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Mapping hotspots and coldspots of soil erosion along the watershed running into Tomini Bay

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Abstract: The extensive use of geospatial information technology in predicting erosion rates has been considerable. However, previous studies have not considered aspects of landscape connectivity based on spatial dependence in mapping erosion-prone zones. This research eliminates this weakness by using the GEE-R-GIS framework. Specifically, this experiment aims to 1) assess spatiotemporal variations in soil erosion rates in 2000 and 2020 along watersheds in the Tomini Bay region, Indonesia, 2) map soil erosion hotspots and coldspots using spatial autocorrelation for rehabilitation priority areas watershed. The findings show that 1) the spatiotemporal of soil erosion in 2000 and 2020 is primarily consistent in the central part of Central Sulawesi Province; others are spread in the western mountainous area of the study region, stretching from north to south; 2) there is a difference in the area of hotspot and coldspot between 2000 and 2020. Hotspots are mostly spatially aggregated in the southern and western regions of the research area, while coldspots are concentrated in the northern region. In 2000, hotspots covered 11.13% of the study area, with a significance class of <0.05. Coldspots occupied 28.42% of the study region with a significance class of <0.05. In 2020, the area of hotspots decreased to 9.98%, and the soil erosion coldspots increased slightly to 28.68%. Hotspots and coldspots information can be treated as a reference for spatial priority in watershed environmental rehabilitation planning.

Keywords: GEE-R-GIS framework, RUSLE model, spatial autocorrelation, soil erosion, Tomini Bay

INTRODUCTION

Soil erosion has been stated as the main cause of increasing land degradation (Borrelli *et al.*, 2020), and affects social and economic aspects in worldwide (Sartori *et al.*, 2024). In recent decades, the rate of soil erosion has exceeded the tolerance limit, causing a decrease in soil stability and productivity (Loba *et al.*, 2021). In addition, the magnitude of soil erosion has exceeded the natural soil formation process (Wuepper, Borrelli and Finger, 2019). More specifically in tropical areas, with favourable climate conditions and high rainfall, soil erosion will occur more rapidly (Browning and Sawyer, 2021). Eroded soil becomes susceptible to water pollution (Wang *et al.*, 2023) and a decrease in the soil's capacity to store water (Tirkey, Ghosh and Pandey, 2016). The negative impacts caused are reduced crop yields (Mirzabaev, Strokov and Krasilnikov, 2023) which can threaten food availability (Deresse, Ereso and Geremu, 2023). Therefore, understanding the spatiotemporal variations of soil erosion is critical to prevent land degradation and support priority plans to restore degraded watersheds.

The Indonesian government has established a watershed management plan for land and water conservation. Government Regulation Number 37 of 2012 regulates this management plan. This regulation is in line with the strategies framework established by the United Nations Convention to Combat Desertification (UNCCD) to tackle land degradation (UNCCD, 2018). Through the Ministry of Environment and Forestry, the government carries out intervention efforts to restore watershed land conditions every year. This restoration activity certainly requires enormous material resources and budget allocations. The results of the 2018 mapping showed that there were 2,149 watersheds with the status of restored carrying capacity or 56.47%

of the watershed area in Indonesia (KLHK, 2022). The soil erosion index is one of the indicators used to measure carrying capacity and determine the status of watershed recovery. Limited material resources and the large area the watershed covers are challenges in determining priority locations. Therefore, in planning conservation actions, it is vital to involve a spatial priority procedure to support targeted decision-making (Tallis *et al.*, 2021; Pusparini *et al.*, 2023). Determining the order of the watershed based on the vulnerability to soil erosion is vital for deciding soil and water conservation priorities (Godif and Manjunatha, 2022).

Various soil erosion models have been generated and implemented by many researchers worldwide. The Revised Universal Soil Loss Equation (RUSLE), which is a modification of the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978; Renard *et al.*, 1991) is the most popular model in the world. The Global Applications of Soil Erosion Modelling Tracker (GASEMT) database proves that the RUSLE model is the most widely utilised by researchers worldwide to simulate soil erosion rates (Borrelli *et al.*, 2021). The RUSLE model has progressed and can be adapted to computer programs (Elnashar *et al.*, 2021). The development of geospatial information technology in remote sensing makes this model easy to apply by utilising satellite imagery data. Based on a search of scientific literature, the use of geospatial technology tools to predict the rate of soil erosion can be grouped into two major categories. First, soil erosion rate prediction using desktop software, such as QGIS and ArcGIS, as demonstrated in the research by Duressa *et al.* (2024), Halder *et al.* (2024), Nahib *et al.* (2024), Olii *et al.* (2023). This approach allows spatial data analysis with various spatial analysis tools owned by the device. Implementing the RUSLE model in this approach faces challenges related to data limitations from several RUSLE parameters. Other limitations include small area coverage and difficulty adapting methods when using local data. The second group uses a modern cloud computing platform, Google Earth Engine (GEE). Several studies utilise this device are Elnashar *et al.* (2021), Fentaw and Abegaz, (2024), Islam *et al.* (2022), Sud *et al.* (2024). The latter device is an alternative platform to address the challenges of fast and flexible spatial data and analysis needs (Gorelick *et al.*, 2017).

However, to our knowledge, previous studies have yet to consider the landscape relationship factor (spatial dependence) in identifying erosion hotspot areas. Determination of hotspot zones still refers to the level of soil erosion vulnerability obtained from the literature, for example, recent studies by Ambarwulan *et al.* (2021), Fentaw and Abegaz, (2024), Nahib *et al.* (2024). In identifying soil erosion hotspot areas, elements of landscape relationships based on spatial dependence must be included in the analysis (Li *et al.*, 2017). Therefore, our research contributes to identification of soil erosion hotspots and coldspots areas using the GEE-R-GIS framework. We rely on the GEE platform to collect multi-source satellite imagery data, perform image processing, and estimate soil erosion rates.

Furthermore, researchers explore the ability of the R tool to identify soil erosion hotspots and coldspots areas. The concept of hotspots and cold spots was adapted from several previous studies such as in Cunha *et al.* (2023), Pal *et al.* (2023), and Liu *et al.* (2024). In the context of soil erosion, a hotspot refers to a location that has high erosion values and is surrounded by other locations with high erosion values. On the other hand, a cold spot is a representation of a location that has low erosion values and is surrounded by other locations with low erosion values. Hotspots and coldspots information is relevant for planning watershed restoration actions (Li *et al.*, 2017). Thus, the purposes of this investigation are to 1) map and estimate the level of soil erosion spatially and temporally from 2000 to 2020 along the Tomini Bay watershed, Indonesia, 2) identify hotspot and coldspot areas using spatial autocorrelation for priority areas for watershed rehabilitation.

STUDY AREA AND METHODS

THE STUDY AREA

The study was carried out along a watershed that flows from the mountains and empties into the waters of Tomini Bay. It covers an area of 32,150 km^2, as shown in Figure 1. The research area is in Sulawesi, Indonesia, and covers most provinces, namely Gorontalo and Central Sulawesi. Geographically, the area stretches between a longitude of 119°53'E–123° 43'E and a latitude of 2°18'S–0°59'N. This region is in the tropical Af climate zone based on the Köppen–Geiger climate classification (Beck *et al.*, 2018). The average temperature in Center Sulawesi is 27.2°C (BPS, 2023b), and Gorontalo is 28.7°C (BPS, 2023a). The Tomini Bay area refers to the boundaries set out in the Zoning Plan document for the Tomini Bay inter-region area as mentioned in Peraturan (2022). This area has high biodiversity and ecological value, as it is home to several endemic animals of Sulawesi (Supriatna *et al.*, 2020). The topography along the shores of Tomini Bay is primarily a coastal area dominated by lowlands with an altitude of 0 to 200 m a.s.l. Hilly areas with elevations around 200–1,000 m a.s.l. are scattered in the central region and away from the coastline. The mountainous region is spread across the north and south sides of Tomini Bay and in the study area's southwest, northwest, and northeastern parts.

DATA SOURCE AND TYPES

This study uses data from various sources and institutions that can be easily accessed, as shown in Table 1. This dataset includes watershed boundary data used to determine research boundaries. Other environmental data, such as precipitation, soil texture, digital elevation model (DEM), normalised difference vegetation index (*NDVI*), and land use/land cover (LULC) are used as inputs to calculate soil erosion.

RESEARCH METHODS

The GEE-R-GIS framework is a combination of free and open-source geospatial software. The GEE provides facilities for scientific research and has a dataset of remote sensing data from various sources (Tamiminia *et al.*, 2020). Researchers can access this data set quickly, at no cost, and adapt to research needs. All environmental data can be obtained from the catalogue and entered into the GEE interface to estimate the average annual soil erosion rate. Collecting, processing, analysing data, and visualising results can be carried out simultaneously. This approach can quickly create spatial maps, extract statistical information, and be adapted for similar case studies.

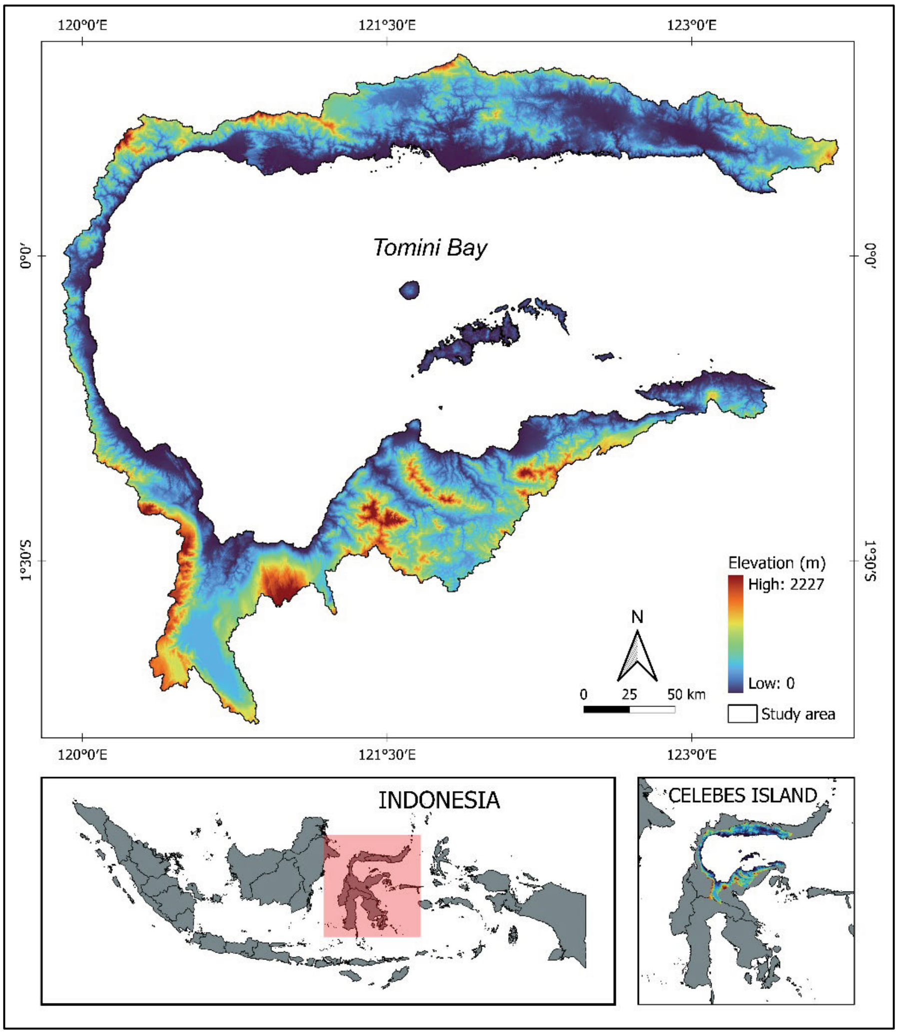

Fig. 1. Study area map with elevation; source: own elaboration

Table 1. The datasets source

Data	Provider	Resolution	References
Watershed boundary	Ministry of Environment and Forestry of Indonesia	1:50000	KLHK (2024)
Precipitation	University of California Santa Barbara, Climate Hazards Group	5,566 m	Funk *et al.* (2015)
Soil	EnvirometriX Ltd.	250 m	Hengl (2018)
DEM	NASA Jet Propulsion Laboratory	30 m	Farr *et al.* (2007)
NDVI	USGS	30 m	USGS (2024)
LULC	University of Maryland	30 m	Potapov *et al.* (2022)

Explanations: DEM = digital elevation model, *NDVI* = normalised difference vegetation index, LULC = land use/land cover.
Source: own elaboration.

Data collection and processing

The preparation and processing stage starts with entering watershed boundary data as a basis for determining the coverage of the research region. The boundary data is in vector format and is the basis for processing other environmental data. Processing activities are implemented in an interface as a code editor that allows users to develop environmental data processing algorithms. Similar techniques were also applied in research by Elnashar *et al.* (2021) and Sud *et al.* (2024).

Soil erosion mapping

The RUSLE empirical model requires six environmental data components as factors that influence the rate of soil erosion (Renard *et al.*, 1991). These components are rainfall erosivity, soil erodibility, slope length, slope steepness, plant management, and supporting conservation practices. The rainfall erosivity factor (*R*) is determined based on annual rainfall data. Soil erodibility (*K*) is estimated, considering the soil texture data of the study area. Length and steepness (*LS*), crop management (*C*), and supporting conservation practices (P) were calculated using DEM and LULC data, respectively. All this data is available in raster format with different scales. Furthermore, the erosion rate was calculated using the following formula:

$$A = R \cdot K \cdot LS \cdot C \cdot P \tag{1}$$

where: A = the average annual soil loss per unit area (Mg·ha^{-1}·y^{-1}), R = rainfall erosivity factor (MJ·mm·ha^{-1}·h^{-1}·year^{-1}), K = soil erodibility (Mg·h·MJ^{-1}·mm^{-1}), LS = length and steepness (–), C = crop management (–), and P = supporting conservation practices (–).

1. Rainfall erosivity factor (R)
   Determination of the erosivity factor of rainfall using the formula established by Babu, Dhyani and Kumar (2004) and used by Jain and Das (2010).

$$R = 81.5 + 0.38P \tag{2}$$

   where: P = the annual precipitation (in mm), with 340–3,500 mm values. Annual precipitation data for 2000 and 2020 were derived from the Climate Hazards Center InfraRed Precipitation with Station data (CHIRPS).
2. Soil erodibility factor (K)
   The K factor is related to the degree of soil sensitivity to erosion, measured based on soil characteristics such as texture. Determining the K value is based on research (Bouguerra *et al.*, 2017). Soil texture data for this study was obtained from the OpenLandMap Soil Texture Class (USDA System) through the GEE catalogue.
3. Length and steepness factor (LS)
   The LS factor is determined through the equation developed by (David, 1988), as follows:

$$LS = 0.1 + 0.21S^{\frac{4}{3}} \tag{3}$$

   where: S = the slope steepness (in percent), calculated from DEM data derived from the Shuttle Radar Topography Mission (SRTM) V3 product data.
4. Cover management factor (C)
   Soil loss is closely related to vegetation conditions. This study adopted the C factor calculation formula by Durigon *et al.* (2014) developed by utilising *NDVI* data from 2000 and 2020. Almagro *et al.* (2019) has also proven this approach. According to Colman *et al.* (2018), this formula is suitable for application to watersheds in tropical regions.

$$C = \frac{-NDVI + 1}{2} \tag{4}$$

5. Control practices factor (P)
   This factor represents soil conservation procedures such as planting in the form of terracing, contouring, and contour strips. In this study, the P value refers to research by David (1988) and Benavidez *et al.* (2018) based on LULC data and the slope of the research location.

Spatial autocorrelation analysis

This analysis focuses on the soil erosion variables in 2000 and 2020, which are the estimated quantity of soil loss in the study location. Spatial autocorrelation is a spatial analysis tool used to understand the spatial relationship between observed variables and themselves in space (Haining, 2001). The Global Moran's I statistics method (Moran, 1950) was chosen to assess spatial autocorrelation across the study area. This approach is the most commonly used indicator to measure spatial autocorrelation (Lin, 2023). The degree of spatial autocorrelation is visualised in Moran scatter plots. However, the Global Moran's I autocorrelation test did not indicate the existence of high or low soil erosion groups.

Furthermore, the local indicators of spatial association (LISA) statistic (Anselin, 1995) was chosen to analyse the size of significant spatial patterns of soil erosion variables at the local level. This analysis can detect the presence of hotspots and cold spots from high and low clusters of observed variable values (Gedamu, Plank-Wiedenbeck and Wodajo, 2024). The results are visualised as a local Moran cluster map (Dong *et al.*, 2023). This analysis was carried out using open-source R software through the rgeoda package.

RESULTS

SPATIOTEMPORAL VARIATIONS OF SOIL EROSION OF 2000 AND 2020

The estimated average soil erosion rate in the study area in 2000 was 56.06 Mg·ha^{-1}·y^{-1} and in 2020, it was 57.68 Mg·ha^{-1}·y^{-1}. Spatial and temporal variations in soil erosion in 2000 and 2020 are illustrated in Figure 2. The spatial variation of severe soil erosion in 2000 and 2020 was consistent primarily in the central part of the study area. Administratively, this place is the domain

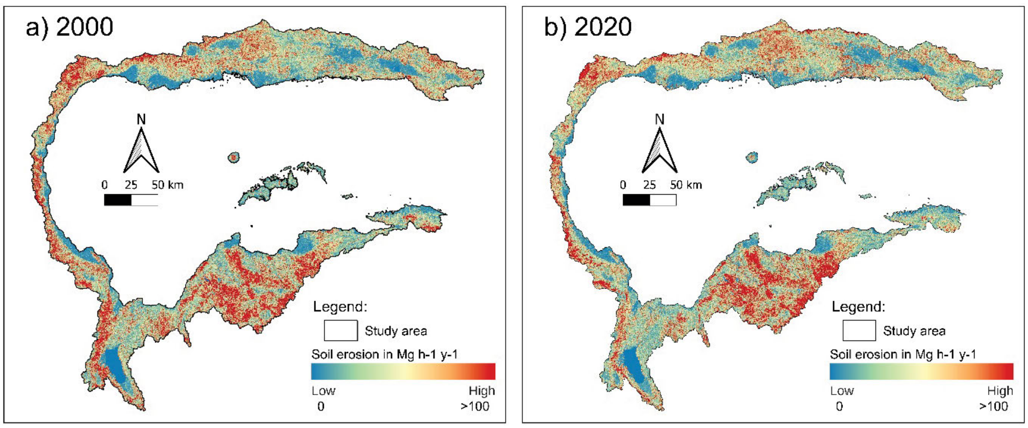

Fig. 2. Spatial variation in soil erosion intensity in the study area in: a) 2000, b) 2020; source: own study

of Central Sulawesi province. Some others are spread across several mountainous regions of the western part of the study area that stretches from north to south.

HOTSPOTS AND COLDSPOTS OF SOIL EROSION IN 2000 VS 2020

The results of the Moran's I Global test experiment for soil erosion data in 2000 and 2020 indicate a high level of spatial connectivity in the study area, as indicated by the positive Moran's I value (Tab. 2). The Moran's Global index for 2000 and 2020 is similar, at 0.58. This figure indicates a consistent positive spatial autocorrelation for both observation periods. The same thing is also shown in the Moran scatterplot (Fig. 3) with a positive slope line. The x-axis shows the observed variable, soil erosion, while the y-axis shows the spatial lag variable. Most observation points appear in the first quadrant (H-H), and a few are scattered in other quadrants (Fig. 3). This means that areas with high degrees of soil erosion tend to be adjacent to other areas with high erosion values, and vice versa for regions with low levels of erosion.

Table 2. Global Moran's I statistic of soil erosion

Year	Moran's I	*z*-score	*p*-value
2000	0.58	199.97	0.00
2020	0.58	199.77	0.00

Source: own study.

Based on the results of the Local Moran statistic calculation, the distribution of spatial relationships of soil erosion consists of four categories, such as high-high agglomeration (H-H), low-low agglomeration (L-L), high-low agglomeration (H-L), low-high agglomeration (L-H), as shown in Figure 4. Each category is symbolised by a different colour, namely H-H (red), L-L (blue), H-L (pink), and L-H (light blue). The H-H class represents the soil erosion hotspot zone and L-L as the soil erosion coldspot zone. In general, the concentration of hotspots and coldspots, in 2000 and 2020, appears to remain consistent in several places. The H-L and L-H categories only appear in the form of spots with small sizes and evenly distributed in the study area. The hotspot zone is spread in the western and southern parts of the study area, while the coldspot zone is concentrated in the northern part of the study area. Based on the results of the comparison of the two years of observation, the spatial pattern of the hotspot and coldspot zones has changed. Clusters of hotspot and coldspot changes are shown with yellow boxes in Figure 4. In 2000, hotspot areas covered 11.13% of the study area, while coldspot zones occupied an area of 28.42% of the study area. In 2020, hotspot areas decreased in area to 9.98%, and areas with soil erosion coldspots increased slightly in area to 28.68%.

DISCUSSION

This study uses a different strategy by implementing the GEE-R-GIS framework to investigate the spatiotemporal variations of soil erosion along the watershed contributing to the Tomini Bay area.

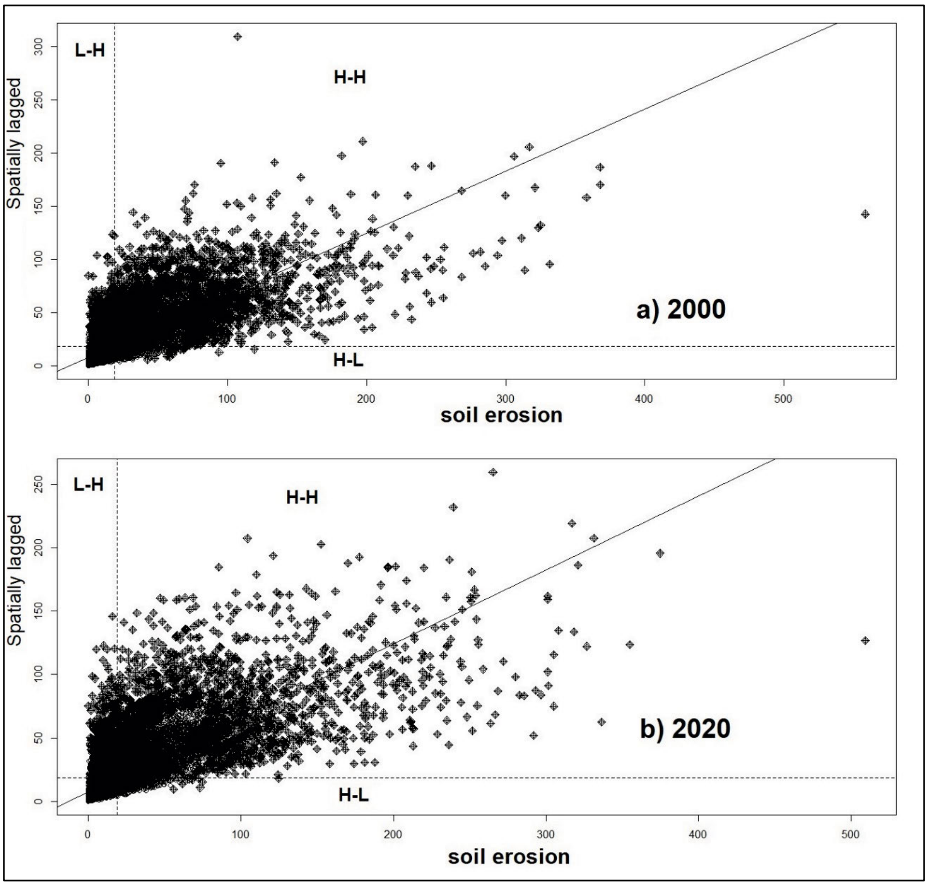

Fig. 3. Moran scatterplot for soil erosion in: a) 2000, b) 2020; H = high, L = low; source: own study

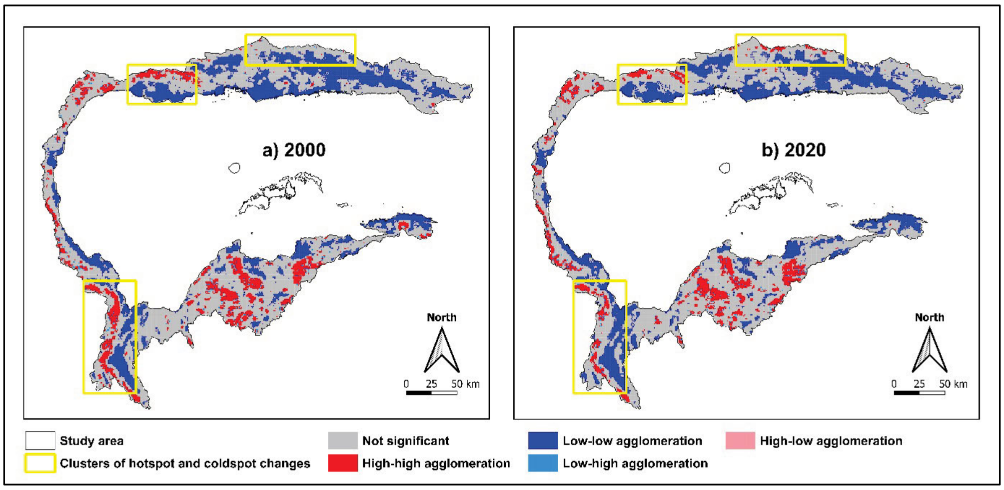

Fig. 4. Local Moran cluster map of soil erosion in: a) 2000, b) 2020; source: own study

The combination of cloud computing and open-source geospatial software provides several benefits. First, GEE is a modern geospatial technology tool that provides effective and efficient ways to process the required data (Gorelick *et al.*, 2017). Second, this study involves sizeable remote sensing datasets from RUSLE components, which must be processed quickly and easily without downloading. In addition, GEE technology enables researchers to access remote sensing data from various sources with greater ease (Tamiminia *et al.*, 2020). The QGIS, as open-source software, has tools for conducting spatial analysis, raster-to-vector conversion, and layout visualisation. The R programming language is a freely available computing tool with statistical and graphical computing capabilities. The experimental results in this study indicate that the Global Moran's I analysis, statistical information, and LISA can be run effectively and efficiently. The data used as input in the analysis is large in raster and vector formats.

However, the performance of the GEE-R-GIS model needs to be evaluated by comparing the output with independent studies conducted in Indonesia and several locations in or near the study area. This evaluation procedure is based on research by Nahib *et al.* (2024). This study is in line with the results of a survey by Adimiharja (2008), which showed that soil erosion in Indonesia ranges from 35 to 220 $Mg \cdot ha^{-1} \cdot y^{-1}$. Legowo (2007) has studied erosion and sedimentation with GeoWEPP in the Limboto watershed and proved that the total erosion was 3,409,067.36 $Mg \cdot y^{-1}$ or an average of 44.69 $Mg \cdot ha^{-1} \cdot y^{-1}$. This figure is in line with the extraction results of this study, specifically in the Limboto Watershed, namely soil erosion in 2000 of 32.36 $Mg \cdot ha^{-1} \cdot y^{-1}$. These findings indicate that the RUSLE model is reliable in this research area.

The results of this study provide an overview of the potential rate of soil erosion in 2000 and 2020 along the watershed leading to Tomini Bay. In particular, this study successfully identified hotspots and coldspots that provide new insights into the spatial-temporal variation of soil erosion rates. The spatial statistical approach used to explain the spatial relationship between hotspots and coldspots and soil erosion rates is in line with research by Li *et al.* (2017). However, this study differs from several recent studies that also use the RUSLE model, GIS and GEE technology, such as in Elnashar *et al.* (2021), Jodhani *et al.* (2023), Alebachew *et al.* (2025), Yousuf *et al.* (2025). The contribution of thought provided by this study is the application of statistical analysis in the form of spatial autocorrelation to detect hotspot and coldspot areas. By knowing the geographical hotspot and coldspot areas, resources can be allocated to the right areas (Schröter and Remme, 2016). Overall, these results can support decision-making for sustainable watershed management.

Hotspots and coldspots show changes in soil erosion rates in 2000 and 2020 at the study site, as shown in Figure 4. However, in the context of spatial management in watersheds, we need to consider local conditions and environmental factors (Adem Esmail *et al.*, 2024). For example, the disappearance of hotspots and the emergence of new hotspots in the northern cluster of the study area in 2000 and 2020 were related to increased rainfall in the area. Likewise, hotspot changes occurred in the southern cluster of the study area. This can be interpreted that rainfall factors have a significant influence on changes in hotspots in the study area. This interpretation is in line with research by Browning and Sawyer (2021) that in tropical areas with high rainfall can increase the rate of soil erosion. Thus, this example provides knowledge for decision makers to determine priority areas in more effective and efficient watershed management.

CONCLUSIONS

Overall, this study demonstrates that the GEE-R-GIS framework can effectively and efficiently identify soil erosion hotspots and coldspots in the years 2000 and 2020 along the watershed leading to Tomini Bay. Collecting, processing, and estimating this framework automates soil erosion and spatial autocorrelation analysis. The results indicate that the spatial distribution of severe soil erosion in 2000 and 2020 is concentrated in the central part of Central Sulawesi province. The spatial statistical approach can identify the distribution of soil erosion hotspots and coldspots in 2000 and 2020 by considering landscape connectivity based on spatial dependence. The distribution of these hotspots contains information about high land degradation risks with significant soil erosion levels. Therefore, watershed restoration actions are focused on this area because it is more targeted. Thus, this study offers a framework with a spatially explicit model for prioritising watershed rehabilitation.

CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

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