



Impact of 2018 Kerala Floods on Soil Erosion: Need for Post-Disaster Soil Management

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Received: 1 November 2019 / Accepted: 27 August 2020 / Published online: 10 September 2020
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Abstract

Extreme precipitation events lead to flash floods, which can trigger soil erosion and landslides. While damages to infrastructure and livelihoods are rapidly assessed on economic terms, damages to natural resources are not estimated due to limited observation record. This study conducted an analysis using remote sensing data to estimate changes in soil erosion rates before, during and after the Kerala 2018 floods, based on the Universal Soil Loss Equation (USLE). The USLE was driven by multiple data including: in situ rainfall data from Indian Meteorological Department (to estimate rainfall erosive factor), soil maps prepared by Food and Agriculture Organization (to estimate the soil erodibility factor from the properties of soil that consists of the percentage of clay, loam and silt), digital elevation model (to estimate topographic slope and length) from Shuttle Radar Topography Mission and multispectral imagery (to estimate cover management factor and conservation practice factor) from Landsat-8 satellite. Data from these sources were analysed using a Geographic Information System (GIS) platform. Results indicate a state-wise average increase of 80% (31–56 metric tons $\text{ha}^{-1} \text{year}^{-1}$) in soil erosion rate during the floods. Of the districts, Idukki showed the highest increase, of 220% and more susceptibility to soil erosion, which is in comparison with government survey records. Results show that the floods and associated erosion were not only due to the rainfall event but also due to the rapid change in land use and land cover, from natural to human settlements. Therefore, government agencies need to protect land cover and reduce unsustainable development in ecologically sensitive environments, which if managed properly can act as a buffer for soil erosion extremes in Kerala.

Keywords Floods · Soil erosion · Kerala floods · Landslides · Sedimentation

Introduction

Climate change-induced disasters are increasing globally and affecting almost every country, especially developing and under developed nations (Chinnasamy and Sood 2020;

Lacombe et al. 2019). Of such calamities, extreme precipitation and associated flooding have become one of the most devastating phenomena induced by climate change (Chinnasamy 2017). Frequency of such floods and extreme events has been steadily increasing in the past decade, and in some cases, ordering for a change in the flooding indices such as flood frequency (e.g. definition of 100-year flood) or recurrent flood levels (Milly et al. 2002; Guhathakurta et al. 2011). Even with rainfall and flood prediction models, the impacts of heavy rainfall and flood are challenging to contain and prepare. As such, mitigations and adaptation plans are often post-disaster, i.e. “reactive” and less prepared before natural calamities, i.e. “proactive” measures. Across the world, annually, millions of people are directly impacted by heavy rainfall events and floods, especially due to heavy damage on infrastructure and agricultural sectors. Such damage and impact have

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been increasing due to floods in India, almost annually in various regions (Papalexioiu and Montanari 2019).

Many studies have shown that in recent decades, there is considerable increase in extreme precipitation and flood events in India (Mishra and Nagaraju 2019; Guhathakurta et al. 2011; Ali and Mishra 2018). Just in the past decades, India witnessed many severe extreme precipitation and flood events resulting in heavy livelihood and economic damages. For example, studies have shown that there is a substantial increase in the flood frequency and intensity in the Ganges River (Dhar and Nandargi 2002; Shrestha and Bajracharya 2013). In another study, Dhar and Nandargi (2002) reported a total of 1300 flood events within ten major tributaries of the Ganges over the last 14 years. In addition, annual flooding had been reported at the confluence of the Ganges and the Brahmaputra, due to upstream flooding in India (Shrestha and Bajracharya 2013). Other studies showed that 10 million people were affected due to 2005 Mumbai floods (Gupta and Nair 2011); Uttarakhand extreme precipitation event of 2013 caused a loss of \$3.8 billion (Kumar 2013); and the extreme precipitation event in 2015 in Chennai caused a loss of over \$3 billion (Boyaj et al. 2018). Jain et al. (2007) report that Bihar state was affected by Koshi floods in the years 1978, 1987, 1998, 2004 and 2008, thus becoming a frequent location for high flooding events. It is noted that the 1998, 2004 and 2008 floods caused an economic loss of 1.1, 1.4 and 0.5 billion USD, respectively, resulting from damage to agriculture and infrastructure. This has frequent flooding that has changed Bihar's Koshi to be known as the "river of sorrow" by name. For any nation, this frequent loss is unsustainable and unacceptable. Mostly damage to infrastructure and agriculture is reported for economic loss, but not damage to natural resources, and long-term damage and rehabilitation.

Of the natural resources damaged due to floods, soil losses due to flood erosion is an important phenomenon. Eroded soils lead to future erosion and triggers landslides. Kumar (2013) indicated that the 2013 Uttarakhand floods induced many landslides and caused mass erosion of the top soil. The study also showed occurrence of landslides across the Himalayan regions with floods. Bormudoi and Nagai (2016) reported serious soil erosion and landslide, over 15% of land cover loss due to high rainfall events in the north-eastern regions of India. These studies indicated massive erosion is often across India during monsoon seasons and how it is aggravated due to high-precipitation events resulting in excess soil erosion and land cover degradation. The review of the literature indicated that flood-related soil erosions were increasing across India and in particular along regions with undulating topography, elevation gradients and high rainfall events. The south Indian state of Kerala is one such region that witnesses

periodic damage to natural resources due to high monsoon rainfall (3100 mm annually) and undulating topography, from the presence of the Western Ghats.

Kerala is a region with heavy monsoon rainfall, changing landscapes (due to conversion of wetlands to agricultural fields) and steep gradients in slope. Many devastating floods have occurred in Kerala, with the July 1924 floods, which were titled as the "Great Flood of 99", being one of the worst with highest rainfall of 4850 mm in Munnar (in July 1924) and leading to huge displacement of people. Many dams of the state were breached and caused considerable damage to natural resources, agriculture and infrastructure. After this event, there had been many floods in Kerala (almost annually in some isolated locations), with frequent damage to livelihood and resources. In addition, with the removal of wetlands, there has been increased soil erosion with floods in Kerala (Abraham 2015). Nair et al. (1997) argued that in the past 80 years, Kerala had witnessed approximately 500 landslides; most of them triggered due to the 1324% change in land cover of ecologically sensitive zones and Western Ghats. After the 1924 flood event, as per the India Meteorological Department (IMD), Kerala received 2394 mm rainfall during the south-west monsoon (rainfall) period of June to August 2018, which was 693 mm higher and 42% higher than the long-term normal. During this season, many floods occurred and 14 districts were severely impacted, with the Government of Kerala projected loss of \$3 billion (Sankar 2018). While there have been many studies documenting change in land cover, agricultural loss and economic loss due to the 2018 Kerala floods, limited studies have quantified the actual increase in soil erosion rates due to the floods. While the relation between high rainfall events and soil erosion is well documented, such studies have not been conducted after the 2018 floods. The floods erode the top soil and expose the fragile saturated soil, leading to future soil erosion and increased flooding (due to less soil for recharge). A documentation of an increase in soil erosion (if any), post-floods, can aid in channelizing post-disaster management efforts to protect soil erosion zones from further erosion and landslides. This current study aims to achieve this by the objectives explained in the following section.

Objectives

The primary objective of the current study is to document the increase in soil erosion rates during and post-Kerala 2018 floods. The secondary and tertiary objectives include identifying spatial variations in soil erosion rates and prioritizing risk zones, wherein relief and post-disaster work can start immediately after future floods (Fig. 1).

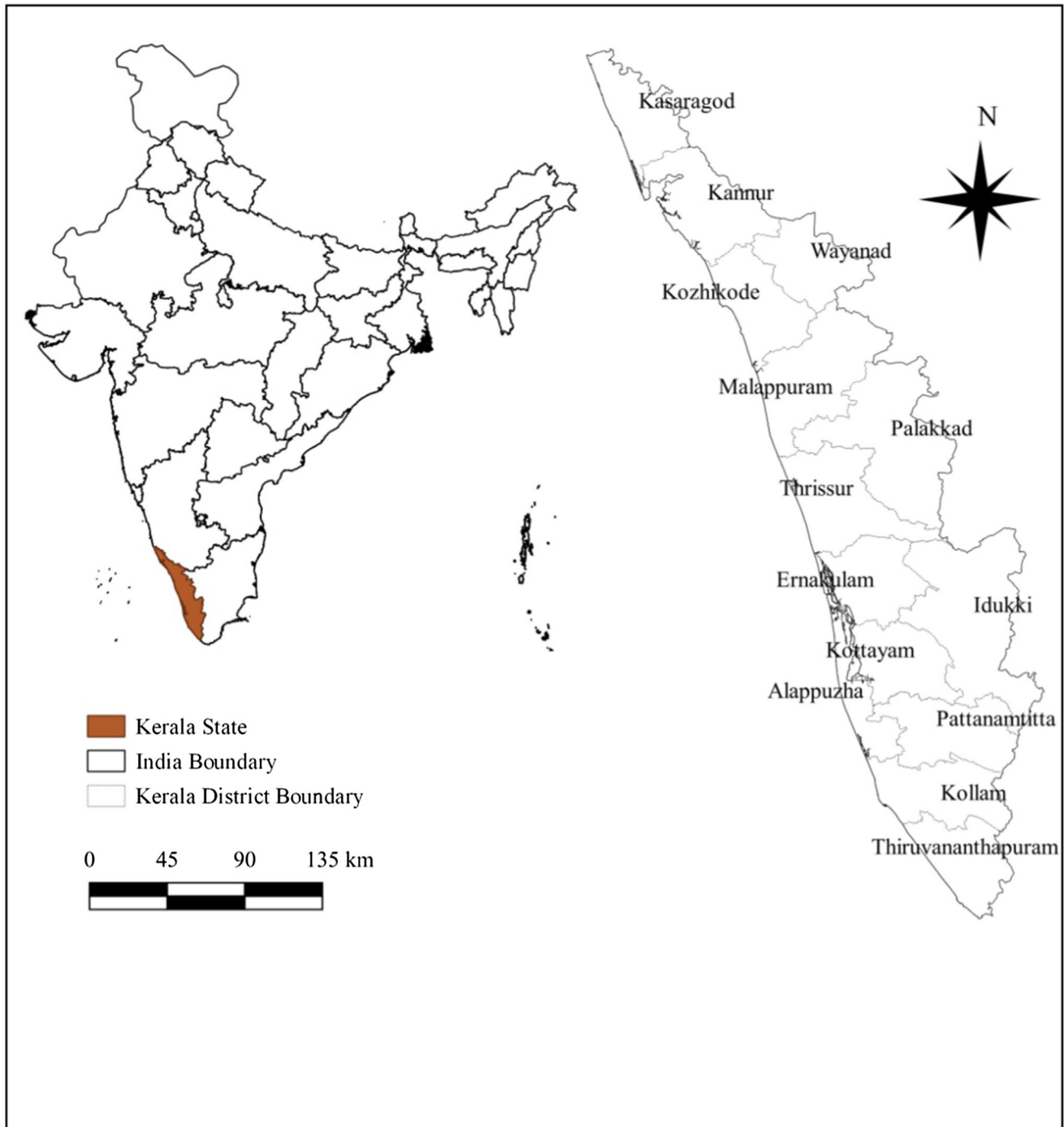


Fig. 1 Location of Kerala in India and districts

Methods

Study Area

Kerala is a southern state in India and is the 23rd largest state by area (38,863 km²). Kerala is located on the western slopes of the Western Ghats between 74° 7'47" and 77° 37' 12" east longitudes and 8° 17'30" and 12° 47" north

latitudes. It is bordered by Karnataka to the north and north-east, Tamil Nadu to the east and south and the Arabian Sea to the west. It is divided into 14 districts with the capital being Thiruvananthapuram. Kerala has a total population of 33.4 million people, with 51.5% and 48.5% women and men, respectively (Census of India 2011).

In terms of climate, Kerala state is categorized by sub-tropical climate with eastern highlands (rugged and cool

mountainous terrain), the central midlands (rolling hills) and the western lowlands (coastal plains). The topography consists of a hot and wet coastal plain gradually rising in elevation to the high hills and mountains of the Western Ghats. Kerala state has diverse types of soil such as red, ferruginous, sandy, black, peat and loamy soil (Giosan et al. 2017). The state also has forested regions with an area of 9400 km² comprising tropical wet evergreen partly evergreen forests (Balagopalan 1995).

The climate is mainly wet and maritime tropical, heavily influenced by the seasonal heavy rains brought up by the monsoon. Kerala experiences an average annual rainfall of 2923 mm, with peaks observed from June to August corresponding to the south-west monsoon and the rest from September to December corresponding to north-east monsoon. Concentration of heavy rainfall in the monsoon month makes the area prone to severe floods and erosion (India Meteorological Department, 2018).

Model and Associated Equations

Soil erosion is a process closely associated with the hydrologic cycle. With water movement, some soil is eroded, transported and resettled in different locations. This phenomenon can be triggered and accelerated by natural and anthropogenic activities. In the natural setting, soil erosion is influenced by a variety of factors such as rainfall distribution, soil types, topography and land cover types. These factors are usually represented in models, governed by physical process-based equations, to predict sediment loading and sediment concentration. In the current study, such an approach is used and presented with the temporal and spatial variability using geographic information systems (GIS) technique. The overall methodology, equations used and data collection are shown in Fig. 2. Well-renowned soil loss equation was used, for which an array of data was collected from observation data and remote sensing-based data platforms. The following sections give a description of model and various data used for assessing the sediment erosion and loading.

Average Soil Loss (*A*)

The Universal Soil Loss Equation (USLE), developed by the US Department of Agriculture's Agriculture Research Service (USDA-ARS) scientists Wischmeier and Smith, has been one of the widely acknowledged, recommended and used equation to estimate soil loss, for more than 20 years (Zhang et al. 2011). It is to be noted that the USLE model has been updated by many researchers (e.g. MUSLE—Modified Universal Soil Loss Equation, RUSLE—Revised USLE, etc.), enabling the estimation of soil erosion by raindrop impact and surface runoff,

worldwide. The USLE (Universal Soil Loss Equation) allows one to estimate average annual soil loss for given natural and anthropogenic conditions. It was created as a support to soil conservation planning at the field scale. This model can also predict sheet and rill erosion on field slopes (Wischmeier and Smith 1978). In this study, soil erosion rates in Kerala, for the 2018 floods, were estimated using the USLE (Wischmeier 1965; Wischmeier and Smith 1978):

$$A = R \times K \times LS \times C \times P \quad (1)$$

where *A* is the computed average annual soil loss per unit area (metric tons ha⁻¹ year⁻¹), *R* is the rainfall erosivity factor (MJ mm ha⁻¹ h⁻¹ year⁻¹), *K* is the soil erodibility factor (metric tons ha⁻¹ year⁻¹ R unit⁻¹), *LS* is the topography factor (dimensionless), *C* is the cover and management factor (dimensionless) and *P* is the conservation practice factor (dimensionless). Each of these factors is explained in the following sections.

Rainfall Erosivity Factor (*R*)

In the USLE, the rainfall erosivity index (*R*) factor quantitatively represents the impact of rainfall on the soil surface (Wischmeier 1965). In terms of physics, the kinetic energy of the falling water raindrops is converted to be the potential rainfall energy, when colliding with the topsoil, which in turn determines the severity of erosion. This *R* factor is directly proportional to average annual rainfall, and their relationship can be used as a proxy to estimate the *R* value (Arnoldus 1980). For the current study, the *R* factor is determined using the following equation as per Choudhury and Nayak (2003):

$$R = 79 + 0.363 \times Xa \quad (2)$$

where *Xa* is the average annual rainfall in mm over the study area.

Soil Erodibility Factor (*K*)

The soil erodibility factor (*K*), in the USLE, aims to estimate the susceptibility of soil to erosion and derived as a function of the physico-chemical properties that affect detachability, transportability and infiltration capacity of soils (Wischmeier and Smith 1978). The equation to derive *K* is also (Wischmeier and Smith 1978; Williams 1978) based on the particle-size distribution, soil organic matter content, soil structure and soil permeability. It is to be noted that soil with high fraction of silt is more erodible than soil with low fractions of sand or clay, due to size classes. On the other hand, the presence of organic matter in soil reduces *K* because it increases the aggregation and fixing of particles in soil. Therefore, a soil's *K* varies,

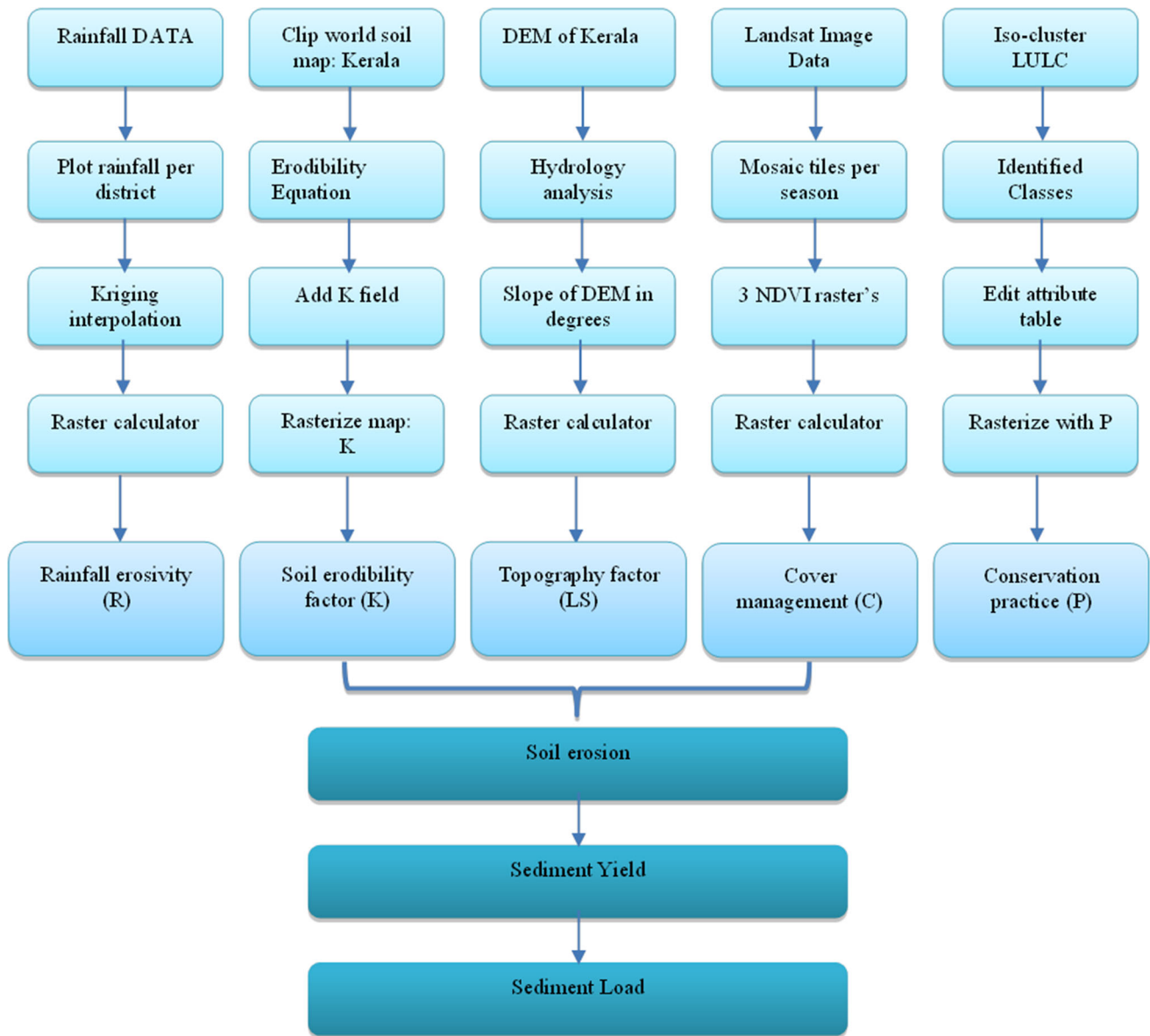


Fig. 2 Methodology to estimate soil erosion in Kerala due to 2018 floods

depending on complex interactions with the environment and on the soil’s physical and chemical properties (Williams 1978).

The *K* factor of Kerala was defined using the relationship between soil texture class and organic matter content (Wischmeier and Smith 1978; Williams 1978) as follows:

$$K = f_{Csand} \times f_{CLsi} \times f_{org} \times f_{hisand} \tag{3}$$

The values were calculated using the following equations (Thuy and Lee 2017):

$$f_{Csand} = \left\{ 0.2 + 0.3 \exp \left[-0.256m_s \left(1 - \frac{m_{silt}}{100} \right) \right] \right\} \tag{4}$$

f_{Csand} is a factor that gives low soil erodibility factors for

soils with high coarse sand contents and high values for soils with little sand,

$$f_{cl.si} = \left(\frac{m_{silt}}{m_c + m_{silt}} \right)^{0.3} \tag{5}$$

$f_{cl.si}$ is a factor that gives low soil erodibility factors for soils with high clay-to-silt ratios,

$$f_{org} = \left\{ 1 - \frac{0.25orgC}{orgC + \exp[3.72 - 2.95orgC]} \right\} \tag{6}$$

f_{org} is a factor that reduces soil erodibility for soils with high organic carbon content and

$$f_{\text{hisand}} = \left\{ 1 - \frac{0.7 \left(1 - \frac{m_s}{100}\right)}{\left(1 - \frac{m_s}{100}\right) + \exp[-5.51 + 22.9 \left(1 - \frac{m_s}{100}\right)]} \right\} \quad (7)$$

f_{hisand} is a factor that reduces soil erodibility for soils with extremely high sand contents.

As per Wischmeier and Smith (1978), K factor can be estimated using the soil texture and most importantly the composition of clay, sand and silt. For the current study, four major classes are defined and listed in Table 1 (Wischmeier and Smith 1978).

Topography Factor (LS)

The topography factor (LS) in the USLE quantifies the effects of topography on soil erosion. LS factor requires a DEM as an input parameter in order to quantitatively represent the continuous variation of topographic features across the landscape (Phinzi and Ngetar 2019). Topographic data were processed to get elevation information which in turn was processed to generate slope gradient and LS factor maps.

In the past decade, there has been a considerable increase in the assimilation and use of remote sensing data (Chinnasamy and Ganapathy 2018) for assessing topographic features. With newly developed equations, grid cells from remote sensing platforms can be used to estimate topography factors that govern flow direction, erosion and flow accumulation in watersheds. These remote sensing-based topographic data are called digital elevation models (DEMs), and since they are digital in nature, allow for direct calculation of the LS factor using arithmetic equations. Amongst the space missions, the ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) and SRTM DEMs have been the most widely applied products, probably because these are freely available to the research community and provide near-global coverage. More information on the type of DEM used and specifics on the satellite mission are explained in the data sections.

The LS factor was determined using the equation as listed by (Wischmeier and Smith 1978)

Table 1 Soil erodibility factor values for different soil types

K value	Soil
0.05–0.15	Soil high in clay
0.05–0.2	Sandy soil
0.25–0.4	Slit loam soil
< 0.4	High slit soil easily detached

$$LS = \left(\frac{f \times \text{cell size}}{22.13} \right)^{m \times (0.065 + 0.045s + 0.0065s^2)} \quad (8)$$

where LS is the topography factor (dimensionless), f is the flow accumulation expressed as the number of grid cells, m is the constant dependent on the value of gradient [for this study 0.3 was taken from Roy (2009)] and S is the slope (in degrees).

The hydrology analysis tools for DEM in GIS environment are used to estimate flow fill and then flow direction which leads to flow accumulation as follows:

Flow Fill = > FlowDirection = > FlowAccumulation.

Cover Management Factor (C)

When raindrop falls on topsoil, erosion can occur due to the kinetic energy carried by the raindrop. Vegetation cover and other management cover scenarios can act as a buffer for the topsoil by dissipating the raindrop energy before reaching the soil surface. These cover management factors (C) can be calculated as they depend primarily on the vegetation type, stage of growth, management scenario and cover area percentage. Many studies calculate C as a range, with the rule that C with values 0 is well-protected soil, i.e. less susceptible to soil erosion, whereas C is near 1 for bare soil, i.e. more susceptible to soil erosion (Vicente et al. 2007).

As per Wischmeier (1965), for specific C estimation purpose, value of C is calculated as a ratio of soil loss from land with specific vegetation to the soil loss from a fallow land. The value of C can be calculated as follows:

$$C = e^{\left(\frac{-2 \times \text{NDVI}}{1 - \text{NDVI}}\right)} \quad (9)$$

where NDVI is normalized difference vegetation index explained in the following section.

Normalized Difference Vegetation Index (NDVI)

With the use of remote sensing missions and spectral signatures from these missions, many indices have been developed to quantify the vegetation dynamics (Bannari et al. 1995; Xue and Su 2017). These vegetation indices are able for better delineation and grouping of vegetation, barren soil and vegetation growth, based on the spectral reflectance from plants. Of these indices, the most widely used is the normalized difference vegetation index (NDVI). The NDVI is used to identify vegetated areas and their condition, and it remains as one of the most well-known and used indices to detect abundance of vegetation in multispectral remote sensing data (Xue and Su 2017).

Different spectral signatures and bands are used to estimate the NDVI factor. The spectral reflectance difference between near infrared (NIR) and red is used to calculate NDVI (Jensen 2000). The formula can be expressed as (Rouse et al. 1973)

$$\text{NDVI} = \frac{\text{NIR} - \text{Red}}{\text{NIR} + \text{Red}} \quad (10)$$

NDVI values range from -1.0 to 1.0 , where higher values are for green vegetation and low values for other common surface materials. Barren and fallow soil is represented with NDVI values which are closest to 0, and water bodies are represented with negative NDVI values, which makes it easier for classification.

Conservation Practice Factor (P)

The conservation factor (P) quantifies the impact of different water and soil conservation measures on runoff generated and sediment yield (Rahaman et al. 2015). In general, the P factor is closely related to the C factor as they are both meant to reflect the positive impacts of management practices in minimizing soil erosion and surface runoff (Renard et al. 2011). Of the various factors that can impact P factor, land use patterns are notable, as the processes associated with a particular land use type and land cover type can impact the amount of water and sediment yield from a particular landscape. Different land use areas, shapes and patterns can also influence soil erosion. Due to this relationship between activities on land, water and sediment yield rates, land use and land cover (LULC) data are used widely in soil erosion studies. Data to assess LULC change have become easier, due to the use of multispectral and high-resolution spatiotemporal satellite-based remote sensing data acquisition. Depending on type of land use and its vulnerability to soil erosion, ranks are assigned as given in Table 2, as per Wischmeier and Smith (1978).

Table 2 Values of conservation practice (P) factor for different land use classes

Land use class	P values
Dense vegetation	1
Sparse vegetation	0.8
Built-up	1
Water bodies	1
Scrub land	1
Cropland	0.5
Fallow land	0.9
Barren land	1

Land Use and Land Cover (LULC) Change

Many methods exist to construct land use and land cover (LULC) maps from satellite imagery (Chinnasamy and Parikh 2020). Of these, the iso-cluster classification is used to identify cluster patterns in land imagery, from which classifications are made. These classifications may be unsupervised methods (no groundtruthing data available and purely based on cluster trends) or by supervised classification methods (if groundtruthing data exist). Using Google Earth Pro imagery (high-resolution imagery) and government databases, eight different classes were created as a basemap. These classes were then given appropriate P factors from the table (Table 1) provided by USDA handbook (Valor and Caselles 1996).

For the current study, all data and rasters are used to find A (Eq. 1) for the three time periods, i.e. before, after and during the 2018 Kerala floods. In addition, slope and erosion maps are extracted for each of the 14 districts to find sediment yield for three time periods. Resulting soil erosion map is generated, which gave the quantity of soil eroded for the each study period. Sediment yield and area of each district are used to calculate quantity of sediment load for three periods at district level.

Sediment Yield (SY)

Sediment yield (SY) is defined as the rate at which sediment passes a particular point in a drainage basin per unit time and is usually measured in mass removed (i.e. weight of sediment) per unit area per unit time. Mostly, soil erosion is reported as a static rate; however, since soil erosion can be impacted by natural and anthropogenic factors, it would be more logical to report soil erosion rates at particular records in time. Therefore, this aligns with the study aim of identifying rates before, during and after the floods, which would have direct impact on soil erosion rates. Sediment yield depends on: (1) input functions such as soil erosion, mass wasting and dust fallout, (2) intra-basin storage (e.g. deposition and retention of soil in gullies, bunds or valleys and (3) output pathways and mechanisms such as stream sediment load (Meyer and Wischmeier 1969). Therefore, a basin's SY directly determines stream sediment loads within a drainage basin. Sediment yield for a watershed has a direct relationship with average erosion intensity and sediment delivery ratio (Williams 1978)

$$SY = \text{SDR} \times A \quad (11)$$

where A is the total gross erosion computed from USLE.

$$\text{SDR} = 0.627 \times (\text{SLP})^{0.403} \quad (12)$$

where SLP is the percentage slope.

Sediment Load (SL)

Stream sediment load (SL), measured in tonnes per year, refers to the amount of sediment transported by rivers and streams (Evans and Seamon 1997) and is the function of SY and area of the study region

$$SL = SY \times \text{Area of district.} \quad (13)$$

All the aforementioned equations were derived using multi-sensor and diverse data records, which are explained in the following section.

Data Collection

In order to estimate the soil loss from the aforementioned equations, a plethora of data from observation records, survey reports and remote sensing and satellite platforms were used in this study. The following sections describe the data collected, processed and used in this study.

Rainfall Data

In this study, precipitation data and statistics records were procured from the India Meteorological Department (IMD) hydrometeorological services, which is an agency of the Government of India. Customized Rainfall Information System (CRIS) by IMD was used to understand rainfall pattern in the study area. High spatial (0.25×0.25 degree) gridded rainfall dataset is developed by IMD using 6995 observation rain gauge stations in India, by inverse distance weighted (IDW) interpolation method (Pai et al. 2015). Pai et al. (2015), while comparing different methods for interpolation, claimed that this IDW method successfully captured the variations in the Western Ghats (Kerala) and was capable of capturing extreme rainfall events accurately. The study by Pai et al. (2015), which was part of the Government of India's project, claimed that this gridded dataset had correlation coefficient of 0.99, a root mean square difference of 0.11 mm/day and a bias of 0.05 mm/day. Due to this high accuracy, the gridded dataset has been widely used across India and widely cited (more than 358 times). From these data, the average monthly rainfall of Kerala for 5 years (2014–2018) was obtained. All 14 districts in Kerala were plotted on the map, and from this point (i.e. vector data), using kriging interpolation, final rainfall erosivity factor is generated for Kerala.

Digital Soil Map

In the year 1961, the Food and Agriculture Organization (FAO) of the United Nations (UN) and The United Nations Educational, Scientific and Cultural Organization

(UNESCO) decided to develop a Soil Map of the World at a scale of 1:5,000,000. (FAO/UNESCO 1971–1981; Nachtergaele et al. 2010). The map provides for estimates of physical (% sand, % silt, % clay, bulk density) and chemical properties (pH, organic carbon, CEC, base saturation, C/N ratio, CaCO_3 content) in the topsoil and subsoil (FAO 2019).

For the current study, the soil classification of Kerala was obtained from the FAO Digital Soil Map of the World (DSMW), version 3.6, which superseded the Harmonized World Soil Database. Digital Soil Map of World (DSMW) was extracted to Kerala state and analysed. Many attributes and soil properties were extracted from the DSMW. Then, using the attributes containing soil type, *K* field is created in the attribute table using Williams erodibility equation (Eq. 3). The soil data in vector format are then converted into raster image.

Elevation Data

Elevation data are needed to estimate the topography factor used in the soil erosion estimates. Physical toposheets can be used; however, digital elevation models (DEMs) have been widely used for better accuracy and spatial resolutions. One such widely used DEM, the Shuttle Radar Topography Mission (SRTM) DEM (with a 90-m resolution), was used to find topography factor in the current study. The SRTM digital elevation data are produced by National Aeronautics and Space Administration (NASA), USA. The global availability (almost 80% of the Earth surface) of SRTM data provides baseline information for many types of the worldwide research. The DEM for the study area was made from SRTM's 90-m DEM version 4, provided in mosaic 5×5 degree tiles.

Satellite Imagery

In order to estimate various indices, in the current study, there was a need to procure satellite imagery for Kerala state. For the current study, remote sensing imagery from the United States's Landsat-8 satellite, which was launched in February 2013, was used. The Landsat-8 Payload consists of two instruments—the operational land imager (OLI) and the thermal infrared sensor (TIRS). These two sensors provide seasonal coverage of the global landmass at a spatial resolution of 30 metres (visible, NIR, SWIR), 100 metres (thermal) and 15 metres (panchromatic) (NASA 2019). For analysis part of the current study, Landsat 8 imagery data were acquired from August 2018 to August 2019 from the USGS website (www.earthexplorer.usgs.gov). It is to be noted that all the other satellite products were resampled to 30-by-30-m grids to be consistent with the Landsat 8 imagery.

Results and Discussion

Rainfall Erosivity Factor (*R*)

The district-level rainfall observation data indicated spatial variations across Kerala, with the districts near the Western Ghats getting more rainfall, of which the highest rainfall was recorded in the district of Idukki. The *R* factor ranged from 133 to 179, with Idukki district having the highest value, while Thiruvananthapuram had the lowest. The average *R* value was 162 MJ mm ha⁻¹ h⁻¹ year⁻¹. The results indicate spatial variations in *R*, across Kerala (Fig. 3). This was mostly due to the spatiotemporal variations in rainfall pattern across the state and the orographic nature of the rainfall, due to the presence of the Western Ghats.

Soil Erodibility Factor (*K*)

As per Wischmeier and Smith (1978), based on soil texture and spoil type, the different *K* factor can be classified (Table 2), with zero indicating soils with least vulnerability to erosion and greater than 0.4 indicating soils highly vulnerable to soil erosion. The results based on soil maps indicate the *K* factor as shown in Fig. 4, wherein regions along the Western Ghats have higher vulnerability to soil erosion. The range of *K* values was from 0.10 to 0.17, with the highest values of 0.17 recorded in Alappuzha district, while Malappuram district had the least value of 0.10. The Government of Kerala's report (GoK 2018) also indicated that due to undulating topography of the Western Ghats, there is the presence of high erosion class soils (severe to very severe) in Kerala.

Topography Factor (*LS*)

Results indicate that the value of “*LS*” increases with an increase in hill slope length and steepness, since runoff accumulates and accelerates in the down-slope direction from higher potential to lower. Therefore, steeper slopes produce higher surface flow velocities, and longer slopes accumulate runoff from larger areas, also resulting in higher flow velocities. Results from the DEM and remote sensing data-based analysis indicate that the *LS* factor ranged from 0 to 19 with an average value of 3.66, and Palakkad district has the highest value of 19.

Cover Management Factor (*C*)

Vegetation cover protects the soil by dissipating the rain-drop energy before reaching soil surface (Roy 2009). Since soil erosion is highly sensitive to vegetation cover, the *C*

factor is based on NDVI, which is derived from Landsat satellite imagery. Lower value of *C* factor indicates that the land possesses good vegetative cover and higher value indicates barren/open land. Results for Kerala in 2018 indicate that the average *C* factor was 0.46, 0.75 and 0.43 in January 2018, August 2018 and January 2019, respectively (Fig. 5). This indicates that due to the floods, there is a 63% increase in *C* factor, indicating more land converted to near barren condition, leading to a scenario more susceptible to soil erosion (Vicente et al. 2007). Most of the increase in *C* occurred in the districts of Idukki, Kottayam, Ernakulam and Thrissur, which, according to government records, were the most impacted regions during the 2018 floods (Sankar 2018).

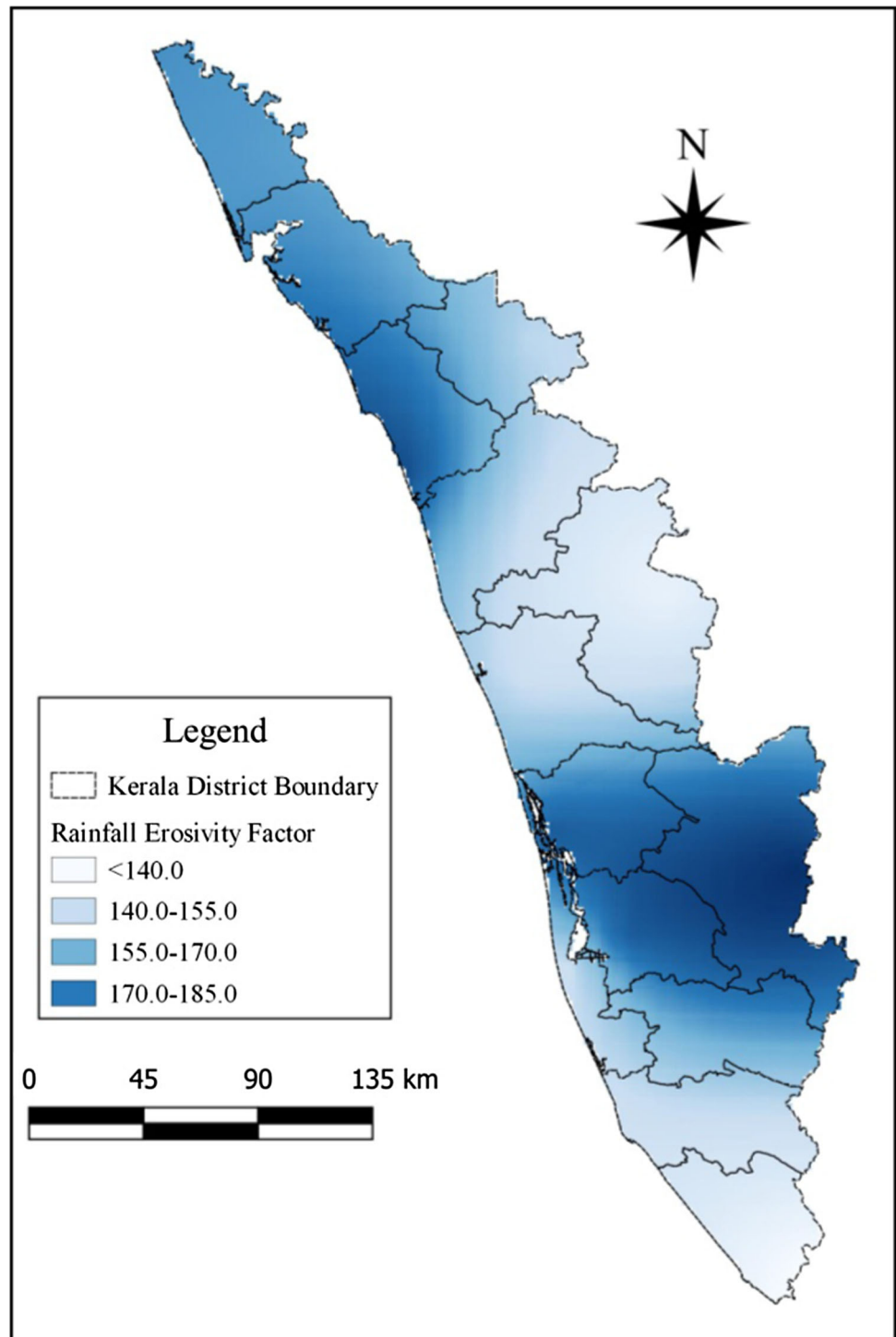
Conservation Practice Factor (*P*)

The interpretation of the *P* values is given in Table 1. Results indicate that the average *P* factor was 0.8, 0.89 and 0.8 in January 2018, August 2018 and January 2019, respectively (Fig. 6). This indicates that during the floods, there was a slight increase in *P*, indicating flood inundation. In particular, districts of Idukki, Kottayam, Ernakulam and Thrissur noticed an increase of *P* value from 0.5 to 1, which indicates a conversion from cropland to water bodies and barren, i.e. inundated with crops and soil washed away. Even post-floods, the damage still persists, as remote sensing analysis showed higher values of *C*. Results from another study by Vishnu et al. (2019) also show an increase in water cover by 90% in key flood inundated districts of Idukki and Alappuzha.

Average Soil Loss (*A*)

After completing the data input procedure (Fig. 2) and estimation of *R*, *K*, *C*, *P* and *LS* maps as data layers, they were multiplied in QGIS platform as per Eq. (1) to estimate the erosion risk maps. Results for Kerala 2018 floods indicate that the average soil erosion was 56.23 metric tons ha⁻¹ year⁻¹, for August 2018, which were higher than that of pre-flood and post-flood values of January 2018 (31.79 metric tons ha⁻¹ year⁻¹) and January 2019 (30.01 metric tons ha⁻¹ year⁻¹), respectively (Fig. 7). Results indicate an 80% increase in average soil erosion rates due to the Kerala floods, which also are concurrent with the government study that was conducted post-2018 floods. Results of a study on the status of soil health after the 2018 floods, conducted by the Government of Kerala (GoK 2018), indicated that approximately 71% of the total area in Kerala was eroded due to the 2018 floods, while that in Idukki district 94% area was eroded. Such high area eroded will result in high increase in sediment loads. However, the report was not able to quantify the actual volume in

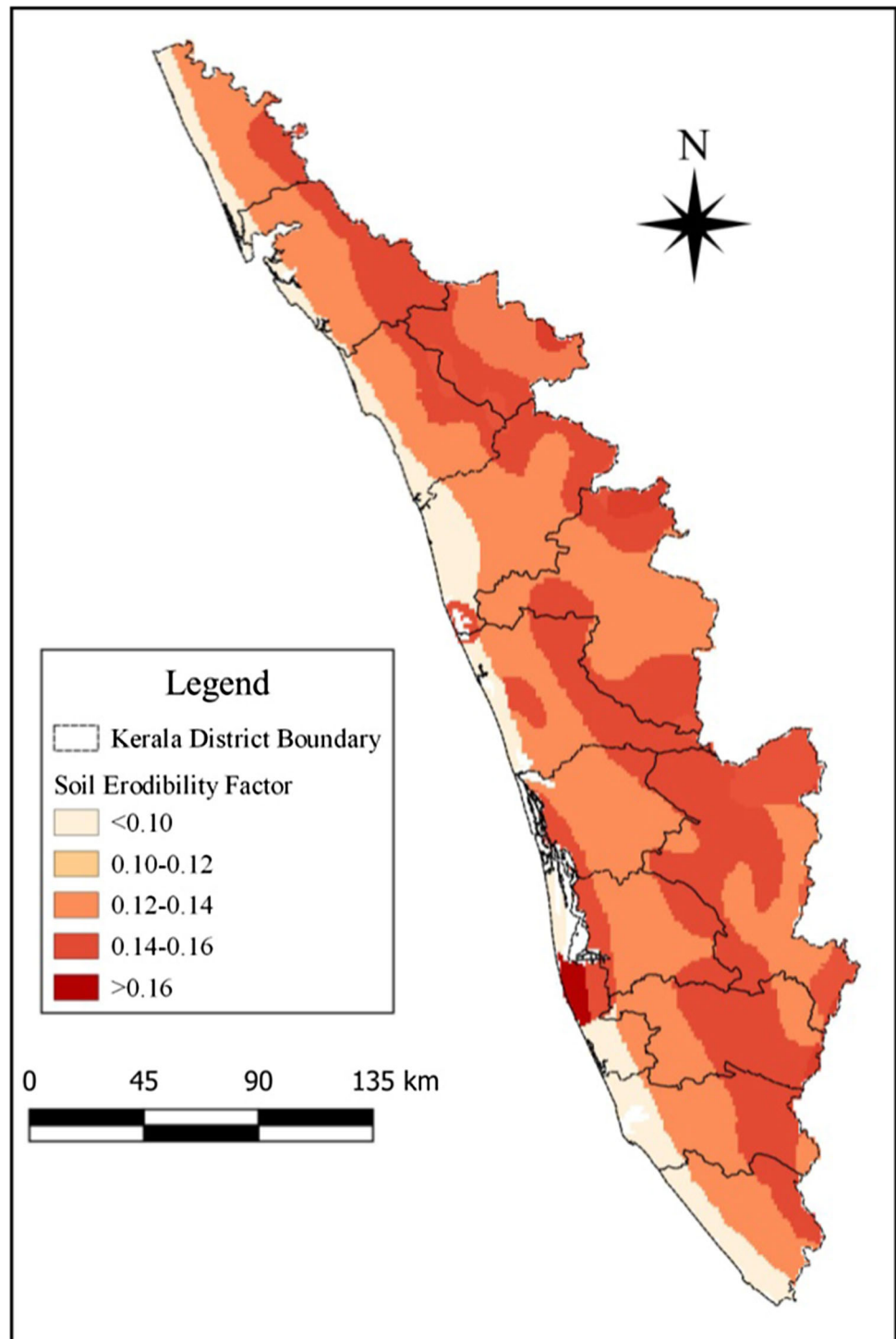
Fig. 3 Spatial variations in Rainfall erosivity (R) for Kerala during 2018 floods



sediment loss due to the high erosion rates. Nevertheless, the fact that Kerala experienced 53% above normal rainfall and that six out of seven main reservoirs were filled more than 90% of their full capacity (Mishra et al. 2018), the high volume of rainfall and associated discharge could have resulted in high topsoil removal and transportation of sediment.

The comparison of A between districts shows indications of spatiotemporal variations of the flood damage and also the ability of certain districts, due to protective land cover and management type, in reducing soil erosion. While all districts showed an increase in A , some districts had unsustainable losses, while others had less damage. The district of Idukki faced the highest soil erosion

Fig. 4 Spatial variations in Soil erodibility (K) across Kerala in 2018



between pre- and post-floods, with an increase of 220% (Fig. 7). This was followed by Ernakulam with 95%. It is to be noted that these two districts have the Western Ghats bordering them, so high rainfall, and also have unprecedented growth in urbanization. For example, Mani (2012), in a study conducted in Idukki, shows that the total forest cover reduced by 4%, the plantations increased by 2% and

the urban areas increased by 40%. Another study by Ramachandran and Reddy (2017) indicated that the forest cover in Idukki district declined by 44% from 1925 to 2012. In the same period, the study notes that the plantations increased by 8% and settlements increased by 400%. All these changes to land cover, especially in an undulating topography with high rainfall, necessitate a scientifically

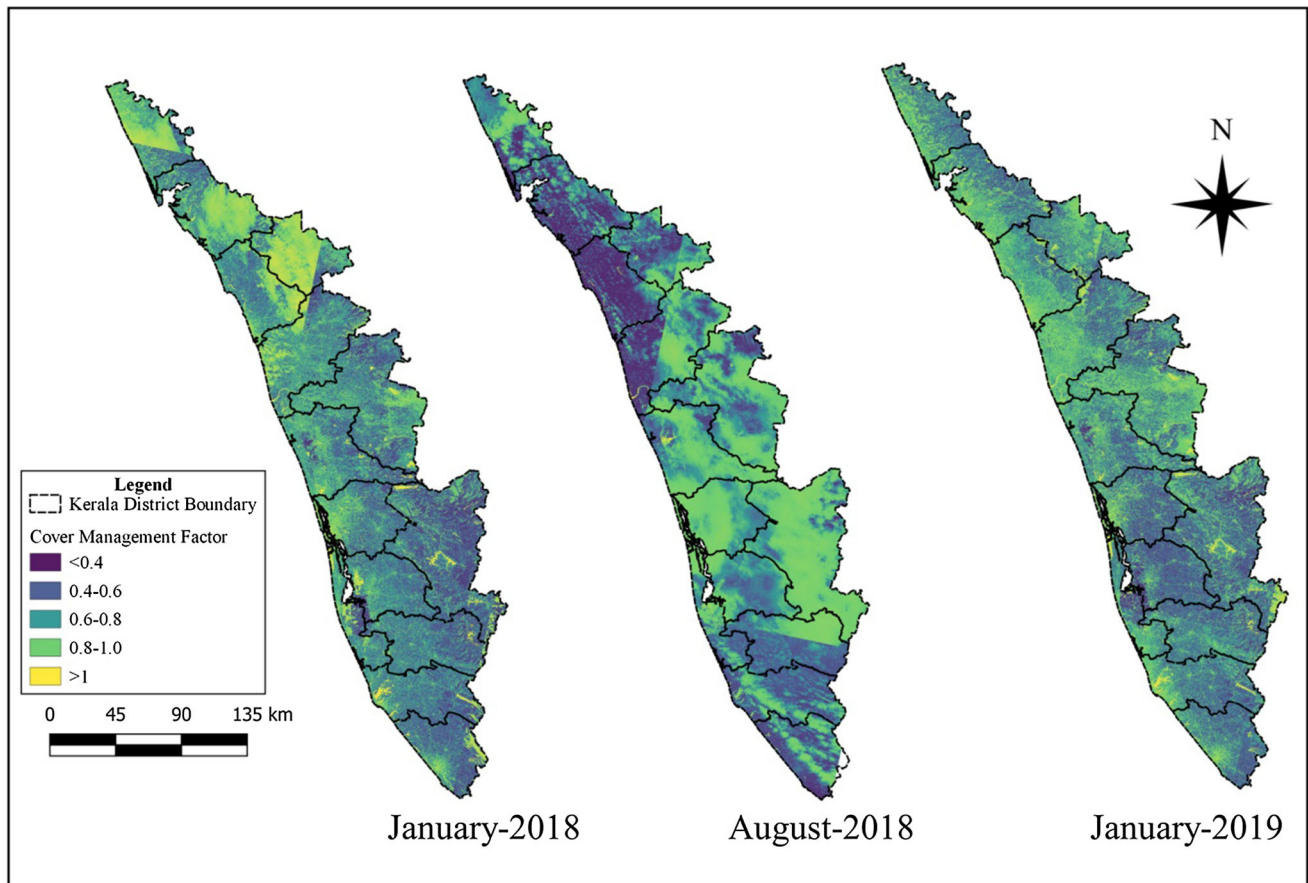


Fig. 5 Spatial variations in Cover management (C) factor for Kerala during 2018 floods

validated management plan to reduce induced soil erosion, floods and landslides. However, this is not the current case in Kerala, where recurrent floods occur frequently. This has caused devastating effects to the soil ecosystem and triggered major landslides, post-peak floods.

The damages due to the soil erosion are still witnessed in Kerala, with loss of crop productivity, loss of tree cover and decrease in groundwater recharge. For example, the government data from the Centre for Water Resources Development and Management (CWRDM) in Kozhikode indicate that the groundwater levels decreased across Kerala, after 2018 floods, especially in the most inundated districts. This is because that the seasonal rainfall, which should have been spread across months, occurred with a couple of days. This leads to less time for the water to infiltrate and recharge into the groundwater aquifers (Varua et al. 2016; Jadeja et al. 2018; Chinnasamy et al. 2018), and most importantly erosion of top soil reduced groundwater recharge, as without top soil the rainfall water cannot be harvested, percolated and recharged into the aquifers. As a result, the CWRDM noted a fall in groundwater level of 1–4 m across Kerala. In addition, the CWRDM officially noted that the floods could also be increased due to an

increase in conversion of land cover from natural vegetation (e.g. forests, grasslands) to commercial land use (e.g. settlements, unplanned roads, plantations and factories).

Sediment Yield (SY) and Sediment Load (SL)

The sediment yield rates results show that average values during the floods were 47% higher than those before the floods. The Kerala 2018 flood records also indicated Idukki district to be the most severely hit district, which was reflected in the current study remote sensing database and by government records (Sankar 2018). Similarly, the sediment load rates were the highest during the flood period, when compared against the pre- and post-floods. District-wise sediment load results indicate that the highest was recorded in Idukki district, with the least recorded in Alappuzha. While the extremes were similar to sediment yield rates, more variation was noted in the other districts for sediment load rates. The soil erosion rates were high also in the flood months, when compared to pre- and post-floods. Idukki was the district with the highest soil erosion rates, followed by Ernakulam in second and Kozhikode the least. Compared to sediment yield and loads, less variation

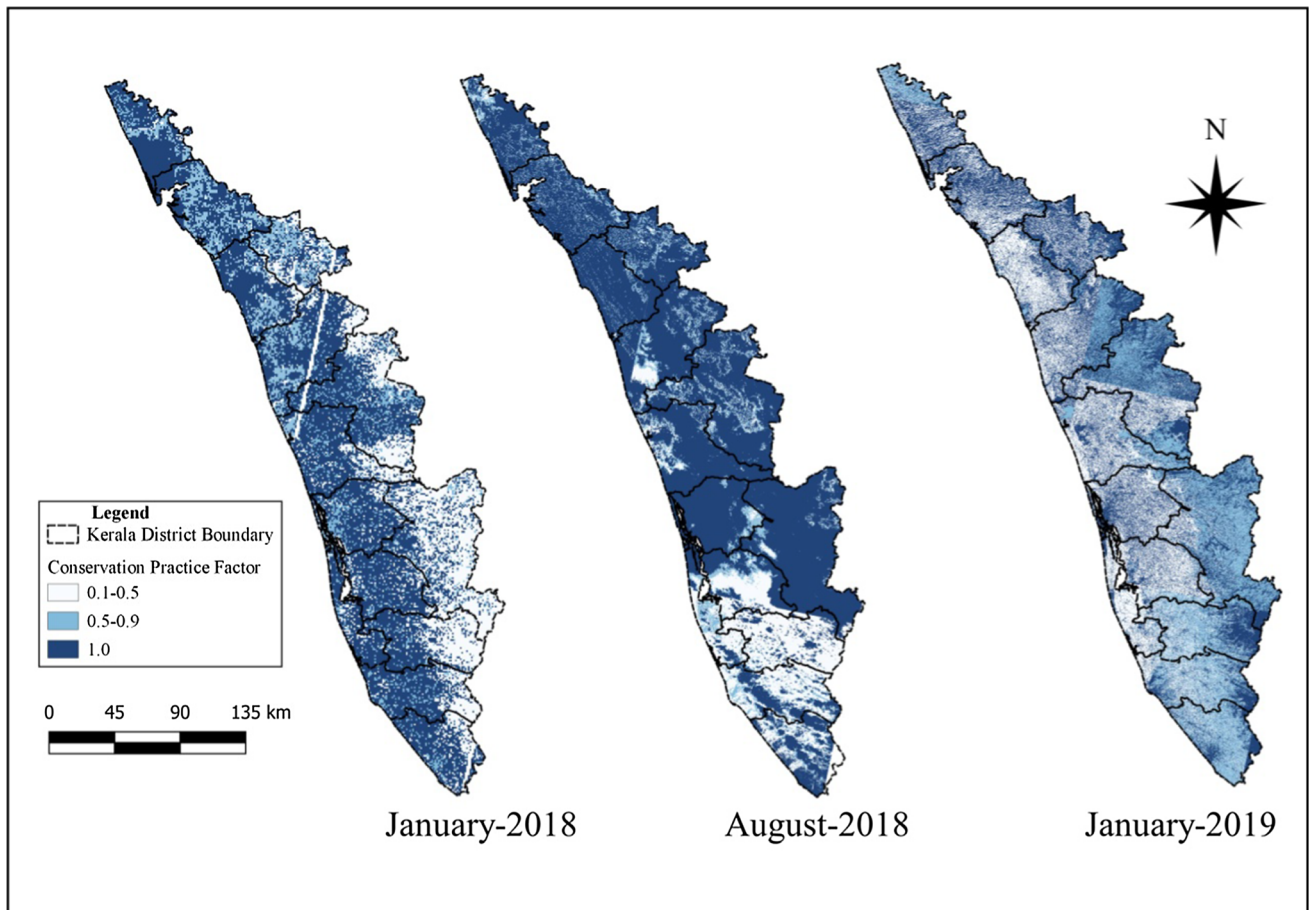
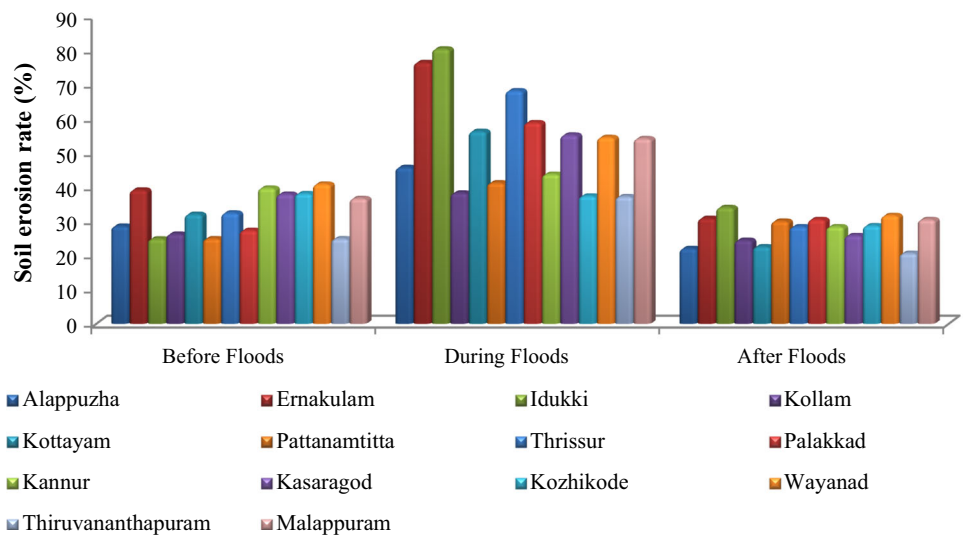


Fig. 6 Spatial variations in Conservation practice (*P*) factor for Kerala during 2018 floods

Fig. 7 Soil erosion (%) rate comparison between before floods (January 2018), during floods (August 2018) and after floods (January 2019) at district level in Kerala



was noted across the districts. The post-flood assessment report of the Government of Kerala (Gok 2018) also indicated high soil erosion leading to high sediment yield and load due to the Kerala floods. The report also noted

that there were many incidences of landslides and soil erosion in regions with more than 33% slope.

Since the study was conducted using remote sensing data, there were some limitations and challenges. Of these, Cloud-free data are important for remote sensing estimates

of various parameters that went into this study. However, in many instances, cloud-free (i.e. zero % cloud cover) data were absent due to the desired specific time interval, study area and season (monsoon time when cloud cover is naturally high). Under these conditions, the study could only use the available open access data, which had some percentage of cloud cover. Nevertheless, in order to reduce the associated errors, satellite images with 20% or more cloud cover were not considered. The current study used the FAO soil database as it has been used successfully by various past studies in Kerala. However, the FAO database is at a coarser resolution (~ 8 km resolution) compared to the national soil database (~ 5 km resolution), and therefore, future studies could investigate the differences between the two datasets. Similarly, the use of high-resolution data could improve the confidence in the results; however, such an exercise would incur high data costs and also high computational power, which is needed to process high-resolution imagery. Since the study was conducted on open-access data, the confidence on the results is based on the quality of the data. In addition, Alewell et al. (2019), in a review of USLE limitations, indicated that uncertainty in the USLE soil erosion estimates is difficult to quantify as the soil erosion measurement process is itself complex with uncertainties. Therefore, without good physical measurements of soil erosion, it is difficult to validate the uncertainties in the results. However, Alewell et al. (2019) concluded that when compared against the widely used complex models, USLE had the lower uncertainty errors due to the simplified set-up of the model. The review also concluded that future research should focus on improving methodologies to reduce uncertainty errors in measurement data, which can be used to reduce uncertainty errors in USLE modelling approach.

Summary and Conclusion

The extreme rainfall in Kerala during 2018 August was one of the worst floods in the past century. Kerala witnessed high damages to infrastructure and displacement of people. While most reports focussed on economic losses, this study focussed on soil erosion and associated damages and triggers to landslides. There are challenges and limitations in securing observation data for estimating pre- and post-flood soil erosion to identify soil erosion due to floods. Therefore, in this study, a conceptual modelling framework based on indicators driven by remote sensing data and the USLE model were used to map the average soil loss in Kerala due to the 2018 floods. The current study started with analysing rainfall and associated factors that lead to soil erosion as per the USLE formula. The current study found that the soil erosion rates increased

rapidly by 80% due to the Kerala 2018 floods. This high increase in soil erosion is not sustainable, given that shorter rainfall events can now easily erode more soil and trigger landslides. The high increase in soil erosion rate can be attributed to severity of rainfall, change in land cover due to washing away by the flood event and the associated loss of vegetation and tree cover. As a result, the top soil could have been eroded as noticed from our post-flood results, leading to a higher soil erosion rate. The districts of Idukki and Ernakulam had the highest increase in soil erosion rates of 220 and 93%, respectively. Therefore, soil conservation practices should be more concentrated in these key districts, to avoid further soil loss. In addition, since these districts are along the Western Ghats, there are many stream and rivers that originate from these areas, wherein high soil erosion rates can lead to downstream erosion and further increase in soil sediment loading. In addition, these high erosion rates were not only due to the concentration of rainfall events, but also due to the unsustainable conversion of land from natural to settlements. Therefore, in order to prepare for future climate change extremes, there is a need to understand climatic variations and also how the land is sustainably managed to buffer climate variations. This can lead to reducing climate change impacts and associated damages to infrastructure and the ecosystem.

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