infrastructure, including pipes, culverts, and drains, which rapidly diverts runoff through engineered conveyance systems, significantly altering the behavior and dynamics of surface runoff [2, 15, 28]. Recent research studies and engineering practices have therefore increasingly relied on manual delineation methods to incorporate urban infrastructure details [29–31], offering improved realism but at the cost of increased time and potential for human error [32, 33]. Thus, an advanced understanding of urban runoff that integrates both natural topography and built changes—without depending on manual efforts and subjective decisions—is essential for effective urban stormwater management to mitigate flooding risks, enhance water quality, and improve overall urban resilience [34–36].

With the emergence of computing since the 1960s, Geographic Information Systems (GIS) has acted as a pivotal and widespread spatial data integration and visualization platform, allowing professionals of multiple fields (i.e., urban planners, engineers, geographers) to synthesize diverse spatial data sources into a cohesive system. Through GIS, vital factors influencing stormwater management, such as land use patterns, topography, infrastructure networks, and natural features, can be examined concurrently, fostering a comprehensive understanding of the urban landscape and its hydrological behaviors [37–40]. Researchers and practitioners in stormwater management utilize GIS technologies in various capacities. For instance, spatial analysis functions in GIS, like surface interpolation, watershed delineation tools, and overlay analysis are leveraged to assess land use impacts and runoff pathways [41–43]. Specifically, detailed procedures for conventional DEM-only natural catchment mapping methods using ArcGIS (ESRI) are introduced in [44]. Additionally, hydrological modeling tools such as the Geospatial Hydrologic Modeling Extension (HEC-GeoHMS) and the Stormwater Management Model (SWMM) are also integrated within GIS platforms for enhanced runoff simulation and analysis [45–47]. Despite these advancements, there remains a significant research gap in developing a standardized method or comprehensive toolset specifically tailored for fine-scale stormwater catchment boundary delimitation in the GIS realm. Thus, the precise delineation of stormwater catchment boundaries, facilitated by GIS, is crucial to form the foundation for context-specific stormwater management strategies [48, 49].

Recognizing the limitations of both relying solely on topography and manual, subjective processes in urban stormwater catchment delineation, this study underscores the need for enhanced mapping methods that leverage spatial and analytical advancements to more accurately represent these zones. We advocate the significance of incorporating GIS tools and spatial analysis of stormwater pipeline infrastructure networks in the delineation of stormwater catchment. This study contributes to the field by evaluating different GIS-based approaches for mapping stormwater catchment, aiming to alleviate the challenges of urban stormwater management posed by infrastructure development. We present the mapping methodology employed in our study, which includes acquiring and integrating high-resolution spatial data, GIS-based mapping procedures, and validation processes for urban stormwater catchment delineation. Additionally, the implications of our research for urban stormwater management and planning are further discussed. The methodology was applied on the University of Maryland (UMD) campus—United States (US), serving as a pilot testing bed for applying these spatial approaches. The implementation of this approach in practice through real-world urban environment applications may showcase the potential of such methods and provide further insight into challenges and limitations. In this paper, the overarching goal is to develop a set of integrated GIS-based mapping methods that incorporate both natural topography with high-resolution spatial data, such as Digital Elevation Models (DEMs) and stormwater pipeline network information to delimitate urban stormwater catchments at the fine scale. It uses an interactive and integrated mapping environment, contributing to effective stormwater management with informed spatial decision-making for urban planning with resilience.

2 Data and methodology

2.1 Site description

The University of Maryland (UMD) Campus, located in College Park, Prince George's County, Maryland (US) has approximately 1,335 acres with every type of land use designation, including residential, agricultural, industrial, and educational sectors [50] (Fig. 1). Notably, the main campus area features approximately 40% impervious surfaces, contributing to urban runoff and associated pollution and pluvial flooding concerns [50, 51]. This diverse land use mix has implications for potential point and non-point water contamination and runoff pollution, from agricultural runoff containing excess fertilizers and pesticides to urban runoff laden with oil, trash, sediment, and toxic chemicals [52–54].

The stormwater sewer systems of the UMD are characterized by the Municipal Separate Storm-Sewer Systems (MS4) composed of inlets, pipes, and outfalls. This stormwater infrastructure collects and conveys stormwater runoff only, and is “separate” from the sanitary sewers. MS4s ultimately discharge the stormwater collected into nearby waterbodies. The U.S. Environmental Protection Agency (EPA) regulates MS4s to ensure that non-point source pollutants, picked up by stormwater runoff along the path to discharge, do not exceed specified effluent standards [55]. As per the phase II MS4 Permit for Small Municipalities operated by the State of Maryland, there are over 40 outfalls throughout the campus area that discharge stormwater collected by upstream stormwater infrastructure to the natural water body, Paint Branch of the Potomac River. The university's facilities management traditionally delineates catchment areas using topographical information alone, which forms the basis for the current stormwater management strategies. However, such reliance on DEM-derived topographical information alone has proven to yield inaccurate catchment boundaries, underscoring the genesis of this study. Accordingly, this research selected three

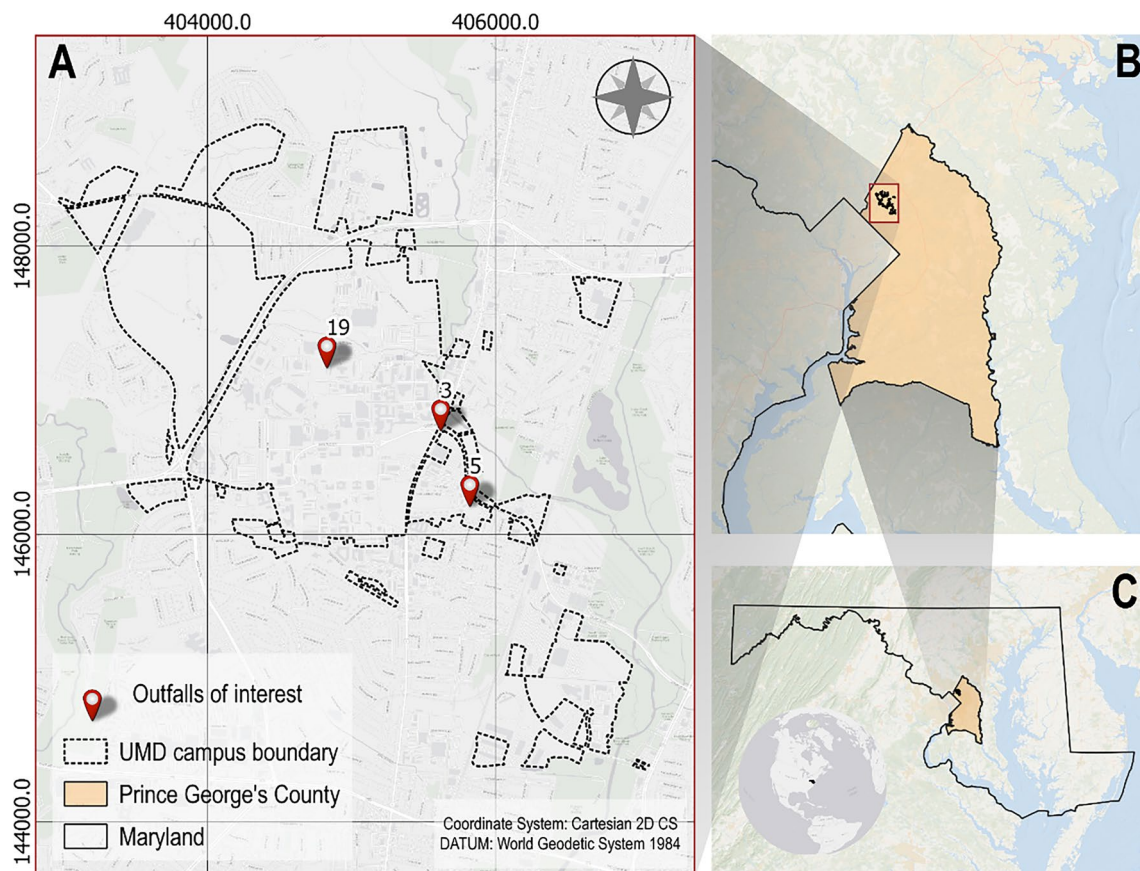


Fig. 1 UMD campus and interested stormwater infrastructure outfall locations (#3, #5, #19) (a), in relation to Prince George's County (b) and Maryland (c)

outfalls within the UMD campus (Outfall #3, #5, and #19) as pilot-interested sites to refine and validate catchment delineation practices beyond conventional topographic constraints. (Fig. 1).

2.2 Data collection and preprocessing

The DEM raster data was obtained from public-accessed Maryland's GIS Data Catalog [56]. The stormwater pipeline infrastructure information for the UMD campus was acquired from UMD Enterprise GIS and the Department of Environmental Safety Sustainability & Risk through an internal administrative request in direct support of an ongoing stormwater project between campus facilities and our research team. The DEM data was collected and processed in 2018 from the LIDAR data and developed into a raster file using the NAD_1983_HARN coordinate system with one band and one XY cell size (1 foot). The UMD campus map information was filed as various vector shapefile layers based on the coordinate system NAD_1983_StatePlane_Maryland_FIPS_1900_Feet. This information encompasses the installed stormwater infrastructure network (inlets, outlets, and pipelines), buildings, impervious surfaces, and the locations of Best Management Practices (BMP) implementations. The stormwater pipeline connection maps were acquired from the UMD Facility Management Department and Maryland Environmental Service Operations Group. To streamline data and processing, the DEM raster was first clipped with the campus boundary. Subsequently, the *Fill* tool was used to address the sinks of the original DEM. Valid inlet facilities were identified by selecting and keeping existing catch basin inlets and manholes while excluding any unstructured infrastructure and roof inlets.

2.3 Stormwater catchment delineation

To accurately delineate the drainage area of the selected outfalls at UMD, this study employs three distinct spatial approaches integrating natural topography and stormwater pipeline information (Fig. 2). First, the "depression digging" method in ArcMap manually adjusts elevations at stormwater inlets, altering surface runoff directions to mimic real-world scenarios (Sect. 2.3.1). Second, the "stream burning" technique also modifies the DEM along pipeline paths to simulate water flow toward stormwater infrastructure in ArcMap (Sect. 2.3.2). Lastly, the GRASS plugin in QGIS is used for automated catchment mapping, considering stormwater inlets as natural depressions, too (Sect. 2.3.3). In addition, the manual catchment mapping method is covered in the following section (Sect. 2.3.4) for comparative and accuracy assessment purposes. It is important to note that the analysis primarily targets runoff that enters the stormwater infrastructure through inlets and is channeled to the outfalls via underground pipelines, originating from the delineated catchment area. This encompasses runoff across varied landscapes contributing to the stormwater system, eventually reaching natural water bodies. While acknowledging the diverse pathways stormwater can take, our focus is explicitly on delineating catchment areas based on the segment of stormwater directed into the pipeline system rather than water infiltrating through pervious surfaces such as bare soil and green spaces, as the former is most relevant to the objectives of urban stormwater infrastructure assessment.

2.3.1 Inlet "depression" digging (AG1)

In ArcMap 10.7.1, each location of the stormwater pipeline inlet on the original DEM raster was assigned to an elevation drop of 3 ft. This can be likened to artificially excavating depressions on the ground surface ("Depression Digging"), mimicking the phenomenon of directing and intercepting surrounding runoff towards the inlet [55]. The vector shapefile of stormwater infrastructure inlets was initially converted to raster by the Point to Raster tool in order to merge with the DEM raster for corresponding elevation change. The following series of raster calculations were conducted by the Raster Calculator tool, including: (a). binarily separating the UMD campus map based on the locations of inlet facilities; (b). assigning -3 ft elevation change at each inlet location to the original DEM raster while keeping elevations of any other areas original. The Mosaic to New Raster tool was used to combine the DEM maps with and without surface elevation change to be able to depict the whole canvas of the UMD campus.

The raster with flow direction information was then generated by applying Flow Direction and Flow Accumulation functions to the inlet-changed DEM raster layer. Moreover, the Basin tool in the Spatial Analyst Toolbox was used to delineate the boundaries of drainage basins based on the flow direction and pour points (sinks) with inlet locations identified in DEM. In this case, each inlet of stormwater infrastructure will be considered as the outlet of the sub-catchment system. Based on the stormwater infrastructure network information, the sub-catchments of connected inlets will be manually selected and merged to a joint sub-catchment set of each stormwater pipeline outlet. The sink of each sub-catchment

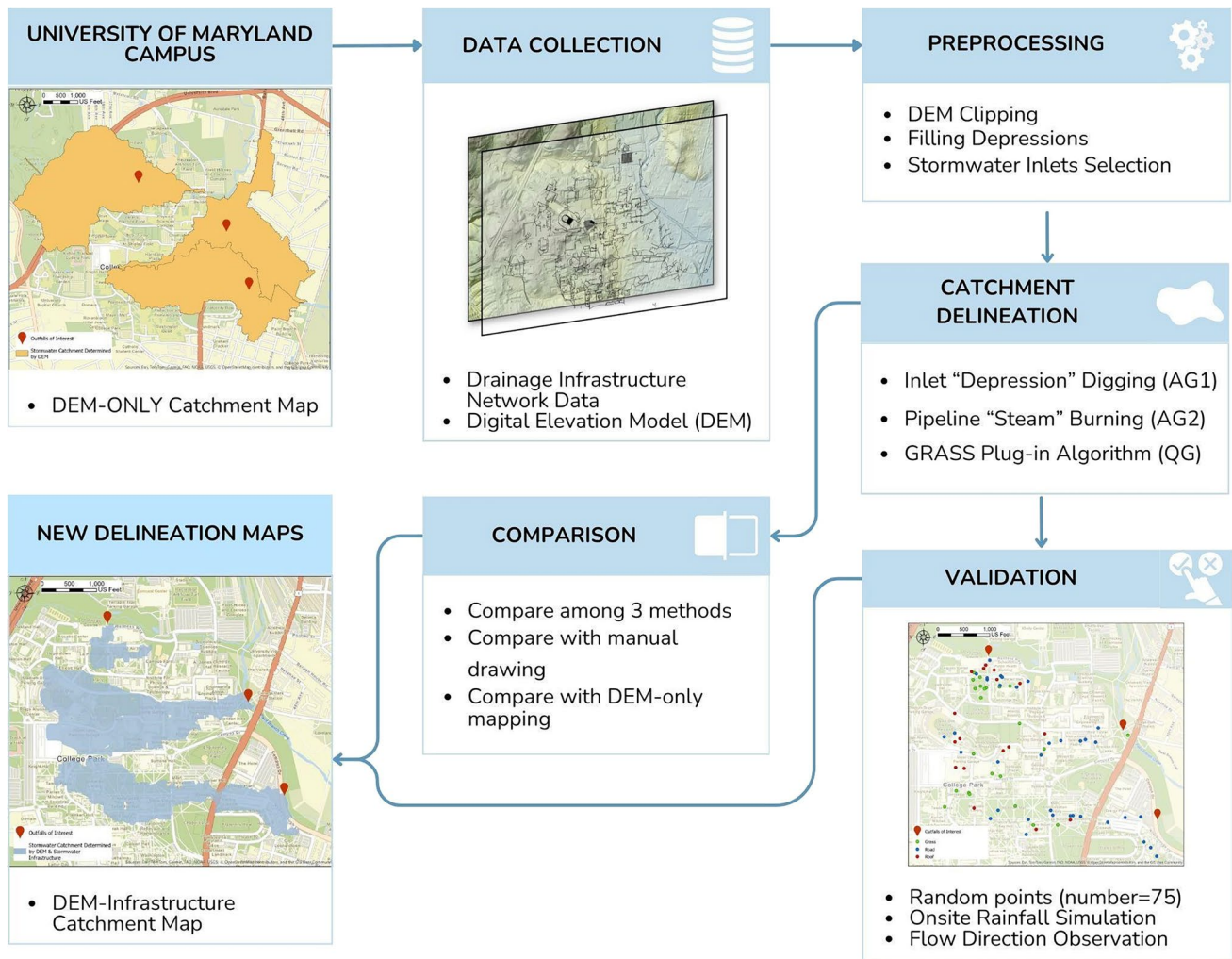


Fig. 2 Flowchart of the methodology

area was compared with the physical inlet facility location, to prove the reliability of the sub-catchment area results from Basin analysis, making sure that the inlets play roles in collecting surrounding surface water.

2.3.2 Pipeline "stream" burning (AG2)

Drawing on the "stream burning" technique, which lowers DEM cell elevations to map natural watercourses in the previous studies [57], we likened our method to this by treating the manmade stormwater pipeline as a conduit for surface water, similar to natural streams. This adaptation helped in capturing and directing urban surface flow pathways, integrating the stormwater pipeline network into the DEM to mirror the function of natural streams in conveying surface water to downstream areas. Similar to the previous procedures of adjusting pixel elevations for inlet points in ArcGIS 10.7.1 (AG1), the pipeline "stream burning" method required the mosaic combination of natural DEM with modified elevation raster, reducing pipeline pixel elevations by 5ft to establish a pronounced direction flow towards the pipeline structures.

The same procedures were followed as the AG1 approach for delineating the stormwater pipeline sub-catchment boundaries and outlet catchment integration, including using a set of functions (i.e., Flow Direction, Flow Accumulation, Basin, etc.). The assumption included in this method was that it simplified the surface runoff movement by considering the underground pipeline system as surface open channels, to which water could enter at any location along its pathway. In real-world applications, surface runoff enters the pipeline system exclusively via pipeline inlets (manholes, curb inlets, etc.). However, the inaccuracy of this assumption can be minimized by the dense distribution of surface inlets on campus, with an average nearest neighbor distance of 54.41 feet between inlets and approximately 25 inlets per mile

of pipeline, in accordance with MS4 regulations (Sect. 2.1). This dense arrangement could ensure effective capture and conveyance of runoff into the underground pipeline system.

2.3.3 GRASS hydrology algorithm (QG)

Integrated within QGIS 3.24.3, the Geographic Resource Analysis Support System, commonly called GRASS, was utilized in this mapping approach. GRASS provides an automated watershed analysis program (R.watershed), enabling automatic stormwater facility inlet identification as it provides an additional input option [58]. Unlike methods AG1 and AG2, which require user-defined topographical changes on the DEM raster, R.watershed module algorithmically identifies drainage divides based on the integration of elevation and infrastructure data [59]. The input option “depression” specifies and manipulates the inlet as sinkholes that store surface runoff from the storm event. In this setting, water would flow into but not out of depressions, as well the stormwater inlet infrastructure acts on the runoff flow. A filled DEM raster of the campus area, with a resolution of 10ft, was employed as an elevation dataset to initiate the delineation process. This procedure allows a representation of the topographic characteristics of the campus terrain. Furthermore, selected inlet facilities, with a resolution of 1ft, representing actual depressions on the campus, were incorporated into the analysis. A comparative analysis of various input parameter-setting scenarios was conducted as the sensitivity check of the embedded algorithm. As a result, the minimum basin size criterion was determined as 500 pixels. This threshold was selected to strike a balance between capturing meaningful sub-catchment and avoiding excessive fragmentation. Based on the information on the drainage infrastructure network and manual catchment drawing, the drainage basin of each inlet that connects to the interested outfalls will be selected and merged as the drainage area of the corresponding outfall.

2.3.4 Manually drawing (MN)

As highlighted in the Introduction, manual delineation of fine-scale catchment boundaries in urban settings remains a widely applied practice among researchers and practitioners, utilizing techniques such as AutoCAD drawings or physical surveys. As a rough reference, in this study, the manual drawing of catchment boundaries was conducted by combining campus carto-information and the stormwater pipeline network, while also considering the fundamental principle that water flows from high to low. The process commenced with a detailed analysis of the topographic features within the study area, utilizing high-resolution elevation data (DEM). From there, key high and low points were identified, forming the initial sketch of catchment boundaries. The existing stormwater pipeline network was incorporated into the delineation process to refine further and validate the boundaries determined by manual mapping. The spatial information provided by the pipeline network allowed for identifying the potential flow paths, contributing to the more accurate demarcation of catchment boundaries. Google Map StreetView was utilized as a reference during the process of catchment border determination. However, it is important to note that the manual process involved judgment and decision-making based on the collective expertise of the research team. The resulting maps serve as a valuable reference for mapping accuracy assessment and comparison. It is not included as a part of the explored GIS-based toolset for urban catchment delineation that forms the major focus of this study.

2.4 Validation

In order to verify the accuracy and reliability of the catchment delineation processes, we undertook field observations and comparisons between observed runoff flow directions and the corresponding results obtained during the catchment delineation process. This comparison serves as a validation step to evaluate the effectiveness of the GIS-mapping methods used because the flow direction determined by the manipulated DEM and topographic information is the key foundation of the determination of catchment area and boundary. In this sense, 25 locations within each of the resulting catchment maps were randomly selected in ArcMap 10.7.1 using *Create Random Point* in the Data Management toolbox in ArcGIS software as observation points for this validation exercise.

Due to the lack of sufficient natural rainfall events during our study period, we employed a systematic water application method at these selected locations to simulate rainfall events and runoff movements, ensuring no residual runoff influenced our observations. This involved gently applying tap water to the surrounding surface using a sprayer to create consistent rainfall conditions, allowing for direct, visual assessment and recording of the observed surface water flow direction at each point. Special attention was given to identifying the predominant flow paths and any

deviations from the expected directions. These field observations provided a qualitative assessment of the runoff flow patterns within the study area.

Field observations were compared with flow direction results obtained from the catchment delineation process. In this comparison analysis, the corresponding flow direction outputs were extracted from the delineated catchment map and visualized by employing an embedded tool in QGIS 3.24.3 called “*Gradient Vectors from Surface*”, which uses arrows to intuitively indicate the flow direction of interested surface areas (Fig. 3.1). These results were then scrutinized and compared against the observed flow directions at the respective validation points. Any inconsistencies between the observed and delineated flow directions were carefully noted and analyzed.

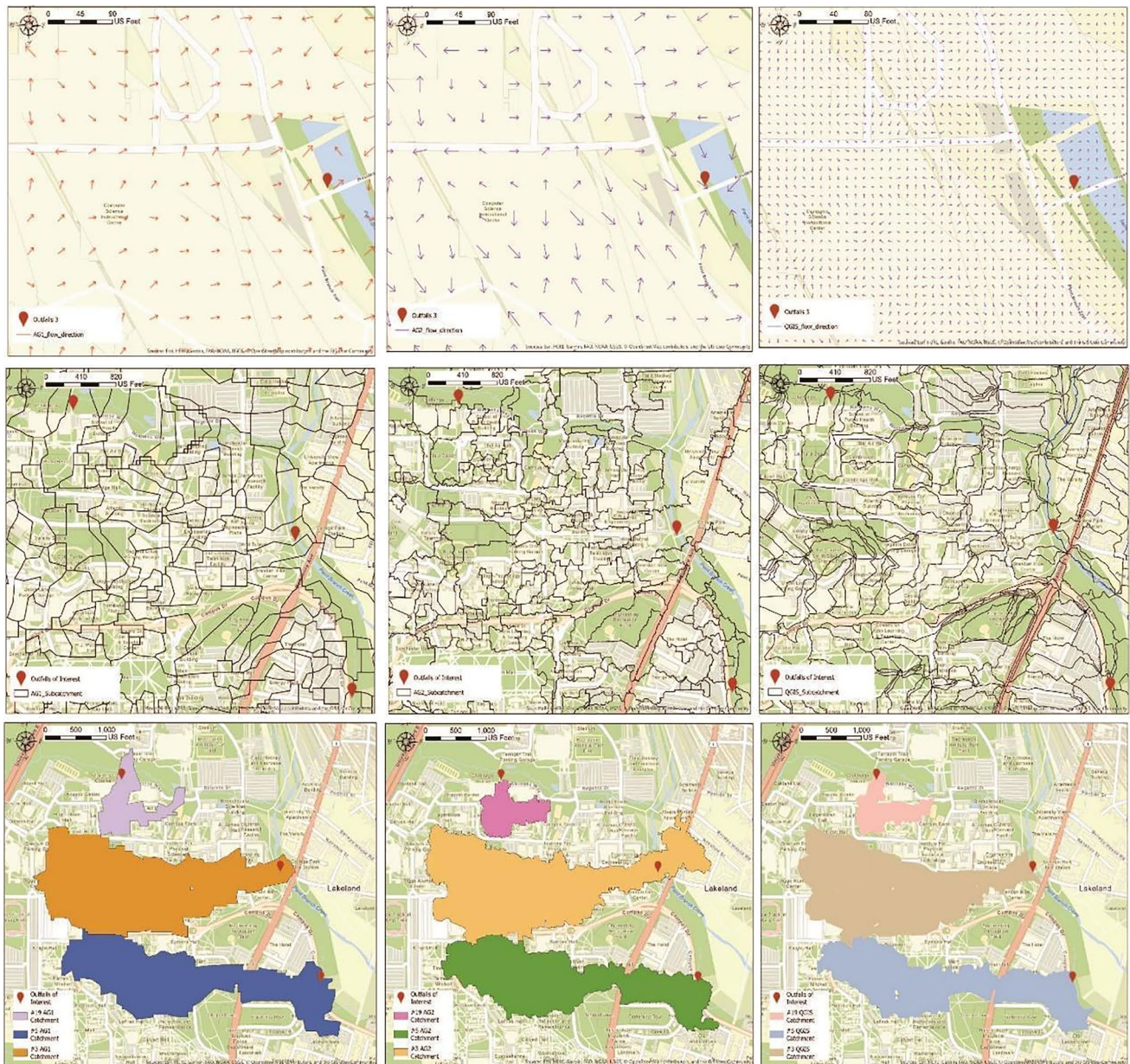


Fig. 3 Top row: Calculated surface flow directions of the UMD campus by methods AG1 (left), AG2 (middle), and QG (right); Middle row: Sub-catchment boundaries being determined by the corresponding surface flow results; Last row: Catchment boundary mapping results of interested outfalls (#3, #5, and #19) of the UMD campus generated by the corresponding methods

2.5 Map comparisons

To evaluate the consistency and replicability of the methods applied, statistical analyses were performed using RStudio software, such as Dice Similarity Coefficient (DSC) Index, and geospatial Friedman test. The DSC index provides a quantitative measure of the spatial overlaps and similarities between a pair of delineated catchment boundaries obtained from the different approaches, denoted as A and B (Eq. 2.5.a). The DSC measures the agreement between two maps by considering the ratio of the intersection to the sum of the areas of the two maps. The range of the DSC index is from 0 to 1, where a value of 0 indicates no overlap or agreement between compared maps, and a value of 1 represents a perfect spatial alignment between mapping results.

$$\text{DSC}(A, B) = 2(A \cap B)/(A + B)$$

Additionally, we conducted the Friedman test, which is a non-parametric alternative to the repeated measures ANOVA, to assess the catchment areas and perimeters of three selected pipeline outfalls. This was undertaken to evaluate the similarity that the employed catchment delimitations (three GIS-based methods and manual drawing) shared in terms of catchment area and perimeter results. It determines if any observed spatial differences are significant and indicates whether the maps are statistically equivalent. This analysis provides insights into the level of agreement and consistency across the different methods, highlighting potential variations in their accuracy.

To statistically compare the new catchment boundary maps generated using the GIS approaches with the catchment map that was based only on DEM information, both the DSC index and the Mann–Whitney U test, as a non-parametric test comparing spatial parameters (i.e. boundary perimeters, catchment coverage), were employed between maps. These assessments were conducted by considering the common catchment area derived from the GIS-method approaches introduced in this paper as a reference for comparing and contrasting the maps based on DEM alone.

3 Results and discussion

The results of this study demonstrate the effectiveness and applicability of the developed GIS-based toolset for high-resolution urban catchment delineation. The following sections present and discuss the key findings, including the visual representation of flow direction and catchment boundaries from three GIS-based approaches and the spatial analysis and validation process results.

3.1 Flow direction and catchment boundaries

Figure 3 illustrates the maps of surface water flow direction, sub-basin contributing to the inlet and /or pipeline systems generated by the developed GIS-based toolset within the overall UMD campus area, and the delineated catchment zones for the interested pipeline outfalls (Outfall 3, 5, 19) based on the UMD stormwater infrastructure connection information. The following series of map result analyses and validation discussions are based on Fig. 3.

3.2 Map spatial analysis

The analysis of the DSC index showed a significant level of agreement among the catchment maps generated from three GIS-based approaches and the manual drawing method. The geometric mean of the DSC index is 0.80, with individual method-paired comparison values ranging from 0.60 to 0.92 (Fig. 4). According to [60], the resulting DSC in this study was within the range of good reproducibility from the aspect of map segmentation. This consistency is further supported by the Friedman test, which did not reveal significant statistical differences between these catchment maps delineated with the consideration of stormwater infrastructure in terms of catchment area and boundary perimeters at the significant level of 0.05 ($Q=2.6$, $p=0.4575$, and $Q=3.4$, $p=0.3340$, respectively) (Table 1).

However, it is notable that when comparing maps generated from manual drawing methods to those from GIS-based approaches, the average DSCs remained above the threshold of good reproducibility, yet they exhibited greater variability and were generally lower compared to those among GIS-based maps (Fig. 4). This fluctuation highlights the inherent

Fig. 4 Boxplot of Dice Similarity Coefficients comparing resulting catchment maps among delineation methods, including 3 GIS-based stormwater catchment mapping methods (AG1, AG2, QG), manual drawing (MN), and DEM-only delineation method (DEM)

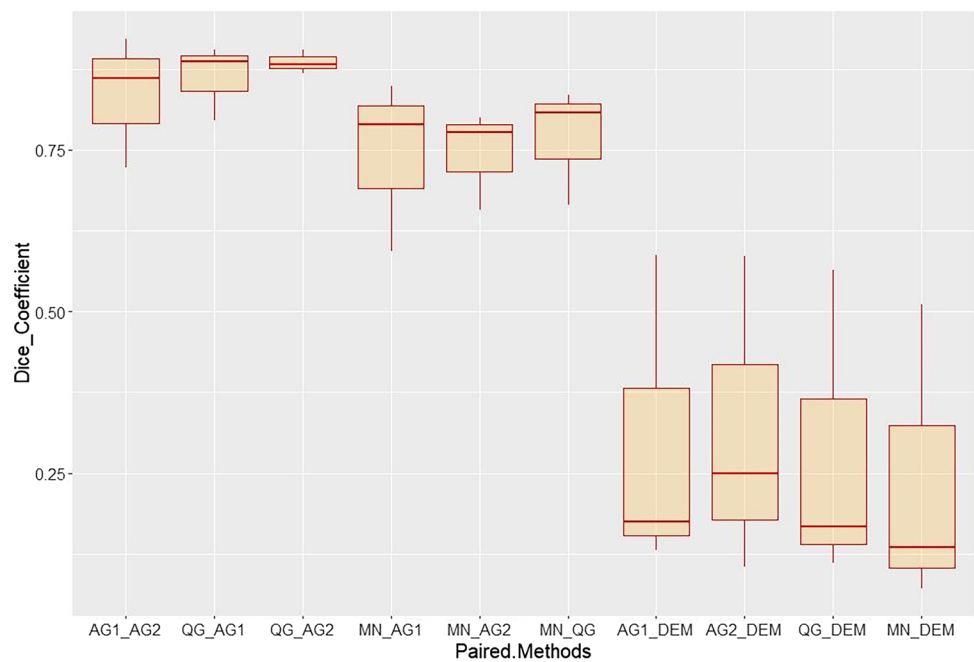


Table 1 The geographical Friedman testing results—comparing the catchment boundary maps created by different GIS approaches explored in this study

	Friedman Chi-squared	P-value
Catchment area size	2.6	0.4575
Catchment boundary perimeter	3.4	0.3340

subjectivity and potential inconsistency associated with manual delineation. Overall, the DSC Index and the Friedman test indicate that the developed GIS-based toolset consistently produces similar catchment delineations, validating its reliability and robustness.

Contrasting the catchment maps incorporating stormwater infrastructure in this study with those determined solely based on the DEM information derived from the UMD Facilities Management resources, a notable disparity was observed (Fig. 5). The average DSC values for these comparisons were markedly lower (Fig. 4, right four boxplots), demonstrating the profound impact of integrating stormwater infrastructure into delineations. The Mann–Whitney test results also indicated a statistically significant difference between the two groups of maps ($z = -1.964$, $p = 0.049$) in terms of catchment area and perimeter metrics. These results together demonstrate that delineations that combine natural topographical data with the stormwater infrastructure network significantly deviate from those based only on DEM, underlining the influence and necessity of integrating stormwater infrastructure into the catchment mapping process.

3.3 Validation results

The validation process involved on-site field observations of runoff flow direction in randomly selected locations within the study area. A qualitative comparison was made between the observed flow direction and the corresponding flow direction results obtained from the catchment delineation processes. The results show a relatively high level of agreement with an average agreement rate of 78.2% ($n = 75$), indicating that the majority of the randomly selected locations within the delineated catchment boundary exhibit consistent surface flow directions with the real-world flow direction. As Table 2 shows in detail, the method of Inlet Depression Digging using ArcGIS achieved the highest agreement percentage of 84.40% for the specified sample size. These results indicate a strong alignment between the delineated catchment boundaries and the ground-truth surface water data. Methods of pipeline burning-in and GRASS hydrology algorithm obtained lower agreement percentages of 72.04% and 78.12%, respectively. While the levels of agreement were slightly reduced compared to the first method, they still indicate reasonably good

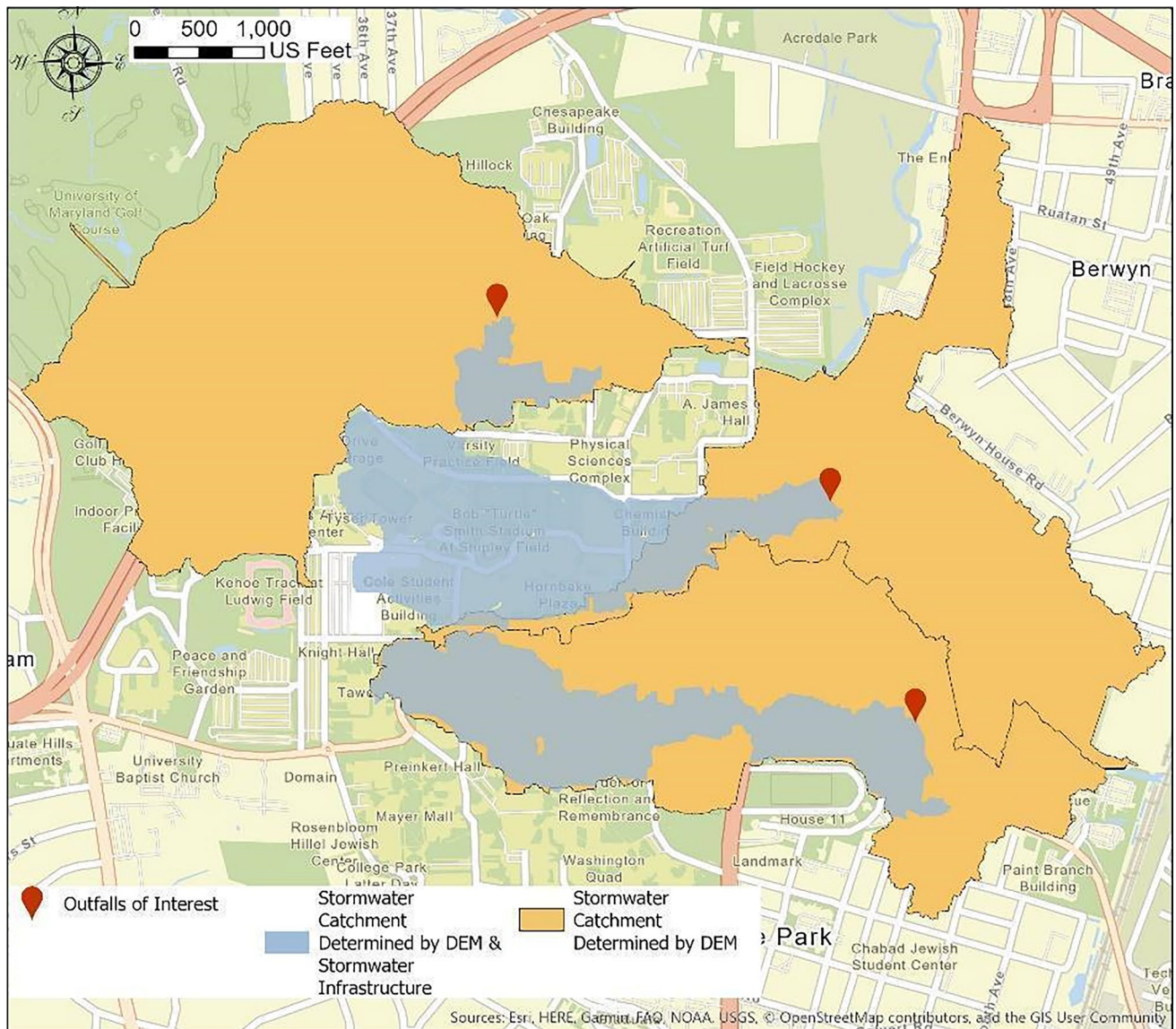


Fig. 5 Combined catchment areas of outfalls 3, 5, and 19 on UMD Campus, showing the boundaries determined solely from DEM (orange polygons, source: UMD GIS Enterprise team) and the common area identified in this study's resulting maps (blue polygons)

Table 2 Detailed validation results

Method	Sample size (n)	Agreement%	Land cover type	Sample size (n)	Agreement%
AG1	75	84.40	Grass	23	76.67
AG2	75	72.04	Road	34	79.17
QG	75	78.12	Roof	18	78.57

AG1 is the mapping method of the inlet depression digging

AG2 represents the pipeline stream burning method, and QG stands for the delineation using the GRASS hydrology algorithm

correspondence between the catchment boundary outcomes and the ground-truth observations. Regarding the different land cover types among the selected 75 observing locations, the agreements between GIS-calculated and field-observed surface water directions of grass-covered land, road, and building roofs were 76.67%, 79.17%, and 78.57%, respectively. To sum up, the validation results show relatively promising performance for all methods across

different land cover types, suggesting the effectiveness and reliability of the developed toolset in capturing the actual surface water flow patterns in the urban environment.

3.4 Discussion

Overall, the findings from the visual representation of flow direction, and catchment boundaries with the following spatial analysis and validation collectively affirm the effectiveness and reliability of the developed GIS-based toolset for high-resolution urban catchment delineation to some extent. The integration of topographical information and stormwater pipeline infrastructure data has proven to be a valuable approach for capturing the complexities of surface runoff behaviors in highly heterogeneous urban areas. These results lay the foundation and potential for improved urban stormwater management strategies and related decision-making processes. For example, by accurately delineating catchment boundaries and considering the impacts of both, natural and anthropogenic factors, in the urban setting, the toolset provides far-reaching insights for infrastructure planning, flood risk assessment, and sustainable urban development. The high-resolution spatial data-driven approach offers improved accuracy and precision, enabling urban planners and decision-makers to make informed decisions regarding stormwater infrastructure design, green space allocation, and land-use planning for short-term and long-term planning.

When it comes to selecting the specific mapping method used by environmental professionals and decision-makers, it is crucial to thoroughly understand the distinct advantages and disadvantages of each GIS-based method employed in the study. On the one hand, AG1 and AG2 are primarily characterized by their user-driven DEM intervention and detailed customization capabilities, allowing mappers to specifically tailor the delineation process to particular urban infrastructure configurations based on different types of infrastructure data (inlet locations vs. pipeline pathways). This manual adjustment provides a high level of control and adaptability but requires user input and detailed context knowledge. On the other hand, the method QG offered a more automated alternative, streamlining catchment delineation by leveraging the GRASS algorithm to incorporate inputting stormwater infrastructure information systematically. This automated approach facilitates quicker delineations, particularly beneficial for large-scale applications. However, this automation comes at the cost of reduced transparency and customization of its embedded calculation and algorithm in QGIS. In this case, while efficient, the QG method doesn't have the same level of explicit detail and customization as AG1 and AG2. Therefore, the selection among these methods should be guided by the specific needs and available resources. If detailed control is paramount, AG1 or AG2 can be preferable based on the reliability and access to either inlet locations or pipeline system layout. The QG method can be chosen for broader analysis requiring faster processing, albeit with an acceptance of less understanding of the processing algorithm.

Despite its significant contributions, the developed GIS-based urban catchment mapping approach set has certain limitations that warrant discussion. Firstly, while these approaches demonstrated relative accuracy and consistency based on the spatial statistical analysis, variations have been observed in the resulting maps generated by the three GIS-based approaches. These variations are evident from the discrepancies in catchment coverage (Fig. 6) and validation agreements against surface water flow directions (Table 2). This discrepancy underscores the necessity for ongoing investigation and refinement of the methodologies employed. For instance, we applied the Fill process before adjusting the DEM for stormwater infrastructure, appropriated for our specific context. Yet, we recognize that applying the stormwater pipeline network burn-in technique before filling could offer alternative perspectives, especially regarding terrain near embankments or culverts. Moreover, when assigning DEM drops at stormwater infrastructure locations, our approach did not fully consider significant man-made topographical features, such as high embankment structures, and green infrastructures, overlooking the alterations these ground structures bring to the flow dynamic [61, 62]. Future research should explore adjusting elevation drops based on local landscape features and validate the mapping toolsets' applicability in diverse urban geographic contexts to improve mapping fidelity. Additionally, validating the toolset's performance across different urban settings revealed variations in agreement rates among varied land covers (Table 2). Hence, we recommend future research involving detailed analysis of ground-truth stormwater data to examine the characteristics of delineated catchment areas more thoroughly. For instance, the runoff quantity (i.e., flow rate) and quality (i.e. turbidity, pH) parameters collected from the discharging water samples or continuously monitored by sensors at target outfalls, allowing for a more thorough examination of the characteristics and intricacies of the delineated catchment areas. In this sense, incorporating advanced modeling techniques, such as the PC-Stormwater Management Model (PCSWMM), holds promise for assisting with the precision of catchment boundary determination.

In summary, by implementing the developed GIS-based toolset in the pilot testing area, the UMD campus sets the stage for its potential adoption in other urban environments for stormwater control and management. Collaborative

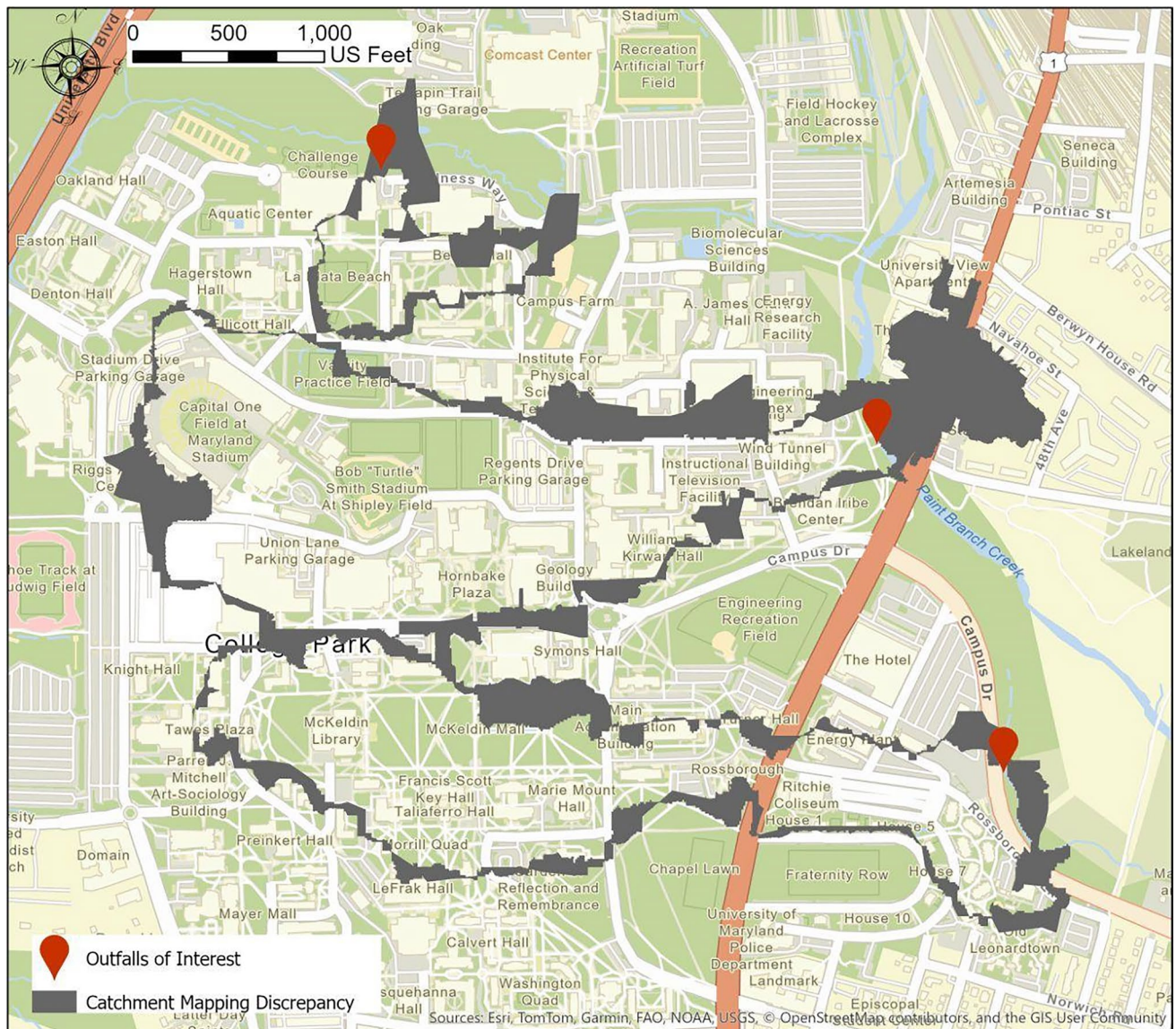


Fig. 6 Spatial discrepancy from three GIS-based mapping methods used for the UMD Campus

efforts between researchers, urban planners, and local government agencies are crucial for the real-life implementation of stormwater management like this toolset for urbanized stormwater catchment delineation. The accomplishments of this work can never be met without these collaborations, which facilitate the collection and sharing of up-to-date spatial information and foster interdisciplinary research integrating experience from varied professional fields. The methods being explored, used, and tested in this study would effectively support evidence-based decision-making processes for targeted stormwater management strategies at a localized level.

4 Conclusion

Humans have made a notable impact on natural surface water dynamics through centuries of development of the built environment. The primary motivation behind this research was to address the pressing need for a fine-scale approach to stormwater catchment delineation in urban settings. By combining geospatial analysis techniques and incorporating the complexities of surface water characteristics introduced by both natural topography and stormwater infrastructure, this study aimed to develop a novel GIS-based toolset and method options for urban hydrological drainage area delineation

and to enhance our understanding of urban surface water behaviors and provide an effective tool for urban stormwater management and planning.

Three distinct approaches were employed to delineate urban catchment boundaries, taking the UMD campus as a testing bed. Firstly, the GRASS plugin in QGIS was utilized, allowing for the consideration of stormwater inlets as depressions and automated algorithms for drainage area calculation. Secondly, the “depression digging” method was conducted using the ArcGIS platform, where manual adjustments to elevation were made at the locations of stormwater inlets, redirecting the natural surface flow while adhering to the general topography. Lastly, similar to the “depression digging” approach, the “stream burning” technique involved manually modifying the elevation of the stormwater pipeline to simulate natural streams and derive catchment boundaries from the resulting changes. All of the methods being developed above generated sub-catchments of stormwater inlets or specific pipeline sections. The integrated catchment area of corresponding interested outfalls was determined based on the stormwater pipeline network and connection information from the university records.

By integrating these methodologies, the developed toolset provides methods for urban stormwater catchment delineation with approach options, particularly at the outfall scale. Enhanced catchment mapping, leveraging high-resolution data and GIS techniques, offers benefits for urban stormwater management and planning. Specifically, the improved accuracy in catchment determination aids in identifying critical hotspots for stormwater runoff and potential flooding areas. This, in turn, supports informed decision-making on context-based management to prioritize infrastructure investments and retrofitting efforts more effectively. Furthermore, the field validation process and statistical analysis have confirmed the consistency and the replicability of the resulting catchment maps from different GIS-based approaches, highlighting the potential and reliability of the toolset. This reliability empowers stormwater managers with the confidence to apply these tools in varied urban contexts, adapting to the changing climate conditions and urban development patterns. We also notice and discuss the uncertainties introduced in urban catchment determination when excluding stormwater drainage system data from delineation. Ignoring the nuances of urban stormwater infrastructure can lead to misrepresentations of actual surface runoff paths and catchment boundaries, potentially resulting in inefficient stormwater management and misguided planning efforts.

Future research derived from this study could be the advancement of validation techniques that incorporate ground-truth surface runoff data and the utilization of advanced hydrologic models. Additionally, case-based optimal mapping method selection should be explored, considering the specific urban settings (land use/cover types) and local management measures to enhance the precision and applicability of the delineation process. With further refinement and application, the explored toolset from this study could potentially support resilient and sustainable urban development under different urbanized scenarios, ensuring effective stormwater management and enhancing overall urban resilience across a wider geographical area.

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Data availability Due to the university's public safety and security protocols, certain utility data analyzed was not public while the other datasets are available from the corresponding author upon reasonable request.

Declarations

Competing interests The authors declare that they have no competing interests or financial disclosures related to this research project.

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