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Geochemical distribution and occurrence of rare earth elements in stream sediments of Tamiang, Aceh, Indonesia

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Abstract

This study investigates the geochemical distribution of rare earth elements (REEs) in stream sediments from the Aceh Tamiang Regency, Aceh Province, Indonesia, an area characterized by a complex geological framework and potential lanthanide-bearing source rocks. Rare earth elements such as lanthanum (La), scandium (Sc), and yttrium (Y) are essential to modern high-technology and clean-energy applications, yet baseline data from this region remain limited. A total of forty stream sediment samples were collected from the Simpang Kanan, Simpang Kiri, Tamiang, and Tenggulun rivers to determine the spatial distribution and concentration levels of La, Sc, and Y. All three elements were detected in the riverbed sediments in the study area, with La showing higher concentrations (average 11 ppm) compared to Sc (2 ppm) and Y (3 ppm). Higher values are observed in upstream sediments underlain by igneous and metamorphic rocks, while lower values occur in downstream sedimentary zones. This distribution pattern indicates that the enrichment of REEs is primarily derived from the weathering of upstream source rocks. Additionally, the presence of active tectonic structures in the region may have contributed to the mobilization and accumulation of these elements. This study establishes a baseline of REE distribution in stream sediments of Tamiang and provides valuable data that may support broader regional geochemical investigations.

Keywords: Lanthanum, scandium, yttrium, ICP-OES, fluvial sediments

1. Introduction

Rare Earth Elements (REEs) represent a group of 17 chemically similar elements, including the 15 lanthanide elements, along with scandium (Sc) and yttrium (Y), which share similar physical and chemical properties (Debruyne et al., 2016; Alhassan & Aljahdali, 2021; Milinovic et al., 2021; Thomas et al., 2024). These elements play a critical role in modern high-technology industries, including renewable energy, advanced electronics, aerospace components, transportation, and green technologies (Alhassan & Aljahdali, 2021; Milinovic et al., 2021; Aida et al., 2025). Lanthanum (La) is extensively employed in ceramic capacitors, glass polishing, optical glass, rechargeable batteries, camera lenses, and petroleum cracking (Christie et al., 1998; Milinovic et al., 2021). Scandium enhances the strength of

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aluminum alloys used in aircraft and sports equipment, and it is also utilized in X-ray tubes, polymerization catalysts, hardened Ni-Cr superalloys, and dental porcelain (Christie et al., 1998). Meanwhile, yttrium plays a crucial role in lasers, superconductors, and various electronic applications (Jaireth et al., 2014).

Rare earth elements (REEs) in the Earth's crust typically occur at low concentrations and are predominantly hosted within complex minerals such as silicates (~43%), carbonates (23%), oxides (14%), and phosphates (14%), rather than as native metals (Broom-Fendley et al., 2017; Kynicky et al., 2019; S. Wang et al., 2024). These minerals are commonly associated with specific rock types, including carbonatites, dolomite breccias, granites, pegmatites, and skarns, which provide the primary sources of REEs in the crust (Chakhmouradian & Wall, 2012; Goodenough et al., 2016). The upstream sections of the Simpang Kanan, Simpang Kiri, Tamiang, and Tenggulun rivers in Tamiang, Aceh, Indonesia, are characterized by complex geological structures, including faults and folds, indicative of active tectonic processes that may enhance the release and accumulation of rare earth elements (REEs) in these areas (Kynicky et al., 2019). As these primary rocks undergo weathering, rivers act as natural agents that transport the weathered minerals downstream. Consequently, stream sediments integrate the signals of upstream mineralization, making them valuable indicators and frequently targeted materials in early-stage geochemical exploration (Shi et al., 2023; Coțac et al., 2024; Fakolade et al., 2024).

Globally, the demand for REEs continues to rise due to their strategic importance and limited supply, with most production concentrated in only a few countries (Jaireth et al., 2014). The demand for rare earth elements in 2010 was estimated at approximately 125,000 tons, with China accounting for 95% of the supply (Haque et al., 2014). Indonesia, particularly Aceh, possesses significant geological potential for REE resources (Aida et al., 2025). The country's complex tectonic and magmatic history, marked by multiple orogenic events and varied lithological assemblages, provides favorable conditions for various types of REE mineralization, including lateritic, alluvial, and primary hard rock deposits (Maulana et al., 2014; Doherty et al., 2023). However, despite the region's diverse geology and abundant mineralization, the potential for REE resources remains underexplored (Nahan et al., 2023; Aida et al., 2025). Systematic studies of REE geochemistry in Indonesia are still limited. Stream sediments, which act as natural collectors and transporters of mineral particles eroded from source rocks (Al-Saady et al., 2023; Coțac et al., 2024), have rarely been investigated as proxies for REE prospecting in Indonesia. Identifying new sources of REEs is crucial to support domestic industries and reduce dependency on imported critical minerals (Nahan et al., 2023).

The Tamiang River Basin, located in the eastern part of Aceh Province, northern Sumatra, represents a geologically promising but underexplored region. The basin drains a heterogeneous terrain comprising igneous complexes, metamorphic rocks, and sedimentary formations, which may host REE-bearing minerals such as monazite, xenotime, and allanite. In tropical regions, intense chemical weathering and active fluvial processes can play a significant role in the concentration and redistribution of REEs within stream sediments (Maulana et al., 2014; H. Wang et al., 2022). Understanding the distribution, fractionation patterns, and enrichment characteristics of REEs in stream sediments is therefore crucial for establishing regional geochemical baselines, identifying possible source lithologies, and delineating areas of potential economic interest.

Despite the importance of baseline data, there is currently limited information on the geochemical distribution of REEs in stream sediments in Tamiang Regency, Aceh, Indonesia. This area is geologically promising but remains under-investigated for rare earth potential. To address this gap, a geochemical survey was conducted to analyze the presence and distribution of lanthanum, scandium, and yttrium in stream sediments. Lanthanum represents the light rare earth group, while yttrium behaves similarly to heavy rare earth elements (Milinovic et al., 2021; Thomas et al., 2024), and Sc is often included in geochemical assessments due to its comparable geochemical behavior and association with REE-bearing minerals (Surour & Korany, 2021; Sager & Wiche, 2024; Rezaei et al., 2025). This research is limited to three rare earth elements (La, Sc, and Y).

The concentrations of La, Sc, and Y were measured using Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES), a reliable method for detecting trace elements with high accuracy. Spatial analysis using ArcGIS was then applied to visualize the distribution patterns. La, Sc, and Y are key rare earth elements with environmental and economic significance, making their study in stream sediments of Aceh Tamiang Regency particularly relevant. The findings are expected to provide essential baseline geochemical data for the region and contribute to future mineral resource assessments and exploration of rare earth elements in Indonesia's underexplored areas.

2. Geological setting

The geological setting of the Tamiang area is illustrated in Figure 1. The bedrock is predominantly composed of various sedimentary and metamorphic rock types, while igneous rocks are restricted to the upstream region of the river in the northwest part of the regency, beyond the Tamiang area (Cameron et al., 2007). The general distribution pattern shows progressively younger rocks towards the northeast (NE) and older rocks towards the southwest (SW). The younger rocks in the NE belong to the Lhoksukon Group, which ranges in age from the Late Miocene to the Pleistocene, and consists of the Julu Rayeu Formation, Seurula Formation, and Keutapang Formation. Towards the SW, the rock units transition into the Jambo Aye Group, dated from the Early Miocene to the Late Oligocene, which includes the Baong Formation, Buluh Member, Peutu Formation, Belumai Member, Ramasa Member, Rampong Formation, Bampo Formation, and Bruksah Formation. In the southwestern part of Tamiang, the sequence continues with the Meureudu Group (Tampur Limestone Formation, Early Oligocene), the Peusangan Group (Kalau Limestone Formation, Late Triassic), and the Tapanuli Group, which comprises the Kluet Formation and the Bohorok Formation, dated from the Late Carboniferous to the Early Permian (Cameron et al., 2007).

The igneous rocks in the Tamiang region comprise both extrusive and intrusive types. Extrusive rocks include the Sembuang Volcanics (Pleistocene), consisting of andesitic pyroclastics, and the Sematen Volcanic Formation (Late Oligocene to Early Miocene), dominated by green, mainly intermediate pyroclastics. Intrusive rocks include the Locop Intrusion (possibly Middle Miocene), represented by small stocks and dykes of fine-grained leucogranites exhibiting argillic and sericitic alteration. In addition, the Pasca-Kluet Formation, which is presumed to predate the Peusangan Group and may be assigned to the Middle Permian, is associated with a sequence of intrusions. These include the Dalam Intrusion, characterized by flow-banded pinkish biotite microgranite; the Telege Intrusion, comprising small but complex stocks of hornblende granodiorite and early melacliorites; and the Serbajadi Batholith, dominated by fresh biotite granites, with subordinate muscovite granites, hornblende granodiorites, and diorites, some of which are foliated, accompanied by aplitic dykes (Cameron et al., 2007). Several geothermal prospects have been identified in Tamiang, including Kr. Peureulak, southwest of Bunin, approximately 1 km southwest of Lokop, north of Pining, and along the Simpang Kiri River (Fig. 1).

3. Material and methods

3.1. Study area

The study was conducted in Aceh Tamiang Regency, located in the eastern part of Aceh Province, northern Sumatra, Indonesia (Fig 2). This region covers an area of approximately 1,900 km² and is characterized by varied topography ranging from lowland floodplains to hilly upland terrains with elevations between 50 and 800 meters above sea level. The area is part of the northern extension of the Bukit Barisan Mountains, which form an integral section of the active Sunda Arc tectonic system. The regional climate is tropical humid, with an average annual rainfall exceeding 3,000 mm and mean monthly temperatures ranging from 25°C to 28°C. The high rainfall and tropical conditions promote intense chemical weathering and erosion, which contribute to the continuous input of sediments into the river systems.

The drainage network consists of four main rivers: the Simpang Kanan, Simpang Kiri, Tamiang, and Tenggulun rivers, which originate in the upland zones and flow southeastward toward the Malacca Strait. The river catchments drain areas composed mainly of weathered igneous and metamorphic rocks that are locally in contact with sedimentary formations (Cameron et al., 2007). Extensive forest cover and mixed-use agricultural land dominate the catchment area, influencing sediment supply and transport processes. Previous geological surveys have indicated that the region contains various lithologies, including granitic intrusions and metamorphic complexes, which may act as primary sources for rare earth element (REE) mineralization (Alabi & Olasehinde, 2024). The general geological framework, including lithology, structural setting, and potential source rocks, is presented in detail in the Geological setting section and Figure 1.

The lithological composition of the Tamiang area, Aceh (Fig. 1), comprises a diverse sequence of sedimentary, volcanic, and metamorphic units ranging from the Triassic to Quaternary in age (Cameron et al., 2007). The youngest deposits consist of coastal and fluviatile deposits (Qh) composed of gravels, sands, and clays, followed by the Idi Formation (Qpi) characterized by gravel, semi-consolidated sand, and clays. The Julu Rayeu Formation (QTjr) contains rhythmic sandstone, mudstone, and lignitic clays, whereas the Seureula Formation (Qps) comprises mudstone with alternating sandstone layers. The Keutapang Formation (Tuk) includes minor conglomerates, sandstones, mudstones, and carbonaceous sandstones, over-

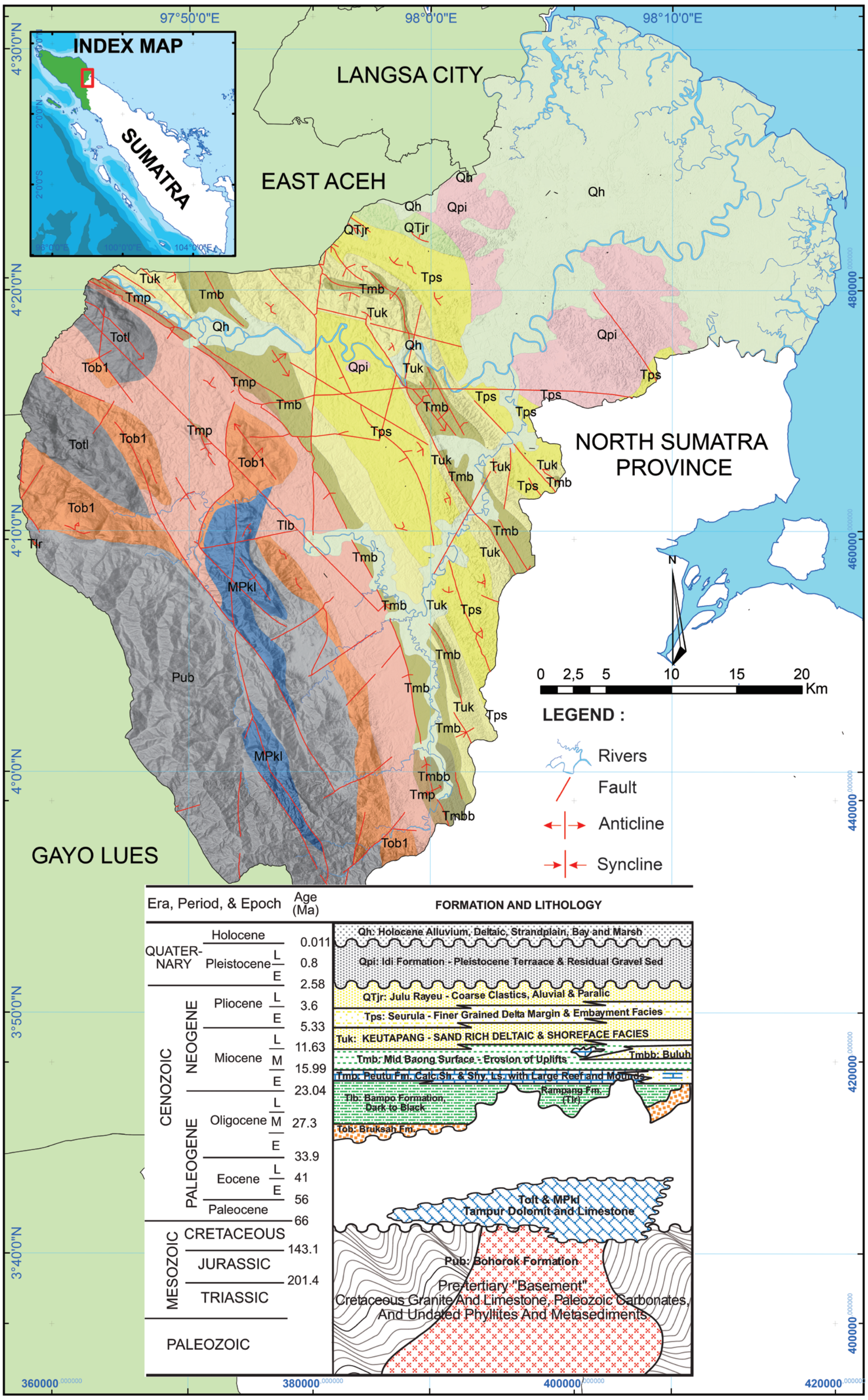

Fig. 1. Geological map and generalized stratigraphy of the Tamiang area, Aceh, Indonesia (Cameron et al., 2007; Bachtiar et al., 2012). Qh – Holocene alluvium; Qpi – Idi Formation (gravel, sand, clay); QTjr – Julu Rayeu Formation (sandstone, mudstone, lignitic clay); Tps – Seurula Formation (mudstone, sandstone); Tuk – Keutapang Formation (sandstone, mudstone, conglomerate); Tmb – Baong Formation (sandstone, mudstone); Tmbb – Buluh Member (calcareous sandstone); Tmp – Peutu Formation (carbonaceous mudstone, calcareous beds, sandstone); Tlb – Bampo Formation (sandstone, siltstone, mudstone); Tlr – Rampang Formation (siltstone, mudstone, sandstone); Tob – Bruksah Formation (sandstone, conglomerate, thin coal beds); Totl – Tampur Limestone Formation; MPkl – Kaloi Limestone Formation; Pub – Bohorok Formation (metawacke, slate, quartzite, metalimestone).

lain by the Baong Formation (Tmb) consisting of sandstones, glauconitic sandstones, and calcareous mudstones, with its Buluh Member (Tmbb) dominated by calcareous sandstones. The Peutu Formation (Tmp) is represented by carbonaceous mudstones, calcareous beds, and fine sandstones. The Rampang Formation (Tlr) consists mainly of siltstones, euxinic mudstones, and volcanic sandstones deposited within the Lesten Basin, while the Bampo Formation (Tlb) comprises sandstones, laminated siltstones, and dark to black pyritic euxinic mudstones. The Bruksah Formation (Tob) is composed of calcareous and micaceous sandstones, conglomerates, and thin coal beds. Carbonate sequences include the Tampur Limestone Formation (Totl), reef limestones and dolomites with chert nodules and the Kaloi Limestone Formation (MPkl), which consists of massive limestones flanked by Triassic shales, sandstones, and limestones. The oldest unit, the Bohorok Formation (Pub), is composed of

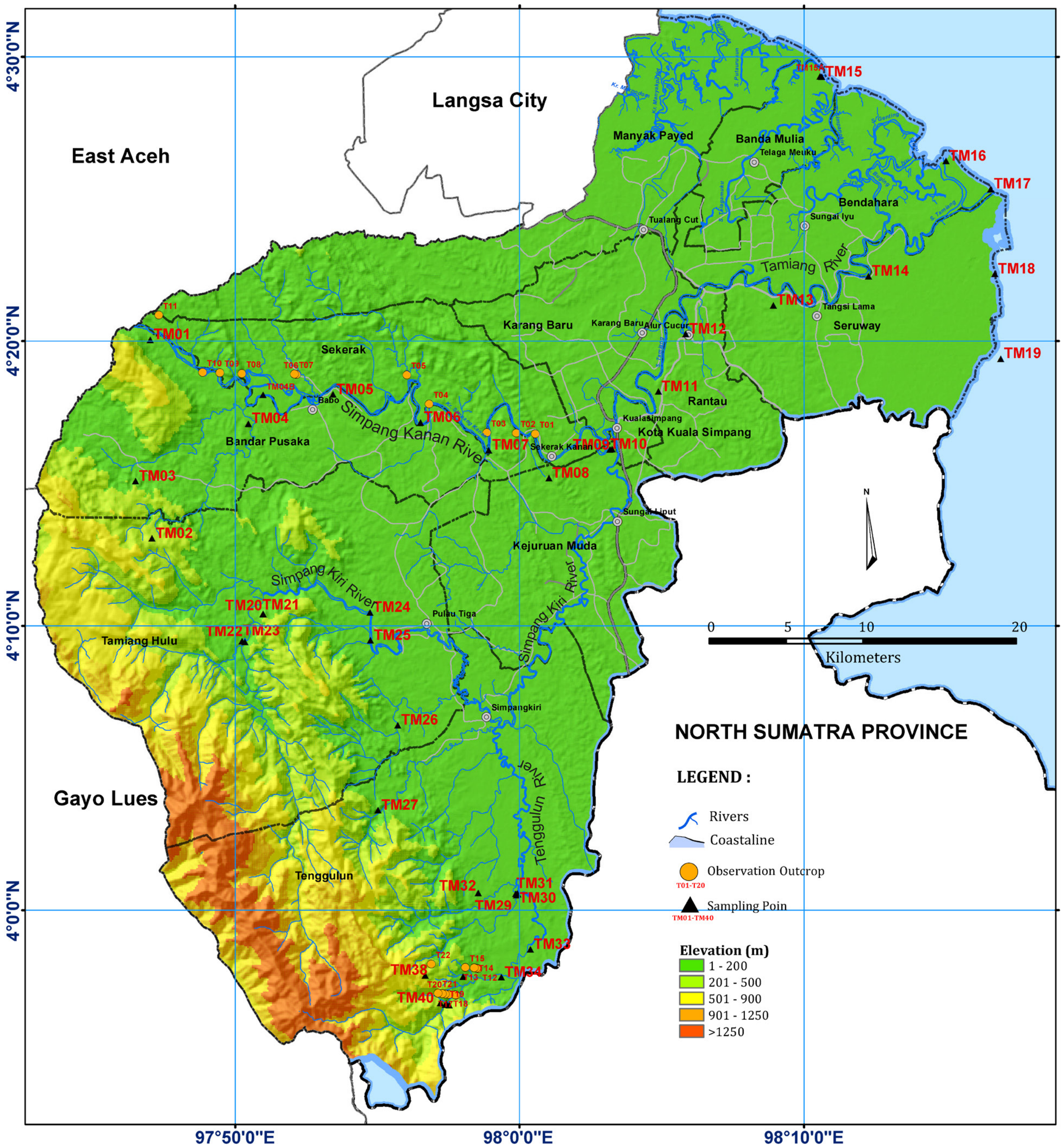

Fig. 2. Location map of stream sediment sampling sites along the rivers in Tamiang from downstream to upstream.

unbedded conglomeratic metawackes, slates, minor quartzites, and metalimestones.

3.2. Sampling

Stream sediment sampling was conducted during a field survey carried out between May and July 2017, representing both wet and dry season conditions. Only one sample was collected at each sampling point. A total of 40 representative sampling points were systematically selected along the upstream, midstream, and downstream sections of the Simpang Kanan, Simpang Kiri, Tamiang, and Tenggulun rivers. Sampling sites were chosen based on accessibility, river morphology, flow conditions, and proximity to potential source rocks to ensure adequate spatial coverage of the catchment areas. At each site, approximately 1 kg of active channel sediment was collected using a stainless-steel scoop and hand auger at a depth of 0–10 cm to represent recently deposited sediments. Where the riverbed was coarse-grained, finer sediment fractions were targeted by selecting depositional features such as point bars and inner meander bends.

To minimize cross-contamination between sites, all sampling equipment was thoroughly cleaned with deionized water before and after each collection. Each sample was placed in a clean, labelled polyethylene bag, sealed, and stored in a dry, shaded container during transport to the laboratory. Upon arrival at the laboratory, all samples were air-dried at room temperature to prevent chemical changes caused by microbial activity. Metadata, including site coordinates (recorded with a handheld GPS), sampling date, river name, and basic field observations, were systematically documented for each sampling point.

3.3. Sample preparation and analysis

Sediment samples were air-dried and subsequently cleaned of clay and organic debris by wet sieving with an 80-mesh sieve (0.177 mm) to isolate the fraction suitable for geochemical analysis (Mardiyah et al., 2025). The stream sediment samples were collected from active channel and riverbank deposits, where finer clay and silt fractions are typically absent or poorly represented. Therefore, the analyzed samples mainly consist of sand- and gravel-sized materials.

Grain size measurements were not conducted in this study. Stream sediment samples were collected using wet sieving through an 80-mesh (0.177 mm) sieve, which excludes finer clay and silt fractions. Consequently, the analyzed samples primarily represent sand- and gravel-sized materials, and caution should be exercised when interpreting sediment characteristics or relating them to finer particle fractions. Clay and organic fractions were removed during sample preparation to isolate the fraction suitable for geochemical analysis. Therefore, the study focuses on the geochemistry of coarser stream sediments, and the results may not fully capture elemental distributions in finer sediments. Only selected rare earth elements (La, Sc, and Y) were analyzed. While these elements provide insight into geochemical patterns and source lithologies, the absence of measurements for other REEs limits a complete characterization of the overall REE distribution in the Tamiang River sediments.

The cleaned samples were sent to the Intertek Testing Laboratory, South Jakarta, for elemental analysis. Concentrations of lanthanum (La), scandium (Sc), and yttrium (Y) were determined using Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES; PerkinElmer Optima 8300) equipped with a dual-view optical system and a solid-state CID detector at Intertek Laboratory, Jakarta, following the analytical procedure described by Balaram (2019). The detection limits for La, Sc, and Y were 0.5, 0.2, and 0.3 ppm, respectively (Balaram, 2019). Quality assurance and quality control (QA/QC) procedures included the use of certified reference materials, analytical blanks, and duplicate samples to ensure data reliability.

3.4. Data processing and statistical analysis

The analytical results from ICP-OES, along with sampling coordinates, sample weights, and collection dates, were compiled and processed using Microsoft Excel. Statistical analysis was performed to describe the distribution of each element, including calculations of mean values, standard deviations, detection limits, and histogram distribution curves. Spatial distribution maps of the geochemical elements were generated using ArcGIS software (Moghimi et al., 2024). Element concentrations were plotted as points on the map, with symbol colors classified into ranges from low to high concentrations to visualize geochemical patterns.

3.5. Geochemical threshold determination

Field geochemical data are independent observations that reflect local environmental responses such as mineralization processes. Concentrations vary between locations, so defining threshold values is essential for interpreting geochemical survey results (Ayodele, 2018). The background value represents the normal or original concentration not affected by any geological anomaly and generally remains stable over time. It was calculated using the following formula:

Background value = mean + standard deviation (Sojka et al., 2021).

Anomalous values are those that deviate significantly from the normal background level, indicating possible mineralization. An anomaly is defined as any value that exceeds the threshold value. The threshold for each element was calculated using the formula:

Threshold = median + 2 × standard deviation (Ayari et al., 2022).

This approach helps to distinguish normal background concentrations from potential geochemical anomalies, providing a clearer basis for interpretation of rare earth element distribution in the study area.

4. Results

4.1. Geochemical characteristics

The geochemical analysis shows that the concentrations of La, Sc, and Y vary within relatively narrow ranges (Table 1). The La content ranges from 11 to 44 ppm, with a median of 25 ppm and a standard deviation of 6 ppm. The calculated background value is 31 ppm, whereas the threshold is 37 ppm. A single anomalous point for La (sample TM05) exceeds the threshold value, indicating a potential REE enrichment zone. Scandium varies between 2 and 9 ppm (median: 6 ppm), with a low standard deviation (1.67 ppm). The background level (8 ppm) and threshold (9 ppm) suggest no significant Sc anomaly in the area. Yttrium content ranges from 3 to 13 ppm, with a median of 8 ppm and a standard deviation of 3 ppm. The background (11 ppm) and threshold (13 ppm) indicate no clear Y anomaly above the threshold in the sampled points. These results highlight the presence of localized La enrichment, whereas Sc and Y appear relatively uniform. To facilitate geochemical comparison, the average concentrations of La, Sc, and Y in the upper continental crust were added to Table 1. The reference values were taken from Taylor & McLennan (1985) and Rudnick & Gao (2003), which provide widely accepted global averages for crustal composition. These data allow assessment of REE enrichment relative to typical crustal levels.

4.2. Lanthanum (La)

Lanthanum was detected in all stream sediment samples, with concentrations ranging from 11 ppm to 44 ppm (Fig. 3). The highest concentration was observed at sampling point TM05, located in the Sekerak area, reaching 44 ppm, which exceeds the general background threshold for lanthanum in non-mineralized environments. The lowest concentration was recorded at sampling point TM018 in the Seruway area, at 11 ppm. The average lanthanum content for the entire study area was 25 ppm.

Spatially, higher lanthanum concentrations were generally found in the upstream and midstream sections of the rivers, particularly in the Sekerak and Tenggulun areas. This pattern may indicate potential source rocks or localized mineralization upstream. The spatial distribution of lanthanum concentrations is presented in Figure 3, showing a clear clustering of higher values in specific river segments.

Figure 4 illustrates the distribution of lanthanum concentrations in the stream sediment samples from the Aceh Tamiang rivers. Most samples have concentrations between 20 and 30 ppm, showing a relatively consistent pattern of La occurrence throughout the study area. However, sample TM05 stands out with an anomalously high concentration of about 44 ppm, which is significantly higher

Table 1. Mean, median, standard deviation (SD), background, and threshold concentrations of the analyzed elements (ppm).

Elements	Min	Max	Median	SD	Background	Threshold	Anomalous location	UCC (T&M, 1985)	UCC (R&G, 2003)
La	11	44	25	6.4	31	37	TM05	30	31
Sc	2	9	6	1.7	8	9	–	11	14
Y	3	13	8	2.6	11	13	–	21	21

UCC (upper continental crust) data from Taylor & McLennan (1985) and Rudnick & Gao (2003).

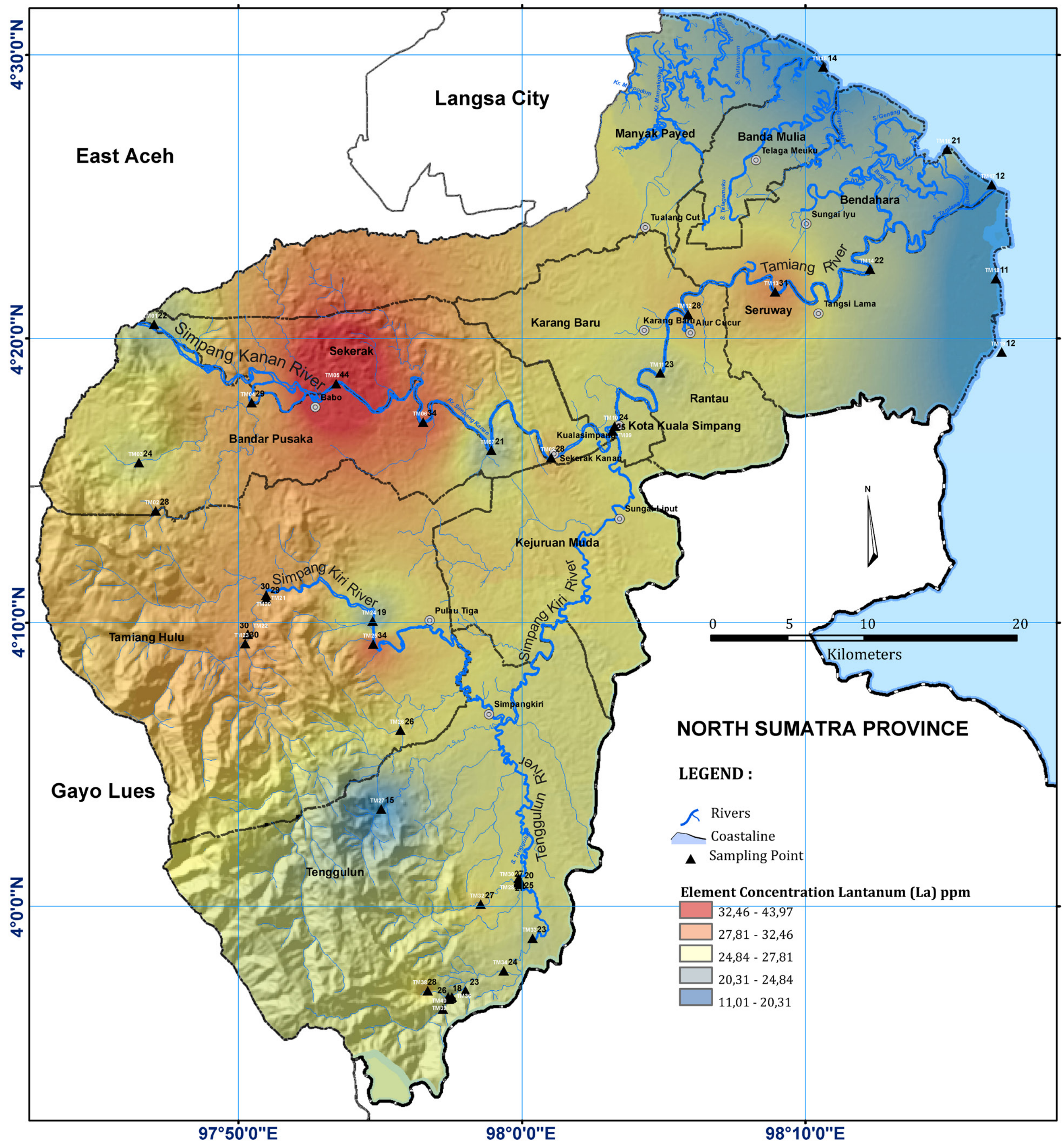

Fig. 3. Spatial distribution map of lanthanum (La) in Tamiang, Aceh, Indonesia.

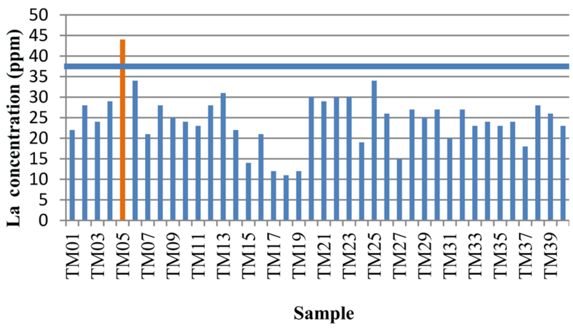

Fig. 4. Distribution of lanthanum (La) concentrations in 40 stream sediment samples collected from the Aceh Tamiang rivers. Blue horizontal line - threshold value; red bar: anomaly.

than the regional mean value. This peak indicates a possible local enrichment zone, potentially linked to the presence of REE-bearing minerals such as monazite or xenotime in the upstream lithologies. On the other hand, a few samples, such as TM17 and TM19, exhibit lower La concentrations, in the amount of 12 ppm. The mean La concentration is around 25 ppm, indicating a low REE potential in the stream sediments. This overall pattern highlights both the general background level of lanthanum and localized anomalies that may warrant further investigation.

4.3. Scandium (Sc)

The spatial pattern of scandium distribution is shown in Figure 5. Sc was detected at all sampling points throughout the study area. Concentrations ranged from 2 ppm to 9 ppm, with an average value

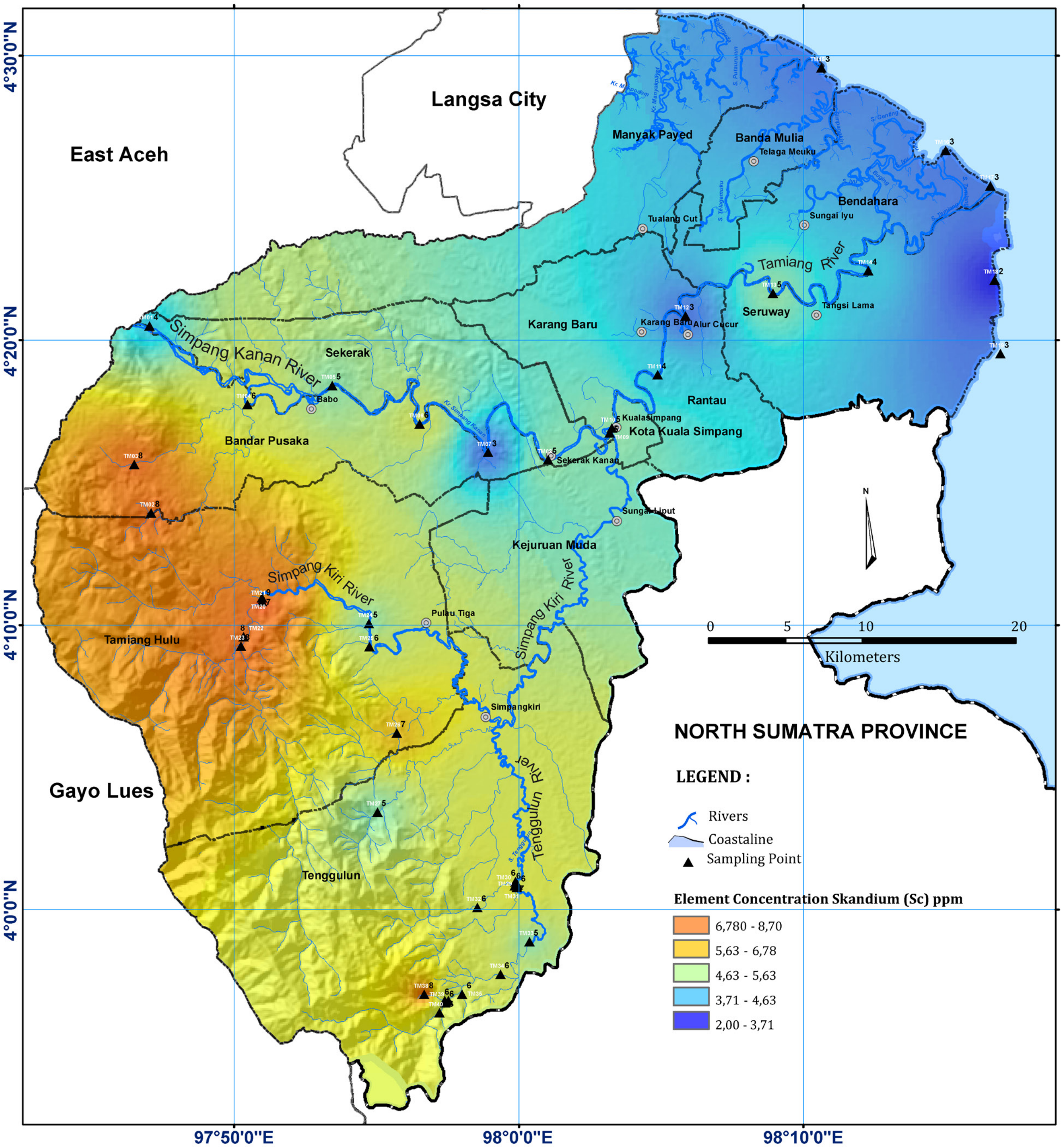

Fig. 5. Spatial distribution of scandium (Sc) in Tamiang Regency, Aceh, Indonesia.

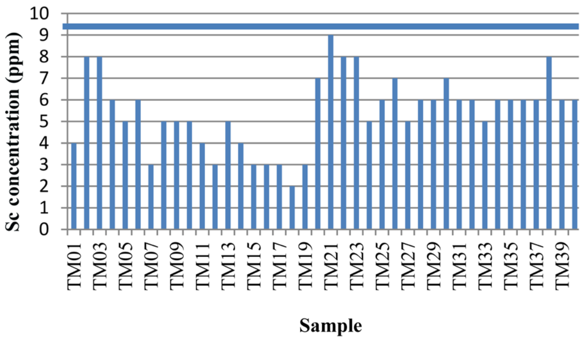

Fig. 6. Distribution of scandium (Sc) concentrations in 40 stream sediment samples (ppm). Horizontal line - threshold value.

of 6 ppm. The highest scandium concentration was found at sampling point TM021, located in the Tamiang Hulu area, with a value of 9 ppm. The lowest concentration was observed at sampling point TM018 in Seruway, at 2 ppm. Overall, higher scandium values were generally recorded in upstream sections, especially in Tamiang Hulu, indicating a possible upstream source for Sc-bearing minerals.

Figure 6 shows the distribution of Sc concentrations in 40 stream sediment samples collected from the Aceh Tamiang rivers. Most samples show concentrations clustered between 5 and 7 ppm, with a few samples such as TM03 and TM21 exhibiting relatively higher Sc values, approaching 8–9 ppm. On the other hand, some samples, such as TM11 and TM15, display lower concentrations amount 3 ppm. Overall, the mean Sc concentration was approximately 6 ppm, indicating low Sc concentration in the study area's stream sediments. This pattern suggests a generally uniform distribution of scandium, likely influenced by the source-rock lithology and sediment-transport processes (Halkoaho et al., 2020).

4.4. Yttrium (Y)

The spatial distribution of yttrium concentrations is presented in Figure 7. Yttrium was also detected in all sediment samples analyzed, with concentrations varying across the sampling sites. The highest concentrations, reaching 13 ppm, were recorded at three sampling points: TM02 and TM03 in Tamiang Hulu, and TM013 in Seruway. The lowest yttrium concentration was found at TM018 (Seruway) with a value of 3 ppm. The average yttrium content across all samples was 8 ppm. Similar to scandium, higher yttrium values were mostly observed in the upstream Tamiang Hulu area, suggesting possible upstream mineral sources.

Figure 8 shows the distribution of yttrium concentrations in 40 stream sediment samples collected from various river sections in Aceh Tamiang Regency, Aceh, Indonesia. The average concentration is about 8 ppm, suggesting that the overall Y distribution is relatively consistent, with minor local variations. These variations likely reflect differences in source rock mineralogy, weathering intensity, and sediment transport dynamics within the river catchments.

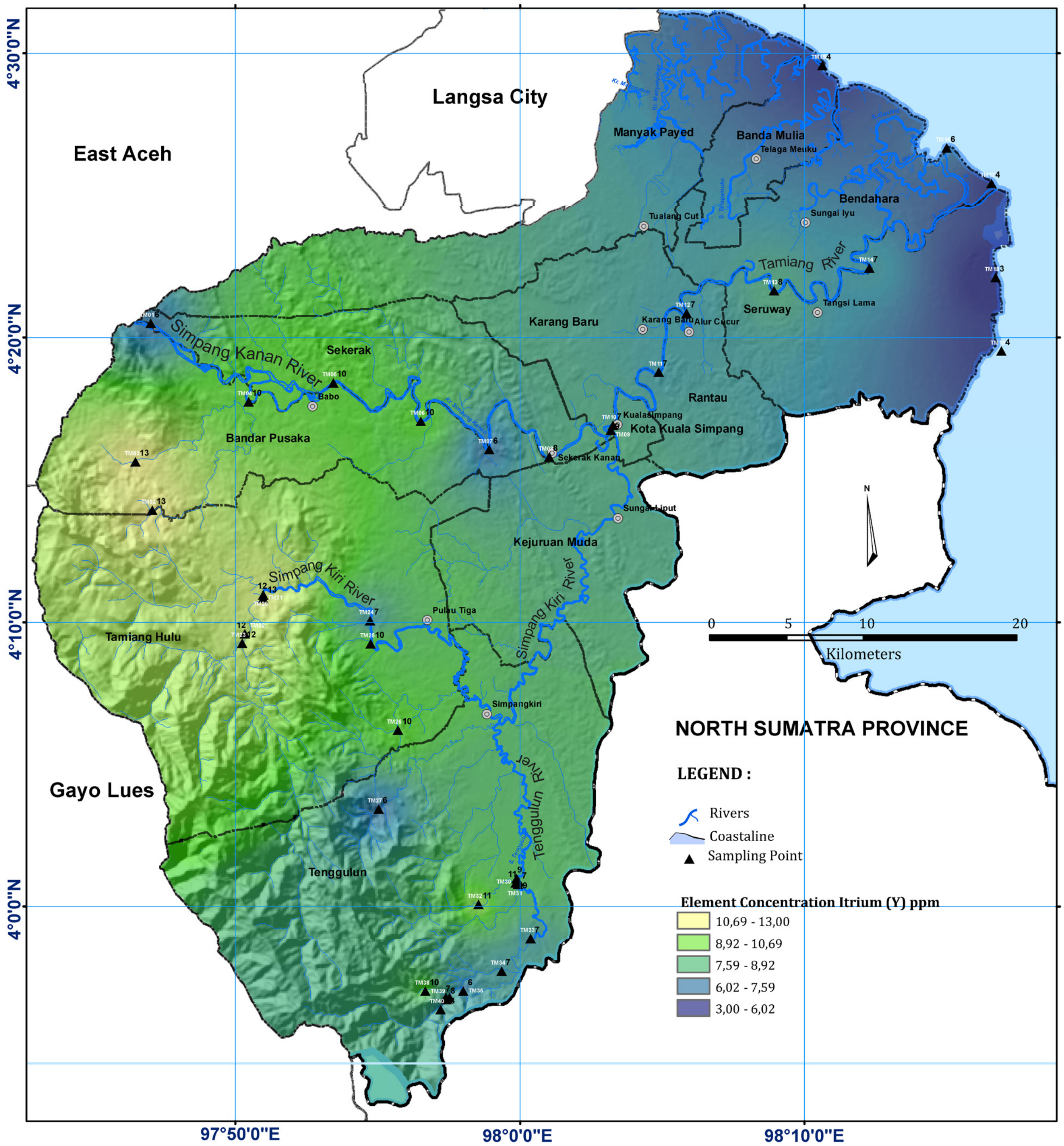

Fig. 7. Spatial distribution of yttrium (Y) in Tamiang Regency, Aceh, Indonesia.

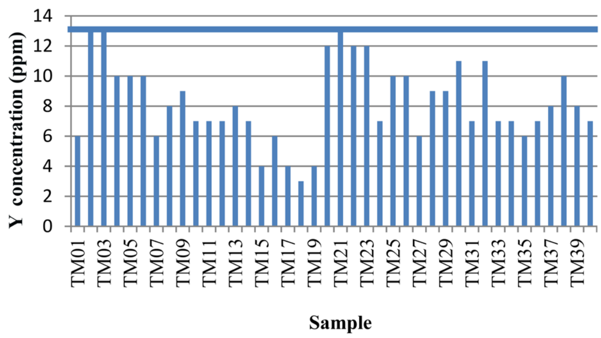

Fig. 8. Distribution of yttrium (Y) concentrations in 40 stream sediment samples (ppm). Horizontal line - threshold value.

5. Discussion

In this study, only La, Sc, and Y were analyzed as representative trace elements that can indicate REE potential in stream sediments. The concentrations of La, Sc, and Y in stream sediments across Aceh Tamiang show notable spatial variation, which appears to reflect differences in the underlying lithology. Elevated levels of these elements in upstream areas suggest a strong influence from older igneous and metamorphic rocks, whereas lower concentrations downstream are likely related to sedimentary rock dominance. This pattern suggests a clear link between REE distribution and bedrock composition, highlighting the importance of geological context in geochemical interpretation.

The spatial distribution patterns mapped in ArcGIS further support the hypothesis that the upstream bedrock lithology plays a key role in supplying these rare earth elements (REEs) to the river system through erosion and weathering processes. Other possible contributing factors include minor REE-bearing minerals originating from metamorphic rocks, fragments of sedimentary rocks derived from various formations within the study area, as well as secondary enrichment through alluvial processes and input from hydrothermal alteration zones in the upper catchment (Cameron et al., 2007; Madukwe et al., 2020; Surour & Korany, 2021). These possibilities remain preliminary and require further field investigation and mineralogical analysis to be confirmed.

The growing use of clean energy technologies is projected to increase global REE demand by over 40% by 2040 (Andrews-Speed & Hove, 2023). Elements such as La, Y, and Sc are important for applications in catalysts, advanced alloys, and electronic components, including smartphones and LCD displays (Currie & Elliott, 2024). This global demand highlights the strategic importance of identifying new REE sources, particularly in underexplored regions such as Aceh Tamiang. The geochemical data from this study reveal a localized enrichment of La at one site, while Sc and Y concentrations remain low across the study area, with no detectable anomaly. These observations highlight interesting geochemical variations and suggest that further investigation of other REE may provide a more complete assessment of the area's geochemical potential.

Lanthanum exhibits the most notable anomaly among the three elements studied. Concentrations of La were generally higher in the upstream region of the Tamiang River, particularly in the Sekerak area, located in the upper reaches of the basin near 97°54'E, 4°18'N. The highest value was recorded at sampling point TM05, where La reached 44 ppm. This value exceeds typical background levels reported for unmineralized sedimentary environments and also surpasses the average concentration of La in the upper continental crust (30–31 ppm) (Taylor & McLennan, 1985; Rudnick & Gao, 2003), highlighting the presence of a moderate but distinct enrichment zone. Such an anomaly indicates that the upstream geology in Sekerak may include rocks enriched in REE-bearing minerals, and further investigations are required to confirm this potential.

Previous studies have shown that lithologies such as carbonatite intrusions, dolomite breccias, or pegmatite bodies are often associated with elevated lanthanum concentrations (Jaireth et al., 2014). In the Tamiang area, the potential source rocks for lanthanum consist mainly of carbonate rocks, sandstones, and granitic intrusions exposed in the upstream segment of the Sekerak River within East Aceh Regency. The spatial position of sampling point TM05 (4.307°N, 97.89055°E), located within the Sekerak area, lies near a geological transition zone between weathered granitic bedrock and overlying lateritic soils (Alabi & Olasehinde, 2024). This zone is significant not only because it reflects intense chemical weathering typical of tropical environments, but also because such granitic-lateritic contact zones are commonly associated with the enrichment of LREEs, particularly lanthanum. The geochemical behavior of La in this setting may be influenced by residual-concentration processes and its incorporation into secondary phosphate or oxide phases (Coțac et al., 2024; Rukhlov et al., 2024; X. Wang et al., 2024). Therefore, the relatively high La concentration observed at TM05 (44 ppm) is likely related to these weathering-driven enrichment mechanisms operating within this lithological boundary (Neal, 2005).

Prolonged weathering and leaching under tropical climatic conditions may mobilize LREEs from parent rocks, including the Tampur Limestone Formation (Totl; reefal limestone and dolomite with chert nodules), the Bruksah Formation (Tob; calcareous and micaceous sandstones, conglomerates, and thin coal beds), and the Lokop Granite Intrusion (Til; coarse-grained biotite granite) (Cameron et al., 2007). These lithologies, which dominate the upstream catchment of the Tamiang River, represent potential sources of LREEs that could be redistributed within residual lateritic profiles or downstream sedimentary environments (Christie et al., 1998; Bayon et al., 2023).

Scandium (Sc) concentrations in the Tamiang Hulu area are generally low, with observed values ranging from 2 to 9 ppm and averaging around 6 ppm. This is consistent with the absence of mafic to ultramafic lithologies within this part of the catchment. The upstream region is predominantly underlain by the Lokop Granite Intrusion (Til), which is felsic in composition and not typically associated with high Sc concentrations (Cameron et al., 2007). The low Sc concentrations in Tamiang Hulu (97°50′E, 4°10′N) and Bandar Pusaka (97°46′E, 4°15′N) are likely related to the weathering and erosion of surrounding bedrock units, particularly the Tampur, Bruksah, and Bohorok Formations (Taylor & McLennan, 1985; Rudnick & Gao, 2003; Cameron et al., 2007). These formations are dominated by andesitic to basaltic volcanic and volcaniclastic rocks, including tuffs and breccias, and they contain lithic fragments within conglomeratic units, which may contribute minor Sc through weathering.

Yttrium concentrations in the Tamiang River sediments are relatively uniform from the upstream headwaters to the lower reaches, suggesting that its distribution is primarily controlled by the lithology of the catchment rather than downstream sediment transport or sorting processes (Klimpel & Bau, 2023). The spatial analysis conducted in ArcGIS supports the interpretation that upstream lithology and geomorphology are the dominant controls on the distribution of REEs in the Tamiang sediments. The observed geochemical anomaly is characterized by elevated concentrations of lanthanum in the stream sediments relative to background levels.

The localized enrichment of REEs in the geomorphological traps likely contributes significantly to the geochemical anomalies observed along the river course. Comparable sedimentary controls on REE accumulation have been reported for the bedrock-dominated Miño River (NW Spain), where surface sediments trapped in rock cavities exhibited higher concentrations of REEs (Álvarez-Vázquez et al., 2022). This highlights the potential role of natural depositional features in controlling REE distribution in bedrock-influenced river systems.

Furthermore, recent studies (Al-Saady et al., 2023) confirm that tectonically active fluvial systems, such as the Lesser Zab River Basin in northeastern Iraq, exhibit spatial variations in REE concentrations that reflect both provenance and geomorphological influences. These findings reinforce the interpretation that fluvial REE anomalies are not solely governed by weathering processes but are also shaped by sediment sorting and the geomorphological setting of the basin. Although the concentrations recorded in this initial survey fall within the moderate range compared to globally known economic REE deposits, the detection of a clear La anomaly at TM05 provides a compelling basis for follow-up exploration. Further field investigations should include systematic bedrock sampling, detailed mineralogical studies to identify the primary mineral hosts, and targeted geophysical surveys to delineate potential mineralized bodies. Such integrated approaches are essential to assess the continuity, extent, and grade of the identified REE occurrences and to evaluate their economic viability (Aida et al., 2025).

The concentrations of La, Sc, and Y in the Tamiang stream sediments fall within the range of natural background values typically reported for sedimentary environments underlain by felsic to intermediate igneous rocks, as well as for tropical weathering profiles in tectonically active settings. Nevertheless, these concentrations are generally lower than the average levels reported for granitoid-derived stream sediments from Southeast Asia and portions of the Amazon Basin, which have been documented for Sc, La, and Y at 10–20 ppm, 25–50 ppm, and 15–30 ppm, respectively (Klimpel & Bau, 2023). The geochemical patterns observed in the Tamiang stream sediments provide insight into local variations and elemental distributions, while highlighting the need for further investigation of additional REEs and finer sediment fractions to achieve a more comprehensive understanding of the area's geochemical characteristics.

6. Conclusions

The geochemical distribution of rare earth elements (REEs) in stream sediments of Tamiang, Aceh, Indonesia, was investigated, focusing on lanthanum, scandium, and yttrium. The results indicate that REE concentrations across the study area are generally low. Lanthanum exhibits mostly low concentrations, with one sampling point in the Sekerak area showing a locally elevated value compared with other sites; however, this increase is confined to that single location. Scandium and yttrium display uniform concentrations across all sampling points and do not exhibit anomalous patterns. Overall, the REE patterns observed in this baseline study do not indicate any widespread enrichment within the surveyed sediments. The dataset provides a useful reference for characterizing REE distributions in Tamiang and forms a foundation for future geochemical or mineralogical investigations.

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Authors' contributions

G.S.N.: conceptualization, methodology, writing - original draft preparation, writing - review and editing, investigation, supervision; H.N.E. and M.T.: investigation, formal analysis, visualization; F.F.: project administration. All authors have read and agreed to the published version of the manuscript.

Conflicts of interest

The authors confirm that they have no financial interests or personal relationships that could have influenced the work presented in this paper.

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