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WETLAND HYDROLOGY AND GEOMORPHOLOGY

Modelling the Hydrological Response to Urban Land-Use Changes in Three Wetland Catchments of the Western Himalayan Region

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Abstract

Assessing the impact of land use land cover (LULC) changes on runoff is crucial for the sustainable management of wetland catchments. This study modelled the impacts of LULC changes on runoff in three urban wetland catchments using the United States Environment Protection Agency's Stormwater Management Model (SWMM). Land cover maps of 1980 and 2017 delineated from satellite data were reclassified using the geographic information system (GIS) to derive impervious surfaces of three wetland catchments in Srinagar city. The findings revealed a drastic reduction of the pervious area from 2249.6 ha to 1883 ha and a corresponding increase in the impervious surfaces from 321 ha to 704.8 ha including all three catchments. Runoff simulations revealed that from 1980–2017, runoff volume increased by 154%, 76.3%, and 159.5% in the Anchar, Brari Nambal, and Khushalsar catchments, respectively. The results indicate that increased runoff and peak volumes are driven by the land-use change, particularly the increase of urban spaces in wetland areas. For mitigating the negative impacts of runoff, rain gardens, a best management practice (BMP) with low impact development (LID) properties were distributed in the catchments based on the availability of open space, cost, and effectiveness. Simulations indicate that the rain gardens would reduce runoff volume by 46.8%, 10.8%, and 48.6% at 50% of runoff treated, and by 89.4%, 13.4%, and 86.8% at 100% of runoff treated, in the Anchar, Brari Nambal, and Khushalsar catchments, respectively. The results of this study could support environmentally-friendly land use planning for the protection and management of wetland catchments.

Keywords Himalayan Region · Land system changes · Stormwater modelling · SWMM · Urban Hydrology · Wetlands

Introduction

Urbanization and land development are associated and interwoven with LULC changes that involve the conversion of undeveloped lands (the natural environment) to industrial, residential, and other commercial land uses (Izakovičová et al. 2017). Land development has significant impacts on the hydrology of urban areas (Dar et al. 2021a), influencing the hydrological characteristics and nature of runoff (McGrane 2016; Wang et al. 2020). Expansion of urban centers increases the imperviousness of the area, which reduces infiltration and runoff lag times, and increases runoff peaks and concentration of contaminants as they wash off the land (O'Driscoll et al. 2010). As a result, runoff starts immediately with larger volumes, leading to increased turbidity, stream bank erosion, water pollution, combined sewer overflows and increasing the risk of susceptibility and potential for flood damage (Dar et al. 2021b; Feng et al. 2021). Consequently, the hydrology of urban areas tends to be very different from natural conditions (Guan et al. 2015).

Assessment of hydrological responses to the LULC changes has become a growing area of research interest in hydrological modelling (Bronstert et al. 2007; Zhao et al. 2016; Spruce et al. 2020). Various hydrological models were developed and widely used for estimating the urban stormwater quantity and quality response to LULC changes in recent decades (Yan et al. 2013). Integration of urbanization with hydrological studies is made possible because both utilize LULC data. Assessment of LULC change impacts on hydrological regimes is crucial for understanding the impacts on hydrological processes (Garg et al. 2019; Dar et al. 2021c) and assessing the implementation of stormwater management practices (Haghighi et al. 2020).

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In the growing context of the negative effects of runoff on receiving water courses, further investigations and working efforts have been focused on the management of stormwater (Bell et al. 2016; Jefferson et al. 2017). During the past few decades, urban centres have seen the growth of various pollution remediation techniques for the management of stormwater (Chouli et al. 2007; Fletcher et al. 2013), commonly known as stormwater best management practices (BMPs). The latest of these can be classified as Low Impact Development-Best Management Practices (LID-BMPs), explained in greater detail in Fletcher et al. (2015). LID-BMPs offer the best available intervention strategies that are projected to minimize, reduce/eliminate pollution, and control peak discharges (Jia et al. 2013), by reducing runoff primarily through infiltration and evapotranspiration, or treatment through filtration (Liu et al. 2016) besides providing a wide range of social and sanitary considerations (McNett et al. 2011). Various LID-BMPs such as the bioretention cells, infiltration trenches, rain gardens, detention ponds, green roofs, grass swales, rain barrels, and porous pavements (USEPA 2012; Fujioka et al. 2015) were developed and implemented as a measure to sustain the pre-development settings of the catchments and control runoff (Monaghan et al. 2007; Khadka et al. 2021). These treatment systems in addition to being economical and effective measures for improvement of water quality provide various other benefits like recharge of groundwater, storage of floodwaters, and aesthetic and recreational sites (Raei et al. 2019; Risal et al. 2021). Appropriate outset and execution of LIDs and other approaches rely on accurate assessment of their aptness and effectiveness in given hydrological settings (Rammal and Berthier 2020). However, due to variations in watershed characteristics like LULC, the placement of LID-BMPs and their assessment of hydrological responses within a catchment area remains a challenge.

Srinagar is the major and fastest-growing urban city in the Kashmir Himalayan region. During the last century, Srinagar has grown from 12 km^2 to 278 km^2 (Kuchay and Bhat 2014). The Greater Srinagar Master Plan mentions that the city will expand to 766 km^2 by 2030. In Srinagar city, the growth and increase of urbanized areas are predominantly attributed to the transformation of water bodies into other land uses (Chettry and Surawar 2021). The rapid and unplanned growth of the city has caused great damage to wetland ecosystems within or adjacent to the city and led to other environmental problems (Rashid and Aneaus 2019; Dar et al. 2021c). It is pertinent to mention that wetland ecosystems all over the world provide a variety of important services and functions of high value (Mader et al. 2020; Barua et al. 2021). The effects of changing LULC on wetlands lead to loss of wetland ecosystem services such as loss of wildlife habitat, flood storage, and hydrological alterations (Zorilla-Miras et al. 2014; Nazif and Eslamian 2015; Dar et al. 2021d). The encroachments and large-scale urbanization have disturbed the natural hydrological regimes of Srinagar making it vulnerable to floods (Anees et al. 2020). Therefore, assessing the effects of changing LULC on the hydrological regimes of urban areas is important for understanding the dynamics of wetlands to transient changes in their watersheds, and for developing management strategies. The rapid expansion of urban centres without proper land use controls and management strategies has increased the volume of runoff and led to other associated impacts. During a normal rainfall event, the city centre is inundated as drainage channels that used to remove floodwaters have disappeared because of encroachments, unplanned urbanization, and pollution (Rashid and Naseem 2008; Dar et al. 2021e). Additionally, the rapid urban development has direct impacts on the hydrological regimes, water quality, and groundwater with a high potential to cause floods in the city (Ahmad et al. 2019). With the intensification of impervious surfaces, often a small duration rainfall event waterlogs much of the city. It is pertinent to mention here that no runoff data are available for the city, nor does it have any hydrological gauging stations on rivers and streams either within the city or nearby. To prevent further degradation of wetland ecosystems due to urbanization, robust information about hydrological response through observations and models is paramount. Incorporating wetland characteristics into a hydrological model can help quantify the impacts of development (Hughes et al. 2014). The model can make better predictions of how a change in catchment influences wetland hydrology (Krasnostein and Oldham 2004). Keeping in view the ecological degradation of the wetlands in Srinagar city mainly due to unplanned urbanization, this study is aimed at exploring hydrological responses within three urban wetland catchments using SWMM under changing LULC scenarios. The present study is a first of its kind describing the use of SWMM and LID-BMPs for mitigation of runoff from the Kashmir Himalayan Region where unplanned urbanization and land transformations affect the wetland hydrology and incidence of stormwater floods. In this context, this study focused on understanding the response of stormwater runoff in urbanized wetland catchments of Srinagar city and suggested BMPs for mitigating the stormwater runoff.

Study Area

Srinagar city spread over 234 km^2 is located between 33° 59′ 14″—34° 12′ 37″ N latitudes and 74° 41′ 06″—74° 57′ 27″ E longitudes at an elevation of 1580 m asl towards the centre of Kashmir Valley (Fig. 1). The city has a temperate type of climate, with the air temperature ranging from -10 to 33 °C (Zaz et al. 2019). The district receives ~ 710 mm of precipitation annually with the spring season receiving

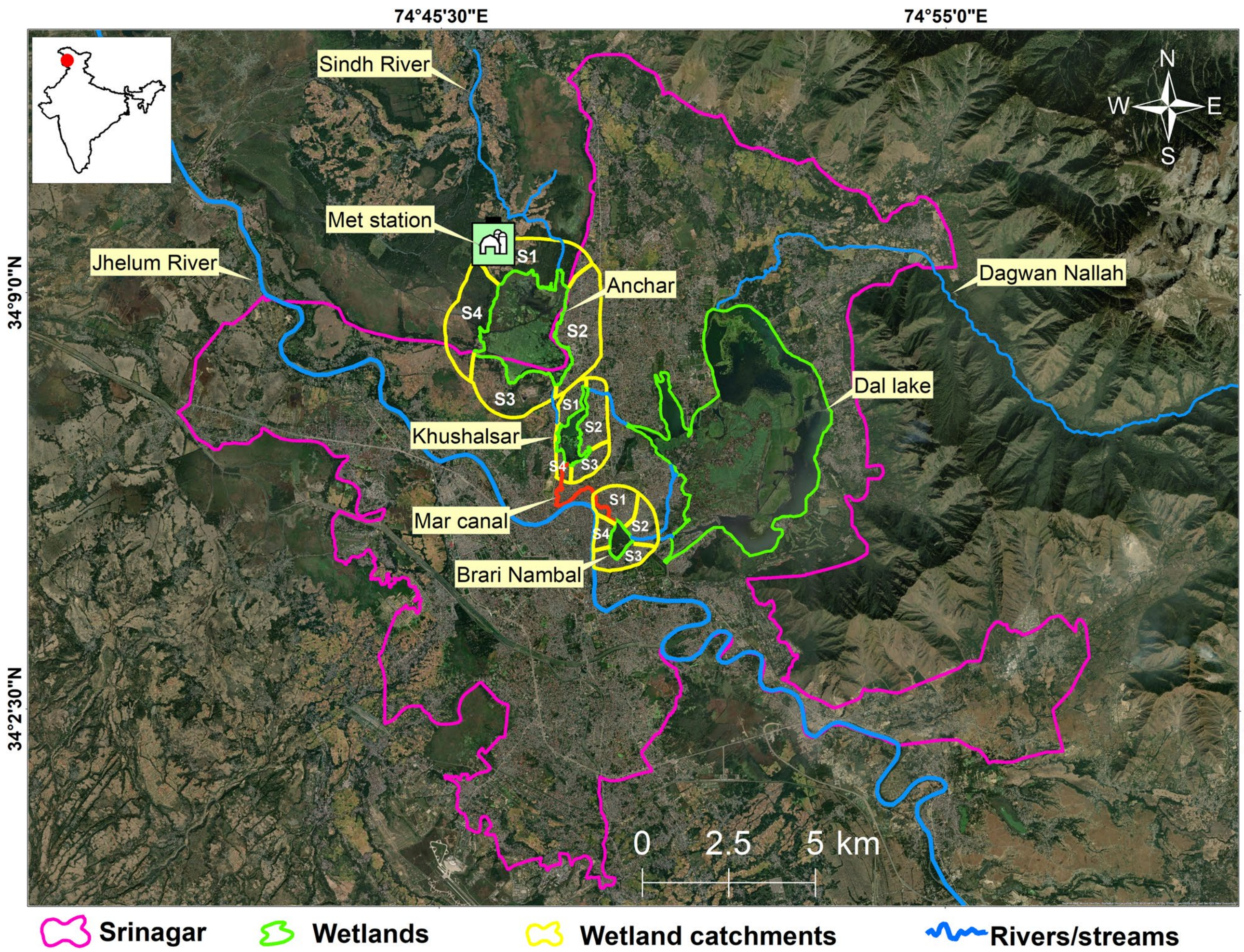

Fig. 1 Study area map showing the location of major wetlands in Srinagar city

maximum rainfall of 219.7 mm (Dad et al. 2021). During spring and summer, the melting of glaciers is high contributing to peak stream flows. The city is densely populated with a population of 1.22 million with projections of about 3.6 million by the year 2051 (Census 2011). The city is characterized by strongly heterogeneous landscapes with steep hills in the East and North East, and uplands with moderate slopes towards the North dotted with numerous wetlands (Dar et al. 2020a). The soils of the city are composed of clay, silt, and sand (Zahoor et al. 2019).

Three wetlands, Anchar, Brari Nambal, and Khushalsar (Fig. 1), were chosen for predicting the negative effects of changing LULC on wetland hydrology. Although there are several wetlands in Srinagar city, but keeping in view the geographical location and high population densities around the wetlands in the city, three major and prominent wetlands were selected. The wetlands selected are located in the central part of the city and most of the stormwater is drained into these systems. Further, these wetlands provide important functions such as buffering of floodwaters, water purification, recreation, and aesthetics and serve as important natural buffers for the city, mitigating the negative impacts of floods by acting as absorption basins of floodwaters (Dar et al. 2020a, 2021f). However, due to unplanned growth and an increase in the human population wetlands of this region face increasing anthropogenic pressures and are progressively being degraded (Dar et al. 2021d). It is in this context that three wetlands of the city were chosen to assess the dynamics in rainfall-runoff responses because of LULC changes.

Materials and Methods

Datasets Used

The study used an integrated approach of assimilating multisource datasets that include satellite data, digital elevation model (DEM), soil characteristics, rainfall data, and field surveys to model and understand the hydrological changes due to changing LULC. The particulars of various datasets used in the study is reflected in Table 1.

Satellite Data

To assess the changes in the rainfall-runoff scenario in the catchment area within the context of changing LULC, it is essential to have historic LULC data of the study area. The historical satellite data of the year 1980 with 1.87 m resolution was obtained from earth explorer. The updated LULC map for the year 2017 was digitized from the Google Basemap Imagery having a resolution of 1.65 m. The different LULC classes were categorized into pervious and impervious surfaces.

Digital Elevation Model

The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) DEM with a spatial resolution of 30 m obtained from the United States Geological Survey (USGS) was used as the basis for the wetland catchment delineation. Environmental Systems Research Institute (ESRI) ArcGIS 10.1 was used to digitize wetland and catchment boundaries and execute other geoprocessing tasks such as area estimation, slope, and LULC analysis. The slope was calculated using the Zonal Statistics tool accessible in the Spatial Analyst Zonal Toolset in ArcGIS 10.1.

Soil Data

The data for soil types and hydrological soil groups present in the wetland catchments were obtained from Badar et al. (2013) and Nisar (2016). The values for suction head, hydraulic conductivity, field capacity and porosity of different types of soils in wetland catchments were obtained by comparing the soil types with the soil group definitions of the US Department of Agriculture (USDA), Soil Conservation Service (SCS), and Natural Resources Conservation Service (NRCS) (Table S1). The hydrological groups of soils were used to recognize the variables for Green-AMPT infiltration, i.e., the value of suction head, initial deficit, and saturated hydraulic conductivity (Green and Ampt 1911). Each soil group corresponds to a range of saturated hydraulic conductivities. The median of each range of conductivities was used, and a weighted average was calculated based on the representative areas of soil groups B and D within each sub-catchment. These conductivities were then matched with a suction head value that corresponded to the appropriate soil type. As described by James et al. (2010), the initial deficit was calculated as the difference between soil porosity and field capacity assuming completely drained soils.

Rainfall Data

Rainfall data were obtained from the meteorological station established by the Department of Environmental Science, University of Kashmir supported by the Ministry of Earth Sciences, Government of India, in the 1 km vicinity/catchment of the Anchar wetland (Fig. 1). Since the historical hourly rainfall data for the region was not available, as an alternative we looked for the highest rainfall event from the available data. It was found that the highest rainfall event in the region was experienced on 11th July 2019. A 12-h rainfall event (Fig. 2) was used for runoff simulations for both 1980 and 2017 LULC in the study area.

Methodology

Satellite data obtained from USGS was used to classify the different LULC features and identify pervious and impervious surfaces. The slope of the area under study was obtained from the 30 m resolution DEM. The percentage of pervious and impervious cover along with soil, rainfall, and catchment characteristics were used as input parameters for SWMM. Sensitivity analysis which defines the parameters to which the model is most sensitive was performed. After that, the SWMM model was calibrated adjusting key parameters such as catchment area, slope, overland flow width, and coverage of the impervious area. The SWMM model was run for the estimated impervious cover of 1980 and 2017. Additionally, to minimize the impacts of runoff, LID-BMPs were introduced in the study area and runoff simulations were

Table 1 Details of the datasets used in the study

Sensor	Acquisition Date	Spatial Resolution	Source
CORONA	07 October 1980	Resolution: 1.87 m	http://earthexplorer.usgs.gov/
High-resolution Basemap	13 September 2017	Panchromatic: 0.46 m Multispectral: 1.65 m Accuracy: 8.47 m	ESRI Basemap
DEM	28 October 2017	30 m	http://earthexplorer.usgs.gov/
GPS data	Oct-Nov 2017	Point data	Ground survey
Soil data	12 October 2017	Spatial data	Nisar 2016; Badar et al. 2013
Rainfall data	26 July 2019	Spatial data	Meteorological station

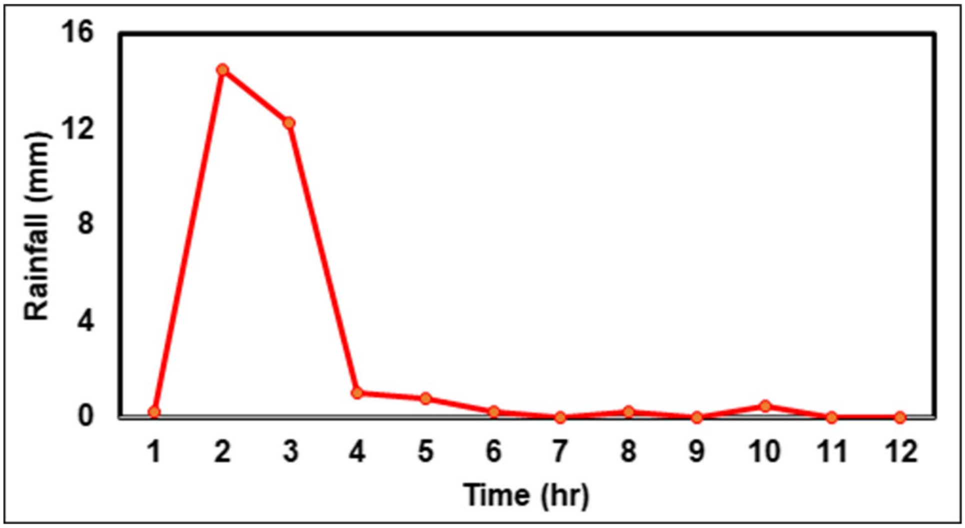

Fig. 2 Rainfall data used in the study for runoff simulations

performed. The overall research framework of this study is summarized in Fig. 3.

Mapping Pervious and Impervious Cover

The satellite images were classified into different LULC categories using head-on digitization at a 1:3000 scale in ArcGIS v. 10.1 and pervious and impervious surfaces were identified. The resultant maps were classified using the standard methodology (ISRO 2005). For accuracy assessment methods, a total of 724 random points (239 for Anchar, 253 for Brari Nambal, and 232 for Khushalsar) were collected for various land use categories. The impervious and pervious cover was delineated manually between 1980 and 2017.

Stormwater Modelling

The United States Environment Protection Agency's (USEPA) Stormwater Management Model (SWMM) 5.1, a process-based hydrological model, was selected to assess the effects of LULC change on the hydrological response and also to assess the effect of proposed LID-BMPs on runoff. SWMM was selected as the modelling software because it takes into account the spatial variability of catchment characteristics; each sub-catchment receives influxes from rainfall and creates overland flow built on the allotted sub-catchment characteristics e.g., average slope, area, imperviousness, and width of overland flow (Rossman and Huber 2016a). The model is dynamic and has been extensively used for rainfall-runoff estimations for both single and continuous events in urban and rural settings (Rossman 2010; Babaei et al. 2018; Xu et al. 2019; Arjenaki et al. 2021). The model has simple flow routing and is suitable in small catchments having areas less than 100 km^2 (Paule-Mercado et al. 2017). Natural channels were assumed to have a trapezoidal shape, and the width of the sub-catchments was calculated with an estimation technique suggested by USEPA (Rossman 2017). The Green-Ampt Method used for computing infiltration of rainfall into soil assumes there is a sharp wetting front that moves down from the surface, separating saturated soil above from drier soil below. SWMM requires input data for several catchment variables such as soil properties, rainfall, and LULC. Based on the estimates of flow accumulation and direction using the DEM, each of the three wetland catchments was delineated into four major sub-catchments in ArcGIS 10.1 (Fig. 1). The values of Manning's roughness coefficient for overland flow, surface depression storage, and soil infiltration were obtained from the literature (Rawls et al. 1983; ASCE 1992; McCuen et al. 1996) (Table S2).

Dynamic wave routing was chosen because this method solves the one-dimensional Saint–Venant flow equations, decreases flow continuity errors, and produces the most theoretically accurate results for surcharging conditions (James et al. 2010; Majeed et al. 2021). The Saint–Venant equations used in SWMM are expressed as:

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

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

where x is the distance along the conduit, t is time, A is the cross-sectional area, Q is the flow rate, H is the hydraulic head of water, S_f is the friction slope, h_L is the local energy loss per unit length, and g is the acceleration of gravity.

The Green-Ampt infiltration (Green and Ampt 1911) option was used for characterizing the site-specific soil hydrology as it is based on measurable physical parameters. The input parameters required are the initial moisture deficit of the soil, the soil's hydraulic conductivity, and the suction head at the

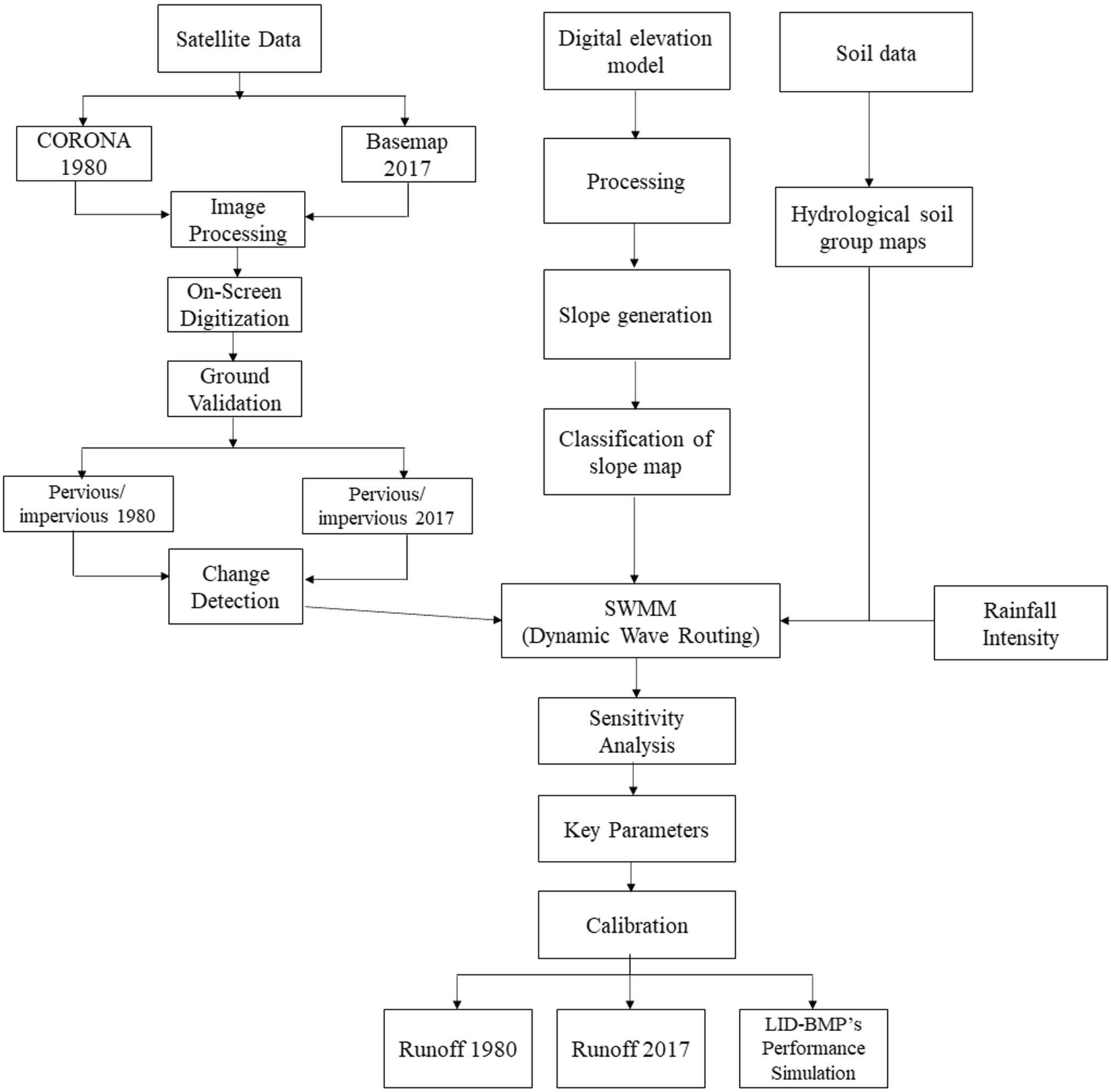

Fig. 3 Flowchart of methodology adapted for runoff simulations

wetting front. It produces theoretically accurate soil infiltration properties that are less than and exceed the rate of rainfall. The Green-Ampt infiltration is represented as:

$$f = f_p \tag{3}$$

$$f_p = K_s\left(1 + \frac{S.IMD}{F}\right) \tag{4}$$

where f is the infiltration rate (ft sec^{-1}), f_p is the infiltration capacity (ft sec^{-1}), I is the rainfall intensity (ft sec^{-1}), F is the cumulative infiltration volume of this event (ft), F_s is the cumulative infiltration volume required to cause surface saturation (ft), S is the average capillary suction at the wetting front (ft), IMD is initial moisture deficit for this event (ft/ft), and K_s is the saturated hydraulic conductivity of soil (ft sec^{-1}).

Several assumptions are made within SWMM when modelling LID practice hydrologic performance for this study (Rossman and Huber 2016b; Rossman 2017):

1. The cross-sectional area of the unit remains constant throughout its depth.

2. Flow, through the unit, is one-dimensional in the vertical direction; there is no lateral exfiltration from the soil, sand, or storage layers.
3. Inflow to the unit is distributed uniformly over the top surface.
4. Initial moisture content uniformly distributes throughout the soil layer.
5. Matric forces within the storage layer are negligible so that it acts as a simple reservoir that stores water from the bottom up.

Management Strategies

Stormwater management strategies are specifically designed to minimize the effects of hydrologic alterations due to LULC changes (Pour et al. 2020). Keeping in view the requirements and functionalities of different LID-BMPs in practice, the rain garden LID-BMP was selected. A rain garden is a depressed area, planted with grasses, flowers, and other plants, that collect rainwater from impervious areas such as roofs, walkways, streets, parking lots and driveways and allows it to infiltrate into the ground. The design and construction of LID-BMPs depend upon site characteristics, availability of land, needs and money and resources available. Suitable LID-BMPs were determined by taking care of design and construction considerations such as rainwater design criteria, impervious to rain garden area ratio, overflow drain height, soil selection, use of underdrains, depth of rain garden, trees/plantings, the direction of infiltrated water, weed control, binding of soil layers during construction, rock trenches, perforated drains, and interim sediment and drainage management. Further, the materials for construction such as native soils and rocks, the sand layer above the rocks and filter fabrics are important before placing the growing medium. The rain garden LID-BMPs were applied in open spaces available in the study area and considering that runoff from the impervious areas diverts to the applied LID-BMPs before being drained into the wetlands. In the first scenario, all the open and green spaces available in the study area were treated as rain gardens and the simulations were performed. Then, four rain gardens in four directions each were designated for each wetland. Half (50%) and total (100%) runoff from the catchments respectively was diverted to these rain gardens. The LID-BMPs were used on runoff control efficiencies and characteristics of the study area. After defining appropriate LID-BMPs, runoff scenarios were simulated for the post-development LULC of 2017.

Results

LULC Change from 1980 to 2017

The wetland catchments experienced a significant conversion of agricultural and open space areas into urban land uses. The LULC maps of the three wetland catchments are shown in Fig. 4 and the details of LULC transformations are provided in Table S3. During the period from 1980–2017, a total of ~ 137.6 ha of cropland, 81.6 ha of open space area, and 121.3 ha of wetland area were converted to urban land uses. The results reveal that from 1980 to 2017, the Anchar catchment experienced the highest loss in the spread of open water (59.5%) followed by open spaces (37%). However, throughout the same period, the highest increase was observed in urban structures (224%), and roads (95%). The Brari Nambal catchment experienced the highest loss of area in the cropland category (89%), followed by the plantation area (~ 66.8%). While during this period, green spaces in the catchment increased by 731%, roads by 89.4%, and other urban structures by 77.7%. The Khushalsar catchment experienced drastic conversions of plantation and cropland areas into the urban area. During 1980–2017, about 59% of the plantation, and 48% of cropland areas were lost to other land uses while urban structures increased significantly by 119% and roads by 63%. Similar results were reported by Rashid and Aneaus (2019) while working on the LULC changes in the catchment of Narkara wetland located on the outskirts of Srinagar city. The authors pointed out that due to LULC changes, there has been a drastic reduction of cropland area by ~ 78% whereas the urban surfaces mainly built-up areas increased by ~ 2663% from 1965 to 2016.

The major highlights of analysis in impervious cover revealed that from 1980–2017, a total of ~ 383.6 ha of pervious area has been converted to impervious areas in the three wetland catchments increasing runoff volume and peak discharges (Table 2). The pervious and impervious land cover maps for three wetland catchments Anchar, Brari Nambal, and Khushalsar, are shown in Fig. 5. During the period from 1980–2017, Anchar catchment experienced a total loss of 169.5 ha of pervious area, Brari Nambal catchment experienced a loss of 116 ha of pervious cover and Khushalsar catchment experienced a loss of 97 ha of pervious cover to impervious areas. The results conform with the findings of Paule-Mercado et al. (2017) who worked on a mixed LULC catchment of Gyeonggi, South Korea. The study suggested that during the early phases of development, bare areas increased from ~ 5% to 31% between 2010 to 2013 and the impervious cover increased from ~ 18% to ~ 31% during the late active phase of land development between 2014 to 2015.

Runoff Simulations

Sensitivity analysis of rainfall-runoff modelling revealed that overland flow width, slope, and impervious cover (%) were the most sensitive parameters that affect runoff peak and volume. Other parameters such as soil depth, infiltration parameters, soil moisture, depression storage, and

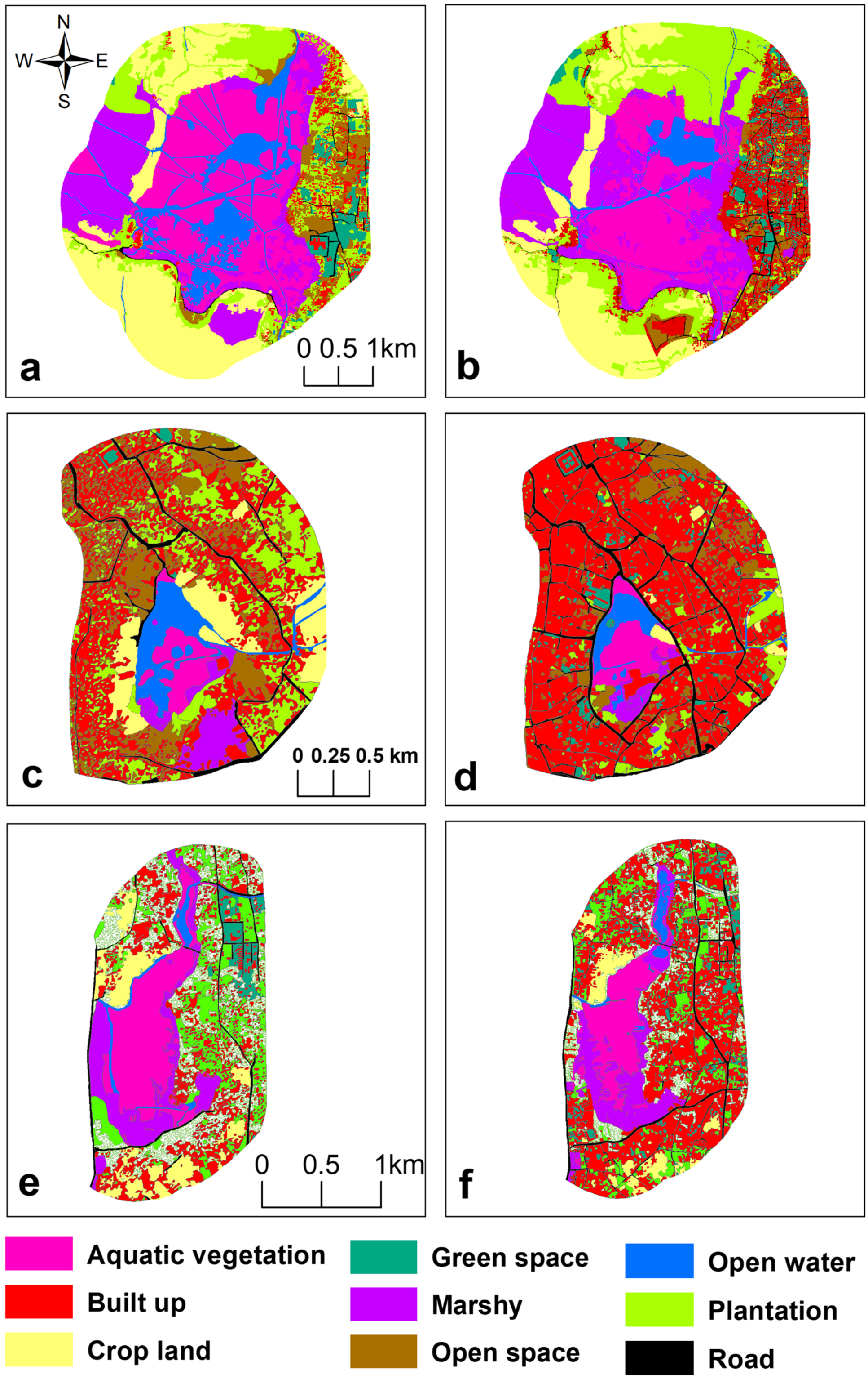

Fig. 4 LULC in the study area around the three wetlands

groundwater release were having moderate to low impact on the runoff generation and peak formation. The percentage of impervious cover turned out to be the most sensitive parameter having a significant influence on the total runoff volume and peaks. Overland flow width and slope of the catchment area influence the time duration of runoff peaks. To facilitate the analysis and for prioritizing areas runoff data were classified into 4 major sub-catchments for the three wetlands. The rainfall intensity for the simulation of runoff for a single event was kept the same for the simulation

Table 2 Pervious and impervious land cover in the wetland catchments

Land Cover (ha)	Anchar				Brari Nambal				Khushalsar			
	1980 (ha)	2017 (ha)	Change (ha)	% Change	1980 (ha)	2017 (ha)	Change (ha)	% Change	1980 (ha)	2017 (ha)	Change (ha)s	% Change
Pervious	1717	1547.5	-169.5	-9.9	230	113.3	-116.7	-50.7	302.6	205.2	-97.4	-32.2
Impervious	85.3	254.8	169.5	198.7	147.6	264.3	116.7	79.1	88.3	185.7	97.4	110.3

of the 1980 and 2017 periods. A summary of the simulation results is presented in Table 3. In response to the LULC changes, the total runoff in the Anchar catchment during pre-development levels (1980) was 0.37 inches (Fig. 6a); which increased to 0.94 inches in 2017 (Fig. 6b). Similarly, runoff from the Brari Nambal catchment in 1980 was 2.24 inches (Fig. 6c) that increased to 3.95 inches during 2017 (Fig. 6d). Runoff in the Khushalsar catchment during 1980 was 1.11 inches (Fig. 6e) that increased to 2.88 inches during 2017 (Fig. 6f). The results reveal that the changing patterns of runoff in the three wetland catchments were dominated by the land-use change demonstrated by 198.7%, 79.1%, and 110.3% increases in impervious surfaces for Anchar, Brari Nambal, and Khushalsar wetlands respectively. The peak runoff increased from 101.88 cfs in 1980 to 191.01 cfs during 2017 in the Anchar, 184.43 cfs during the 1980 to 287.99 cfs during 2017 in Brari Nambal, and 64.41 cfs in 1980 to 98.79 cfs in 2017 in the Khushalsar catchment.

Management Measures

Three scenarios were used to test the efficacy of rain garden LID-BMPs in reducing runoff. In the first scenario, all of the open space areas were used as rain gardens and 100% of runoff from the catchments was diverted to rain gardens. This resulted in no runoff generation. In the second scenario, 50% of runoff from the catchment area is diverted to rain gardens. This revealed that the rain garden BMPs were highly efficient in reducing runoff peak and volume to pre-development levels (Fig. 7a, b, c). The rain garden LID-BMPs resulted in a high reduction of runoff volume by 46.8% in Anchar, 10.8% in Brari Nambal, and 48.6% in Khushalsar catchment (Table 4). The detailed simulation results using LID-BMPs at a 50% treatment level of surface runoff are presented in Table S4. After that 100% of runoff from the catchment areas was diverted to LID-BMPs and the simulations were performed. The results showed a drastic reduction in the surface runoff from the catchment areas (Fig. 7d, e, f). A detailed summary of the results at 100% runoff treatment is presented in Table S5. It was observed that at 100% runoff treatment LID-BMPs were highly efficient in runoff reduction, decreasing runoff by 89.4% in Anchar, 13.4% in Brari Nambal and 86.8% in Khushalsar catchment. Although the reduction in Brari Nambal is low, it means few more LID-BMPs need to be installed in the catchment area to minimize the runoff. The reduction in runoff using the rain garden LID-BMPs is shown in Fig. 7 and presented in Table 4. As expected, the implementation of LID-BMPs in the catchment area of wetlands means that more runoff was collected, infiltrated, stored, or treated resulting in the mitigation of negative impacts. Although the minimization of runoff volume in some sub-catchments was not necessary, since the open spaces are available in the area, the LID-BMPs can significantly reduce the runoff volume from wetland catchments considering the waterlogging and flood situation of Srinagar city.

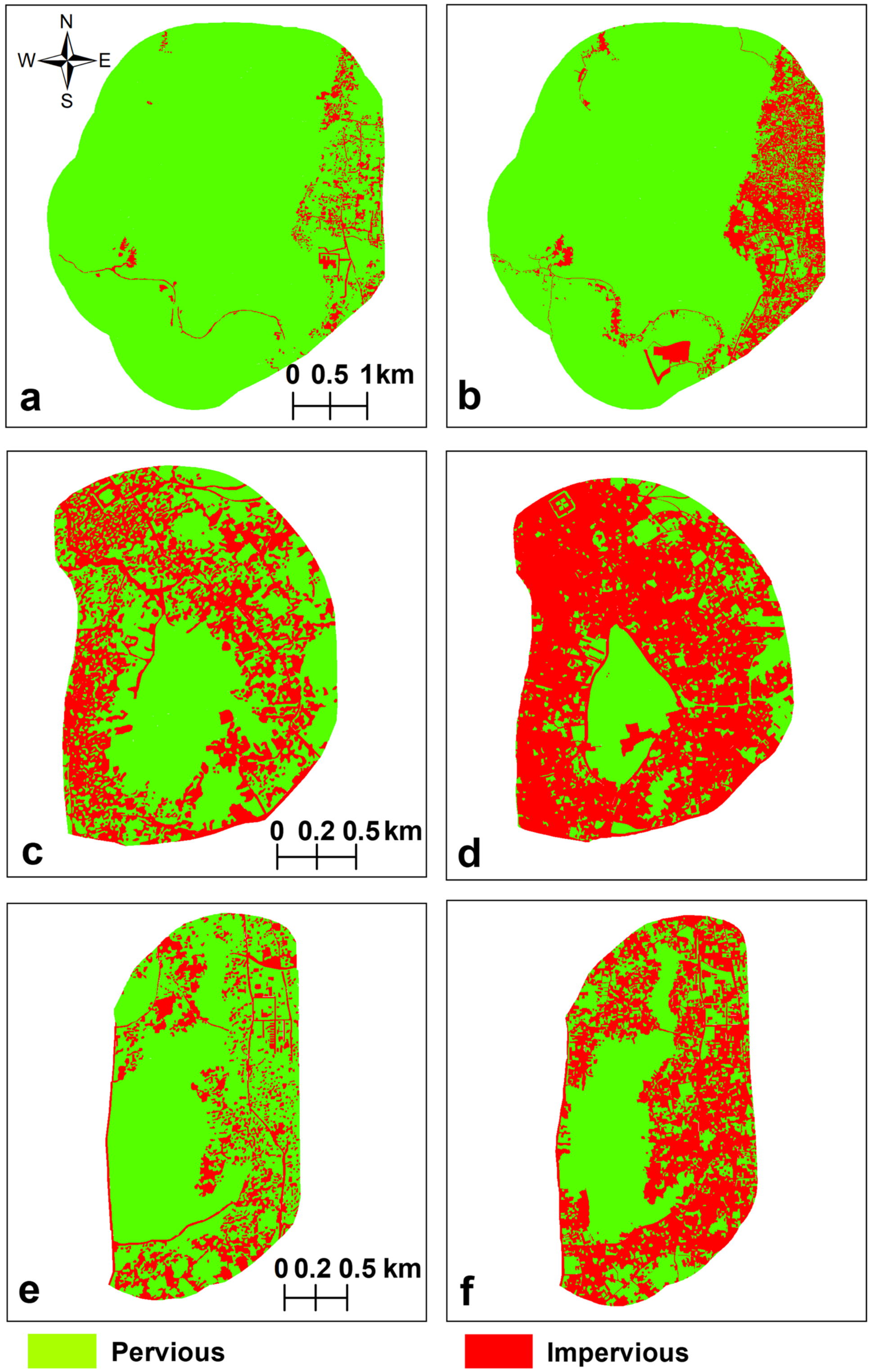

Fig. 5 Map showing impervious cover around the three wetland catchments

Discussion

The Kashmir Valley experienced significant changes in the patterns of LULC during the past three decades (Alam et al. 2020; Dar et al. 2021a). The main factors responsible for large-scale LULC changes are large population increases and associated urbanization (Dar et al. 2021b). Furthermore, the LULC changes are more pronounced in the Srinagar district which hosts the business hub, markets, and tourism infrastructure. During the last 4 decades, substantial LULC

Table 3 Summary of the runoff simulations for the pre-development (1980) and post-development (2017) periods

LULC data	Sub-catchment	Total precipitation (in)	Total infiltration (in)	Total runoff (in)	Total runoff 10^6 gal	Peak runoff CFS	Runoff Coefficient
Anchar 1980	S1	1.17	1.12	0.05	1.35	17.17	0.043
	S2	1.17	0.96	0.20	4.76	59.03	0.173
	S3	1.17	1.10	0.07	1.24	15.80	0.058
	S4	1.17	1.12	0.05	0.84	9.88	0.042
	Total	1.17	4.3	0.37	8.19	101.88	0.316
Anchar 2017	S1	1.17	1.07	0.10	2.73	36.79	0.088
	S2	1.17	0.54	0.60	14.13	99.45	0.513
	S3	1.17	1.01	0.17	3.05	40.93	0.143
	S4	1.17	1.11	0.07	1.11	13.84	0.056
	Total	1.17	3.73	0.94	21.02	177.17	0.8
Brari Nambal 1980	S1	1.17	0.51	0.67	5.26	71.64	0.573
	S2	1.17	0.56	0.62	3.13	43.52	0.532
	S3	1.17	0.62	0.57	3.00	45.09	0.485
	S4	1.17	0.80	0.38	1.62	24.18	0.329
	Total	1.17	2.49	2.24	13.01	184.43	1.92
Brari Nambal 2017	S1	1.17	0.29	0.88	6.92	88.02	0.754
	S2	1.17	0.03	1.14	5.72	67.06	0.973
	S3	1.17	0.19	1.02	5.38	78.05	0.869
	S4	1.17	0.29	0.91	3.83	54.86	0.778
	Total	1.17	0.8	3.95	21.85	288	3.374
Khushalsar 1980	S1	1.17	0.84	0.31	1.21	15.73	0.267
	S2	1.17	0.85	0.30	2.81	32.13	0.259
	S3	1.17	0.71	0.43	1.30	13.45	0.368
	S4	1.17	0.10	0.07	0.19	3.10	0.061
	Total	1.17	2.5	1.11	5.51	64.41	0.955
Khushalsar 2017	S1	1.17	0.56	0.58	2.27	22.26	0.500
	S2	1.17	0.43	0.71	6.58	46.29	0.607
	S3	1.17	0.10	1.03	3.09	18.73	0.877
	S4	1.17	0.58	0.56	1.51	11.51	0.479
	Total	1.17	1.67	2.88	13.45	98.79	2.463

changes were observed in the city (Nengroo et al. 2017). As a result of urbanization, the city underwent land transformations of open spaces, cropland, and plantation area into urban land uses (Mehraj et al. 2021). The results corroborate the findings of Asgher et al. (2021) who also reported the massive growth of urban structures and roads at the cost of aquatic ecosystems in Srinagar. Pervious areas such as plantation land, cropland, and open space decreased during the 37 years. Further, the massive growth of settlements, housing complexes, and residential buildings has resulted in a decrease in pervious cover. The reduction in pervious areas is mostly related to the conversion of open spaces, cropland, and plantation area into urban structures and roads (Dar et al. 2021c). The urban structures and road network paved the way for the increase of impervious cover, leading to huge stormwater flows and waterlogging conditions. As is very much clear from the findings that the study area experienced a significant conversion of pervious area into impervious area during the period from 1980 to 2017. The decrease in pervious cover is mainly related to the conversion of open spaces, cropland, and plantation area into urban structures and roads in Srinagar city (Dar et al. 2021b).

The low runoff peaks and volume during the pre-developmental period (1980) can be attributed mainly to high ground infiltration of rainfall due to the presence of a significant percentage of pervious areas in the city. During the 1980s it could be observed that around the wetland ecosystems a significant percentage of the area was under pervious cover (open spaces, croplands, and plantations) allowing huge amounts of rainfall to percolate to the ground. However, due to the large development of urban surfaces (Dar et al. 2020b), haphazard and unplanned urban development, and lack of stormwater management

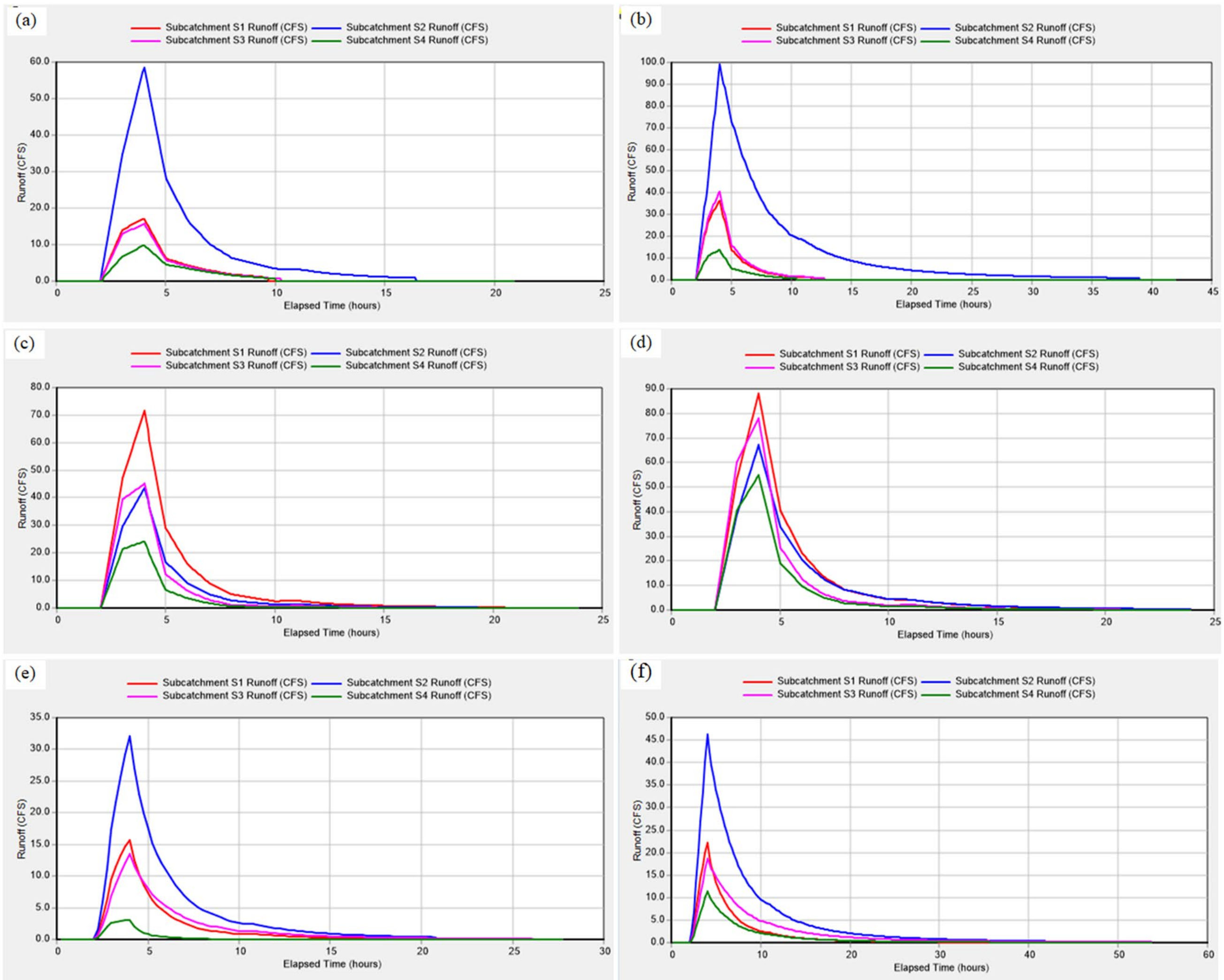

Fig. 6 Runoff simulations during the pre and post development periods for the three wetland catchments

facilities in Srinagar city, the surface runoff has increased during 2017 with significant impacts on the wetland ecosystems. Various studies have demonstrated that infrastructure development leads to an increase in runoff (Akhter and Hewa 2016; Karamage et al. 2017; Li et al. 2018; Luan et al. 2019). It is pertinent to mention here that during the period from 1901 to 2011, the population in Srinagar has grown 12 times from 0.12 million to 1.2 million while the urbanized centres have grown by 23 times from 12 km^2 to 278.1 km^2 (Kuchay and Bhat 2014). This unplanned urbanization with exacerbated population growth together with lack of stormwater management appears to be the main factors responsible for wetland degradation in Srinagar city making it prone to stormwater flooding.

Due to the continuous decrease in pervious areas in Srinagar city, there is a high need for developing sustainable stormwater management strategies and policies to manage the problems of stormwater generation (Bilal and Rather 2021). While the procedures signifying different designs and strategies for mitigation of LULC changes impacts already exist (USEPA 2010), no such guideline has been adapted by the city planners as they do not seem to have clarity on local hydrology, LULC, and catchment characteristics. The implementation of rain garden LID-BMP adopted in this study resulted in an appreciable reduction of runoff peaks and volume. Similar results were obtained by Nowogoński (2021) using the rain garden LID-BMP technology in Gorzów Wielkopolski, Poland. LID-BMPs installed in three wetland catchments were highly efficient in reducing runoff and peak flows, because in these catchments, the percentage of available space, where the LID-BMPs can be implemented, is large.

Modelling Uncertainties

The scarcity of hydrometeorological observations in the Kashmir region poses a constraint to validating the models

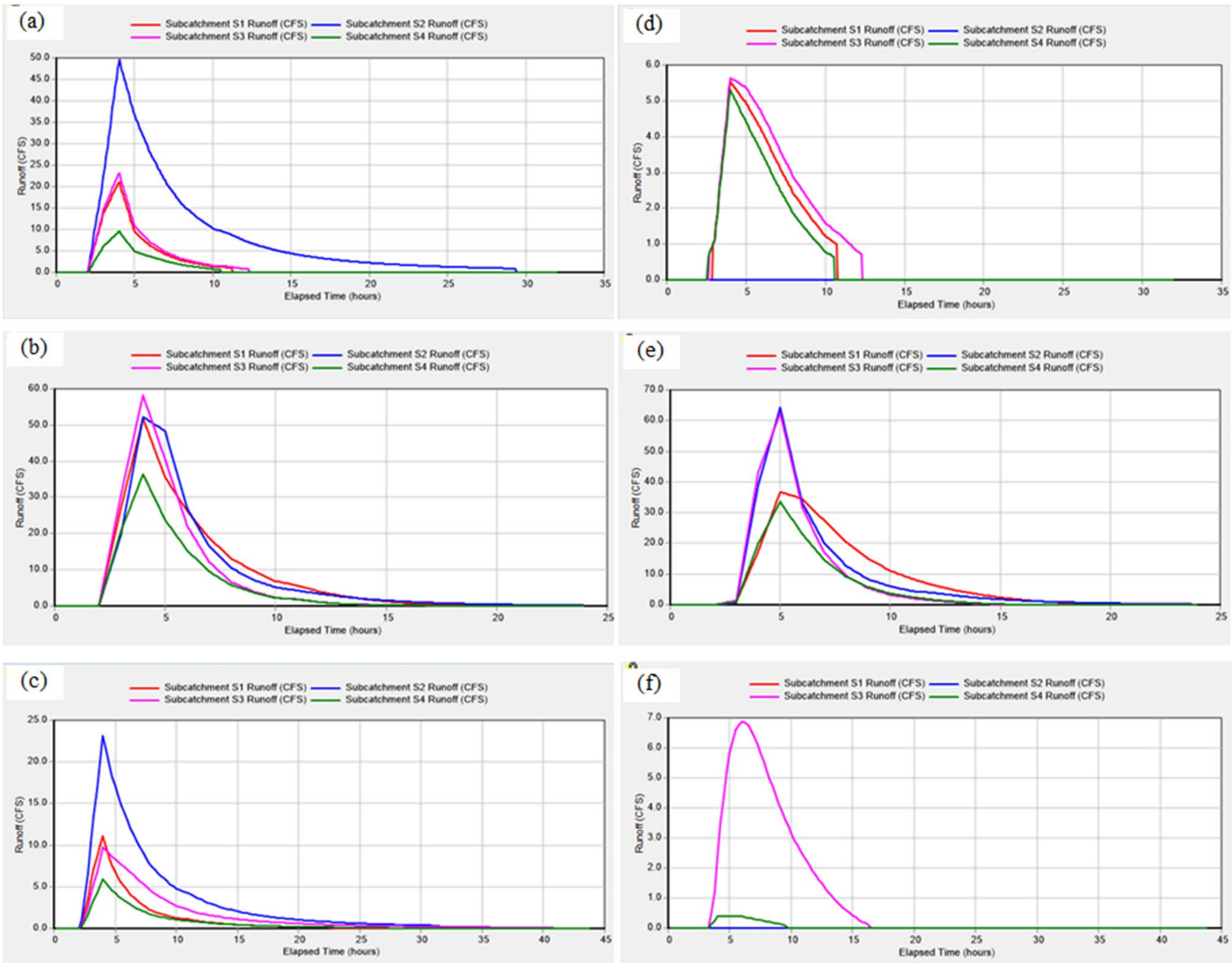

Fig. 7 Runoff simulations for the post development period using LID-BMPs

Table 4 Runoff scenarios for the three wetland catchments using LID-BMPs at 50% and 100% treatment levels

Catchments	Runoff (in)			Runoff (in) using LID-BMPs			
	1980	2017	% Change	at 50% treatment	Reduction (%)	at 100% treatment	Reduction (%)
Anchar	0.37	0.94	154	0.5	46.8	0.1	89.4
Brari Nambal	2.24	3.95	76.3	3.52	10.8	3.42	13.4
Khushalsar	1.11	2.88	159.5	1.48	48.6	0.38	86.8

with observations (Rashid et al. 2019; Majeed et al. 2021). The results of the study are limited to the simulated flows because of the limitations in data gathering including measurement of runoff at the study sites. Generally, measurements of runoff based on gauge stations are the best way to accurately quantify rainfall runoff in the study area which also constitutes a valuable source of data for validating the simulated flows. But it is pertinent to mention here that no instrumental runoff records are available for validating the model simulations generated in this study. Therefore, the lack of gauging stations around the wetland catchments poses an impediment to validating the model simulation.

In this study, the modelling uncertainties were related to rainfall data available over the region and limitations in the model structure. During model development, the rainfall data used was obtained from a point-based rainfall gauge station and then applied uniformly over the whole catchment area. Rainfall as such was a lumped input into the model.

Although topography affects the spatial variability of rainfall, we assumed uniform rainfall in the current approach. Limitations in model structure can affect the model output and therefore can lead to inaccurate estimation of runoff by the SWMM. For instance, during the model setup, infiltration into the soil and unsaturated zone moisture content was assumed to be uniform over the entire sub-catchment. These assumptions can have a significant impact on soil moisture characteristics. The soil moisture content in the unsaturated zone controls flow from the unsaturated zone to the saturated zone in SWMM. While we opine that such assumptions might contribute to uncertainties, the calibration and validation of the SWMM simulations are constrained by the lack of hydrometeorological observations around the wetland catchments. It is, however, noteworthy to point out that SWMM offers a robust modelling framework that has been used extensively to understand the impact of stormwater deluges (Krebs et al. 2014; Petrucci and Bonhomme 2014; Paule-Mercado et al. 2017; Yang et al. 2021; Zeng et al. 2021; Hussain et al. 2022).

Conclusion

This research used a combined modelling method that monitored the LULC change to determine the impact of ongoing land development on runoff, and its mitigation using LID-BMPs in SWMM. The study indicated large-scale conversion of cropland, plantation, and wetland area into urban spaces between 1980 and 2017. The main factors responsible for LULC change were identified as urbanization (119%) and population increase in Srinagar city. SWMM analysis revealed that the runoff volume under the pre-development phase was considerably lower due to the high infiltration of rainwater in pervious surfaces. Simulations during the post-development phase demonstrated that runoff peaks and volume significantly increased due to the increase of 119% in the impervious cover. Runoff simulations using rain-garden LID-BMPs displayed a substantial reduction in the runoff and development of peaks. The installation of appropriate LID-BMPs is important for mitigating the negative effects of LULC changes on runoff generation, however, study area characteristics, design of LID-BMPs, and cost need to be considered before planning any such intervention.

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Author Contributions Irfan Rashid: Conceptualization, Supervision, and Editing. Shahid Ahmad Dar: Conceptualization, Methodology, Data curation, Software, Data Analysis, Interpretation of Results, Writing-original draft. Sami Ullah Bhat: Conceptualization, Supervision, and Editing.

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Data Availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing Interests The authors have no relevant financial or non-financial interests to disclose.

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