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Pattern Analysis of Periodic Sediment Elevation Data: A Decision Support Framework for Deposited Sediment Management in Coastal Environment

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Abstract

This research explores sediment deposition patterns in coastal areas by employing synthetic data representing wandering set and recurrent patterns, utilizing Fourier transformation and power-law analysis to characterize frequency content and scaling behavior. The study employs fundamental models to interpret observed patterns and investigates the relevance of Poincaré's theorem in understanding recurrent patterns. Leveraging Python-based computation systems and open-source satellite data, the findings reveal contrasting behaviors in power-law exponents between scenarios, with wandering set patterns exhibiting scale-free characteristics and recurrent patterns displaying structured frequency distributions. This holistic approach advances scientific knowledge on sediment dynamics, informing evidence-based decision-making for effective sediment management and coastal resilience planning. Through its methodology and insights, the research contributes to understanding sediment deposition processes, elucidating underlying mechanisms driving coastal sedimentation, and providing practical approaches for monitoring and studying sediment dynamics in coastal environments, ultimately enhancing strategies for coastal management and conservation.

Keywords: Sediment Deposition, Coastal Dynamics, Satellite Remote Sensing Data, Fourier Analysis, Wandering Set Theory, Poincare's Theorem and Power Law, Asian Institute of Maritime Studies

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INTRODUCTION

School coastal areas are vital ecosystems experiencing dynamic sediment transport and deposition processes, impacting both natural habitats and human activities (Yadi et al., 2023). Traditional sediment analysis methods often rely on field measurements, limiting spatial coverage and temporal resolution. However, leveraging remote sensing data from satellite imagery offers a promising avenue for comprehensive sediment analysis. This study proposes a systematic approach using synthetic data as proxy from satellite imagery to analyze sediment deposition patterns along coastlines, aiming to provide decision-makers with actionable insights for coastal management. This methodological shift aligns with recent advancements in remote sensing technology and spatial analysis techniques, facilitating a more comprehensive understanding of sediment dynamics in coastal environments. The profound current change in scientific research on coastal sediment dynamics is driven by rapid technological advancements and growing societal concerns, enabling a revolution in approach and paving the way for improved knowledge and better management of coastal areas (Haddadchi and Rose, 2022; Zi and Albertson, 2029; Dethier et al., 2022; Dethier and Renshaw, 2020; Bendô et al., 2023; Ouillon, 2019; Pargev et al., 2023). More so, it is believed that an effective sediment deposition pattern analysis should necessitate mechanistic and quantitative understanding of coastal interface processes. However, there must be a balance between detailed resolution and broad-scale classification for integration into modeling frameworks as argued by Ward et al., (2020). Profoundly, a series of satellite imagery was utilized by Pandey et al., (2016) to develop an elevation-area curve in their study, informing proposed manual and mechanical sediment removal combined with flushing for desilting deposited sediment to enhance reservoir live storage capacity of the study site. The role of physically-based model of sediment transport coupled with fine sediment deposition and re-entrainment processes within the gravel bed was emphasized in Haddadchi and Rose (2022), while Zi and Albertson, (2029); Dethier et al., (2022); Dethier and Renshaw, (2020); Bendô et al., (2023); and, Ouillon (2019) stress the need for multiparameter modeling for robust sediment analysis towards sediment yield estimation.

The need for effective sediment management strategies is evident, given the ecological and economic implications of sediment deposition (Bendô et al., 2023; Pargev et al., 2023). Satellite imagery provides a non-invasive and cost-effective means to monitor sediment distribution patterns over large spatial extents and extended timeframes (Dethier and Renshaw, 2020; Mouyen et al., 2018). Remote sensing is increasingly utilized for estimating suspended sediment concentrations in rivers due to logistical and financial constraints of direct measurements (Dethier and Renshaw, 2020). This approach enhances our ability to understand sediment transport dynamics, identify areas prone to excessive deposition, and inform sustainable coastal resource management strategies. Relevant literature supports the efficacy of satellite imagery in monitoring coastal sediment dynamics, including studies by Li et al., (2024); Pandey et al., (2016); Cudahy et al., (2016); Dethier et al., (2022); Dethier and Renshaw, (2020); Wagh and Manekar, (2021); Best, (2019); Mouyen et al., (2018); and, Nagel et al., (2023) highlighting its utility in coastal management decision-making processes. Interestingly, Bendô et al., (2023) emphasizes the effectiveness of hydromorphodynamic modeling, focusing on dredge-and-dump strategies, to enhance natural mechanisms, positively impacting channel depth and stability, while also enabling prediction of adverse changes in physical parameters over the medium and long term. Satellite remote sensing of suspended and deposited sediment relies on the absorption properties of water, with sediment reflecting incoming radiation more strongly, particularly in visible and near-infrared wavelengths (Dethier & Renshaw, 2020). This has helped in facilitating the development of empirical relationships between surface reflectance and suspended sediment concentration in several works (Dethier & Renshaw, 2020; Dethier et al., 2019; Pandey et al., 2016; Heeget et al., 2014; Latrubesse et al., 2017). Effort to develop model for quantification of sedimentation from river to the sea was made in by Mouyen et al., (2018) who introduces a novel geodetic method leveraging GRACE mission data to quantify sediment discharge from major rivers, aiding in understanding global-scale erosion dynamics and their susceptibility to anthropogenic pressures.

Silted estuaries with prograding sand-bars present complex management challenges that require careful consideration of ecological and economic factors according to the Fondriest Environmental, Inc., and British Geological Survey. While dredging and de-silting may offer short-term solutions, they can disrupt habitats and introduce contaminants into the ecosystem. Conversely, leaving sediment in place can lead to hydraulic inefficiencies and ecological degradation hence, sediment accumulation, which occupies water management volume and reduces reservoir effectiveness necessitates constant monitoring (Dethier et al., 2022; Pargev et al., 2023). A nuanced understanding of sediment dynamics, facilitated by satellite imagery, is crucial for balancing these conflicting interests and developing sustainable management strategies. Literatures by Luijendijk et al. (2017); Gao et al. (2023); Lauer and Parker (2008); Cudahy et al. (2016); and, Nagel et al. (2023) underscore the importance of integrated sediment management approaches to succeed the numerical modeling output of morphological response in coastal ecosystems, advocating for the incorporation of physical data modelling into decision-making frameworks. One of the key reasons for monitoring for decision support is to foster better coastal management system as argued in the work of Schenone and Thrush (2020) where the need for coastal habitats sediment analysis was promoted, particularly tidal flats, which are crucial for biodiversity and ecosystem function, yet the study stated how their deterioration threatens these valuable ecosystems; understanding the ecological consequences of species interactions in transition zones is vital for quantifying overall ecosystem functioning and addressing management challenges. On the geological significance of such measurement and documentation, Schumer and Jerolmack, (2009) highlights the importance of estimating erosion and deposition rates over geological time and their coupling with tectonics and climate change, supporting sediment deposition analysis by providing insights into landscape evolution.

In sediment transport modeling, the concept of Wandering Set Theory could offer a valuable framework for understanding system behavior under perturbations. By identifying regions of sediment accumulation or erosion based on river-sediment interactions, this theory informs predictive sediment transport models crucial for effective management. Utilizing synthetic data as proxies for satellite-derived sediment elevation data from transition zones allows for robust model validation and calibration. Synthetic data offer controlled environments for testing model assumptions and uncertainties, aiding in the development of accurate sediment transport models applicable to coastal and riverine ecosystems. The relevance of synthetic data as proxies for satellite-derived data is supported by studies such as that by Wu et al. (2020), which highlights the utility of synthetic data in enhancing the reliability of remote sensing-based analyses. Cao and Carling (2015) provide an in-depth examination of mathematical models for alluvial rivers, stressing the necessity of enhanced modeling techniques to tackle intricate phenomena like turbulent flow, sediment transport, and morphological changes, underscoring the continual evolution and need for further research in this field. On this note, the utilization of sediment mathematical modeling to generate the fundamental equations of open-channel flow, sediment transport, and empirical relations has been attempted (Snow & Slingerland, 1995; Slingerland, 1978). This was done to simulate longitudinal river profiles, with power functions often fitting profiles dominated by spatial discharge changes, while exponential functions may represent sediment size reduction, highlighting the complexity of sediment dynamics in river systems. However, the use of simple satellite sediment imagery which are easily obtained should also be explored using the sediment elevation data in addition to the pattern recognition models and power law which are easily implemented as well for decision support over spatiotemporal scale. Moreover, Wang et al., (2023) examined the morphological response to episodic flooding of river with sediment of the Yellow River Delta to Water-Sediment Regulation Schemes revealing the significant influence of discharge fluctuations on delta morphology and emphasizing the necessity of accurate discharge schematizations and comprehensive consideration of flow-sediment interactions. It is believed that these dynamics can be monitored using satellite imagery for periodic decision planning and management.

Obtaining sediment elevation data from both field sampling and satellite imagery is crucial for enriching the scientific community's understanding of spatial sediment patterns. While field sampling provides direct measurements at specific locations (Li et al., 2024; Nagel et al., 2023; Wagh and Manekar, 2021; Cudahy et al., 2016; Stevens et al., 2023), satellite imagery offers a broader spatial coverage, allowing for the observation of sediment dynamics across larger areas, including transition zones and river channels. Integrating these two sources of data provides a comprehensive picture of sediment distribution and movement, enabling more robust spatial pattern analysis. Additionally, employing advanced pattern analysis techniques, such as frequency representation of original data through Fourier analysis, enhances decision support for sediment management. By extracting frequency components from sediment deposition data, patterns such as periodicity or irregular fluctuations can be identified, aiding in the development of targeted management strategies tailored to the unique characteristics of sediment dynamics in coastal and riverine environments. This holistic approach to data collection and analysis does not only advance scientific knowledge but also informs evidence-based decision-making processes for effective sediment management and coastal resilience planning. For instance, Wagh and Manekar (2021) proposed a methodology for assessing reservoir sedimentation using satellite remote sensing, focusing on estimating sediment-induced loss of storage capacity and suggesting remedial measures, exemplified by the Ujjani reservoir in Maharashtra State, India. Moreover, Mouyen et al., (2018) explored a global-scale quantification of sediment discharge from major rivers, aiding in monitoring contemporary erosion and informing landscape dynamics research.

The integration of remote sensing and advanced modeling techniques facilitates evidence-based decision-making for sustainable coastal management, addressing complex challenges in sediment management and paving the way for resilient coastal ecosystems and thriving communities which in turns would drive the Blue Growth (BG) and Green Port (GP) concepts; pivotal strategies driving sustainable growth in marine and maritime sectors (Bianchini et al., 2019), aiming for innovation and inclusive economic development while addressing pressing ecological concerns (Eikeset et al., 2018). More so, the use of continental-scale mineral maps derived from satellite imagery enhances our understanding of weathering, erosion, and depositional processes, providing valuable insights into the impact of changing weather, climate, and tectonics on Earth's surface (Cudahy et al., 2016). The integration of satellite imagery and advanced modeling techniques presents a transformative approach to sediment management in coastal ecosystems by harnessing the power of remote sensing technology and theoretical frameworks such as Wandering Set Theory and its opposite scenario argued in Poincare's Theorem for periodic or conservative patterns with geometrical fractal implications as established by H. Poincare in 1881.

This research contributes to a deeper understanding of sediment dynamics and informs evidence-based decision-making for sustainable coastal management. Through interdisciplinary and innovative methodologies, this study seeks to address the complex challenges of sediment management, paving the way for resilient coastal ecosystems and thriving communities as exemplified in the study of Yadi et al. (2023) where the Chudao Island sea area off the coast of Shandong Peninsula, China was subjected to a comprehensive investigation employing high-precision bathymetric survey, sediment sampling, and grain-size trend analysis. The hydrodynamic numerical modeling reveals zonal distribution of grain size parameters parallel to isobaths, with sediment transport trending from island shore to sea, influenced primarily by near-bottom flow velocity and submarine topography, while human activities, such as aquaculture, further impact sediment dynamics underscoring the need for detailed analysis to inform coastal management practices. Similarly, Gao et al., (2023) analyzed water, sediment, and deposition characteristics during the initial impoundment period of the Baihetan Reservoir, highlighting the significant impact of sediment deposition on the comprehensive operation of cascade reservoirs in the lower Jinshajiang River, underscoring the necessity for future research integrating climate trend analyses, human activities, and sediment production monitoring for improved understanding and management of sediment dynamics. On this note, Qi et al., (2022); highlighted the sediment dynamics and deposition processes in the distal muddy deposit off the Shandong Peninsula, revealing varying suspended sediment concentrations influenced by hydrodynamic conditions and wind events, with re-suspension and advection playing significant roles. This research contributes to a deeper understanding of synoptic to seasonal variations in sediment transport and accumulation rates in distal mud deposits, and as such, the evident seasonal pattern observed from the above study motivates further research using spatial data from deposited sediment. It is worth stating the recent implementation of observational satellites in investigating and monitoring the dynamics of meandering rivers, facilitating advances in understanding their ecological services and interactions with surrounding floodplains by Negal et al. (2023). Here, they documented the output from the Ganges/Brahmaputra and Amazon Basin, predominantly utilizing Landsat imagery and satellite time-series for river monitoring, though there is potential for further exploration with Synthetic Aperture Radar satellites and cloud computing platforms. In addition, Recent advancements in remote sensing techniques and data availability have facilitated the use of satellite imagery to quantitatively reconstruct the spatiotemporal patterns of erosion and sediment transport in warming-affected headwater basins on the Tibetan Plateau (Li et al., 2024). This study reveals the significant increases in sediment flux in 63% of rivers despite 30% of suspended sediment flux being temporarily deposited within rivers, thereby providing valuable insights into sediment dynamics and associated landscape transformations. Furthermore, Lauer and Parker (2008) developed a theory for the movement of suspendible sediment through the floodplain of an actively migrating river, incorporating sediment storage reservoirs, multiple river bends, and lateral channel migration, with sediment deposition and removal models driving changes in floodplain volume and elevation over time. While Bradley and Tuker (2013) investigated the relationship between sediment age and erosion in fluvial systems, revealing a non-exponential distribution of sediment storage times and proposing an alternate model based on diffusive channel motion, impacting sediment dynamics and floodplain evolution which are relevant for understanding sediment dynamics in fluvial systems. However, these models say little about the sediment level by elevation measurement and management decision support over spatial scale. Hence, with the work of Carson et al. (1999), whose provisioning of the comprehensive synthesis of the riverine sediment balance of the Mackenzie Delta over the past two decades, indicated a significant sediment inputs and transfers within the delta, which is relevant for understanding sediment dynamics and deposition patterns in coastal environments. But this approach only accounts for sediment entrainment and loss, and less on the post-result decision support over larger surface area of which a satellite imagery records of the sediment elevation or volume accounting could have help on this regard.

METHODOLOGY

Data Acquisition. The study utilizes synthetic data of spatial distributions of deposited sediment obtained from satellite remote sensing imagery, of which similar could be done particularly using Google Earth Pro software. The imagery provides high-resolution elevation data, allowing for detailed characterization of sediment deposition patterns along coastlines.

Preprocessing. The synthetic deposited sediment data extracted from python programming random sampling method which mimics the data from satellite imagery; and, processed to remove noise and artifacts, ensuring accurate representation of sediment elevations. This involves filtering techniques and quality control measures to enhance data reliability.

Theoretical Framework. The study was anchored on the Wandering Set Theory. This was applied to analyze the spatial distribution of sediment deposition and identify recurrent patterns or anomalies.

The Poincare's Recurrence Theorem was also utilized. Poincare's theorem is used to assess the periodicity of sediment deposition patterns and characterize the long-term behavior of sediment dynamics. Poincaré's theorem establishes that the sum of the indices of a vector field's isolated singular points on a closed two-dimensional Riemannian manifold equals the manifold's Euler characteristic (Alexandroff and Hopf, 1935). The representation of the Poincaré's theorem formulation with regards to pattern recognition using periodic sediment data for dominant frequency identification is as follows:

$$\sum_{i=1}^{k} j(X, A_i) = \chi(V) = \chi(V)$$

Where:

- (X, Ai) is the index of the isolated singular point Ai with respect to the vector field X;
- (V) is the Euler characteristic of the smooth closed two-dimensional Riemannian manifold V; and,
- k is the total number of isolated singular points.

This equation allows for the identification of dominant frequencies in sediment deposition patterns, enabling the recognition of whether the patterns exhibit fractal or non-fractal characteristics based on the Euler characteristic of the manifold. Fractal patterns would correspond to a non-zero Euler characteristic, while non-fractal patterns would correspond to a zero Euler characteristic.

To incorporate the wandering set theory into the analysis of sediment elevation data, the researcher utilized a combination of Wandering Set Theory and Fourier analysis. First, the identification of the wandering points of the sediment elevation data was made from the spatial analysis of the satellite imagery, which represents regions where sediment deposition is influenced by stochastic fluctuations or irregular dynamics. These wandering points can be identified by analyzing the variability or randomness in sediment elevation over time or space. Fourier analysis was then used to examine the frequency content of the sediment elevation data and identify dominant frequencies associated with uniform patterns or fractal-like structures. Sediment elevation data exhibiting dominant frequencies would indicate non-wandering points or regions displaying more regular sediment deposition patterns.

The equation for this combined analysis is as follows:

- Wandering Set Points: Dwandering (t) = Dfield (t) + (t)
- Wandering Set Points: Dwandering(t) = Dfield(t) + ϵ(t)
- Non-Wandering Set Points: Dnon-wandering (t) = Asin(ωt+ϕ)
- Non-Wandering Set Points: Dnon-wandering(t) = Asin(ωt+φ)

Where:

- Dwandering(t) represents the sediment elevation at wandering set points over time t, which is influenced by stochastic fluctuations represented by $\epsilon(t)$;
- Dfield(t) represents the field-measured sediment elevation at wandering set points;
- Dnon-wandering(t) represents the sediment elevation at non-wandering set points over time t, exhibiting a periodic oscillation pattern;
- A is the amplitude of the oscillation at non-wandering set points;
- ω is the angular frequency associated with the dominant frequency of the oscillation; and,
- ϕ is the phase angle determining the starting point of the oscillation.

Incorporating the power-law component, the equation for the Fourier analysis of the sediment elevation data can be expressed as:

- Y=a·XbY

Where:

- Yrepresents the magnitude of the Fourier spectrum;
- X represents the frequency of the sediment elevation data;
- a is a constant scaling factor; and,
- b is the exponent characterizing the power-law behavior of the sediment elevation data's frequency spectrum.

By combining wandering set theory with Fourier analysis and power-law analysis, an effective differentiation between sediment elevations data exhibiting wandering points as influenced by stochastic fluctuations and non-wandering points displaying dominant frequencies characteristic of uniform patterns or fractal-like structures was made. This approach provides valuable insights into the spatial and temporal dynamics of sediment deposition patterns in coastal environments.

Computational Analysis

Fourier Analysis. Fourier analysis is employed to decompose sediment elevation data into frequency components, allowing for the identification of dominant frequencies and periodicities in sediment deposition patterns.

Fourier analysis decomposes sediment deposition data into frequency components, aiding in the understanding of sediment dynamics in rivers and floodplains, with notation distributions such as:

$$D(t) = \sum_{n=1}^{N} A_n \cdot \sin\left(2\pi f_n t + \phi_n\right)$$

Where:
- (t) represents sediment elevation over time;
- An is the amplitude of the n-th frequency component; and,
- fn is the frequency, and ϕn is the phase angle.

Power Law and Regression Analysis. Power-law distribution and regression analysis are used to examine the relationship between frequencies and magnitudes of sediment deposition, indicating tendencies towards fractal geometry and providing insights into sediment dynamics. To classify the two scenarios as wandering set pattern and recurrent pattern using power law and regression analysis, the analysis of the spectral properties of the sediment deposition data was made. Wandering set patterns typically would exhibit a power-law decay in their Fourier spectrum, while recurrent patterns show distinct peaks at specific frequencies. The python code that performed this analysis can be seen in appendix B. The code defines a power-law function for fitting power-law decay and analyze sediment data function to analyze the sediment data. It calculates the average Fourier spectrum of the sediment profiles, fits a power law to the spectrum, and plots the results. The exponent of the power law fit is then printed, providing a measure of the decay behavior.

RESULTS

The application of the proposed methodology to coastal sediment data reveals valuable insights into sediment deposition patterns and dynamics. The analysis identifies recurrent patterns, periodicities, and trends in sediment distributions, enabling informed decision-making in coastal management. A wandering set pattern typically exhibits a low exponent close to 0, indicating a slow decay in the Fourier spectrum. In contrast, a recurrent pattern would show distinct peaks in the spectrum, suggesting a higher exponent. By analyzing the power-law behavior, we can classify the sediment deposition patterns and guide management decisions accordingly.

Distinguishing Wandering Set and Recurrent Patterns

1. Wandering Set Theory Model. If given that set WW of wandering points and set MM of non-wandering points in a dynamical system, where WW is open and MM is closed in the phase space RR. The sets WW and MM are invariant and, in a compact space RR, wandering points tend to MM as time approaches infinity.

   To appropriately represent the study on sediment deposition and analysis, the equations can be modified as follows:

   - W = Set of all sediment deposition points with wandering dynamics
   - W = Set of all sediment deposition points with wandering dynamics
   - M = Set of all sediment deposition points with non-wandering dynamics
   - M = Set of all sediment deposition points with non-wandering dynamics
   - (p,t) = Function representing sediment deposition dynamics at point p and time

- tf(p,t) = Function representing sediment deposition dynamics at point p & time t
- (q) = Neighborhood of point q in the phase space
- RU(q) = Neighborhood of point q in the phase space R
- R = Compact space representing the phase space
- R = Compact space representing the phase space
- (q,t) = Sediment deposition dynamics at point q and time
- tf(q,t) = Sediment deposition dynamics at point q and time t

These modified equations reflect the study's focus on understanding the dynamics of sediment deposition in a fluvial system, where points are classified as either wandering or non-wandering based on their behavior over time.

- W = Set of wandering points
- M = Set of non-wandering points
- W = {q∈U(q)|f(q,t) for any t}
- M = R\W
- f(q,t)→M as t→±∞

Let (t) represent sediment deposition over time.

- W = Set of wandering sediment deposition points
- M = Set of non-wandering sediment deposition points
- W = {(t)|for any t}
- M = All possible sediment deposition values−W
- (t)→M as t→±∞

More so, in the context of sediment deposition, a wandering set theory model is represented by a stochastic process or random walk. Another possible equation for this model could be a simple random walk equation, where the sediment deposition at each time step is influenced by random fluctuations:

Dt+1=Dt+ϵt
Where:

- Dt represents the deposited sediment at time t.
- ϵt is a random noise term representing the stochastic fluctuations in sediment deposition.

2. Recurrent Pattern Model (Hypothesized in Poincaré's Theorem). Poincaré's theorem deals with the recurrence of trajectories in dynamical systems. In the context of sediment deposition with recurrent patterns, it is considerable to use a sinusoidal oscillation model, where sediment deposition follows a periodic pattern over time:

Dt = A sin (ωt+φ)
Where:

- Dt represents the deposited sediment at time t.
- A is the amplitude of the oscillation.
- ω is the angular frequency, related to the period of the oscillation.
- ϕ is the phase angle, determining the starting point of the oscillation.

These relationships capture the essence of wandering set theory and opposite case where depositional pattern favor recurrent patterns as hypothesized in Poincaré's theorem, providing mathematical models to describe the sediment deposition dynamics considered in this study.

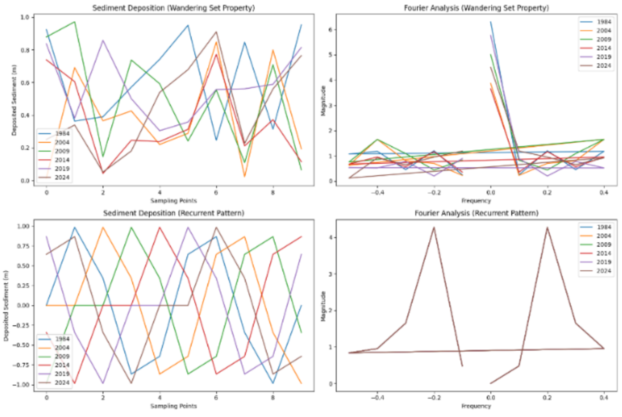

Figure 1
Top and Bottom Plots. Plots of the sediment deposition and the Fourier analysis with wandering set properties and recurrence pattern properties.

The code in Appendix A generates synthetic data representing deposited sediment profiles over ten sampling points for six different sampling regimes: 1984, 2004, 2009, 2014, 2019, and 2024. For the wandering set property pattern, the sediment profiles display random fluctuations with no clear periodicity, as shown by the erratic nature of the sediment deposition over time. The Fourier analysis confirms this, indicating a broad spectrum of frequencies with no dominant peaks as seen in Figure 1, Top plot. Conversely, for the periodic recurrent pattern, the sediment profiles exhibit sinusoidal oscillations with consistent periodicity across the years, suggesting a stable and recurring sediment deposition pattern as seen in Figure 1, Bottom plot. The Fourier analysis reveals distinct peaks at specific frequencies, corresponding to the periodic nature of the sediment profiles. In terms of sediment management, understanding these patterns can inform coastal management strategies: 1) for the wandering set property, adaptive approaches might be necessary to account for the unpredictable nature of sediment deposition; while, 2) for the recurrent pattern, strategies can be designed to capitalize on the predictability of sediment dynamics, potentially optimizing coastal protection, locational dredging, and restoration efforts.

Power-Law Analysis of Sediment Deposition Patterns: Distinguishing Wandering Set and Recurrent Patterns

The code provided in Appendix B performs a power-law analysis on the Fourier spectra of sediment deposition data for both wandering set pattern and recurrent pattern scenarios. The power-law function used in the analysis is $Y=a \cdot Xb$ where X represents the frequency and Y represents the magnitude of the spectrum. By fitting this power-law function to the averaged Fourier spectra, the code extracts the exponent b, which characterizes the scaling behavior of the spectra.

The most suitable equations that reflect the underlying models for the code in Appendix B are as follows:

1. Wandering Set Pattern Model. In the context of the power-law analysis, the wandering set pattern can be represented by a stochastic process with a broad frequency distribution. The power-law behavior suggests a scale-free or fractal-like structure, indicating no dominant characteristic frequency. Therefore, the model equation is represented by:

   $Y=a \cdot Xb$

   Where:
   - Y represents the magnitude of the spectrum.
   - X represents the frequency.
   - a is a constant scaling factor.
   - b is the exponent characterizing the power-law behavior.

2. Recurrent Pattern Model. For the recurrent pattern, the power-law analysis indicates a more structured and peaked frequency distribution, reflecting the presence of dominant frequencies associated with the periodic oscillations. Therefore, the model equation is represented by:

   $Y=a \cdot Xb$

   Where:
   - Y represents the magnitude of the spectrum.
   - X represents the frequency.
   - a is a constant scaling factor.
   - b is the exponent characterizing the power-law behavior, which may be influenced by the periodicity of the recurrent pattern.

The above equations capture the scaling behavior observed in the power-law analysis and provide insight into the underlying models of sediment deposition patterns, distinguishing between the wandering set pattern and the recurrent pattern.

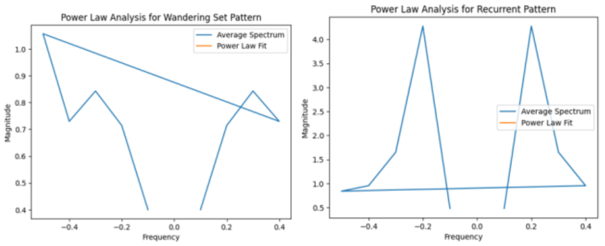

Figure 2

Power Law analysis for wandering set and recurrent patterns obtained from data in two scenarios of deposited sediment regimes.

The results from the power law analysis of sediment deposition data provide valuable insights into the underlying patterns and dynamics of sediment transport. In the case of the wandering set pattern, characterized by a low exponent value close to 0, the Fourier spectrum exhibits a slow decay. This suggests that sediment deposition occurs over a wide range of frequencies, indicating a lack of distinct periodicity in the sediment profiles. In such scenarios, implementing dredging as a sediment management strategy may not be as effective, as the sediment accumulation is not concentrated at specific frequencies and may not respond well to localize removal efforts.

Conversely, for sediment deposition exhibiting a recurrent pattern, characterized by a higher exponent value, the Fourier spectrum displays distinct peaks at specific frequencies. This indicates the presence of recurring sediment deposition events or cycles, which may correspond to natural processes or anthropogenic influences. In these cases, dredging could be a suitable management approach to target and remove sediment accumulations at the dominant frequencies, mitigating the risk of excessive deposition and maintaining navigational channels or ecological balance. Therefore, by utilizing power law analysis of sediment deposition data, decision-makers can better tailor sediment management strategies, considering the underlying patterns and dynamics revealed by the spectral properties of the sediment profiles.

The Decision-Support Implications and Relevance

The systemic approach to analyzing deposited sediment data obtained from satellite remote sensing imagery offers a comprehensive framework for decision support across various domains. Firstly, in infrastructure design and placement, understanding the patterns of sediment deposition along coastlines aids in identifying areas prone to erosion or sediment buildup (Qi et al., 2022). By factoring in these insights, engineers can design coastal structures and infrastructure to withstand erosion and mitigate sedimentation, ensuring their longevity and effectiveness.

Secondly, in ecosystem monitoring and restoration efforts, recognizing recurrent patterns in sediment deposition allows for targeted restoration interventions. Decision-makers can prioritize restoration projects in areas where sediment deposition adversely affects ecosystems, such as mangroves or coral reefs. By restoring these ecosystems, biodiversity can be preserved or enhanced, contributing to overall ecosystem health and resilience.

Thirdly, in dredging operations, knowing the locations and timing of sediment buildup helps optimize dredging efforts. By targeting areas with high sedimentation rates identified through systematic analysis, dredging operations can be conducted more efficiently, reducing costs and minimizing environmental impacts. Additionally, forecasting sediment deposition patterns enables proactive dredging scheduling, preventing sediment-related navigational hazards and maintaining waterway accessibility (Stevens et al., 2023). Efforts to mitigate the constant flooding at the plains of some of the rivers in developing countries through optimized dredging and desilting the clogged sand bars at the transition zone to the sea, while limiting the amount of sediment lost to deeper water offshore is on as measures climate change adaptation and mitigation strategies.

Fourthly, in flood mitigation and control measures, understanding sediment dynamics is crucial for effective flood risk management. By analyzing sediment deposition patterns, decision-makers can identify areas prone to sediment-induced flooding and implement targeted mitigation measures such as levees, flood barriers, or sediment removal. Proactive management of sediment deposition helps reduce flood risks and enhances community resilience to extreme weather events.

Finally, in climate adaptation strategies, leveraging insights from sediment data analysis contributes to more robust adaptation planning (He et al., 2019; Cudahy et al., 2016). Understanding how sediment deposition patterns may shift due to climate change allows decision-makers to anticipate future impacts on coastal and water resources. By integrating sediment management considerations into climate adaptation strategies, coastal communities can better prepare for and adapt to changing environmental conditions, ensuring long-term sustainability and resilience.

DISCUSSION

By extracting frequency components from sediment deposition data, patterns such as periodicity or irregular fluctuations can be identified, aiding in the development of targeted management strategies tailored to the unique characteristics of sediment dynamics in coastal and riverine environments. This holistic approach to data collection and analysis not only advances scientific knowledge but also informs evidence-based decision-making processes for effective sediment management and coastal resilience planning. This research investigates sediment deposition patterns in coastal areas using synthetic data generated to represent two distinct scenarios: wandering set patterns and recurrent patterns. The analysis employs Fourier transformation to examine the frequency content of the sediment deposition data, followed by a power-law analysis to characterize the scaling behavior of the spectra. Two fundamental models are utilized to interpret the observed patterns: a stochastic process model for wandering set patterns and a sinusoidal oscillation model for recurrent patterns. The relevance of Poincaré's theorem in understanding the recurrent patterns is also explored. The study leverages Python-based computation systems, employing libraries such as NumPy, Matplotlib, and SciPy for data analysis and visualization. The findings reveal contrasting behaviors in the power-law exponents between the two scenarios, with wandering set patterns exhibiting scale-free characteristics and recurrent patterns displaying more structured frequency distributions. Moreover, it is suggested that similar analyses can be conducted using open-source satellite data from remote sensing systems, providing a practical approach for monitoring and studying sediment dynamics in coastal environments. This research contributes to the understanding of sediment deposition processes, offering insights into the underlying mechanisms driving coastal sedimentation and informing strategies for coastal management and conservation.

Future Directions. The integration of sediment deposition analysis with computational and frequencies decomposition modeling approaches offers a holistic framework for addressing the challenges posed by sediment deposition in coastal areas. By leveraging satellite-derived sediment data, researchers can develop decision support systems tailored to specific coastal environments, aiding in the implementation of adaptive management strategies. For instance, in the case of the Lingayen Gulf in Pangasinan, Philippines, and so many other transition zones along the country's extensive coastline where sediment influx from the major river present both flood risk and ecological concerns, satellite imagery can facilitate real-time monitoring and predictive modeling of sediment transport dynamics. Moreover, collaborative efforts between researchers, policymakers, and local communities are essential for translating scientific findings into actionable measures for sustainable coastal resource management. Overall, the continued advancement and application of satellite-based sediment monitoring technologies hold immense promise for safeguarding coastal environments and enhancing societal resilience to sediment-related hazards.

Moving forward, the integration of advanced modeling techniques such as Wandering Set Theory and Fourier analysis holds great promise for advancing sediment deposition analysis. By leveraging these mathematical frameworks, researchers can gain deeper insights into the complex dynamics of sediment transport and deposition in coastal and fluvial environments. Additionally, further exploration of sediment storage times and erosion hazards, as highlighted in recent research, presents an avenue for refining sediment deposition models and improving our understanding of sediment dynamics over geological time scales. This research direction not only contributes to the development of more accurate predictive models for sediment management but also enhances our ability to interpret sedimentary records and reconstruct past environmental changes.

Furthermore, the incorporation of modern sediment dating techniques and proxies for climatic and tectonic factors offers exciting opportunities for enhancing sediment deposition analysis. By integrating biological and chemical indicators with sediment deposition data, researchers can unravel the intricate relationships between erosion, deposition, tectonics, and climate change. Future research should focus on refining these techniques and integrating them into comprehensive sediment deposition models to elucidate the drivers of landscape evolution and sedimentary record formation. Ultimately, by advancing our understanding of sediment dynamics and their response to environmental changes, we can better inform sustainable management strategies for coastal and fluvial ecosystems, ensuring their resilience in the face of ongoing environmental challenges.

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