

A weighted basin-scale susceptibility framework integrating river morphology, soil erosion and hydrological alteration in a tropical regulated river system

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ABSTRACT

Understanding watershed susceptibility in regulated tropical river systems requires integrating geomorphic predisposition, sediment generation, and hydrological modification within a unified analytical framework. This study proposes a weighted basin-scale watershed susceptibility framework that synthesizes soil erosion (RUSLE), hydrological alteration (IHA/HAI), and geomorphic maturity (Hypsometric Integral) into a normalized composite index. Unlike conventional single-parameter assessments, the framework applied min–max normalization and a theoretically rationalized weighting scheme (0.40 soil loss, 0.35 flow alteration, 0.25 morphology) to enable cross-parameter comparability and basin-wide prioritization. Application to a multigradient tropical regulated river system revealed pronounced spatial heterogeneity, with composite susceptibility values ranging from 0.15 to 0.92. Batang Padang Catchment recorded the highest index (0.92, Very High), driven by concurrent extreme soil loss and substantial hydrological alteration, while downstream depositional reaches exhibited consistently low susceptibility. The resulting spatial pattern demonstrated a clear upstream-to-downstream gradient consistent with geomorphic first principles. Robustness testing through equal-weight and ± 10 –20% perturbation scenarios produced minimal classification shifts (average index ratio variation <3%), confirming stability of sub-basin rankings. Comparative analysis with prior erosion studies in the basin further supported consistency in magnitude and spatial patterning. The proposed framework advances watershed assessment by transforming standalone erosion and flow metrics into an interpretable basin-scale susceptibility synthesis. Because the methodology relies on widely available DEM, discharge, and land-use datasets, it is transferable to other regulated tropical river systems seeking integrated geomorphic–hydrological prioritization for management and conservation planning.

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1. INTRODUCTION

Channel morphology encompasses the physical characteristics and attributes of a river or stream channel. It involves the examination of the channel's shape, dimensions, and patterns, as well as the underlying processes influencing its formation and development (Robert, 2014). The morphology of a channel is influenced by factors such as sediment type, water flow, slope, and human activities. Common channel forms include straight, meandering, and braided channels, with each displaying distinct patterns of erosion, deposition, and sediment transport (Leopold et al., 2020; Schumm, 2003). A comprehensive understanding of channel morphology is vital for effective water resource

management, flood impact mitigation, and the preservation of aquatic ecosystems. Changes in channel morphology can arise from natural processes like erosion and sedimentation, or human-induced activities such as urbanization and river channelization. The study of channel morphology offers valuable insights for sustainable river management and environmental conservation.

The changes on river morphology is directly influenced by various processes, such as the flow alteration (Yadav et al., 2023), soil loss (Roque et al., 2021), sediment transport (Hirshfield & Sui, 2011; Sulaiman et al., 2017; Sulaiman et al., 2017), extreme flow events (Akay et al., 2020) and land-use change (Kayitesi et al., 2022). Flow regulation

(e.g., dams) alters sediment transport and triggers river narrowing, channel migration, and sediment imbalance. The Yamuna River in India experienced a 67% reduction in channel width after dam construction, linked to reduced sediment supply and altered flow regime (Yadav et al., 2023). Similarly, downstream of the Three Gorges Dam, the Yangtze River showed enhanced erosion and coarsened sediments due to trapped sediment and changed discharge patterns (Xie et al., 2021). In Peru's Mala River Basin, high soil erosion rates (248 t/ha/yr) led to morphological changes such as island formation and channel branching, indicating a strong coupling between soil loss and river morphology (Roque et al., 2021). The Didessa River Basin (Ethiopia) showed that land cover and climate change jointly increased soil loss and modified flow, with sediment yields rising by up to 83.5 t/ha/yr, altering channel morphology (Chimdessa et al., 2018). In the Yellow River, soil erosion from the Loess Plateau significantly increased sediment delivery, leading to morphological instability and altered sediment transport dynamics (Hirshfield & Sui, 2011). The Ofu River in Nigeria lost over 40% of its flow depth due to siltation from high soil inputs, showing a direct link between soil loss and reduced flow capacity (Alfa et al., 2018). UAV-based studies on the Büyük Menderes River (Turkey) found that flood-induced flow alterations caused major erosion and sediment deposition, changing riverbank morphology and channel geometry (Akay et al., 2020).

A meta-analysis of tropical rivers highlighted that land use and climate changes have simultaneously altered river hydro-morphology, sediment yield, and erosion dynamics, especially through deforestation and increased runoff (Kayitesi et al., 2022). Despite extensive research on soil erosion modelling, hydrological alteration, and basin morphometry, these domains remain largely compartmentalized. Single-parameter erosion mapping, while effective for estimating hillslope detachment, frequently overlooks hydrological forcing mechanisms that regulate sediment transport and channel response. Conversely, flow alteration studies emphasize regime deviation without incorporating geomorphic predisposition or terrain sensitivity. Morphological indices such as hypsometric analysis provide insight into basin maturity but are rarely evaluated alongside dynamic anthropogenic stressors, such as flow regulation and land-use change. This fragmentation is particularly evident in regulated tropical cascade-dam systems, where sediment generation, altered discharge regimes, and inherited geomorphic structure interact nonlinearly. To date, no basin-scale framework systematically integrates erosion intensity, hydrological alteration, and morphometric susceptibility into a unified prioritization model. Addressing this methodological gap is essential for advancing watershed-scale risk screening beyond standalone metrics.

A few documented issues have been recorded in Perak river basin related to river morphological changes. In-stream sand mining in the Perak River, particularly near river islands and floodplains, has been shown to cause riverbank erosion and channel instability. Although replenishment rates are high (up to 1245 m³/day), over-extraction risks morphological degradation and bank collapse (Saleh & Abustan, 2017). The confluence between the Kurau and Ara Rivers (tributaries of Perak River) shows localized scour holes and sediment bars due to strong flow velocity gradients (Ali et al., 2019; Muhammad Ali et al., 2024). GIS and RUSLE modelling indicate that 18% of the lower Perak river basin faces extreme soil erosion risk (>100 t/ha/yr), largely linked to land-use conversion from forest to oil palm and urban areas between 2010–2013 (Yusof et al., 2016). A complementary state-wide soil erosion map confirmed that steep slopes and deforested zones are high-risk erosion hotspots (Omar et al., 2018). In the Kinta River sub-basin, sediment yield fluctuated dramatically (1,757–4,062 t/km²/yr) due to land use change and reduced mining, with current erosion rates lower but still above natural baselines (Ismail & Hashim, 2015). Rainfall across Perak has shown a slight long-term decrease, especially during the southwest monsoon, potentially affecting sediment transport and flow variability (Hanif et al., 2022). However, two key limitations are evident in previous studies.

Previous studies in the Perak River Basin have often been limited in scope, with study areas that were not sufficiently diverse to capture the spatial variability of the basin's geomorphic and hydrological characteristics. Furthermore, most analyses have focused on single parameters, without integrating multiple morphological and hydrological factors that jointly influence basin dynamics and landscape stability. The Perak River Basin has experienced progressive reservoir sedimentation, altered flow regimes due to cascade dam systems, and localized floodplain exposure in downstream reaches. These basin-specific challenges necessitate an integrated assessment that links hillslope erosion, hydrological modification, and geomorphic basin maturity. Therefore, the present study applies RUSLE, IHA, and hypsometric analysis not as standalone tools, but as components of a basin-scale susceptibility synthesis framework tailored to the Perak system. In response to the identified research gaps, the study was guided by the following hypotheses: H1: Subcatchments with higher soil loss rates and greater flow alteration exhibit higher composite susceptibility indices; H2: Morphologically mature basins with concave hypsometric curves demonstrate lower susceptibility than geomorphically active subcatchments; H3: An integrated, weighted watershed susceptibility framework provides clearer spatial prioritization than standalone erosion or hydrological assessments. Thus, the present study was designed with

three key objectives: (1) to quantify soil loss, flow alteration, and river morphology within the Perak River Basin; (2) to normalize and assign weightings to each parameter to ensure comparability; and (3) to develop an integrated susceptibility index to assess and map the spatial distribution of geomorphic and hydrological risk across the basin. Unlike conventional studies that apply RUSLE, IHA, or hypsometric analysis independently, this study proposes a weighted, basin-wide watershed susceptibility framework that integrates soil erosion, hydrological alteration, and morphological characteristics into a unified composite index. The novelty of this approach lies not only in the application of established models, but also in the normalization and weighting scheme that enables cross-parameter comparability and basin-scale susceptibility prioritization. This integrative framework provides a more comprehensive assessment of watershed susceptibility by linking geomorphic processes with hydrological regulation within a single analytical structure.

2. LITERATURE REVIEW

2.1 Flow regulation and hydrological alteration in tropical basins

Hydrological regimes in tropical river systems are highly sensitive to anthropogenic disturbances, particularly dam construction, water abstraction, and land-use modification (Stewardson et al., 2017). Numerous studies have demonstrated that river regulation alters the magnitude, frequency, timing, and duration of flows, consequently affecting sediment transport, channel stability, and ecological processes. Applications of the Indicators of Hydrologic Alteration (IHA) framework in Malaysian river basins, including the Selangor (Hairan et al., 2021) and Terengganu systems (Mohd Zamri et al., 2021), have revealed reduced peak discharges during monsoon seasons and elevated minimum flows during dry periods due to reservoir operations and land-use changes. Such alterations modify sediment delivery processes and downstream geomorphic dynamics. While these studies provide valuable insights into flow regime shifts, most assessments remain focused solely on hydrological metrics without linking them to basin-scale erosion or morphological susceptibility.

2.2 Land-use change and soil erosion dynamics

Soil erosion remains one of the primary environmental challenges in tropical watersheds, particularly in regions experiencing rapid land development and agricultural expansion. In Malaysia, the Revised Universal Soil Loss Equation (RUSLE) has been widely applied to estimate spatial soil loss rates using GIS-based modelling. Studies conducted in the Pansoon Sub-basin (Yusof et al., 2019), Lower Perak River Basin (Yusof et al., 2016), and other

Malaysian catchments consistently indicate that deforestation, plantation agriculture, and urbanization significantly increase soil erosion risk. These investigations demonstrate that rainfall erosivity, slope steepness, and land cover are dominant drivers of sediment yield in tropical terrains.

However, most soil erosion studies evaluate erosion potential independently, without considering hydrological regulation effects or long-term geomorphic stability. As a result, while RUSLE provides robust estimates of potential soil loss, it does not fully capture how altered flow regimes or basin maturity influence sediment redistribution and susceptibility at the broader watershed scale.

2.3 Erosion-morphology coupling and hypsometric analysis

Geomorphic evolution plays a critical role in determining basin susceptibility to erosion and sediment transport. The Hypsometric Integral (HI) has long been used as a quantitative indicator of watershed maturity, reflecting the relationship between elevation distribution and erosional development. In Malaysian contexts, hypsometric analyses of basins such as the Pahang River (Anuar et al., 2024) and other regional catchments (Melsse et al., 2025) have identified equilibrium and mature geomorphic stages characterized by concave or S-shaped hypsometric curves.

Lower HI values are typically associated with old-stage basins that have undergone extensive erosion and exhibited subdued relief, whereas higher HI values indicate more youthful or morphologically active landscapes. Despite the relevance of HI in assessing terrain stability and erosion potential, morphological indicators are rarely integrated with soil erosion modelling or hydrological alteration assessments within a unified analytical framework.

3. MATERIALS AND METHODS

This section outlines the geographical context of the Perak River Basin and its sub-basins, followed by a description of the datasets and analytical methods employed to assess river morphology.

3.1 Study area description

Perak River Basin is located in the state of Perak, Malaysia, representing one of the country's most significant hydrological systems, and draining a large portion of the central and northern regions of the state. The basin extends longitudinally from the Temenggor Dam in the north near the Thai border to the river's outlet along the west coast, encompassing several major tributaries including Rui River, Pelus River, Kinta River, Batang Padang River, and Bidor River. The basin is further subdivided into distinct hydrological units such as the Upper, Middle, and Lower Perak River, and

Upper and Lower Kinta sub-basins, each contributing differently to the basin's overall flow regime and sediment dynamics as shown in Figure 1. Four major reservoirs, Temenggor, Bersia, Kenering, and Chenderoh Dams, are distributed along the main river stem and play critical roles in hydropower generation, flow regulation, and flood control. The basin's physiography transitions from steep, forested uplands in the north to low-lying alluvial plains in the south, influencing spatial variability in soil erosion, sediment yield, and river morphology.



Figure 1: Perak River Basin.

3.2 Data collection and preparation

The Soil Loss component of the susceptibility matrix was developed using the Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1997), which integrated climatic, soil, topographic, and land management factors to estimate potential soil erosion. Rainfall Erosivity R was obtained from MSMA 2nd edition (Department of Irrigation and Drainage DID, 2012), while soil data provided the basis for determining the soil erodibility factor (K). The topographic parameters, including slope length and steepness (LS), were derived from a Digital Elevation Model (DEM). A Digital Elevation Model (DEM), with a spatial resolution of 5 m was used for terrain analysis and LS -factor computation. The DEM was hydrologically corrected using fill and flow direction

algorithms prior to slope and flow accumulation derivation. Land use and land cover (LULC) data were utilized to estimate the cover management (C) and support practice (P) factors. Each factor was spatially modelled in a Geographic Information System (GIS) environment to generate a soil loss map. The resulting outputs were categorized into classes representing low, moderate, high, and very high erosion susceptibility zones (Ramasamy et al., 2019), forming the first input layer for the susceptibility matrix.

The Flow Alteration indicator was designed to capture deviations from natural hydrologic conditions, reflecting both climatic variability and anthropogenic pressures. Flow alteration was assessed using long-term daily discharge records obtained from 24 gauging stations within the Perak River Basin. Of these, 13 stations with sufficiently long and continuous records were selected for assessment, while shorter or incomplete datasets were excluded to maintain statistical reliability. The selected stations generally span multi-decadal records between 1960 and 2024, ensuring robust representation of long-term hydrological variability. These flow datasets were analysed using the Indicators of Hydrologic Alteration (IHA) framework (Arévalo-Mejía et al., 2023; Richter et al., 1996). This approach quantified changes in key flow regime parameters, including magnitude, timing, duration, frequency, and rate of change in river discharge. The computed indicators were synthesized into a flow alteration index, representing the degree of hydrological disturbance across the basin. The index was normalized and classified into low, moderate, and high categories, corresponding to increasing levels of hydrologic alteration and potential flood or drought susceptibility.

The River Morphology component was assessed through terrain and basin morphometric analysis using DEM-derived parameters. The hypsometric curve and hypsometric integral were computed to evaluate the erosional development stage and geomorphic stability of the catchment (Strahler, 1957). High hypsometric integral values were interpreted as indicative of youthful, erosion-prone basins, while lower values signified mature and stable landscapes (Langbein, 1947). Additional morphometric indicators, such as slope, relief ratio, and drainage density, were analysed to complement the hypsometric interpretation. This analysis allowed the identification of geomorphologically sensitive zones prone to mass movement, channel migration, or sediment instability, which were then integrated into the morphological susceptibility layer.

Finally, the Susceptibility Classification and Integration phase combined the three normalized indicators, normalized soil loss (SL_n), normalized flow alteration (FA_n), and normalized morphological characteristics (MC_n), using a

weighted linear combination model. Weights were assigned to each indicator based on their relative contribution to risk potential, with 0.40 for soil loss, 0.35 for flow alteration, and 0.25 for morphological characteristics. The composite susceptibility index was computed as $H = 0.4 (SL_n) + 0.35 (FAn) + 0.25 (MC_n)$

The final susceptibility classes were defined using an equal interval classification scheme applied to the normalized composite index ranging from 0 to 1. The equal interval classification scheme was selected to maintain methodological transparency and consistency with the normalized 0–1 composite index. Because the susceptibility index was derived through min–max normalization, the total

possible range was fixed and bounded. Dividing this range into five equal class widths (0.20 intervals) ensured objective and reproducible threshold definition without introducing subjective breakpoints. Accordingly, the classes were defined as: Very Low (<0.20), Low (0.21–0.40), Moderate (0.41–0.60), High (0.61–0.80), and Very High (>0.80). This approach allowed transparent threshold definition and facilitated comparability between sub-catchments within the basin. The final product of the integrated framework was a spatially explicit susceptibility map that highlighted priority areas for soil erosion control, hydrological management, and basin-scale geomorphological stabilization. The complete methodological workflow underpinning the analysis is summarized in Figure 2.

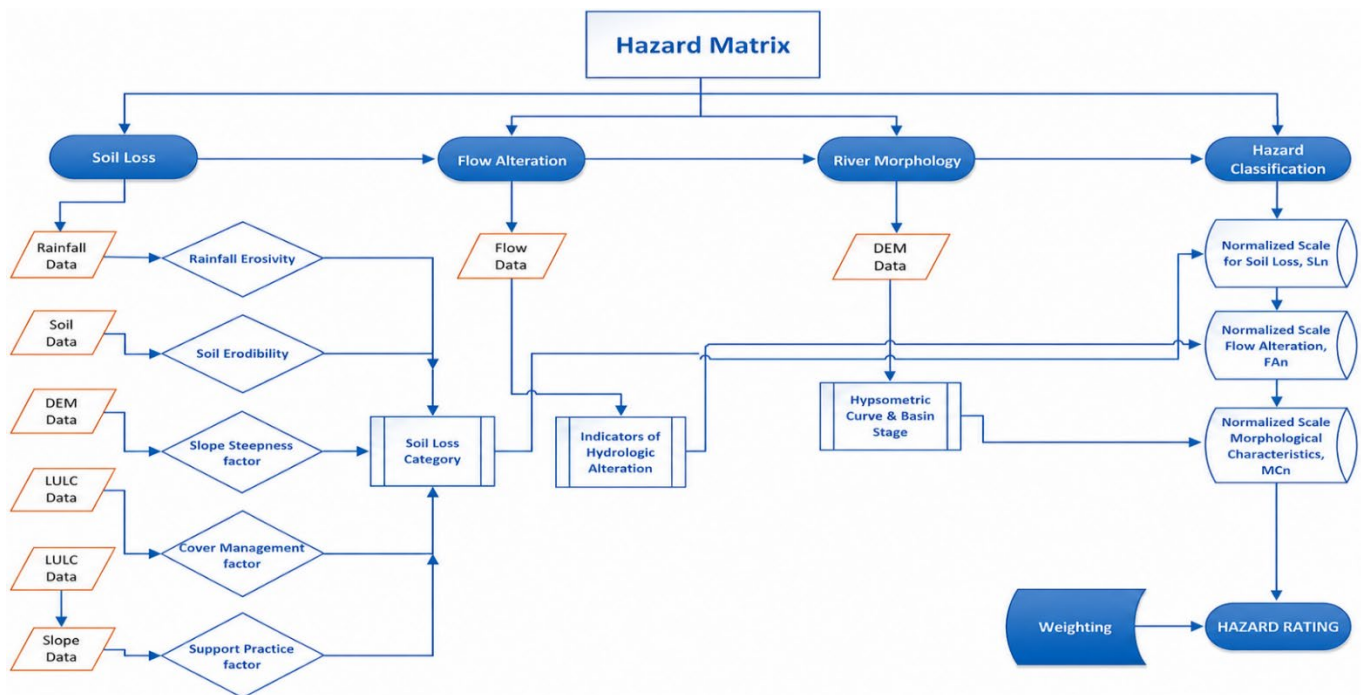


Figure 2: Overall flowcharts of research works

3.3 River morphology assessment

River morphology assessment encompasses a wide range of analyses, including the evaluation of physical form, basin morphometry, fluvial processes, and hypsometric characteristics. In this study, readily available Digital Elevation Models (DEMs) and Geographic Information System (GIS) tools were utilized to efficiently and cost-effectively derive hypsometric attributes for water resources analysis. These attributes are valuable for the planning, design, and management of water systems. Hypsometry involves measuring and analysing the distribution of land elevations within a drainage basin, watershed, or landform. It is typically represented by a Hypsometric Curve, which illustrates the

proportion of land area at various elevations within the basin. The Hypsometric Integral (HI), a quantitative metric derived from the curve, provides insight into the geomorphic evolution stage of a landscape, indicating whether a basin is in a youthful, mature, or old stage of development as shown in Table 1 (Strahler, 1957).

Table 1: Hypsometric Integral Classification.

HI values	Basin Stage	Morphological Characteristics
>0.6	Young	Convex Curve High elevation, steep slopes, active erosion
0.3 – 0.6	Mature	S-Shaped Curve Balanced terrain, moderate erosion, mixed relief
<0.3	Old	Concave Curve Low relief, stable basin, broad valleys

3.4 Soil loss estimation

Soil loss was estimated using the Revised Universal Soil Loss Equation (RUSLE), an empirical model that predicts the long-term average annual rate of erosion caused by rainfall and surface runoff (Renard et al., 1997; Wischmeier & Smith, 1978). The model is expressed as:

$$A = R \times K \times LS \times C \times P$$

where A is the computed soil loss ($\text{t ha}^{-1} \text{ yr}^{-1}$), R represents the rainfall erosivity factor, K is the soil erodibility factor, LS denotes the topographic factor combining slope length and steepness, C is the cover management factor, and P is the support practice factor. In this study, rainfall data were used to derive the R-factor, while soil properties such as texture and organic matter were applied to calculate the K-factor. The LS-factor was extracted from a Digital Elevation Model (DEM), and the C and P factors were determined from land use and land cover (LULC) data. All factors were processed in a GIS environment to produce a spatially distributed soil loss map, which was subsequently classified into erosion severity categories as shown in Table 2.

Table 2: Soil erosion class.

Number	Soil Erosion Class (ton/ha.year)	Values
1	0 – 10	Very Slight / Very Low
2	10 – 20	Slight / Low
3	20 – 30	Moderate
4	30 – 50	High / Severe
5	> 50	Very High / Very Severe
6	> 100	Extremely Severe

3.5 Flow alteration analysis

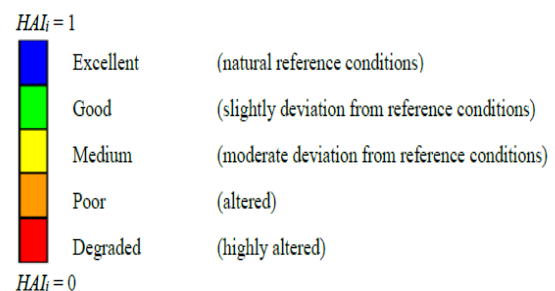
The term hydrological alteration (HA) refers to deviations in the hydrologic regime from its natural variability across any component of the water balance (Stewardson et al., 2017). In river systems, flow regime classification is closely associated with seasonal patterns—typically wet and dry periods—that influence the dynamics of local ecosystems (Arévalo-Mejía et al., 2023). Variations in flow regimes directly affect the distribution, abundance, and survival of aquatic and riparian species, including plants, fish, macroinvertebrates, and amphibians. When significant deviations from natural flow conditions occur, whether due to anthropogenic modifications or climatic factors, it becomes essential to reassess ecosystem sustainability and determine whether these changes remain within acceptable ecological thresholds. It is important to note that hydrological alteration does not inherently translate into geomorphic hazard. The susceptibility interpretation focuses primarily on alterations that influence flow magnitude variability and high-flow frequency, which are known to drive bank erosion, channel widening, and sediment remobilization. In contrast, alterations that merely dampen seasonal variability without increasing erosive power may not

significantly elevate geomorphic risk. Therefore, the flow alteration index is interpreted in relation to its potential to modify hydraulic energy and sediment transport dynamics rather than assuming uniform hazard across all types of hydrological deviation. To quantify the degree of deviation, the Hydrological Alteration Index (HAI) proposed by Martínez Santa-María et al. (2010) was applied. This index evaluates changes between the Natural Hydrological Regime (NHR) and the Altered Hydrological Regime (AHR) by analysing two principal flow regimes: normal values and extreme values. The HAI comprised 20 sub-indices that collectively describe hydrological variability; these were aggregated into two components—a Partial Index and a Global Index—as expressed in the following equation:

$$HAI_i = \frac{HAI_{AHR}}{HAI_{NHR}}$$

where HAI_i = partial index, HAI_{AHR} = is the index for the altered condition and HAI_{NHR} is the index for the natural condition as shown in Figure 3.

It is acknowledged that estimating flow alteration for ungauged subcatchments introduces uncertainty into the watershed susceptibility framework. The spatial averaging approach assumes hydrological similarity between adjacent catchments; however, localized regulation structures, abstraction practices, or micro-scale land use variability may not be fully captured. Consequently, susceptibility rankings in certain ungauged subcatchments may be subjected to minor classification shifts, particularly where flow alteration contributes significantly to the composite index. Nevertheless, the sensitivity analysis demonstrated that moderate variations in weighting produced minimal changes in susceptibility class, suggesting that the overall basin-wide prioritization remained robust despite these uncertainties.



Level I	Level II	Level III	Level IV	Level V
$0.8 < HAI_i \leq 1$	$0.6 < HAI_i \leq 0.8$	$0.4 < HAI_i \leq 0.6$	$0.2 < HAI_i \leq 0.4$	$0 \leq HAI_i \leq 0.2$
$0.64 < GAI_i \leq 1$	$0.36 < GAI_i \leq 0.64$	$0.16 < GAI_i \leq 0.36$	$0.04 < GAI_i \leq 0.16$	$0 \leq GAI_i \leq 0.04$

Figure 3: Ratings of flow Alteration proposed by Arévalo-Mejía et al. (2023)

3.6 Development of susceptibility matrix classification

There were three (3) steps involved in the formulation of the susceptibility matrix. The first step was obtaining the normalization scale as shown in Table 3. Each scale should be normalized (0-1) to ensure that all parameters were comparable.

Table 3: Indicator, description and normalization type for each parameter

Indicator	Description	Typical Data Source and Modelling	Normalization Type	Notes
Soil Loss (SL)	Average annual soil erosion (t/ha/yr)	RUSLE modelling	Min-max normalization	Proxy for erosional susceptibility
Flow Alteration (FA)	Deviation of flow regime (index or %)	Flow Analysis and IHA Modelling	Percent deviation normalized	Proxy for hydrological susceptibility
Morphological Characteristics (MC)	Hypsometric Integral (HI) describes the erosional maturity of a watershed	DEM-derived analysis	Min-max normalization or composite	Proxy for geomorphic susceptibility

These indicators were then assigned with weightage based on the sensitivity rationalization as previously proposed by Haron et al. (2022) and Sulaiman et al. (2021). The weights were assigned to reflect the relative influence of the three processes on basin susceptibility. The weighting scheme (0.40 soil loss, 0.35 flow alteration, 0.25 hypsometric integral) was designed to reflect geomorphic process hierarchy rather than statistical variance contribution. In tropical basins, hillslope erosion constitutes the primary sediment source and directly governs sediment availability within the fluvial system; therefore, soil loss was assigned the highest weight. Hydrological alteration, while not generating sediment, regulates hydraulic energy, transport capacity, and peak flow variability, thereby acting as a process amplifier that influences channel instability and sediment redistribution. Morphological characteristics represent inherited basin predisposition and long-term geomorphic maturity, functioning primarily as a conditioning factor rather than an active stress driver. Besides that, a sensitivity analysis section to evaluate the robustness of susceptibility classification to plausible alternative weighting schemes (equal weights and ± 10 –20% perturbations) was carried out and discussed in the discussion section. Table 4 shows the weightage and rationalization of these numbers. The susceptibility index formula is the adopted as discussed in the previous section.

Table 4: Weightage adopted for each indicator

Indicator	Weight	Rationale
Soil Loss (SL)	0.40	Primary driver of erosion susceptibility
Flow Alteration (FA)	0.35	Hydrological stress influencing sediment transport
Morphology (MC)	0.25	Terrain influence on process amplification

4.

5. RESULTS AND DISCUSSIONS

This section presents the results and discussion of the three main parameters analyzed in this study: morphological characteristics, soil loss, and flow alteration within the Perak River Basin. In addition, a comprehensive susceptibility index was developed using the aforementioned conceptual framework and methodological approach to integrate these parameters into a unified assessment of basin-wide potential susceptibility.

4.1 Morphological characteristics of Perak River basin

The hypsometric integral (HI) values indicate the morphological stage of the river basins, which significantly influences erosion rates, sediment transport dynamics, riverbank erosion, and overall river morphology. The basins are classified into old and mature stages, with their respective characteristics shaping the hydrological and geomorphic processes. The hypsometric analysis of the catchments indicated that most basins, such as Bersia, Chenderoh, Kenering, Lower Sg Kinta, Lower Sg Perak, Middle Sg Perak, Batang Padang, Sg Bidor, and Sg Kinta, were in an old-stage geomorphic phase with low relief and broad valleys as shown in Table 5. These basins exhibited a concave hypsometric curve, signifying limited active erosion due to a well-matured landscape. The primary erosion process is fluvial erosion along valley floors, while hillslope erosion is minimal. In contrast, Sg Pelus, Sg Rui, and Temenggong Dam exhibit an S-shaped curve with an HI ranging from 0.30 to 0.32, indicating a mature-stage basin where moderate erosion still occurred, particularly in steeper regions (see Figure 4). These basins continue to evolve geomorphologically, contributing moderate sediment loads into their river networks.

The sediment transport dynamics differ between old and mature-stage basins. In old-stage basins, erosion has significantly reduced, meaning that sediment transport is dominant over sediment generation. The rivers mainly transport fine sediments, as coarser materials have already been deposited upstream or within reservoirs. In contrast, mature-stage basins still experience some level of upland erosion, leading to greater sediment input into river systems. These basins contribute a mix of fine and coarse sediments, depending on the flow energy and sediment availability from

the upstream regions. The balance between erosion and sediment transport in mature basins plays a key role in channel stability and downstream sedimentation patterns.

The river morphology in old-stage basins is characterized by broad valleys, low-gradient channels, and meandering river systems. With reduced erosion, these rivers accumulate more sediment, leading to shallowing and potential flooding issues. Effective river management in these areas should focus on sediment control, floodplain management, and bank stabilization. In mature-stage basins,

the rivers display a mix of straight, meandering, and braided channels, depending on localized flow conditions and sediment transport processes. These basins may require erosion control measures in steeper sections to prevent excessive sediment input into downstream reaches. Overall, understanding the hypsometric evolution of these basins provides critical insights for erosion control, sediment transport management, and sustainable river engineering strategies.

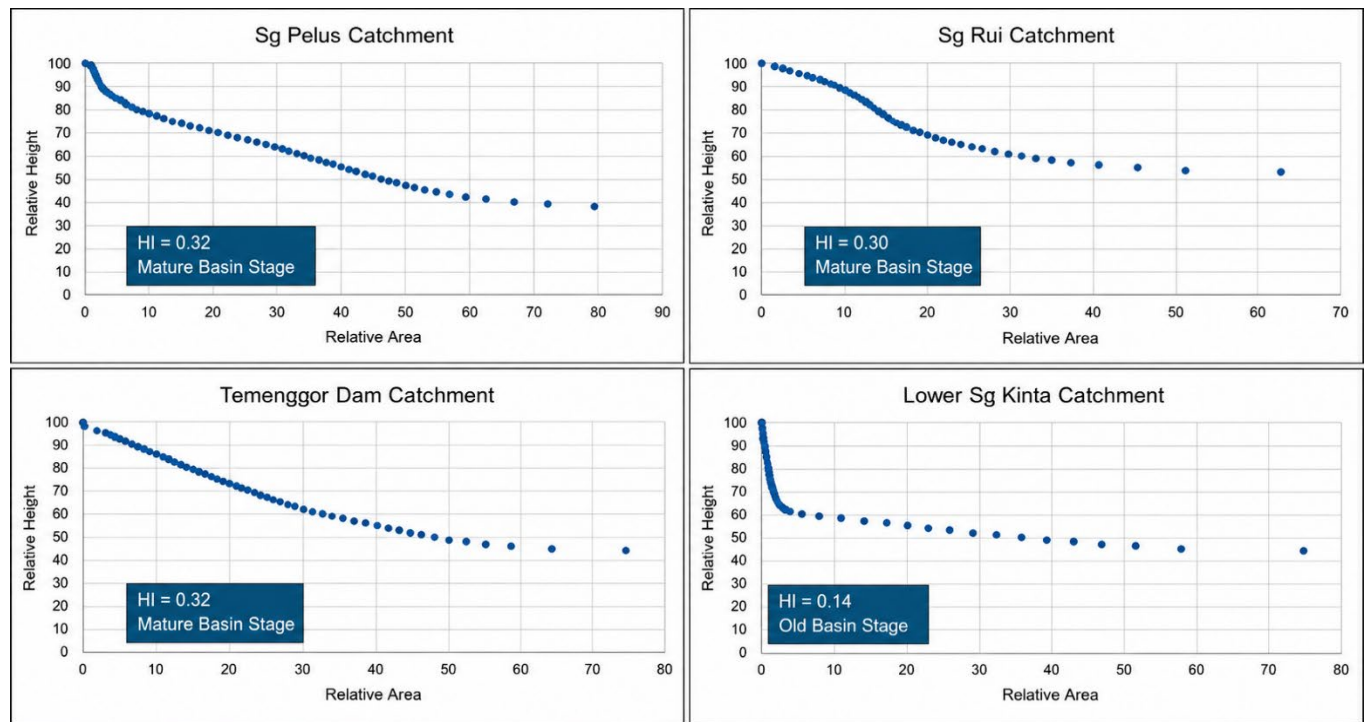


Figure 4: Hypsometric curve for study area

Recent research has increasingly applied the Hypsometric Integral (HI) as a diagnostic tool to evaluate geomorphic evolution and erosion susceptibility in tropical river basins. In Malaysia, the HI has been used to characterize watershed maturity and terrain stability, providing insight into landscape response to erosion and tectonic activity. For instance, a recent study of the Pahang River Basin by Anuar et al. (2024) applied hypsometric analysis using 30 m DEM data and reported HI values ranging from 0.47 to 0.48,

suggesting that the basin was in a state of geomorphic equilibrium (mature), with moderate erosional activity and stable relief conditions. These findings align with typical characteristics of mature basins where uplift and denudation are balanced (Strahler, 1952). Earlier morphometric analyses in Malaysian basins, such as those conducted in Ulu Kuantan and Lepar, also revealed concave hypsometric curves and low to moderate HI values, indicative of advanced erosional development (Vanderwaal & Ssegane, 2013).

Table 5: Hypsometric analysis for study area

No	Catchment Name	Hypsometric Integral, HI	Basin Stage	Morphological Characteristics
1	Bersia Dam Catchment	0.27	Old	Concave Curve, Low relief, stable basin, broad valleys
2	Chenderoh Dam Catchment	0.29	Old	Concave Curve, Low relief, stable basin, broad valleys
3	Kenering Dam Catchment	0.28	Old	Concave Curve, Low relief, stable basin, broad valleys
4	Lower Sg Kinta Catchment	0.14	Old	Concave Curve, Low relief, stable basin, broad valleys
5	Lower Sg Perak Catchment	0.06	Old	Concave Curve, Low relief, stable basin, broad valleys
6	Middle Sg Perak Catchment	0.19	Old	Concave Curve, Low relief, stable basin, broad valleys
7	Batang Padang Catchment	0.28	Old	Concave Curve, Low relief, stable basin, broad valleys
8	Sg Bidor Catchment	0.19	Old	Concave Curve, Low relief, stable basin, broad valleys
9	Sg Pelus Catchment	0.32	Mature	S-Shaped Curve, Balanced terrain, moderate erosion, mixed relief
10	Sg Rui Catchment	0.30	Mature	S-Shaped Curve, Balanced terrain, moderate erosion, mixed relief
11	Temenggong Dam Catchment	0.32	Mature	S-Shaped Curve, Balanced terrain, moderate erosion, mixed relief

When compared with the present study, the Perak River Basin demonstrated a broader range of HI values, reflecting more diverse geomorphic stages across its subcatchments—from old, low-relief landscapes to more active, mature terrains. This variability highlights the influence of both tectono-geomorphic controls and land-use modifications on basin evolution. The wider spatial heterogeneity of HI values observed in the Perak Basin suggests that, unlike the Pahang Basin's overall equilibrium state, parts of Perak remain geomorphically active and more susceptible to erosional processes. This finding is consistent with other regional hypsometric analyses that associate higher HI values with steeper terrain and greater erosion potential, and lower values with stabilized, sediment-depositional zones.

4.2 Soil loss of Perak River basin

Annual soil loss was estimated using Pixel-Based Multiplication Approach in GIS. The soil loss is calculated by multiplying the raster values of each factor on a cell-by-cell basis using map algebra. The pixel-based multiplication approach preserves spatial heterogeneity and is therefore more suitable for GIS-based erosion modelling.

Based on the soil loss distribution in the Perak River Basin (see Table 6), the analysis indicates significant spatial variation in soil erosion intensity across different sub-catchments. The Lower Sg Kinta Catchment exhibited the highest soil loss at 120 ton/ha/year, categorized as high according to the Department of Agriculture (DOA) classification. With an extensive area of 153,385.77 ha, the total soil loss was approximately 18.4 million tons per year, highlighting severe erosion risks. Other catchments with high soil loss included Batang Padang (106.73 ton/ha/year), Bersia

Dam (102.26 ton/ha/year), and Sg Rui (102.15 ton/ha/year), all of which contributed significantly to sediment production in the basin. These areas require urgent soil conservation measures, particularly on steep slopes and deforested regions prone to surface runoff.

Several sub-catchments experienced moderately high soil loss, ranging between 53.30 to 95.89 ton/ha/year. Notably, Sg Pelus (95.89 ton/ha/year), Sg Bidor (53.82 ton/ha/year), and Temenggor Dam Catchment (53.30 ton/ha/year) fell within this category. Despite slightly lower erosion rates than high-risk areas, these catchments contributed substantial sediment loads, such as Temenggor Dam Catchment, which had a total annual soil loss of 18.5 million tons due to its large catchment size (347,215.70 ha). These areas were susceptible to degradation, potentially impacting water quality and reservoir sedimentation.

Moderate soil loss was observed in Kenering Dam (44.01 ton/ha/year) and Chenderoh Dam Catchment (15.11 ton/ha/year). The Kenering Dam Catchment, covering 105,179.46 ha, generated 4.6 million tons of soil loss per year, which could be contributed to sedimentation and reduce reservoir capacity over time. Chenderoh Dam Catchment, with 15.11 ton/ha/year, showed comparatively lower erosion rates but still presented concerns for long-term land degradation and water resource sustainability. Catchments classified under low soil loss included Middle Sg Perak (3.62 ton/ha/year) and Lower Sg Perak (1.74 ton/ha/year), which had the lowest erosion risk in the basin. These regions exhibited stable land cover and lower slopes minimizing sediment transport. The overall spatial soil loss mapping for whole Perak River Basin is illustrated in Figure 5.

Table 6: Averaged soil loss in each catchment

No	Catchment Name	Soil loss (ton/ha.year)	Soil Loss Category – Based on DOA Classification	Area (ha)	Total Soil Loss (ton/year)
1	Bersia Dam Catchment	102.26	High	27,110.58	2,772,327.91
2	Chenderoh Dam Catchment	15.11	Moderate	97,365.46	1,471,192.10
3	Kenering Dam Catchment	44.01	Moderate	105,179.46	4,628,948.03
4	Lower Sg Kinta Catchment	120.00	High	153,385.77	18,406,292.40
5	Lower Sg Perak Catchment	1.74	Low	146,644.48	255,161.40
6	Middle Sg Perak Catchment	3.62	Low	105,727.91	382,735.03
7	Batang Padang Catchment	106.73	High	69,947.41	7,465,487.07
8	Sg Bidor Catchment	53.82	Moderately High	109,605.91	5,898,990.08
9	Sg Pelus Catchment	95.89	Moderately High	140,951.54	13,515,843.17
10	Sg Rui Catchment	102.15	High	88,741.06	9,064,899.28
11	Temenggor Dam Catchment	53.30	Moderately High	347,215.70	18,506,596.81
12	Upper Sg Kinta Catchment	84.67	Moderately High	105,475.38	8,930,600.42

* <10 ton/ha.year = Low ; 10-50 ton/ha.year = Moderate; 50-100ton/ha.year = Moderately High; 100 – 150 ton/ha.year = High; >150 ton/ha.year = Very High

A comparative assessment with previous studies, particularly that of Nazuhan et al. (2018) conducted within the same study area, revealed a close correspondence in the estimated soil loss magnitudes. The current study recorded

soil loss values ranging from 1.74 to 120.00 t ha⁻¹ yr⁻¹, which aligned well with the earlier findings of 0.74 to 62.00 t ha⁻¹ yr⁻¹ reported by Nazuhan et al. (2018). The observed differences between the two studies can be primarily attributed to two key factors: first, land use changes that have occurred between

2018 and the present study period (2025) led to altered surface cover and runoff conditions; and second, the application of a higher rainfall erosivity (R) factor in the current analysis reflected updated climatic data and improved rainfall intensity representation as previously adopted by Nasir Ahmad et al. (2024). These variations underscore the dynamic nature of erosion processes in the basin and the importance of incorporating temporal land-use and climatic variability in long-term soil loss assessments. A comparison with Yusof et al. (2019), who estimated soil loss in the Pansoon Sub-basin, showed that while localized erosion in small tropical catchments could reach extremely high magnitudes (up to $18,473 \text{ t ha}^{-1} \text{ yr}^{-1}$) and the average soil loss of $38.91 \text{ t ha}^{-1} \text{ yr}^{-1}$, the basin-wide assessment in this study yielded a more moderate and spatially consistent range of $1.74\text{--}120 \text{ t ha}^{-1} \text{ yr}^{-1}$. The difference arises primarily from scale, land cover diversity, and the integration of hydrological and morphological factors in the present model, which collectively shows moderate erosion extremes. The findings from the Perak River Basin therefore represent a more realistic long-term erosion trend for large, regulated river systems in Malaysia, complementing earlier localized studies such as Yusof et al. (2019) that focused on small, disturbed catchments.

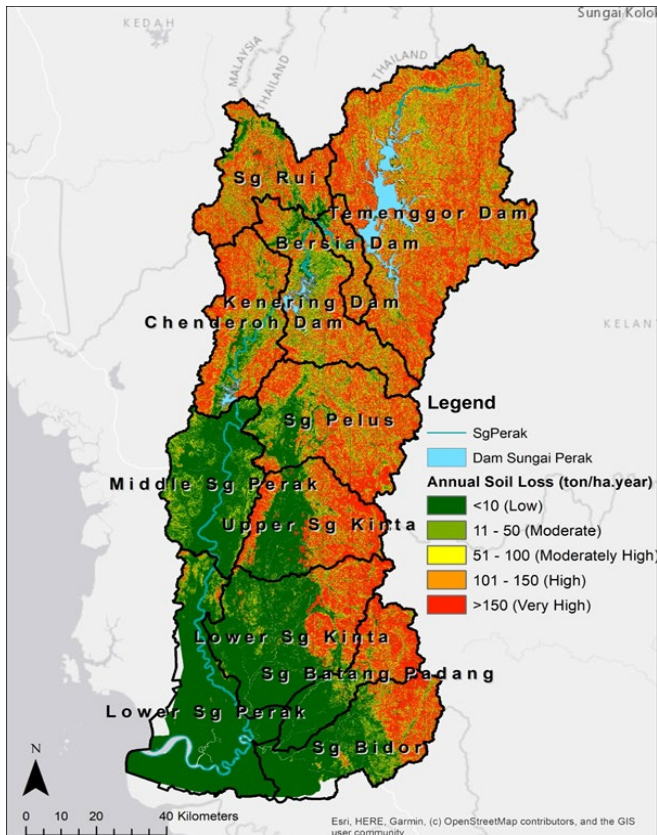


Figure 5: Overall Soil Loss for Perak River Basin

4.3 Flow alteration indexes at Perak River basin

The flow alteration assessment was conducted using the datasets outlined in Table 7. However, some stations were excluded from the analysis due to the unavailability of adequate datasets, specifically those lacking a minimum of 15 years of continuous data. To facilitate a comprehensive evaluation of flow alterations, the data were categorized into two distinct groups: Natural-flow and Altered-flow regimes. This division allowed for a detailed examination of the decadal impacts of land-use changes on streamflow dynamics, providing insights into how these changes have influenced flow patterns over time.

Table 7: Datasets for flow alteration analysis

No.	Station ID	Station Name	Duration	Assessment
1	0180681SF	Sg. Bidor Batu 9 Jln. Anson	1960-1980	No
2	0180691SF	Sg. Bidor at Bidor Perak	1961-2020	Yes
3	0180701SF	Sg. Bidor at Bt. 18 Jln Anson	1960-1980	No
4	0180711SF	Sg. Btg. Padang Perak at Tapah Perak	1964-1974	No
5	0180721SF	Sg. Btg. Padang at Tg. Keramat Perak	1960-2024	Yes
6	0180731SF	Sg. Gedong at Idor Perak	1965-1974	No
7	0180741SF	Sg. Kampar at Kg. Lanjut Perak	1960-2024	Yes
8	0180751SF	Sg. Kinta at Batu Gajah Perak	1960-1984	No
9	0180761SF	Sg. Kinta at Tg. Rambutan Perak	1960-2024	Yes
10	0180771SF	Sg. Pari at Jln. Silibin Perak	1960-2024	Yes
11	0180781SF	Sg. Perak at Jam. Iskandar Perak	1960-2024	Yes
12	0180791SF	Sg. Plus at Kg. Lintang Perak	1960-2024	Yes
13	0180801SF	Sg. Raia at Ldg. Kinta Kellas	1960-1970	No
14	0180811SF	Sg. Sungkai at Jln Anson-Kampar	1960-1983	No
15	0180821SF	Sg. Sungkai at Sungkai Perak	1960-2024	Yes
16	0180841SF	Sg. Kinta at Ipoh Perak	1962-1980	No
17	0180941SF	Sg. Plus at Kg. Pulau mentimun	1965-1973	No
18	0180961SF	Sg. Cenderiangat Bt. 32 Jln. Tapah	1970-2024	Yes
19	0181001SF	Sg. Raia at Keramat Pulau Perak	1978-2024	Yes
20	0181051SF	Sg. Kinta at Weir Tg. Tualang	1976-2024	Yes
21	0181071SF	Sg. Bidor at Bidor Tin Deviation	1976-1978	No
22	0181091SF	Sg. Tumbok at Kg. Gajah / Tg. Tualang	1978-1985	No
23	0181111SF	Sg. Bidor at Malayan Bidor Bhd.	1980-2024	Yes
24	0181141SF	Sg. Rui at Jam. Jln. Raya Perak	1987-2024	Yes

The Alteration Index (HAI) analysis presented in Table 8 provides valuable insights into the degree of hydrological regime modification across selected river stations in Perak River Basin. The HAI evaluates the deviation of flow conditions from natural reference states under three key

scenarios: typical regime (normal flow conditions), extreme maximum values (floods), and extreme minimum values (droughts). The scale ranges from 1.0 (excellent or natural conditions) to 0.0 (degraded or highly altered), with color-coded classifications from blue (excellent) to red (degraded). Based on this assessment, most of the stations (12 out of 13) were categorized as "Altered," while only one station, Sg. Cendering at Bt. 32 Jln. Tapah, maintained a "Non-altered" status, indicating relatively stable hydrological conditions at this site.

A closer examination of the index values revealed that Sg. Bidor at Bidor Perak and Sg. Kinta at Tg. Rambutan Perak were among the most severely impacted stations, showing consistently low HAI values across typical, flood, and drought conditions. These stations fell within the "Degraded" or "Poor" categories, reflecting significant hydrological alterations that might severely affect aquatic ecosystems and river health. In particular, the flood alteration values at Sg. Bidor (0.023) and Sg. Kinta (0.13) were especially low, suggesting strong modification of flood regimes. Similarly, these stations also exhibited low indices under drought conditions, with Sg. Kinta recording one of the lowest values (0.039), implying inadequate minimum flow maintenance which might threaten aquatic species during dry periods.

For the typical regime condition, the same stations again showed alarming values—0.085 for Sg. Bidor and 0.026 for Sg. Kinta—highlighting chronic alterations to their baseline flow patterns. This suggests that beyond extreme events like floods or droughts, the day-to-day flow regime itself has been significantly modified. In contrast, Sg. Cendering at Bt. 32 Jln. Tapah, the only "Non-altered" station, exhibited relatively high HAI values across all three scenarios, with typical, flood, and drought values in the "Good" to "Medium" categories, indicating a closer resemblance to natural flow conditions. Figure 6 shows the mapping of overall alteration status and example of alteration index findings at Sg. Cenderiang at Bt 32.

Several sub-basins exhibited substantial deviation from their typical flow regimes, as reflected by elevated alteration indices, suggesting modified hydrological variability relative to baseline conditions as shown in Figure 7. Elevated alteration indices indicate significant modification of flow magnitude and variability, which may influence peak flow behaviour and hydraulic energy distribution within affected sub-basins. Such changes have the potential to alter channel adjustment processes, including bank erosion and sediment remobilization. The identification of critically altered stations such as Sg. Bidor and Sg. Kinta provides a clear direction for river managers and policymakers to prioritize these locations for targeted interventions, including ecological restoration, improved flow regulation, and catchment management

practices.

Since not all catchments within the Perak River Basin were equipped with permanent flow gauging stations, it was not possible to directly compute the degree of flow alteration for every subcatchment. To address this limitation, the flow alteration values for the ungauged catchments were estimated based on the available data from gauged sites.

Specifically, the alteration indices derived at existing stations were spatially analysed and averaged to represent the expected hydrological alteration in the neighbouring ungauged subcatchments with similar hydrological and physiographic characteristics. This approach assumes that catchments with comparable drainage area, land use, and upstream flow regulation (e.g., dam influence or water abstraction) exhibit similar levels of flow modification. Although this introduces a degree of generalization, it provides a practical and consistent method for representing flow alteration patterns across the entire basin in the absence of comprehensive gauging coverage.

Table 8: Alteration index for selected stations

No.	Station Name	Typical Regime Index	Extreme maximum values (floods)	Extreme minimum values (droughts)	Status
1	Sg. Bidor At Bidor Perak	0.09	0.02	0.11	Altered
2	Padang At Tg. Keramat Perak	0.19	0.36	0.07	Altered
3	Sg. Kampar At Kg. Lanjut Perak	0.46	0.39	0.16	Altered
4	Sg. Kinta At Tg. Rambutan Perak	0.03	0.13	0.04	Altered
5	Sg. Pari At Jln Silibin Perak	0.49	0.41	0.23	Altered
6	Sg. Perak At Jam. Iskandar Perak	0.50	0.30	0.25	Altered
7	Sg. Plus At Kg. Lintang Perak	0.51	0.57	0.21	Altered
8	Sg. Sungkai At Sungkai Perak	0.53	0.25	0.04	Altered
9	Sg. Cenderiang At Bt. 32 Jln Tapah	0.61	0.44	0.49	Non-altered
10	Sg. Raia At Keramat Pulai Perak	0.36	0.33	0.37	Altered
11	Sg. Kinta At Weir Tg. Tualang	0.73	0.34	0.52	Altered
12	Sg. Bidor At Malayan Bidor Bhd.	0.73	0.34	0.52	Altered
13	Sg. Rui At Jam. Jln. Raya Perak	0.64	0.16	0.40	Altered

Recent studies of tropical and subtropical watersheds demonstrate similar patterns of hydrological alteration associated with dams, land-use change, and climate

variability as shown by Hairan et al. (2021). For example, an IHA-based assessment of the Selangor River Basin in Malaysia showed significant shifts in flow regimes, including increased minimum flows and reduced peak flows following long-term regulation (Hairan et al., 2021), which parallels our findings in the Perak River Basin where regulated flow dynamics were evident in normalized flow alteration indices.

Furthermore, broader hydrologic alteration research highlights the sensitivity of flow magnitudes, durations, and frequencies to anthropogenic interventions, strengthening the methodological foundation for using the IHA and environmental flow frameworks in tropical river studies (Zeiringer et al., 2018).

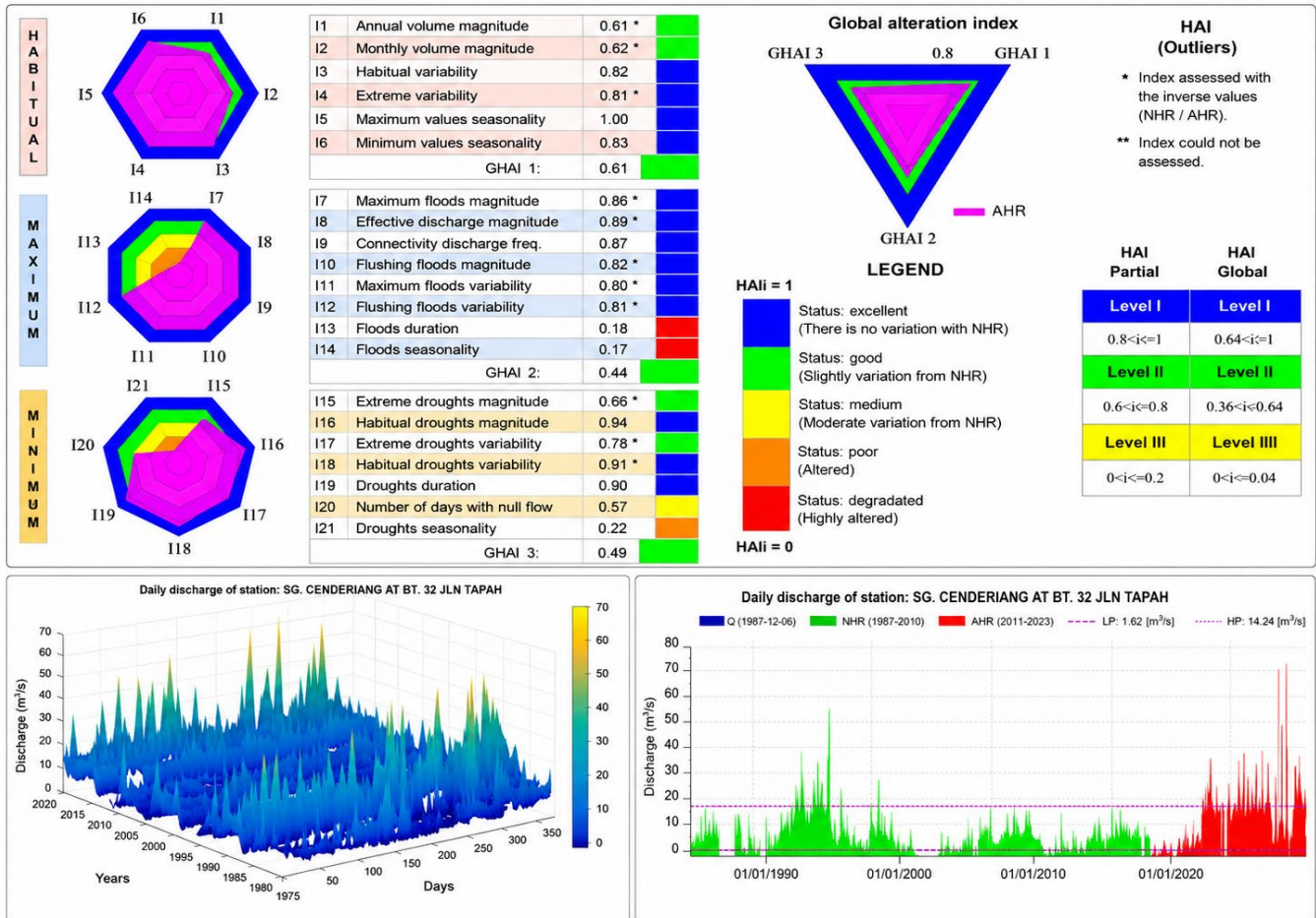


Figure 6: Flow Alteration Index at Sg. Cenderiang@Bt 32 Station

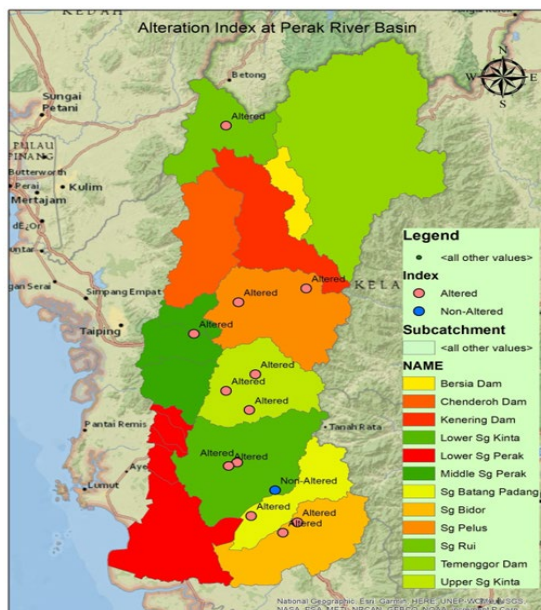


Figure 7: Overall Alteration Index Across Perak River Basin

4.4 Normalization and weightage assessment

Normalization is a critical step in ensuring that multi-parameter susceptibility assessments are both scientifically valid and comparable across different variables. Soil Loss (t/ha/yr), Flow Alteration Index, and Hypsometric Integral (HI) are measured in different units, scales, and magnitudes. If these parameters are combined without normalization, the variable with the largest numeric range (soil loss) will dominate the susceptibility index, making the model biased and unbalanced. Therefore, normalization ensures that all parameters contribute proportionally to the composite susceptibility index, regardless of their original measurement scales or units as shown in Table 9. The most suitable and widely accepted method for environmental and geomorphic indices is Min–Max Normalization as previously adopted by Demir et al. (2025) and Le et al. (2025), defined as:

$$X_{norm} = \frac{X - X_{min}}{X_{max} - X_{min}}$$

where:

- X = raw value of the parameter (e.g., soil loss rate),
- X_{min} and X_{max} = minimum and maximum observed values in the dataset,
- X_{norm} = normalized value (ranging between 0 and 1).

The resulting 0–1 scale is easy to interpret: 0 indicates lowest contribution to susceptibility, and 1 indicates highest contribution. It allows consistent comparison across parameters. Unlike standardization (Z-scores), min–max normalization keeps the relative spacing and ranking between values intact, which is critical for spatial risk mapping.

Table 9: Normalization formula and susceptibility interpretation

Indicator	Normalization Formula	Weight (W)	Susceptibility Interpretation
Soil Loss	$(SL - SL_{min}) / (SL_{max} - SL_{min})$	0.40	Higher SL → higher susceptibility
Flow Alteration	$1 - (FAI - FAI_{min}) / (FAI_{max} - FAI_{min})$	0.35	Lower FAI → higher susceptibility
Morphology (HI)	$(HI - HI_{min}) / (HI_{max} - HI_{min})$	0.25	Higher HI → higher susceptibility

The weighted soil loss matrix revealed distinct spatial variations in erosion potential across the subcatchments of the Perak River Basin. Table 10 reveals pronounced spatial variability in soil erosion across the Perak River Basin, with soil loss values ranging from very low levels in downstream floodplain environments to substantially elevated rates in upstream and midstream catchments. High soil loss is primarily concentrated in catchments characterized by steeper slopes, active land-use conversion, and reservoir regulation influence, whereas low values dominate depositional and low-gradient downstream areas. Catchments such as Lower Sg Kinta, Batang Padang, Bersia, and Sg Rui fell within the high erosion category, reflecting intensified surface runoff, greater slope gradients, and possibly reduced vegetation protection in certain zones. The elevated normalized and weighted soil loss indices indicated that these areas contributed disproportionately to basin-wide sediment production. The presence of steep terrain combined with anthropogenic activities, including agriculture and infrastructure development, likely amplified soil detachment and transport processes in these subcatchments.

Table 10: Normalization and weighted soil loss values

No	Catchment Name	Soil loss (ton/ ha.year)	Soil Loss Category	Normalization Soil Loss	Weighted Soil Loss
1	Bersia Dam Catchment	102.26	High	0.85	0.34
2	Chenderoh Dam Catchment	15.11	Moderate	0.11	0.05
3	Kenering Dam Catchment	44.01	Moderate	0.36	0.14
4	Lower Sg Kinta Catchment	120	High	1.00	0.40
5	Lower Sg Perak Catchment	1.74	Low	0.00	0.00
6	Middle Sg Perak Catchment	3.62	Low	0.02	0.01
7	Batang Padang Catchment	106.73	High	0.89	0.36
8	Sg Bidor Catchment	53.82	Moderately High	0.44	0.16
9	Sg Pelus Catchment	95.89	Moderately High	0.80	0.32
10	Sg Rui Catchment	102.15	High	0.85	0.34
11	Temenggor Dam Catchment	53.30	Moderately High	0.43	0.17
12	Upper Sg Kinta Catchment	84.67	Moderately High	0.70	0.28

The weighted soil loss results highlight a clear upstream-to-downstream erosion gradient, reinforcing the geomorphic control of terrain and slope on sediment generation. When integrated with flow alteration and morphological indicators, these high-erosion subcatchments are expected to exert stronger influence on the composite susceptibility index, particularly where hydrological modification enhances sediment transport capacity. Therefore, erosion control and land management strategies should prioritize upland and midstream catchments to reduce sediment yield and mitigate basin-wide susceptibility propagation.

Table 11 indicates substantial spatial variability in hydrological alteration across the Perak River Basin. The

normalized and weighted flow alteration indices highlighted a contrast between heavily modified subcatchments and relatively stable flow regimes. The distribution suggests that hydrological disturbance is not uniform, but instead reflects localized regulation effects, reservoir influence, and anthropogenic modification of discharge patterns. Batang Padang and Upper Sg Kinta emerge as the most hydrologically altered subcatchments based on the inverse normalized values and weighted flow alteration indices. These elevated values suggest strong deviations from natural flow regimes, potentially linked to reservoir regulation, upstream abstraction, or land-use changes affecting runoff dynamics. Such altered flow regimes may modify sediment transport capacity, channel adjustment processes, and ecological

stability. The dominance of hydrological alteration in these subcatchments reinforces their elevated contribution to the overall composite susceptibility index. The spatial distribution of flow alteration does not strictly follow an upstream–downstream gradient but instead reflects localized regulation intensity and basin management structures. When integrated with soil loss and morphological indicators, flow alteration amplifies susceptibility in catchments where hydrological stress coincides with high erosion potential. Conversely, in subcatchments with low hydrological disturbance, the composite susceptibility index is less sensitive to flow regime modification. These findings underscore the importance of incorporating hydrological alteration into basin-scale susceptibility frameworks, particularly in regulated tropical river systems where flow control structures influence sediment dynamics and channel stability.

Table 12 indicates that the majority of subcatchments within the Perak River Basin are in the old

geomorphic stage, characterized by concave hypsometric curves and relatively low relief. Only three subcatchments, Sg Pelus, Sg Rui, and Temenggor, were classified as mature-stage basins, exhibiting S-shaped hypsometric curves that reflected transitional geomorphic conditions. This distribution suggests that much of the basin has undergone significant erosional evolution, with reduced terrain energy and more stabilized landscape forms. Although most subcatchments were geomorphically mature or old, the variation in normalized HI values demonstrated that terrain susceptibility was not uniform across the basin. Mature basins with higher HI values may amplify susceptibility where coupled with elevated soil loss and flow alteration, whereas old-stage basins may buffer erosional responses despite hydrological stress. Thus, the morphological component acts as a conditioning factor within the susceptibility matrix, modulating the intensity of erosion and hydrological impacts rather than independently driving susceptibility.

Table 11: Normalization and weighted flow alteration values

No.	Station Name	Typical Regime Index	Normalized Flow Alteration	Inverse of Normalized Values	Weighted Flow Alteration
1	Bersia Dam Catchment	0.41	0.48	0.52	0.18
2	Chenderoh Dam Catchment	0.45	0.58	0.42	0.15
3	Kenering Dam Catchment	0.45	0.58	0.42	0.15
4	Lower Sg Kinta Catchment	0.60	0.90	0.10	0.04
5	Lower Sg Perak Catchment	0.45	0.58	0.42	0.15
6	Middle Sg Perak Catchment	0.50	0.69	0.31	0.11
7	Batang Padang Catchment	0.19	0.00	1.00	0.35
8	Sg Bidor Catchment	0.63	0.98	0.02	0.01
9	Sg Pelus Catchment	0.51	0.71	0.29	0.10
10	Sg Rui Catchment	0.64	1.00	0.00	0.00
11	Temenggor Dam Catchment	0.45	0.58	0.42	0.15
12	Upper Sg Kinta Catchment	0.29	0.23	0.77	0.27

Table 12: Normalization and weighted hypsometric integral values

N o	Catchment Name	Hypsometric Integral, HI	Basin Stage	Morphological Characteristics	Normalized HI	Weighted HI
1	Bersia Dam Catchment	0.27	Old	Concave Curve	0.81	0.20
2	Chenderoh Dam Catchment	0.29	Old	Concave Curve	0.88	0.22
3	Kenering Dam Catchment	0.28	Old	Concave Curve	0.85	0.21
4	Lower Sg Kinta Catchment	0.14	Old	Concave Curve	0.31	0.08
5	Lower Sg Perak Catchment	0.06	Old	Concave Curve	0.00	0.00
6	Middle Sg Perak Catchment	0.19	Old	Concave Curve	0.50	0.13
7	Batang Padang Catchment	0.28	Old	Concave Curve	0.85	0.21
8	Sg Bidor Catchment	0.19	Old	Concave Curve	0.50	0.13
9	Sg Pelus Catchment	0.32	Mature	S-Shaped Curve	1.00	0.25
10	Sg Rui Catchment	0.3	Mature	S-Shaped Curve	0.92	0.23
11	Temenggor Dam Catchment	0.32	Mature	S-Shaped Curve	1.00	0.25
12	Upper Sg Kinta Catchment	0.24	Old	Concave Curve	0.69	0.17

4

5 Susceptibility formulation for Perak River basin

The composite susceptibility index revealed a clear spatial differentiation in susceptibility across the Perak River Basin. The integration of soil loss, flow alteration, and morphological characteristics produced a distinct hierarchy of

susceptibility classes, ranging from very high in select upstream catchments to very low in downstream depositional zones. This demonstrates the effectiveness of the weighted synthesis framework in distinguishing geomorphically active areas from relatively stable subcatchments. Batang Padang emerged as the most critical subcatchment, classified as very

high susceptibility. The Very High classification of Batang Padang Catchment (0.92) was driven by a combination of extreme soil loss contribution (0.36) and pronounced flow alteration (0.35), while hypsometric contribution (0.21) played a secondary but reinforcing role. This indicates that the susceptibility in Batang Padang is jointly controlled by hillslope erosion intensity and hydrological modification rather than morphology alone. Independent evidence from the Jor Reservoir Sediment Management Plan (TNBR, 2021) further corroborates the Very High susceptibility classification of the Batang Padang Catchment. Annual sediment inflow into Jor Reservoir is estimated at 47,993–53,860 m³/year, with Sg Batang Padang contributing approximately 9,976–10,576 m³/year alone. Bathymetric surveys indicate that Jor Reservoir has lost more than 50% of its original storage capacity since commissioning, placing it within Phase III of reservoir life, where sedimentation significantly interferes with operational efficiency. The necessity for extensive sediment management measures, including dredging, sedimentation ponds at Sg Batang Padang, and bypass routing, further substantiates the high geomorphic pressure exerted by this subcatchment. These independent reservoir-scale observations align with the composite susceptibility index results, reinforcing the robustness of the Very High classification assigned to the Batang Padang Catchment. Similarly, Bersia, Upper Sg Kinta, and Sg Pelus fell within the high susceptibility category. In these areas, susceptibility amplification was not driven by a single dominant factor, but rather by the interaction between high sediment production, modified flow regimes, and terrain configuration. This confirms the hypothesis that compounded geomorphic and hydrological stresses elevate overall basin susceptibility potential.

Catchments such as Chenderoh, Kenering, Lower Sg Kinta, Sg Rui, and Temenggor were classified as moderate. These subcatchments represented transitional conditions where one or two indicators might be elevated, but not all three simultaneously. For example, some areas exhibited high soil loss but relatively stable flow regimes, while others showed moderate flow alteration, but lower morphological sensitivity. The moderate classification reflects the balancing effect of the weighted framework, where susceptibility is moderated when stressors do not fully coincide.

Middle Sg Perak, Sg Bidor, and particularly Lower Sg Perak demonstrated low to very low susceptibility. These downstream catchments were characterized by low soil erosion, relatively stable morphological conditions, and limited hydrological disturbance. Their depositional setting likely buffers erosional processes, reducing the overall susceptibility contribution. The results reinforce the existence of a pronounced upstream-to-downstream susceptibility gradient within the basin.

Overall, composite susceptibility decreased from 0.92 in Batang Padang to 0.15 in Lower Sg Perak, representing an 84% reduction in index magnitude. This gradient reflects attenuation of terrain energy, reduced sediment generation, and moderated hydrological stress along the basin's longitudinal profile as shown in Figure 8 and 9. This pattern underscores the importance of prioritizing upland catchments, particularly Batang Padang, Bersia, and Upper Kinta, for integrated soil and water conservation planning to minimize sediment yield and maintain basin stability.

Table 13: Final susceptibility class for Perak river basin

Catchment Name	Weighted Soil Loss	Weighted Flow Alteration	Weighted HI	Total Susceptibility Index	Susceptibility Class
Bersia Dam Catchment	0.34	0.18	0.20	0.72	High
Chenderoh Dam Catchment	0.05	0.15	0.22	0.41	Moderate
Kenering Dam Catchment	0.14	0.15	0.21	0.50	Moderate
Lower Sg Kinta Catchment	0.40	0.04	0.08	0.51	Moderate
Lower Sg Perak Catchment	0.00	0.15	0.00	0.14	Very Low
Middle Sg Perak Catchment	0.01	0.11	0.13	0.24	Low
Batang Padang Catchment	0.36	0.35	0.21	0.92	Very High
Sg Bidor Catchment	0.18	0.01	0.13	0.31	Low
Sg Pelus Catchment	0.32	0.10	0.25	0.67	High
Sg Rui Catchment	0.34	0.00	0.23	0.57	Moderate
Temenggor Dam Catchment	0.17	0.15	0.25	0.57	Moderate
Upper Sg Kinta Catchment	0.28	0.27	0.17	0.72	High

The final susceptibility matrix confirmed that no single parameter independently controlled basin susceptibility. Instead, high susceptibility levels arose where erosion intensity, hydrological alteration, and geomorphic predisposition converged. The weighted synthesis approach therefore provides a more comprehensive and realistic

representation of basin vulnerability than standalone soil loss or flow alteration assessments. Importantly, the framework enables spatial prioritization of critical subcatchments for targeted erosion control, hydrological regulation, and watershed stabilization strategies.

4.6 Hypothesis evaluation and statistical diagnostics

The results supported H1, as subcatchments exhibiting concurrently high soil loss and significant hydrological alteration consistently recorded elevated composite susceptibility indices, with Batang Padang Catchment emerging as the most critical case. H2 was partially supported, as morphologically mature basins generally exhibited reduced susceptibility in isolation; however, when combined with high erosion intensity and flow alteration, overall susceptibility remained elevated, indicating morphology acted as a conditioning rather than dominant control. H3 was strongly supported, as the integrated weighted framework demonstrated clearer spatial prioritization and ranking stability compared to standalone metrics, confirmed by minimal classification shifts under sensitivity testing.

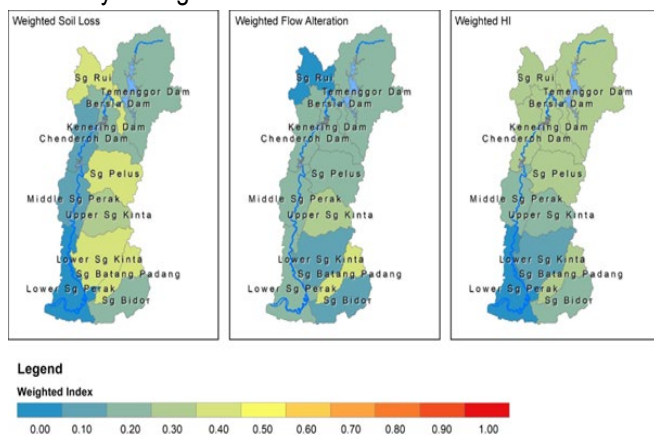


Figure 8: Weighted Index for Soil Loss, Flow Alteration and Hypsometric Integral

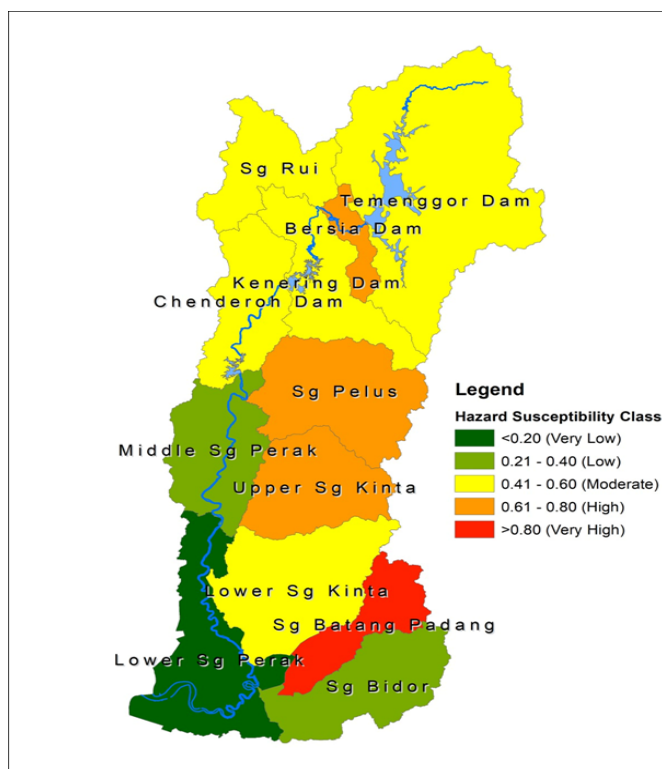


Figure 9: Final Susceptibility Map for Perak River Basin

Apart from hypothesis evaluation, descriptive statistics and sensitivity analysis were performed as well. The composite susceptibility index exhibited a standard deviation of approximately 0.23 across subcatchments, indicating spatial heterogeneity. Soil loss demonstrated the highest dispersion among indicators, confirming its dominant contribution to variability, whereas hypsometric integral showed comparatively lower variance, reflecting its conditioning role. Soil loss exhibited the largest variance range among normalized indicators (0–1), followed by flow alteration, whereas HI values displayed narrower dispersion. This confirms that soil loss exerts the strongest influence on composite index spread. Pearson correlation analysis revealed a strong positive association between normalized soil loss and the composite susceptibility index ($r > 0.80$), indicating that sediment generation exerted the greatest influence on basin-wide susceptibility differentiation. Flow alteration also showed a strong positive correlation ($r > 0.70$), confirming its amplifying role in modifying hydraulic energy and sediment transport capacity. The hypsometric integral displayed a comparatively moderate correlation ($r \approx 0.60$), consistent with its function as a long-term geomorphic conditioning variable rather than an active stressor. The absence of extreme inter-indicator multicollinearity suggests that each parameter contributes complementary information within the integrated framework. Collectively, these statistical diagnostics substantiate the theoretical process hierarchy underpinning the weighting scheme. These descriptive statistical analyses indicated that soil loss exhibited the highest standard deviation across subcatchments, followed by flow alteration, while hypsometric integral displayed relatively lower dispersion. Pearson correlation analysis showed strong positive relationships between soil loss and the composite index, and moderate to strong relationships for flow alteration and morphology. These results quantitatively confirm the dominant role of sediment generation and hydrological forcing in shaping basin-wide susceptibility patterns.

A sensitivity analysis was conducted to evaluate the robustness of the proposed susceptibility synthesis framework under alternative weighting configurations. Two additional weighting schemes were examined: (i) equal weighting (0.33, 0.33, 0.33) and (ii) a perturbed scheme (0.45, 0.30, 0.25), where the soil loss weight was increased while reducing the flow alteration contribution. The results in Table 14 indicate minimal variation in susceptibility classification across schemes. Under both alternative scenarios, only one subcatchment experienced a marginal class shift (from 0.57 to 0.61), representing a transition between adjacent susceptibility categories. Importantly, high-risk subcatchments remained stable across all weighting configurations, demonstrating that the overall spatial prioritization was not

highly sensitive to moderate changes in assigned weights. The average ratio between the baseline and equal-weight susceptibility indices (1.0248) and between the baseline and perturbed-weight indices (1.0023) further confirmed the numerical stability of the composite index (close to unity). Sensitivity testing demonstrated strong robustness of the composite susceptibility framework under alternative weighting scenarios. Relative to the adopted weighting scheme, the equal-weight scenario produced a mean absolute index change of 4.87%, with a maximum deviation of 13.06%. The perturbed weighting scenario yielded an even lower mean change of 3.79% and a maximum deviation of 8.79%. Rank

stability analysis indicated near-perfect prioritization consistency, with Spearman rank correlation coefficients of 0.98 (baseline vs equal weight) and 0.99 (baseline vs perturbed weight). Furthermore, class agreement remained high, with 91.7% of sub-basins retaining identical susceptibility categories across weighting schemes, and only a single sub-basin shifting between Moderate and High classes due to threshold proximity. These results quantitatively confirm that the proposed weighting hierarchy enhances interpretability without materially altering spatial prioritization, thereby demonstrating structural robustness of the integrated susceptibility framework.

Table 14: Sensitivity results of various weight scheme

Weight scheme	Soil loss	Flow alteration	HI	Changes in class?	Notes
Base Weight	0.40	0.35	0.25	–	–
Equal Weight	0.33	0.33	0.33	Minor – Only 1 class changed from 0.57 to 0.61	High-risk catchments stable. The average ratio between baseline and equal weight susceptibility class = 1.0248
Perturbed Weight	0.45	0.30	0.25	Minor – Only 1 class changed from 0.57 to 0.61	High-risk catchments stable. The average ratio between baseline and equal weight susceptibility class = 1.0023

Comparing the current findings from previous study, the results are consistent with Yusof et al. (2016), where the majority of the basin was categorized under very low soil erosion class, with erosion hotspots occurring in cleared and plantation areas. Similarly, Nazuhan et al. (2018) reported that steep slopes and bare land contributed significantly to higher soil loss values, proving alignment with the spatial distribution observed in the present study. These similarities confirm that land use change and topographic factors remain the primary drivers of soil erosion in Perak and surrounding basins. Internationally, integrated watershed risk and susceptibility assessments have increasingly adopted multi-criteria frameworks, often employing Analytic Hierarchy Process (AHP) (Saaty, 1980), entropy weighting (Kumar et al., 2021), or GIS-based overlay techniques (Ashfaq et al., 2025) to combine erosion, land-use, and hydrological indicators. Unlike AHP-based watershed risk models that rely on subjective pairwise comparisons, the weighting scheme in this study reflects a physically interpretable process hierarchy.

Sensitivity testing further demonstrates that prioritization remains stable under alternative weighting assumptions, reinforcing the structural robustness of the framework. While these approaches enhance decision support, many remain primarily expert-driven or statistically derived without explicit linkage to geomorphic process hierarchy. In contrast, the present framework adopts a process-based weighting structure grounded in sediment generation dominance, hydrological amplification, and morphological conditioning. Compared to sediment yield mapping alone, as commonly applied in tropical basins of

Southeast Asia (Poatprommanee et al., 2026), South America (Beskow et al., 2009), and Sub-Saharan Africa (Tamene & Le, 2015), the integrated approach demonstrated here provides improved spatial discrimination by reconciling sediment supply, flow modification, and basin maturity within a single normalized index. This allows prioritization that accounts not only for erosion magnitude but also for transport capacity and geomorphic predisposition, thereby offering a more structurally coherent basin-scale screening tool for regulated tropical river systems.

4.7 Management implications for basin-scale intervention

The susceptibility synthesis results provided a structured basis for prioritizing watershed management interventions according to dominant stressors. In very high and high susceptibility subcatchments, such as Batang Padang, Bersia, Upper Sg Kinta, and Sg Pelus, the compounded interaction between elevated soil loss and hydrological alteration suggested that integrated intervention strategies were required. In these areas, soil conservation measures, including slope stabilization, reforestation, contour farming, and sediment retention structures, should be implemented concurrently with improved flow regulation management to mitigate sediment mobilization and downstream instability. In moderate susceptibility catchments, where only one or two stressors are elevated, targeted interventions may be more effective. For example, in subcatchments characterized primarily by high soil loss but relatively stable flow regimes, erosion control through vegetation restoration and land-use management should be

prioritized. Conversely, in areas where hydrological alteration is the dominant contributor, reservoir operation optimization and environmental flow regulation may be more appropriate. Low and very low susceptibility subcatchments, particularly downstream depositional zones, require maintenance-focused management rather than structural intervention. Monitoring programs, sediment balance assessment, and protection of riparian buffers may be sufficient to preserve existing stability.

Overall, the integrated susceptibility matrix enables differentiated management strategies rather than uniform basin-wide interventions, thereby improving cost-effectiveness and sustainability in watershed planning.

6. CONCLUSIONS

This study developed and applied a weighted basin-wide susceptibility synthesis framework integrating soil loss (RUSLE), hydrological alteration (IHA), and morphological characteristics (Hypsometric Integral) within the Perak River Basin. By normalizing and weighting these indicators, the framework enabled cross-parameter comparability and systematic aggregation into a composite susceptibility index. The results demonstrated clear spatial differentiation of susceptibility across subcatchments, with susceptibility escalation occurring where elevated erosion intensity coincided with significant flow alteration and terrain sensitivity. The sensitivity analysis further confirmed that the classification hierarchy remained stable under plausible alternative weighting schemes, indicating methodological robustness. Collectively, these findings validate the effectiveness of an integrated multi-criteria approach in capturing compounded geomorphic and hydrological stressors within regulated tropical river systems.

From a management perspective, the susceptibility matrix provides a structured prioritization tool for basin-scale intervention. High and very high susceptibility subcatchments require integrated erosion control and flow regulation strategies, while moderate and low susceptibility areas may benefit from targeted or maintenance-focused measures. The framework therefore supports differentiated watershed planning rather than uniform basin-wide intervention. Importantly, the proposed methodology is replicable and scalable to other Malaysian and tropical river basins. The approach relies on widely available datasets, including digital elevation models, land-use maps, rainfall records, and hydrological time series, and applies transparent normalization and weighting procedures that can be adapted to local basin conditions. As such, the framework offers a transferable decision-support model for integrated susceptibility assessment in data-constrained yet environmentally dynamic tropical environments.

The present susceptibility assessment represents a static evaluation based on available rainfall, land use, and hydrological datasets corresponding to the study period. However, tropical river systems are inherently dynamic, with seasonal monsoon variability, interannual climatic fluctuations, and evolving land-use patterns influencing erosion intensity and flow regime alteration. Soil loss rates may increase during extreme rainfall years, while reservoir operations and abstraction practices may vary seasonally, thereby altering hydrological disturbance patterns. Consequently, susceptibility rankings derived from this framework should be interpreted as baseline susceptibility conditions rather than temporally dynamic risk projections. Future research should incorporate time-series modelling, seasonal flow regime analysis, and scenario-based simulations (e.g., climate change projections or land-use transitions) to develop a dynamic susceptibility assessment framework. Integrating temporal variability would enhance predictive capability and improve adaptive watershed management planning.

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