Modelling of surface run-off using SWMM and GIS for efficient stormwater management

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The management of rainwater is of utmost importance in the current climate change scenario. This study assesses the current stormwater management of the Maulana Azad National Institute of Technology (MANIT) campus, Bhopal, Madhya Pradesh, India. It examines the efficiency of the management system with the help of stormwater management model (SWMM) and geographic information system (GIS) modelling. For this study, we have adopted a regional approach (whole campus) of MANIT for stormwater analysis. The quantitative interpretation of surface run-off analysis uses the SWMM model and Arc-GIS at various outfall nodes and proposes planning interventions and strategies for sustainable stormwater management.

Keywords: Educational campus, efficient management, regional approach, stormwater modelling, surface run-off.

DUE to the increase in urbanization and industrial transformation, water demand for urban and industrial uses is increasing at an unmanageable pace. Better water management is a long-felt need that has been neglected over time. Many researchers have emphasized the reuse of treated wastewater by the public and private sectors by utilizing effective and low-cost solutions[1]. The impervious surface areas are growing in leaps and bounds due to urbanization, which has led to hydrological effects globally[2]. The natural water cycle is disturbed, causing more urban rain-island effects, rapid surface run-off, deteriorating water quality, and diminishing groundwater supply[3]. Recent increases in heavy rainfall events due to global climate change are further leading to deterioration of the water system[4]. The expansion of impervious areas and a reduction in vegetated areas cause alteration in the surface run-off hydrology, i.e. run-off volumes and peak flows[5].

The mismanagement of stormwater is due to uncontrolled urban expansion with inadequate infrastructure and the need for integrated planning approaches. The reluctance of socio-political and institutional agencies to embrace new technological innovations is exacerbating the issue of environmental degradation[6]. Traditional urban stormwater management depends on grey infrastructure and developing a drainage network and rainfall drainage[7]. The negative impacts of the traditional urban stormwater management system are leading to degradation of the natural environment[8]. Paved surfaces are increasing local water flow in stormwater, which further contributes to urban flooding, and simultaneously, natural water bodies and vegetated areas are getting converted to paved surfaces in cities. It is necessary to develop an alternative urban stormwater management approach[9]. Increasing percolation of water is a long-established method of stormwater run-off management. There are many benefits of using rainwater harvesting (RWH) as an urban run-off management tool[10].

Global water governance is giving more weightage to integrated water resources management, basin approaches, decentralization and the involvement of multiple stakeholders for better management[11]. Remote sensing technology can help in better spatial and temporal datasets, and mapping of surface water bodies at local and regional levels. The surface water availability-based algorithm can effectively restore water, monitor flood events and map changes in land-use patterns in natural water resources[12]. It is crucial to urgently explore options for mitigating this change by planning and developing stormwater systems in cities, thereby balancing the effects of urbanization and climate change. Management of water resources may be regulated in an integrated manner in the context of local, regional and national levels for sustainable socio-economic and environmental development[13]. The innovative and sustainable approach can be developed using conventional ones powered by new emerging approaches like recycling and reusing stormwater. Stormwater harvesting is an essential strategy for improving the management of urban water resources[14].

Modelling low-impact development (LID) systems can help in better stormwater management[15]. There are many hydrological models like MOUSE (Model for Urban Sewers), SCS (Soil Conservation Service), SWAT (Soil–Water Assessment Tool), Hydro CAD, and the stormwater management model (SWMM)[16]. Bosley[17] undertook sensitivity analysis for different hydrological models and confirmed that SWMM is the most suitable hydrological model in the case of urban simulation analysis. In the present study, a model has been developed to simulate stormwater run-off at the Maulana Azad National Institute of Technology

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(MANIT) campus in Bhopal, Madhya Pradesh, India, under existing development scenarios, using the geographic information system (GIS)-based SWMM5.0 model to bring together urban planning data, geospatial and hydrological information. A campus is defined as a land area or catchment on which institutional buildings are set up, with all the infrastructure facilities for their stakeholders[18].

Natural systems like forests, grasslands, valleys and vegetated areas have good water-retention capacity as there is little or no water run-off, and most of the water is absorbed by the soil[19]. Stormwater quantity and quality are affected by many factors like heavy rainfall, surface conditions and surface structure, which generate irregular run-off. We have tried to minimize the impervious surface with more permeable paving on the footpaths of the MANIT campus and open circulation areas[20]. Cook[21] outlined that green infrastructure like rain gardens, green roofs, porous pavement, flow-through planters, stormwater wetlands and RWH can help better manage stormwater.

Problem statements

This pilot study was conducted to check the efficiency of stormwater management in the MANIT campus, using SWMM and ArcGIS to determine the quantity of surface run-off in different outfalls on the campus. The following problem statements arise:

- How does the slope of the study affect the surface run-off rate and the groundwater potential of the MANIT campus?
- How can planning and design interventions help increase the groundwater recharge potential and efficient utilization of surface run-off?
- To suggest planning and design initiatives on the campus for sustainable water management.

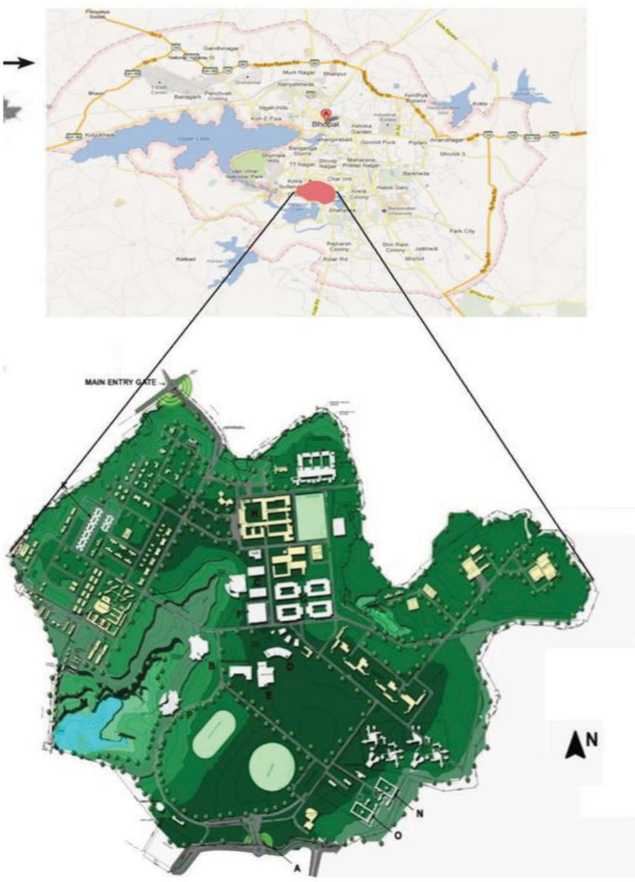

Figure 1. Location of the study area – MANIT campus, Bhopal, Madhya Pradesh, India. (Source: Master plan document of MANIT.)

Study area

The latitude and longitude of the study area are 23.21N and 77.41E respectively. The total area of the MANIT campus is 650 acres and is protected by a boundary wall and ring road. The entire campus has a built-up area, an open and forest area, and a lake area. Figure 1 shows the location of the study area.

To develop SWMM, the entire MANIT campus was divided into 217 sub-catchments based on the land-use pattern, such as built-up roads, parks, water bodies, and open and forest areas. The total number of outflow nodes was 18, with 21 conduits having 23 junctions to connect them with the outflow. All the details discussed above are shown in Figure 2.

Data and methods

A detailed study of the campus was done by compiling an inventory of the existing infrastructure and hydrological conditions. A comprehensive study was undertaken systematically to get sufficient data for using SWMM to understand the ground realities and issues of stormwater management on the campus. A survey of the existing run-off characteristics of the sub-catchments of the MANIT campus was done.

- A survey of existing obstructions based on sensitivity to damages from future flooding or increased run-off.

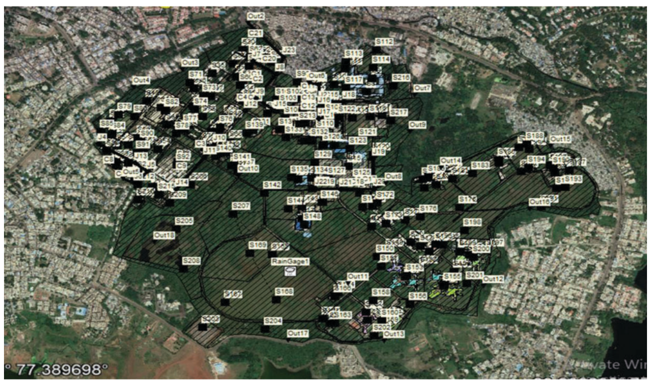

Figure 2. Locations of 217 catchment areas of stormwater in the study area using SWMM.

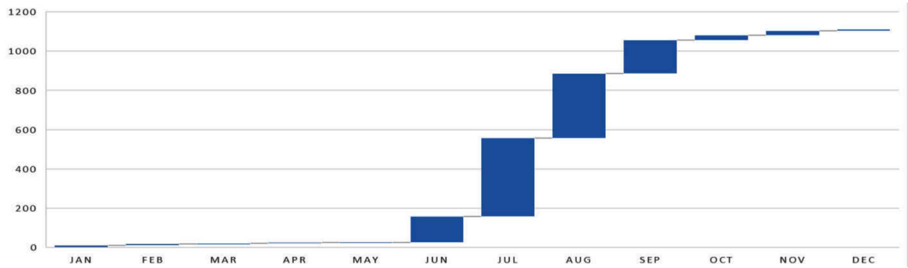

Figure 3. Average rainfall data for the study area (Source: ref. 23).

Table 1. Average rainfall data collected from the Bairagah rainfall monitoring station (based on the average of the last 10 years)

Month	January	February	March	April	May	June	July	August	September	October	November	December
Average rainfall (mm)	10.24	7.5	2.61	4.38	0.49	131	400.05	330.3	168.22	25.14	23.71	6.24

Source: Ref. 23.

- Areas under stormwater collection and control facilities were studied based on parameters and standards for stormwater run-off.

The SWMM tool was developed in 1971 by the United States Environmental Protection Agency and has since been updated to make it better for rainfall–run-off simulation modelling. This model can simulate hydrology using sub-catchments of areas where rainfall is a source of run-off[16]. SWMM is widely used in simulation, analysis and design in urban storm run-off, drainage systems, catchment planning and especially in run-off mitigation[15].

SWMM set-up for the MANIT campus

Mapping of the drainage network was done based on the slope analysis map and digital elevation map (DEM) generated using GIS software, and the same was used in SWMM 5.1 for further analysis.

Figure 2 shows SWMM developed for the study area with the background of the Google Earth image of the campus for clear visualization of the study area. From the figure, we can identify the locations of 217 sub-catchment areas generated by SWMM after analysis and modelling.

In the above SWMM set-up map, there are a total of 217 sub-catchments with the symbol 'S' representing sub-catchment, 'J' for Junction, 'C' for conduits and 'Out' for outfall of the MANIT campus. The generation of sub-catchments, conduits and outlets to simulate run-off quantity in the study area was also done.

The study area was subdivided into different sub-catchment areas. Sub-catchments are categorized based on land use and types of surface. Different outfalls were located on different campus locations based on the flow pattern. Conduits are pipes that provide for the flow of run-off collected from the sub-catchments, leading to the junctions, and finally connected to the possible outfall.

Data collection

Spatial data collected from the Bhuvan portal, such as DEM files and land-use maps were extracted from Cartons-1, 30 m DEM. Rainfall data were obtained from the website of Madhya Pradesh Water Resource Department (MPWRD) and the Central Ground Water Board (CGWB), Bairagarh rain gauge station nearest the study area[22]. We have used long-term (annual average) rainfall data for stormwater analysis.

The total annual rainfall for the region was 1109.88 mm, which provides an overview of the overall precipitation pattern for the entire year as shown in Figure 3 (ref. 23). The wettest months were July and August, with 400.05 and 330.3 mm of rainfall respectively (Table 1).

Data extracted from GIS

Figure 4 shows the DEM file with contours. Colour coding is shown in the legend and various patches of the area. The figure shows various contours of 1 m intervals within the MANIT campus boundary. The highest and lowest elevations of contours are 536 and 518 m respectively, within the campus boundary. The campus has one large water body inside, with a contour of 520 m. Most of the sub-catchments are interconnected along the periphery of the boundary of the campus and lead to the collection of stormwater in a pond on the western side of the campus. As most outfalls are widely distributed, some lead to water flowoutside the campus, which needs to be tapped for a better stormwater management plan.

The slope map of the MANIT campus was generated using ArcGIS. This gives us a clear view of the changes in the slope and direction of the slope of the study area. This information is needed to plan how the storm channels can be integrated for better stormwater management.

Figure 5 shows the slope of the study area, varying degree of green colour is showing on the map, areas of minimum slope which is 1%, and the maximum slope on the campus is 20% on the campus boundaries. The campus has one water body with a slope of 9.5%. This slope % is used as the input parameter in SWMM to simulate the run-off quantity of the study area.

The natural drainage network of the MANIT campus is well suitable for harnessing the rainwater and thus, help in preventing the flooding and water logging in the low lying areas falling outside of the campus. An efficient drainage system helps divert excess water from the roads and buildings, reducing the risk of flooding during heavy rainfall. Planning and construction of building units on the campus have been done so as not to disturb the natural drainage lines (Figure 6). Stormwater run-off of rainfall received on the surface flows into low-lying areas in the study area. The increase in run-off leads to low groundwater recharge.

Input parameters required for SWMM simulation

Various parameters are required for SWMM run-off simulation, including deterministic parameters, Manning's coefficient, run-off coefficient and sub-catchment characteristics. Deterministic parameters are specific and fixed factors that do not change, like the length, area, width, slope and zero-imperviousness of a water conduit[24].

On the other hand, uncertain parameters are variables that can vary, such as N-perv (which relates to the permeability of the soil), D-store impervious (the depth of impervious storage), N-impervious (the Manning's roughness coefficient for impervious surfaces) and conduit roughness (how smooth or rough the inside of the conduit is). Table 2 provides a description of these parameters.

The physical and hydrological characterization of every sub-catchment is necessary. The simulation was carried out to check run-off generated by it during the pre-monsoon and post-monsoonal periods to assess hydrological and environmental changes. For proper calculation of the stormwater run-off, information on the surface type and land use with the respective Manning's coefficient is required (Table 3)[25].

Attari and Hosseini[25] have given a simple, innovative method to calibrate Manning's roughness coefficient. The run-off coefficient of different land uses significantly determines the quantity of run-off generated from a particular area. Table 4 provides the run-off coefficient[26].

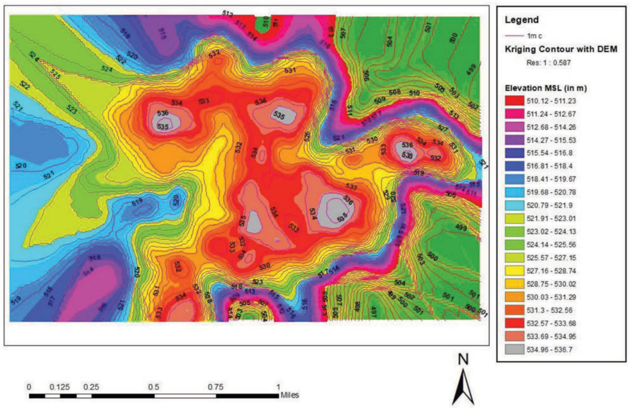

Figure 4. Digital elevation map with contours and basin map.

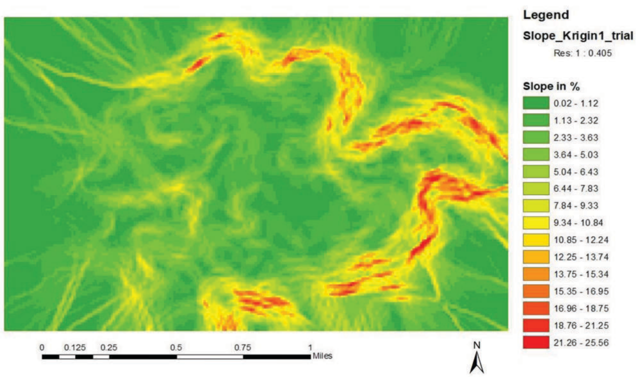

Figure 5. Slope map of the MANIT campus using Arc-GIS.

Results

A dynamic rainfall–run-off model has been developed in this study based on SWMM for the MANIT campus to determine the capacity of the existing drainage system. This model has proved to be effective in assessing catchment run-off quantity. Nearly 35% of the catchments are connected to one central catchment area. This study used the infiltration model to compute infiltration losses and the kinematic wave-routing method for flow-routing analysis. Table 5 shows the total discharge generated in every outfall node.

Table 5 shows the results of the run-off simulation as surface run-off discharges at all the outfall nodes. Maximum flow (MLD; million litres per day) occurs at outfall no. 18. The top three outfall nodes are highlighted in Table 5,

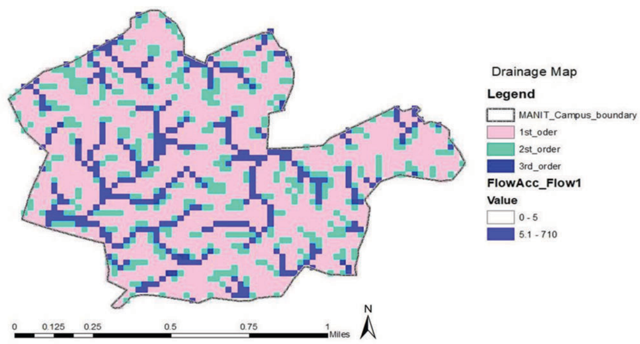

Figure 6. Drainage network map generated using Arc-GIS.

Table 2. Input parameters required for SWMM model simulation

Deterministic parameters	Description	Uncertain parameters	Description
Impervious	Impermeability of the sub-catchment	N-Pervious	Manning's coefficient in permeable area
Conduit length	Pipe length	D-Store-impervious	Depth storage in impervious area
Area	Sub-catchment area	D-Store previous	Depth storage in pervious area
Width	Overflow width	N-Impervious	Manning coefficient in impervious zone
Slope	Slope of sub-catchment	Conduit roughness	Manning coefficient of pipeline
Zero impervious	No depression and impermeability rate	Maximum rate	Maximum infiltration rate

Source: ref. 24.

Table 3. Manning's coefficient

Type of surface	Land-cover/Land-use	Manning's coefficient
Impervious	Built-up area	0.012
	Roads	0.011
Pervious	Cropland	0.17
	Recreational (parks, etc.)	0.15
	Built-up with vegetation	0.13
	Fallow land	0.05
	Vacant land	0.05

Source: ref. 25.

Table 4. Types of surface on the MANIT campus and run-off coefficient

Type of surface	Area (ha)	Percentage of different surfaces	Run-off coefficient
Bituminous pavement road	9.6	3.6	0.65–0.85
Built-up area*	18.0	6.8	0.85–0.95
Concrete road	4.5	1.7	0.85–0.95
Forest area	124.8	47.4	0.05–0.20
Impermeable paving	1.9	0.7	0.70–0.80
Permeable paving	2.1	0.8	0.50–0.60
Open area	83.5	31.7	0.10–0.20
Parks	11.3	4.3	0.10–0.20
Waterbody	7.5	2.9	0.00–0.05
Total area	263.2	100.0	

Source: ref. 26. *This is composed of all the areas falling under some type of roof.

namely Out18, Out16 and Out8. The next higher outflow discharge is at outfall node 16, generating a maximum discharge of 0.029 MLD with a maximum flow of 0.43 MLD. Outfall node 16 is situated in a low-lying area near the study area's boundary, making the nearby slum area susceptible to flooding during the monsoon season. Hence, sanitation and socio-health conditions should be considered to channel the stormwater at this outfall node. Outfall no. 18 occurs at the water body available on the campus, which serves as a storage reservoir for water during the dry season.

As depicted from the simulation outfall, node 18 generates a maximum discharge of 0.033 MLD with a maximum flow of 0.52 MLD. This outfall node occurs at the water body sub-catchment. Since the present capacity of the water body is insufficient to incorporate this inflow, the storage capacity of the lake can be increased by dredging. MANIT has planned to develop a detention pond for multi-purpose recreation of the campus residents and to enhance the natural environment by greening more campus areas with plantations along the stormwater channels leading to the detention pond.

Discussion

The primary goal of this study was to improve the stormwater management system within the MANIT campus, ensuring optimal run-off management while minimizing potential flooding or environmental issues during heavy rainfall events.

The successful integration of SWMM and GIS in the study has proven effective in simulating and analysing the surface run-off patterns on the MANIT campus. By combining these two powerful tools, planners and decision-makers can gain valuable insights into the hydrological behaviour of the campus and identify critical areas that require attention in terms of stormwater management. The modelling results offer a detailed depiction of the surface run-off pattern during various storm events. The simulation identifies high-risk areas prone to flooding or waterlogging, as well as areas where run-off can be effectively managed. Such information is crucial for devising targeted and cost-effective stormwater management strategies, such as implementing green infrastructure or enhancing existing drainage systems.

In the case of the MANIT campus, the outfalls that lead to water flow into the Rahul Nagar's (slum locality near the campus) stormwater drains cause flooding in some nearby areas. Better management of stormwater in the vast campus reduces the probability of flooding due to heavy rainfall during monsoon. There is an increase in impervious surfaces due to the construction of new building units on the campus. Hence, the primary purpose of the stormwater management plan for the campus is to maximize the groundwater recharge potential by minimizing the run-off to outfalls that are falling outside of the campus.

Through the SWMM and GIS-based simulations, the present study provides a foundation for proposing suitable stormwater management solutions tailored to the specific needs of the MANIT campus. The construction of retention ponds, installation of permeable pavements, implementation

Table 5. Results obtained by SWMM simulation

Surface run-off description generated at various outfall nodes			
Outfall node	Average flow (MLD)	Maximum flow (MLD)	Total volume (10^6 litre)
Out1	0.05	0.1	0.006
Out2	0.08	0.14	0.01
Out3	0.03	0.05	0.003
Out4	0.02	0.05	0.003
Out5	0.07	0.13	0.008
Out6	0.11	0.18	0.012
Out7	0.02	0.04	0.003
Out8	0.18	0.32	0.021
Out9	0.04	0.06	0.004
Out10	0.12	0.22	0.014
Out11	0.07	0.14	0.009
Out12	0.09	0.16	0.01
Out13	0.06	0.13	0.008
Out14	0.05	0.1	0.006
Out15	0.03	0.06	0.004
Out16	0.23	0.43	0.029
Out17	0.05	0.09	0.006
Out18	0.27	0.52	0.033
Sum of all the outfall nodes	1.57	2.92	0.189

of rain gardens, and development of sustainable drainage systems can be done. The findings of this study can be utilized to assess resilience to climate change impacts in large cities, such as increased rainfall intensity or shifting precipitation patterns. By considering future climate scenarios, planners can proactively design stormwater management systems that are adaptable and resilient to potential climate-related challenges, ensuring the long-term sustainability of the drainage infrastructure of the MANIT campus. Integrating SWMM and GIS for efficient stormwater management has significant implications for urban planning and sustainable development. The methodology and insights gained from this study can serve as a template for other institutions or municipalities facing similar stormwater management challenges. It promotes an eco-friendly and data-driven approach to urban development, wherein the design and implementation of stormwater infrastructure are based on scientific modelling and analysis. Stormwater percolation into the ground is essential to ensure adequate recharge of groundwater[27]. A multi-purpose detention pond has been suggested for the IIT Kharagpur campus for sustainable stormwater management[28].

Conclusion

The study of rainfall outflow and the utilization of outfall water has shown that there is a potential for water to be collected and used for enhancing the greenery and recharging groundwater. Outfall water can improve water security, reduce water loss and reduce energy costs. With well-planned stormwater management, MANIT can be a lighthouse project for other universities to learn and adopt such an environmentally friendly and sustainable development approach. The thoughtful management of permeable and impermeable surfaces with linking green infrastructure development integrated into the stormwater management plan can make the MANIT campus more sustainable. It has been observed that stormwater management may not have significant financial returns, but the educational benefits are manifold. MANIT can set standards for campus management, such as aesthetic quality, recreational use, and stormwater management.

This study provides insight into MANIT, the campus stormwater management plan. The way forward would be to develop in-depth case studies of other campus stormwater management plans. Simulation and modelling, using specific parameters, can be valuable for comparing stormwater management performance across different universities. This model, designed for an educational campus, will yield crucial insights for future decision-making. The results will guide planning at various scales, from local to regional, to effectively integrate stormwater management and restore the natural hydrological balance. Further research is needed to identify the best engineering solutions, management practices and economic incentives to ensure sustainable use of outfall water.

Conflict of interest: The authors declare that they have no conflict of interest.

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Received 28 February 2023; re-revised accepted 6 October 2023

doi: 10.18520/cs/v126/i4/463-469