



Tracing Sediment and Phosphorus Source Hysteresis During an Extreme Flood in a Subtropical Australian River

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Abstract. Extreme flood events are increasingly recognised as important drivers of suspended sediment (SS) and particulate phosphorous (PP) transport. However, their dynamics remain poorly understood due to the stochastic distribution and limited high-frequency sampling of these events. This study is the first to combine high-resolution rising-stage sampling, hysteresis analysis, and a novel sediment fingerprinting approach based on elemental fractions to quantify the changes in SS and PP sources during the 2025 *Cyclone Alfred* flood in a subtropical Australian catchment. Results show a pronounced figure-eight hysteresis in both the SS and PP concentration-discharge relationship, characterised by an early first flush and a secondary peak at highest discharge. Sediment tracing shows a shift in source contribution, with initial dominance of alluvial bank material (60–80%) transitioning to hillslope sources (~70%) near peak discharge. Despite its short dominance, hillslope material contributed ~60% of the total storm event sediment load, compared to ~30% from alluvium sources. In parallel, PP shifted from predominantly oxide-bound forms during the rising limb (~44–75%) to exchangeable (bioavailable) at peak flow (~70%), wherein the latter contributed ~53% of total event PP export. The *Cyclone Alfred* event alone accounted for ~57% of annual sediment yield and ~65% of annual particulate P export. Extreme events thus non-linearly activate distinct SS and reactive PP sources and dominate yearly PP and SS loads. These findings highlight the need to extend monitoring and management strategies to hillslope sediment mobilisation and identifying the sources of nutrient pulses under intensifying urban development and climate extremes.

1 Introduction

Large flood events are increasingly recognised as key drivers of geomorphic change, as well as of accelerated transport of sediment and associated nutrients in river systems worldwide (Li et al., 2021; Fuller, 2008; Leenman et al., 2023; Carpenter et al., 2018). Despite their importance, extreme events are still poorly captured in river monitoring programmes (Wynants et al., 2025). This limitation is particularly pronounced in (sub)tropical catchments, where intense tropical and monsoonal storms can generate large rainfall volumes over short periods, triggering rapid-onset and highly erosive runoff and flood responses



(Kale, 2003). Australia's eastern coastal catchments are characterised by frequent large flood events resulting from the combined influence of geomorphic, land-use, and climatological factors (Rustomji et al., 2009; Micevski et al., 2006; Verdon et al., 2004). The landscape transitions rapidly from coastal plains to mountainous terrain and in the past two centuries following European settlement, the land cover has undergone intense land clearing, agricultural expansion, and urban development (Olley et al., 2015; Kemp et al., 2019). These geomorphic and land use effects are superimposed on a climate regime characterised by occasional monsoonal lows and atmospheric blocking patterns conducive to intense rainfall over prolonged periods (Micevski et al., 2006; Verdon et al., 2004; Callaghan, 2023). The rivers draining to Moreton Bay, southeast Queensland, have been shown to have increasing sediment yield since European settlement (Olley et al., 2015; Kemp et al., 2015; Coates-Marnane et al., 2016). Large flood events in the past decades have resulted in documented widespread bank failures, large sediment-loaden coastal plumes, and negative impacts on water quality across riverine and coastal environments (Hancock and Caitcheon, 2010; Queensland Government, 2025; McMahon et al., 2017). The urgency of this issue is heightened by rapid population growth and urbanisation in Southeast Queensland, alongside increasing reliance on clean water and healthy ecosystems (Queensland Government, 2025; Council of Mayors, 2015).

Quantifying the mobilisation of all potential sediment and associated nutrient sources is thus required for improving land and water management strategies (Bieroza et al., 2019). River sediment attribution in Southeast Queensland has, to date, heavily relied on fallout radionuclide (FRN) tracing and multi-temporal LiDAR analysis, which pointed to river bank erosion as the dominant sediment source to Moreton Bay (Olley et al., 2015; Wallbrink, 2004). However, tracing studies have mostly relied on low-frequency grab samples or deposited sediments, limiting insight into temporal source dynamics and their contribution to annual sediment loads. Moreover, FRN techniques provide only a binary surface versus subsurface signal, but do not differentiate between different mechanisms or sources of subsurface erosion (Mabit et al., 2014; Wallbrink, 2004). Similarly, post-event LiDAR differencing quantifies net geomorphic change but cannot quantify more diffuse sediment sources or determine how source contributions evolve throughout a flood (Daley et al., 2024). These limitations largely reflect the stochastic, rapid-onset, and often destructive nature of extreme flood events, which hinders high-frequency monitoring and source tracing (Bieroza et al., 2023; Garzon-Garcia et al., 2017; Kirchner et al., 2004). Nonetheless, this observational bias constrains our understanding of the non-linear relationships between discharge, rainfall, and the mobilisation and transport of different sediment sources, during the most hydrologically and geomorphologically active periods (Bracken et al., 2015; Blöschl et al., 2019). Consequently, extreme events remain a major blind spot in sediment budget studies, highlighting the need for improved and integrated methodological approaches to better capture their dynamics.

Rising-stage samplers provide a practical and low-cost mode of overcoming the logistical challenges of monitoring extreme floods. When deployed at multiple heights alongside stage and discharge gauging, they enable sediment sampling and concentration measurements across the hydrograph (Doréan et al., 2020). Hysteresis analysis of suspended sediment concentration-discharge (SSC-Q) and particulate phosphorus concentration-discharge (PPC-Q) relationships can then be used



65 to infer changes in sediment and nutrient source activation and connectivity during storm events (Bieroza et al., 2018; Jing et al., 2025). These relationships may be static, indicating a near-linear response to discharge, or dynamic, reflecting dilution (supply limitation) or concentration effects (enhanced mobilisation and connectivity) during increasing discharge (Bieroza et al., 2018). Dynamic SSC-Q and PPC-Q relationships may also exhibit hysteresis, including clockwise, counter-clockwise, figure-eight, and complex patterns. These patterns are commonly associated with first-flush effects, delayed inputs from distal sources, threshold-driven source shifts, and multiple complex interacting erosion and transport processes, respectively (Jing et al., 2025; Lloyd et al., 2016b). However, SSC-Q and PPC-Q relationships alone provide only indirect evidence of sediment dynamics, and interpretations often remain speculative without independent source-tracing information (Speir et al., 2024). Sediment source tracing provides such complementary information by allowing the quantifying of the proportional contribution of different sources to the sediment mixtures (Owens et al., 2016; Collins et al., 2017). However, currently established tracers, such as fallout radionuclides (FRNs) and broad spectrum geochemistry, often struggle to distinguish between alluvium and hillslope erosive processes in the (sub)tropics (Wynants et al., 2021; Mabit et al., 2014; Evrard et al., 2020), since the former is a product of deposition and reworking of upstream sources over longer periods (Croke et al., 2024). This reliance on coarser signals results in the potential grouping of multiple geomorphological, mineralogical and weathering signals, as well as reducing tracer conservation by including more reactive (and thus by definition less conservative) fractions. However, additional discriminatory signals can be gathered by sequentially extracting sediment and soil materials partitioning elementals across different host-phases based on mineralogy and reactivity (Matula and Wojtkowska, 2025; Ali et al., 2024; Poulton and Canfield, 2005).

This study addresses these scientific and management gaps by combining high-resolution storm-event sediment sampling with a tracer-based mixing model and hysteresis diagnostics to quantify temporal shifts in SS and PP sources during the *Cyclone Alfred* extreme flood event on March 2025 in the Albert River, southeast Queensland. We test the hypothesis that extreme events non-linearly activate different SS and PP sources, reflecting changes in supply and connectivity. Instead of using total element concentrations, we are the first to use elemental partitioning in soil and sediment samples as novel tracers that better represent functional primary and secondary mineralogical and reactivity groups, thus allowing a better selection of conservative tracers and an improved distinction of representative catchment sediment sources. This integrated approach provides new insights into the mechanisms of source mobilisation and transport that govern sediment dynamics in subtropical river systems. Moreover, this study allows the attribution of observed sediment and nutrient pollution to specific hotspots and hot moments, thereby offering evidence to inform catchment management strategies under intensifying climate extremes.

2 Material and Methods

2.1 Study catchment and flood event description

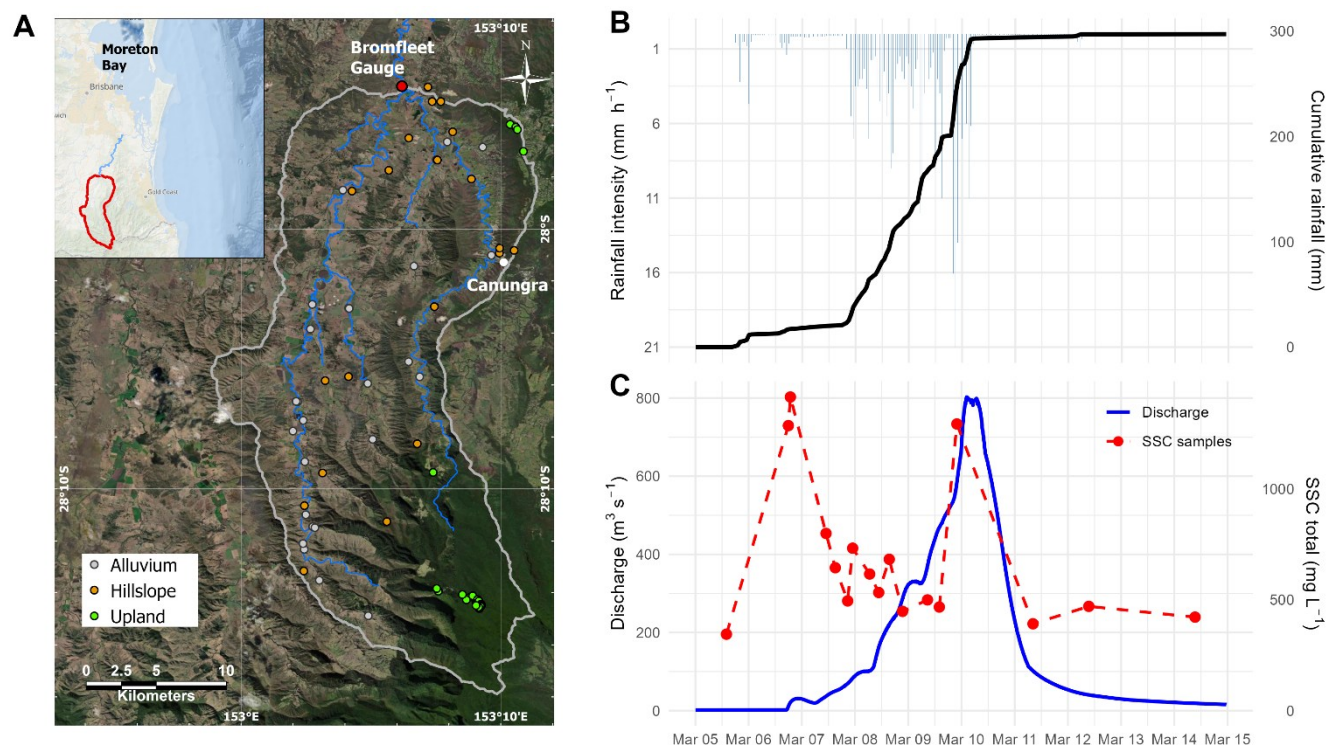


Figure 1: overview figure the study catchment with (A) indication the source sampling locations, and the Bromfleet Gauge where discharge measurements and sediment samples were collected (Source material of basemaps: Esri, TomTom, Garmin, GEBCO, National Geographic, NOAA, NIWA, Geosciences Australia, NaturalVue, Earthstar Geographics | Powered by Esri), (B) detailed storm event rainfall hyetograph and cumulation at Bromfleet, and (C) Discharge and Suspended sediment concentration (SSC) dynamics from the Blomfleet Rising Stage and grab samples together with their sample times.

The Albert River in southeast Queensland, Australia, is a flood-prone catchment representative of subtropical river systems in eastern Australia (Figure 1A). The catchment upstream the Bromfleet gauge (site 145120B; 27°54'33.0"S; 153°06'23.4"E) drains 542 km², featuring a strong topographic gradient from upland areas through steep intermediate hillslopes to flat alluvial valleys. Annual rainfall ranges from ~790 to 1580 mm, strongly influenced by orography and seasonality, with ~70% falling between October and March (Bureau of Meteorology, 2026). Upland areas are dominated by protected subtropical Gondwana rainforest and wet sclerophyll forest, with thin basalt-derived friable clay soils. On the intermediate hillslopes thinning basaltic layers transition to older underlying sedimentary rock, as well as colluvial deposits, whereas the soils range from shallow clays on steep slopes to thicker colluvial duplex soils on foothills, sometimes with sodic subsoils. Land use includes dry sclerophyll forest, grazing land, and expanding urban areas around Canungra, where the former experience regular planned burns. The lower catchment consists of alluvial plains with deep black clay soils with high fertility and water availability, supporting intensive agriculture. Extensive land clearing for intensive grazing, cropping, horticulture, turfgrass production, and animal



husbandry has reduced natural vegetation to narrow remnant strips (Figure S1). The river has incised very deeply in these alluvial soils with over 15m from the channel bottom to the top of the bank at Bromfleet. The drainage network upstream of the Bromfleet gauging station consists of two main branches: the Canungra Creek to the East and the Albert River western
115 branch, which converge about 500 m upstream of the gauge forming the Albert River main branch.

The Albert river has four telemetered river gauges (145102B: Albert River at Bromfleet; 145101D: Albert River at Lumeah; 145103A: Cainbabel Creek; 145107A: Canungra Creek) recording water level and discharge, and are managed by Queensland Government (Queensland Government, 2026). There are 7 rain gauges, of which 5 (40042: Canungra Finch Road; 40197: Mt Tamborine Fern st; 40931: O'Reillys; 40932: Darlington; 40937: Benobble) are managed by the Bureau of Meteorology
120 (BoM) and only record daily rainfall accumulation, and 2 (40936: Lumeah; 40938: Bromfleet) are managed jointly by DETSI and BoM and record both 1 min intervals and daily rainfall accumulation (Bureau of Meteorology, 2026). *Tropical Cyclone Alfred* made landfall as a category 2 in the night of March 7 2025 on Moreton Island ca. 100 km northeast of the study site, quickly weakening to a tropical low moving west inland. Due to the clockwise spinning, the heaviest rainfall was south of the landfall, impacting mostly the NSW Northern Rivers, and the Gold Coast and its hinterland, which includes the study site.
125 This region of Australia is known for its rapid transition from coast to uplands. At the sub-hourly 'Bromfleet' and 'Lumeah' rain gauges, which are both located at the lower altitude alluvial floodplains, the total *Cyclone Alfred* event (05/03/2025-13/03/2025) rainfall was respectively 313 mm (Figure 1B) and 182 mm with a calculated event rainfall erosivity (EI_{30}) of 1542 MJ mm ha⁻¹ h⁻¹ and 608 MJ mm ha⁻¹ h⁻¹. The *Cyclone Alfred* total event rainfall was 602 mm, 505 mm, and 532 mm in the intermediate hillslope stations of 'Benobble', 'Canungra Finch Road', and 'Darlington' respectively, while it was 726 mm and
130 674.7 mm at the upland stations of 'O'Reilly' and 'Mount Tamborine Fern st'. Assuming a similar relationship between total storm erosivity and total event rainfall at the daily rain gauges, EI_{30} would be 4516 MJ mm ha⁻¹ h⁻¹, 3350 MJ mm ha⁻¹ h⁻¹, and 3660 MJ mm ha⁻¹ h⁻¹ in the respective hillslope stations of Benobble, Canungra, and Darlington, while EI_{30} would be 6209 MJ mm ha⁻¹ h⁻¹ and 5482 MJ mm ha⁻¹ h⁻¹ in the respective upland stations of O'reilly and Mount Tamborine. At the Albert River Bromfleet gauging station (145102B), the event produced a rapidly rising stage and discharge from 0.25 m and 1.6 m³ s⁻¹ to a
135 peak stage of ca. 15.03 m with associated discharge peak of 802.7 m³ s⁻¹ in just over 3 days (Figure 1C). The discharges measured during the peak of this event are limited to extreme rainfall events linked to tropical lows or cyclones. In the nearly 100-year record of the Bromfleet station, the discharge has crossed the 800 m³ s⁻¹ threshold for a total of 254 hours, highlighting the relative rarity of the studied event (Queensland Government, 2026).

2.2 Sampling design

140 Suspended sediment was collected during *Cyclone Alfred* at the Bromfleet gauging station using a series of rising stage samplers (RSS) installed at 1.4, 2.3, 3.6, 4.5, 5.7, 6.5, 7.5, 9.1, 11.1, 12.1, 13.1, and 14.1 m above the channel bed (Figure S2). This was supplemented with grab samples during baseflow conditions before and after the event, and falling-stage conditions at 7.6, 3.9, and 2.1 m above the channel. Each RSS captured a discrete sample when water levels intersected the



145 sampler intake, and consequently the time of sampling could be determined, while river heights and discharge could be determined by the time of grab sampling. This yielded a sample time sequence across the flood hydrograph (Table 1).

Table 1: Overview of sampling times with accompanying discharge, height, sediment and total PP concentrations, and particle size.

Type	Sample ID	Collection date-time	Time (h)	Discharge (m ³ s ⁻¹)	SSC (mg L ⁻¹)	PSA % < 63 µm	PP_tot (µg L ⁻¹)
Base 1	PSA28	05/03/25 14:00	0.00	1.6	372.5	82.9	402.2
Base 2	PSA 29	05/03/25 14:00	0.00	1.6	323.5	82.9	349.2
Base 3	PSA24	05/03/25 14:08	0.1	1.6	339.6	82.9	319.3
RSS1.4	PSA99	06/03/25 17:55	27.9	10.8	1286.8	78.4	2005.9
RSS2.3	PSA98	06/03/25 18:50	28.8	21.0	1415.9	80.3	2224.7
RSS3.6	PSA36	07/03/25 10:55	44.9	36.8	800	84.4	1266.3
RSS4.5	PSA40	07/03/25 15:05	49.1	50.1	645.2	81.6	1019.0
RSS5.7	PSA30	07/03/25 20:40	54.7	69.3	495.4	90.2	1721.8
RSS6.5	PSA35	07/03/25 22:55	56.9	82.9	733.3	82.2	1004.5
RSS7.5	PSA37	08/03/25 06:35	64.6	101.9	616.7	88.9	1054.6
RSS9.1	PSA32	08/03/25 10:40	68.7	161.2	533.3	85.9	1197.6
RSS10.1	PSA33	08/03/25 15:25	73.4	220.2	683.3	83.8	1534.4
RSS11.1	PSA31	08/03/25 21:25	79.4	286.4	448.3	76.6	1043.2
RSS12.1	PSA39	09/03/25 08:40	90.7	370.7	500	88.7	1535.8
RSS13.1	PSA38	09/03/25 14:00	96.0	468.6	467.7	87.5	900.6
RSS14.1	PSA34	09/03/25 21:55	103.9	584.4	1294.1	85.7	2881.5
Peak	/	10/03/25 02:20	108.3	802.7	/	/	/
FS7.5	PSA22	11/03/25 08:15	138.3	101.9	392	95.0	817.8
FS3.8	PSA23	12/03/25 09:25	163.4	40.4	470.8	89.1	781.5
FS2.1A	PSA25	14/03/25 09:32	211.5	18.6	480.8	86.7	738.0
FS2.1B	PSA26	14/03/25 09:35	211.6	18.6	363.6	86.7	541.5
all	all	06/03/25 – 14/03/25	/	/	/	/	/
Drape	11791	17/09/2025	/	/	/	/	/

150 Sampling of potential source soils and additional deposited sediment drapes was conducted between September and October 2025. Sampling locations were selected based on accessibility, visible erosion features (e.g. exposed streambanks and road cuts), and representation of the dominant soil and land-use classes across the catchment (Figure 1A & Figure S1). To capture alluvium subsoil, 43 samples of alluvial bank profiles (2-4 sample depths per profile) were collected spread over 14 locations distributed across the Albert River, Canungra Creek, and their major tributaries. Subsoil from hillslopes/colluvium were represented using 5 bank samples from smaller creeks, while upland subsurface soils were represented from 3 samples of track cuts. In addition, 40 composite topsoil samples were collected from the upper 5 cm of soil using approximately 10 trowel



155 scoops within a 4m² plot. These samples were distributed across the three major soil-landuse groups, including agricultural alluvial floodplains, intermediate hillslopes dominated by dry-sclerophyll forest and grazing land, and upland areas under subtropical rainforest or permanent grassland (Figure 1A). Finally, a deposited sediment drape (11791) was also collected from the upper bank at the Bromfleet gauging station. All samples were oven- or freeze-dried, disaggregated, and sieved to <63 µm.

2.3 Laboratory analysis

160 2.3.1 Suspended Sediment Concentration and Particle Size Assessment

The volume of the RSS samples was recorded using a measuring cylinder, and the samples were subsequently transferred to pre-weighted glass beakers. Particle size distribution (PSD) of the suspended sediment samples was determined using laser diffraction spectroscopy (Mastersizer 3000, Malvern Panalytical, Malvern, UK). Samples were subjected to 1 minute of ultrasonic dispersion before analysis to disperse clay aggregates. The Mastersizer uses an integrated paddle stirrer to keep all
165 sediment fractions in suspension and takes a subsample of the suspension to analyse (Doréan et al., 2020). A collimated laser beam passes through a dispersed particle suspension, whereafter the intensity of light scattering is used to calculate PSD. The PSD is reported as the 10th percentile (D10), median (D50), and 90th percentile (D90) of the volume-based distribution. This process was repeated 5 times per sample and the PSD parameters were averaged to mean values. The proportion of particles <63 µm was then calculated by assuming a lognormal particle size distribution (Table 1). The samples were
170 subsequently oven-dried on 60°C and after complete evaporation, the beakers were reweighed to obtain the total mass of the suspended sediment. Suspended Sediment Concentration (SSC) was calculated by dividing mass of sediment by volume of sampled water. Dried suspended sediment samples were transferred to cups for further processing and analysis.

2.3.2 Sequential extraction of major and trace elements

Soil and sediment geochemical fractions were extracted following a modified protocol based on Poulton and Canfield (2005),
175 which while originally developed for iron mineralogy, is suitable for most functional elemental fractions in (sub)tropical soils with high oxide content. The method isolates six operationally defined geochemical fractions: exchangeable, carbonate-associated, three oxide-associated fractions, and recalcitrant. For each sample, roughly 200 mg of <63 µm sieved soil or sediment material was weighed in a 15 ml centrifuge tube. The first step for extracting the exchangeable fraction (ex) was to add 10 ml of 1 M MgCl₂ reagent buffered at pH 7 and shaking the mixture for 2 hours at room temperature. Second, carbonates
180 (car) were extracted by adding 10 ml of 1 M CH₃COONa.3H₂O buffered at pH 4.5 and shaken for 24 hours at room temperature. Third, easily reducible oxides (ox1) were dissolved by adding 10 ml of 1 M NH₂OH·HCl in 25% CH₃COOH and shaken for 48 hours at room temperature. Fourth, crystalline oxides (ox2) were digested by adding 10 ml of a freshly prepared 50 g L⁻¹ Na₂S₂O₄ solution buffered at pH 4.8 and shaken at 2 hours at room temperature. Fifth, poorly reducible oxides (ox3) were extracted by adding 10 ml of 0.2 M (NH₄)₂C₂O₄·H₂O + 0.17 M C₂H₂O₄·2H₂O buffered at pH 3.2 and shaken overnight (6-12
185 hours) in the dark at room temperature. Finally, the recalcitrant fraction (rec) was extracted by adding 10 ml of reverse aqua



regia with 7.5 ml of HNO₃ and 2.5ml of HCl, and left to digest in a hot water bath for 24 hours at roughly 95°C. The HNO₃ was first distilled to remove impurities. Buffers were accomplished with NaOH and CH₃COOH at different concentrations, except for step 4 which was buffered with 0.2 M of Na₃C₆H₅O₇·2H₂O and 0.33 M CH₃COOH. After each step, the extracts were centrifuged at 1500 g and decanted, after which the new reagent was added and the pellet was vortexed until completely
190 in solution in the new reagent. Extracts were diluted 50-fold for reagents 1, 2, 5, and 6, and 100-fold for reagents 3 and 4 in a 2% nitric acid solution. All diluted extracts were analysed by Inductively Coupled Plasma Mass Spectrometry (ICP-MS; Agilent 8900, Agilent Technologies, Santa Clara, CA, USA) for a broad range of major and trace elements (Al, As, Ba, Ca, Cd, Co, Cs, Cu, Fe, Mg, Mn, Mo, Ni, P, Pb, Sb, Se, Ti, U, V, W, Zn), yielding concentrations in each fraction extract. Procedural blanks were used to analyse the background concentration for each step, which were subtracted from the sample
195 concentrations. The limit of detection (LOD) was set as the highest value between three times the standard deviation of the procedural blanks and the concentration of the lowest calibration point. Samples with negative values before and after background correction were noted as below the limit of detection (<LOD). Extract concentrations (µg l⁻¹) were recalculated to dry weight concentration in mg kg⁻¹ using the extracted mass, the reagent volume, and the dilution factor. Additional quality assessment included certified reference materials, calculation of recovery, and replicate analyses. Total elemental
200 concentrations were obtained by summing all fractions, while total oxide-associated fraction concentrations were obtained by summing all oxide fractions (steps 3-5). Finally, the particulate phosphorus concentrations (PPC) per sample were obtained by multiplying the obtained SSC values (mg L⁻¹) with the dry weight concentrations of each PP fraction (mg kg⁻¹) and divided by 1000, yielding PPC of the fractions and total in µg L⁻¹. Due to the evaporative drying of the samples, the dissolved P likely was also extracted in the first extraction step, meaning the exchangeable fraction thus actually represents both exchangeable
205 particulate-bound and dissolved phosphorus fractions.

2.4 Data analysis

2.4.1 Concentration-discharge and hysteresis analysis of suspended sediment and particulate phosphorus

Suspended sediment concentrations (SSC) and particulate phosphorus concentrations (PPC) were plotted against discharge to classify hysteresis patterns and infer shifts in sediment availability and connectivity over the event (Figure 2). Patterns were
210 interpreted following established categories and the total Hysteresis area was calculated. The event-scale Hysteresis Index (HI) was calculated per Eq. (1) following Lloyd et al. (2016a), using normalised discharge and concentration data of SSC and PPC to quantify differences between the rising and falling limbs of the hydrograph. Normalised discharge was divided into ten equal-width intervals (0–1), each representing 10% of the discharge range. Within each bin, mean normalised concentrations on the rising and falling limbs of the hydrograph were calculated. The resulting bin-specific hysteresis indices were
215 subsequently averaged across all bins to obtain a single event-scale HI value:

$$HI = \frac{1}{n} \sum_{i=1}^n \frac{C_{r,i} + C_{f,i}}{C_{r,i} - C_{f,i}} \quad (1)$$



where $C_{r,i}$ and $C_{f,i}$ are the mean normalised concentrations separated for the rising and falling limbs, within discharge bin i , and n is the total number of discharge bins. Positive values indicate clockwise hysteresis, whereas negative values indicate counter-clockwise hysteresis.

220 To characterise short-term shifts in hysteretic behaviour throughout the storm, the raw stepwise hysteresis slope (HS) was calculated by dividing the difference in concentration with that of discharge between each successive sample as per Eq. (2), and subsequently normalised between $[-1,1]$ as per Eq. (3) into the hysteresis slope index (HSI):

$$HS_{step,i} = \frac{\Delta C_i}{\Delta Q_i} \quad (2)$$

$$HSI_{step,i} = \frac{HS_{step,i}}{\max(|HS_{step,i}|)} \quad (3)$$

The HSI provides the relative magnitude of concentration change compared to discharge change for each timestep, where values closer to -1 or 1 indicate a stronger non-linear hysteretic SSC or PPC response. Positive values in HS and HSI indicate 225 that the change in concentration and discharge follow the same direction, while negative values indicate opposing trends. To infer the general influence of discharge and rainfall on sediment and phosphorus dynamics, Spearman correlation tests were performed on the SSC, particle size distribution, PPC fractions and relative proportions of PP fractions and sediment source contributions with discharge, rainfall intensity, and the HS as predictor (Table S1).

2.4.2 Source Grouping, Tracer Selection, and Sediment Unmixing

230 Source Grouping

To optimize mixing model performance and prevent interpretability decline from excessive source complexity (Vale et al., 2022), post-sampling source grouping was explored using Principal Component Analysis (PCA) and Linear Discriminant Analysis (LDA) (Figure S3). This unsupervised and supervised validation confirmed three geochemically distinct source groups mirroring the catchment's lithology and land use: Upland (subtropical rainforest on clay-rich soils derived from younger 235 basalt); Hillslope (dry sclerophyll forest, grasslands, and urban areas on duplex soils derived thinning basalt and older sedimentary rocks) and Alluvium (riverbank profiles and lowland agricultural topsoils on alluvial black clays).

Tracer Selection Framework

Elemental concentrations in the carbonate, total oxide (calculated as the sum of three oxide fractions), and recalcitrant fractions were considered as potential tracers. The exchangeable fraction was excluded because it is unlikely to behave conservatively 240 during sediment transport. Tracers with more than 25% of observations $< LOD$ were removed. For tracers with fewer than 25% of values below the LOD, these observations were replaced with half of the lowest measured concentration. Tracer selection was performed using the FingerPro R package (Lizaga et al., 2020b). Linear mixing models require conservative tracers that



exhibit high discriminatory power and mathematical consistency. To satisfy these assumptions, we applied a comprehensive tracer selection framework comprising the Conservativeness Index (CI), Consensus Ranking (CR), and Consistent Tracer Selection (CTS) methods (Latorre et al., 2021; Lizaga et al., 2020a). A novel hierarchical clustering protocol was integrated into the CTS framework. Herein, tracer pair were filtered by a baseline conservativeness threshold and clustered based on their source contributions using Euclidean distance and Ward's minimum variance method. This allowed the quantitative evaluation and selection of the best-performing tracer sets based on tracer support, error thresholds and mass-balance agreement.

Mixing Model Implementation and Apportionment

Source apportionment was performed using the FingerPro mixing model (Lizaga et al., 2020b). To account for high source heterogeneity without underestimating uncertainty near the physical boundaries (0 or 1), the model algorithm incorporates Linear Variability Propagation. This approach handles uncertainty by analytically propagating source covariances through the Jacobian of the least-squares solution. Notably, the model algorithm does not artificially constrain individual simulation runs to the 0–1 range. While this can yield non-physical outputs for unconservative tracer subsets, it provides significantly more realistic and unbiased source apportionment in mixing systems dominated by a single, high-contributing source (Latorre et al., 2025). The model estimates unknown source proportions by simulating combinations that minimise the mismatch (goodness-of-fit) between predicted and observed mixture tracer concentrations. Uncertainty stemming from natural source variability was propagated through Monte Carlo sampling (1000 iterations), representing final source contributions as probability distributions defined by their mean and standard deviation. The unmixing was performed separately on all sediment samples. In addition, we grouped all storm event samples into one mixture, as well as unmixed a deposited sediment sample (Table 1). The ultimate decision on what cluster mixing outcome to use for the plotting and discussion was based on objective clustering parameters: number of unique tracers, number of tracer pairs, mean conservativeness, mean discrimination, silhouette, and standard deviation (Table S2). These objective parameters were supplemented with literature-based understanding of tracer geochemistry in soil and water, as well as the SSC-Q relationship.

2.4.3 Fine sediment and phosphorus load and budget calculation

Fine SS and PP loads at each sampling time were calculated as the product of SSC or PPC, fine sediment content ($\% < 63 \mu\text{m}$), and river discharge (Q), converted to kg s^{-1} . Total event SS and PP loads were then estimated by multiplying the mean of two successive loads with the corresponding time interval to obtain a partial load, and these partial loads were summed across the event. Source-specific loads were calculated by multiplying the total load at each sampling time by the mean of the proportional source distribution obtained from the unmixing model, with model uncertainty propagated and visualised using the mean $\pm$ standard deviation (Figure 3). As an independent assessment of phosphorus mass conservation of soil-based sources to the suspended sediment, PPC_{ex}, PPC_{car}, PPC_{ox}, and PPC_{rec} were predicted by multiplying the mean proportional contribution of each sediment source by its corresponding mean fractional PPC and summing across all sources. These mass balance estimates were then compared with measured fractional PPC in suspended sediment samples.



275 As a way to contextualise the importance of extreme events and different sources to annual sediment and nutrients budgets, the *Cyclone Alfred* event concentration-discharge hysteresis relationship was also extrapolated to the entire 2024-2025 hydrological year. Five hysteresis states were defined based on water level and hydrograph position (Table S3): (i) Baseflow (<1 m stage), (ii) Rising 1 (1-3 m stage on the rising limb), (iii) Rising 2 (3-13.5 m stage on the rising limb), (iv) Peak (13.5-17 m stage on either limb), and (v) Falling (13.5-1 m stage on the falling limb). Mean SS, fine sediment content, and fractional
280 PP concentrations and source contributions for each state were derived from average measurements and unmixing results obtained during the *Cyclone Alfred* event. These state-specific values were then applied to the full hydrological record to estimate annual fine SS and PP loads and source contributions, and to assess the relative importance of the *Cylone Alfred* event to the total yearly sediment and phosphorus export.

3 Results

285 3.1 Sediment and phosphorus concentration-discharge relationship

The baseflow before the storm event had low suspended sediment concentration (SSC) of $\sim 345 \text{ mg L}^{-1}$ and particulate phosphorus concentrations (PPC) of $\sim 360 \text{ } \mu\text{g L}^{-1}$. During the storm event, the SSC and PPC exhibited two major peaks (Figure 1C & Figure 2). An early first-flush peak occurred at relatively low discharge (at $\sim 2\text{--}35 \text{ m}^3 \text{ s}^{-1}$), where SSC increased sharply to $\sim 1200\text{--}1400 \text{ mg L}^{-1}$ and PPC to $\sim 2000\text{--}2200 \text{ } \mu\text{g L}^{-1}$. A second peak occurred at the highest sampled discharge ($\sim 584 \text{ m}^3$
290 s^{-1}), where SSC rose to $\sim 1300 \text{ mg L}^{-1}$ and PPC to $\sim 2880 \text{ } \mu\text{g L}^{-1}$, thus evidencing phosphorus enrichment compared to suspended sediments at peak flow conditions. These peaks were interspersed with lower concentrations along the intermediate rising limb, where SSC declined to $\sim 500\text{--}800 \text{ mg L}^{-1}$ ($35\text{--}470 \text{ m}^3 \text{ s}^{-1}$) and PPC fluctuated between ~ 900 and $1500 \text{ } \mu\text{g L}^{-1}$. Similarly, on the falling limb, SSC decreased further to $\sim 400\text{--}470 \text{ mg L}^{-1}$ ($100\text{--}20 \text{ m}^3 \text{ s}^{-1}$), with PPC dropping to $\sim 540\text{--}820 \text{ } \mu\text{g L}^{-1}$, remaining slightly above baseflow levels.

295 The resulting SSC-discharge (SSC-Q) relationship thus demonstrated a figure-eight hysteresis loop, with an initial first flush of high SSC at the event onset, followed by a second concentration peak at high discharge (Figure 2A). The PPC-discharge (PPC-Q) relationship followed a similar figure-eight pattern with the main difference that PPC at peak discharge was markedly higher than during the first-flush phase (Figure 2B). The storm event SSC hysteresis index (HI) was strongly positive (0.70), while that of PPC was moderately positive (0.40). Due to the figure-eight hysteresis, the hysteresis slope index (HSI) pattern
300 was complex, with shifts from positive to negative hysteresis and a particularly strong clockwise response at the beginning of the event. Although the second peak exhibited similarly high SSC and even higher PPC compared to the initial peak, the much greater discharge at this stage reduced the relative hysteretic strength, resulting in a less pronounced HSI compared to the first-flush phase. No correlation was found between SSC and Q, likely due to the figure-eight hysteresis.

Neither discharge nor rainfall intensity was significantly correlated with SSC (Table S1). A negative correlation was found
305 between Q and D10 ($\rho = -0.69$, $p\text{-value} = 0.002$) and D50 ($\rho = -0.55$, $p\text{-value} = 0.02$), but not between Q and D90 ($\rho = 0.02$,



p-value = 0.99) and the % < 63 μm ($p = 0.25$, p-value = 0.34). This indicates that discharge primarily decreases the finest portions of the particle size distribution. No significant correlation was found between the HS with SSC, nor particle size or source contributions. No significant relationship was observed between Q and total PP concentration (PPC_{total}), but rainfall intensity was positively correlated with PPC_{total} ($p = 0.02$), and the HS was positively correlated with PPC_{total} (p-value = 0.03) and PPC_{car} (p-value = 0.01), while being negatively correlated with the proportion of PP_{rec} (p-value = 0.01).

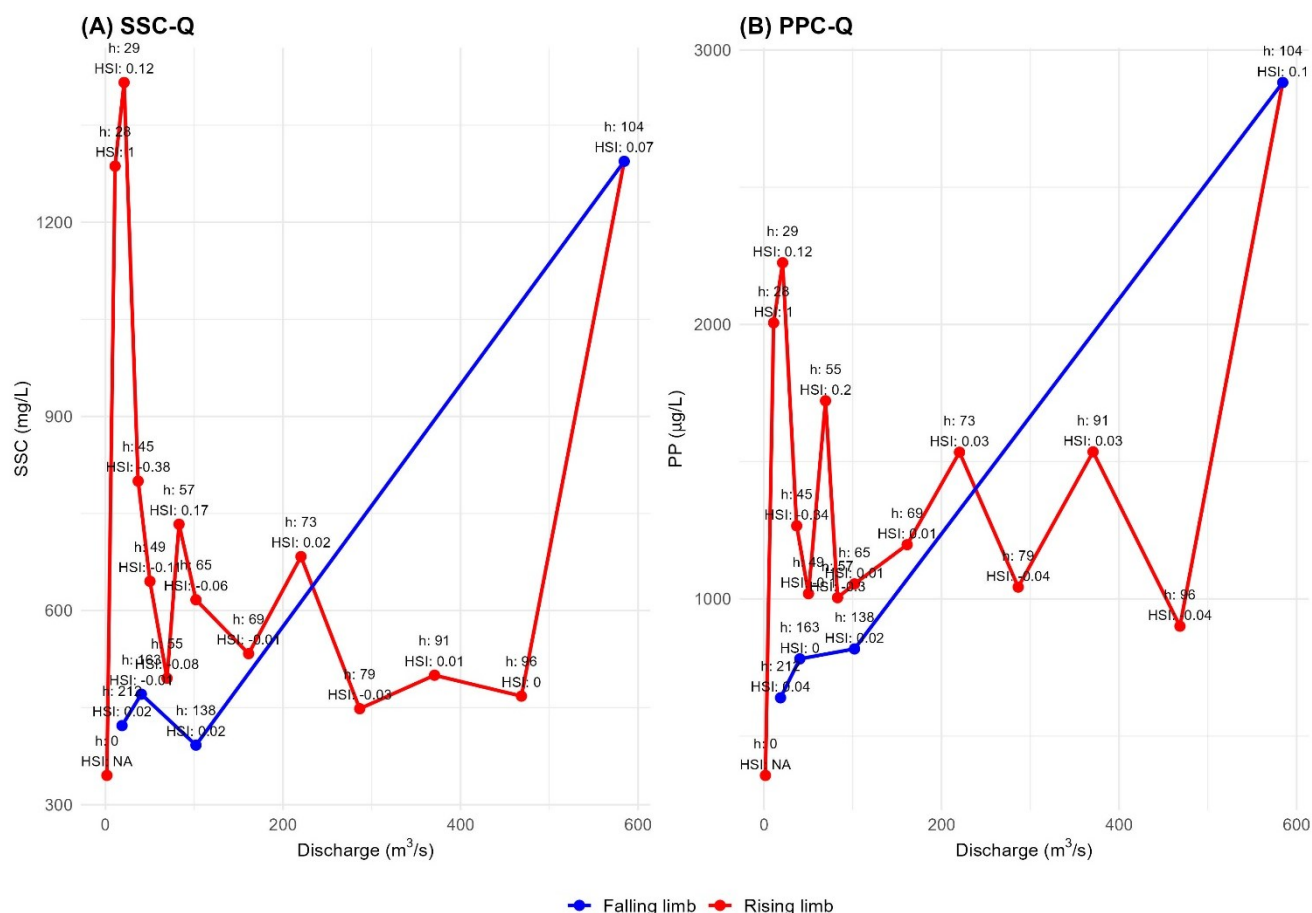


Figure 2: Figure-eight hysteresis loops of (A) SSC-Q, and (B) PPC-Q. The rising discharge limb is red and the falling limb in blue. Each dot shows the sampling time in hours (h) starting from the first sample, as well as the normalised hysteresis slope index (HSI).

3.2 Sediment and Phosphorus source contributions throughout the event

The LDA showed a strong discrimination between the three source groups and was particularly more pronounced when using the elements fractions compared to the total concentration (Figure S3). The selected and non-selected tracer clusters can be found together with their objective support factors in Table S2. Most tracers in selected cluster solutions were recalcitrant and



oxide-associated such as: Ba_oxtot (11), Al_rec (10), Ca_rec (10), U_rec (10), Al_oxtot (9), Ba_rec (9), Co_rec (9), As_oxtot (8), Fe_rec (8), and U_oxtot (8).

320 The mixing model results showed a distinct shift in proportional SS source contribution throughout the storm event (Figure 3A). At baseflow, the mixing model pointed towards either dominance of alluvium or a more distributed mixture. The first flush SSC peaks (at 27-28 h) were dominated by alluvium (ranging between 60-80% contribution) with minor contributions of hillslope (ranging between 20-35% contribution) and negligible contributions of upland sources. The following lower SSC in the rising stage from 44-56 h had similar distribution dominated by alluvium (around 60%). However, from 64 h, a gradual
325 increase in the proportional contribution from hillslope soils could be observed, alternating highest contribution with alluvium (both ranging between 25-60% contribution). From 96 h to the sample with the discharge and SSC peak at 104 h hillslope was clearly the dominant source with around 70% contribution, which included the SSC peak. During the falling stage from 138-211 h, the proportional contribution gradually shifted again from hillslope dominated to alluvium dominated. For the aggregated storm sediment mixture, the mixing model points to alluvium as the dominant source. Similarly, the deposited
330 sediment drape collected after the event shows a dominance of alluvium (Figure S4). Discharge was negatively correlated with the proportional contribution of alluvium ($\rho = -0.49$, $p\text{-value} = 0.05$), weakly positively correlated with hillslope contribution ($\rho = 0.45$, $p\text{-value} = 0.07$), and not correlated with upland. Rainfall intensity was positively correlated with proportional hillslope contribution ($\rho = 0.52$, $p\text{-value} = 0.03$), and had a negative, albeit non-significant relationship with proportional alluvial and upland contribution (Table S1).

335 During baseflow, PP was dominated by over 70% carbonate-associated P (PPC_car), whereas the first flush, rising stage, and falling stages were characterised by dominance of oxide-associated P (PPC_ox) contributing respectively around 75, 44, and 56%. PP fraction dominance shifted markedly at peak discharge, with a pronounced increase to 70% contribution in exchangeable P (PPC_ex). Strong positive correlations were found between Q and PPC_ex and its proportional contribution ($p\text{-value} \sim 0$). Rainfall intensity was also positively correlated with PPC_ex ($p\text{-value} \sim 0$) and PPC_rec ($p\text{-value} = 0.005$). In
340 contrast, the proportion of PPC_ox showed a significant negative relationship with Q ($p\text{-value} = 0.02$).

3.3 Sediment and Phosphorus fractional load calculations

Sediment and PP transport was highly concentrated during the rising limb and peak flow period with an initial slow rise early in the event. The approximately 8-hour interval between 96 and 104h of the storm accounted for ca. 55% of the total event sediment and PP load (Figure 3). Interpolation and summation of the instantaneous sediment loads estimated the total event
345 sediment load at 90,299 tons of which 77,499 tons of fine ($<63 \mu\text{m}$) sediments. Despite alluvial dominance at most sample points throughout the hydrograph, it only contributed ca. 30% of the total event load, mostly during the rising stage and peak of the event. The short peak-flow window was sufficiently sediment-rich so that hillslope materials dominated the event-integrated budget with ca. 60% (Figure 4A). Upland sources were low throughout most of the event and contributed about



10% of the event load. Total PP export during *Cyclone Alfred* at Bromfleet was estimated at approximately 199 t by interpolation, with ~53% exchangeable P mostly during the peak (~106 t), ~25% oxide-bound P mostly during the rising stage (~49 t), ~15% carbonate-bound P (~30 t), and ~7% recalcitrant P (~14 t). This distribution indicates that most exported PP was situated during the event peak but was also highly reactive and therefore likely bioavailable (Figure 4B).

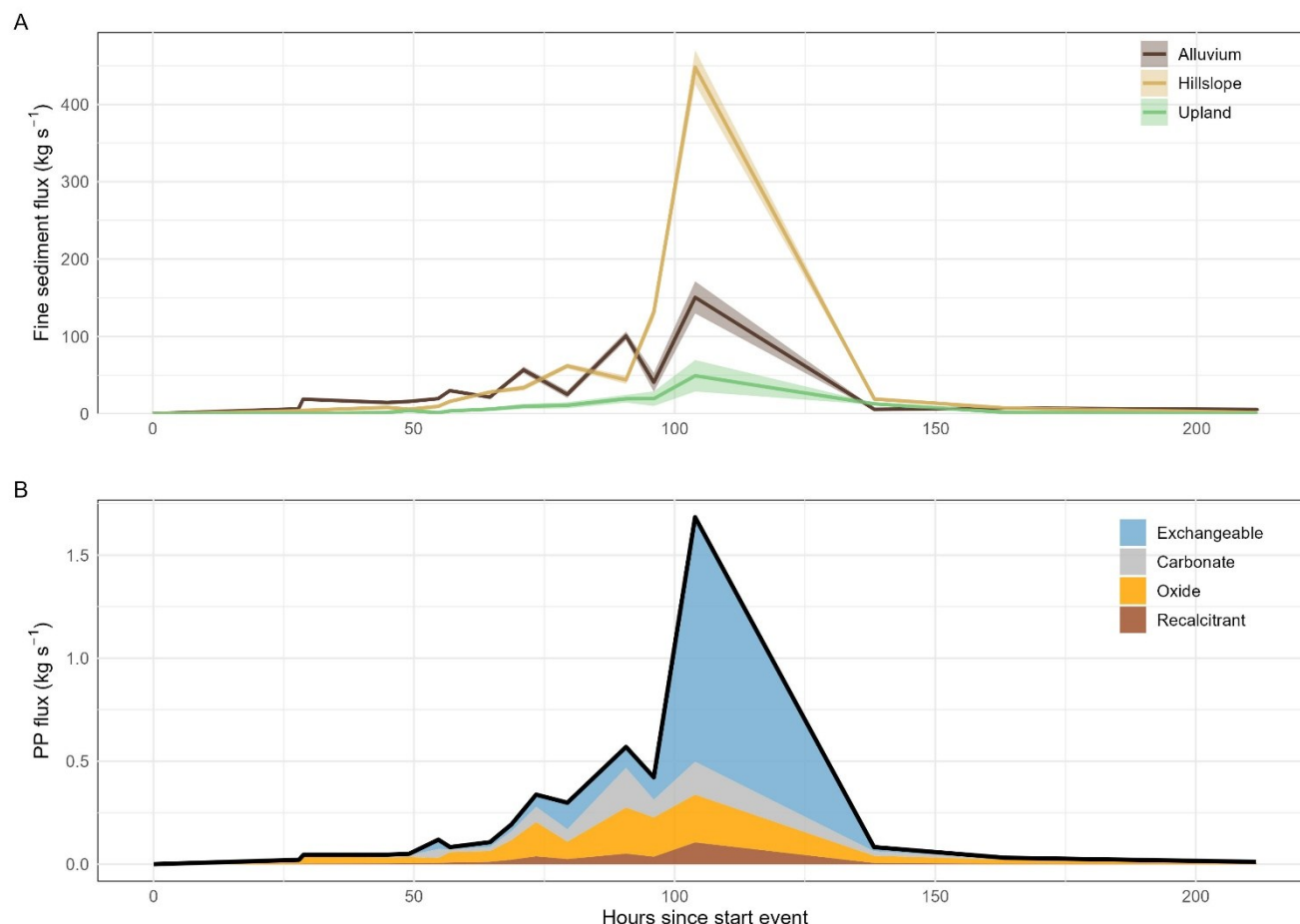


Figure 3: (A) Sediment load in kg s⁻¹ as separated by the unmixing source proportions, and (B) the PP load as separated by P-fraction over the course of the storm event

When extrapolating the SS hysteresis to the July 2024 - June 2025 hydrograph at Bromfleet, the total *Cyclone Alfred* flood was estimated to contribute 57 % of the yearly sediment load. Hillslope dominated the yearly sediment budget with ca. 48% compared to 41% for alluvium (Figure 5A), even though alluvium was the major source for each storm event except the *Cyclone Alfred* flood. Extrapolation of the PP hysteresis relationships suggests that the *Cyclone Alfred* flood contributed approximately 65% of the annual PP export, highlighting the dominant role of extreme events in system-scale P budgets (Figure 5B). Despite contributing primarily during extreme conditions, which only occurred once in the hydrological year, exchangeable P was still the largest annual fraction with 38.6%. Oxide-bound P contributed estimated 33.9% of the yearly



budgeted, mostly through more frequent smaller storm events and initial rising stages. Carbonate-bound P contributed an estimated 20.6% of which most during baseflow.

365 4 Discussion

4.1 Sediment and PP hysteresis and shifts in dominant sources and reactivity throughout large floods

The figure-eight SSC hysteresis pattern reflects sequential activation and exhaustion of sediment sources (Figure 2A). High SSC during the first flush indicates rapid mobilisation of near-channel sediments, likely derived from recent bank collapse, channel margins, and in-channel bars. Sediment tracing confirms this phase was dominated by alluvial sources. As discharge continued to increase, SSC declined, suggesting temporary exhaustion of readily available channel sediments and a period of sediment supply limitation. During this phase, source contributions gradually shifted from predominantly alluvial to increasingly hillslope-derived material. The second SSC peak near maximum discharge indicates activation of more distal sediment sources, which was confirmed by the dominance of hillslope contributions during this period. We hypothesise that sustained high rainfall intensified hillslope erosion and exceeded hydrological connectivity thresholds for intermittent tributaries, thereby linking previously disconnected sediment sources to the main channel network. This interpretation is consistent with higher rainfall totals in the hillslope and upland parts of the catchment than in the lowland floodplain. Although hillslope sources dominated the sediment contribution during this phase, sediment inputs from alluvial sources also continued to increase slightly throughout the rising limb of the hydrograph (Figure 3).

PPC exhibited a similar figure-eight hysteresis pattern (Figure 2B) but with notable shifts in phosphorus composition (Figure 3). During the first flush, PP was dominated by oxide-bound forms, consistent with the mobilisation of alluvial bank sediments that dominated SSC at this stage. As the event progressed, the relative contribution of exchangeable and carbonate-associated P increased. Unlike with SSC, the second PPC peak exceeded the intensity of the first, indicating disproportionate mobilisation of phosphorus relative to sediment. This shift culminated at peak discharge, when exchangeable P became the dominant PP fraction. Such behaviour suggests either (i) preferential mobilisation of sources with high concentrations of labile P, i.e. fertilised cropland soils (Kerr et al., 2011), (ii) enhanced leaching of dissolved P from soils, or (iii) the activation of non-soil derived point sources, such as untreated sewage or slurry tanks overflows, during peak rainfall. Since none of the sampled source materials contained similarly high proportions of exchangeable P (Figure S5) and measured exchangeable P concentrations exceeded those predicted from simple mass balance mixing of source soils by up to two orders of magnitude (Figure S6), these elevated concentrations are unlikely to be explained solely by the mobilisation of the sampled soil sources. Instead, they likely indicate the activation of non-soil-derived point sources during peak rainfall, such as untreated wastewater inputs or slurry store overflows (Suchowska-Kisielewicz and Nowogóński, 2021; Vero and Doody, 2021). Despite the remaining uncertainty on the source of the exchangeable P pulse, this study provides strong evidence that extreme floods transport greater total PP loads, but also higher proportions of bioavailable fractions.



Summarising the flood chronology, at the onset of flood events, previously collapsed bank material was rapidly entrained, producing an initial peak in suspended sediment concentration (SSC) and particulate phosphorus concentration (PPC), characteristic of a first flush. As the supply of easily entrained material became limited, concentrations declined, although the total load continued to increase due to rising discharge and bank scour. At peak rainfall and discharge, a distinct secondary peak in SSC and PPC was caused by activation and connectivity of distal hillslope material and point-source phosphorus inputs. During the falling stage, sediment and PP sources shifted back to predominantly alluvial origins. Following the event, scoured banks gradually collapse, replenishing the pool of easily entrained material available for subsequent floods. Overall, these findings highlight the critical role of non-linear sediment and phosphorus source activation, mobilisation, and connectivity thresholds during extreme events (Kerr et al., 2011; Zou et al., 2023; Malutta et al., 2020).

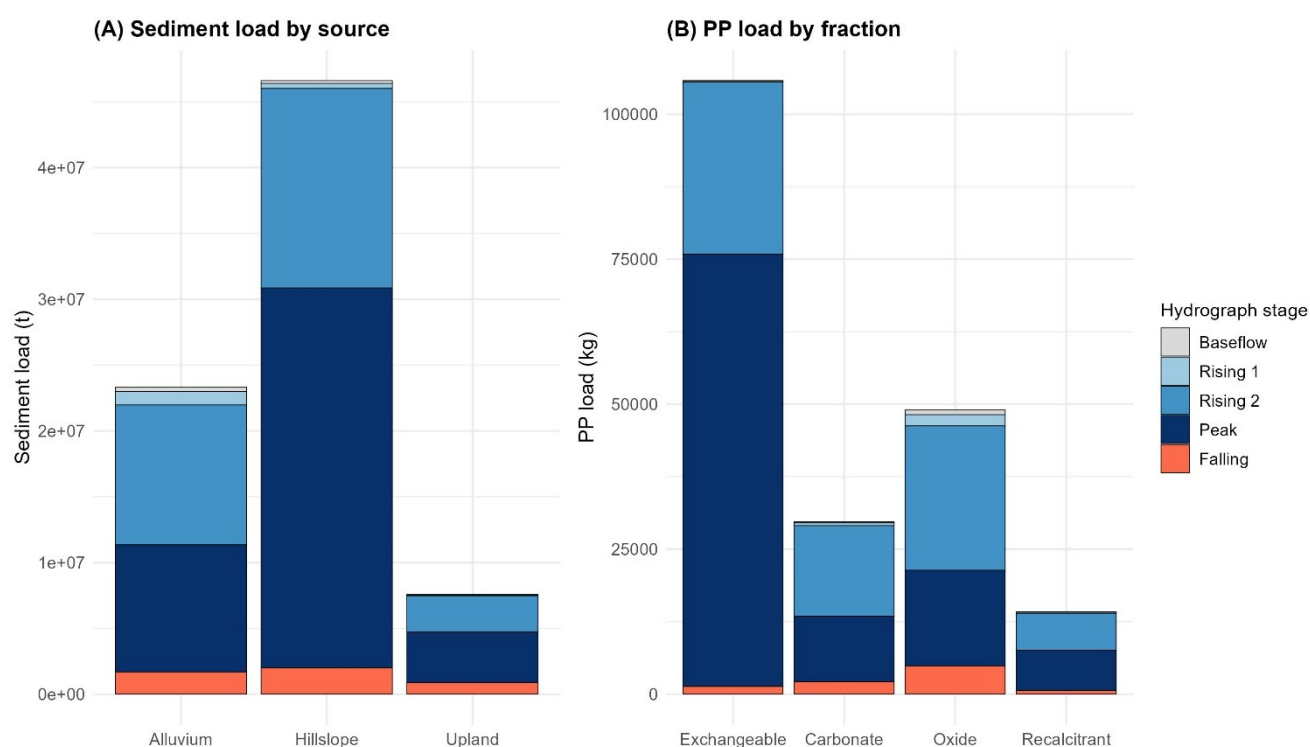


Figure 4: Cumulative *Cyclone Alfred* stacked bar plots indicating contribution from different stages of the hydrograph of (A) fine sediment (< 63 μ m) load separated by sources, and (B) Particulate Phosphorus (PP) load separated by fractions.

4.2 Methodological uncertainties and implications for future scientific applications

Several methodological limitations introduce uncertainty into the sediment concentration and load estimates. The field setup itself was rapidly deployed in response to the rapid onset and unpredictable trajectory of the cyclone, which constrained sampling design. Due to the exponential relationship between stage and discharge, and the fact that the highest river stage could not be sampled for the *Cyclone Alfred* event, the true peak in SSC and PPC might have not been captured. In addition, the initial falling stage could not be sampled due to safety constraints, resulting in gaps in the SSC-Q hysteresis pattern. The



positioning of the Rising Stage Samplers on the vegetated banks may have further contributed to underestimation, as increased surface roughness can reduce local transport capacity and yield lower sediment concentrations compared to the channel centre (Errico et al., 2018). Future studies would benefit from the use of automated samplers, enabling continuous, high-frequency
415 sampling across the entire hydrograph from a consistent channel location. Permanent placement of autosamplers would also improve temporal coverage, including other smaller events and dry-season baseflow conditions (Doriean et al., 2020).

The largest uncertainty likely surrounded the assumptions in load calculations. The event peak classification relied on the observed peak sediment load during the Alfred storm, despite the true discharge peak not being sampled. Consequently, both SSC peaks and total sediment loads are likely underestimated (Malutta et al., 2020). For estimation of total yearly loads and
420 other events, SSC values during Rising Stage 1 and Rising Stage 2 were assumed to be similar to those measured during the *Cyclone Alfred* event. Baseflow concentrations were derived from wet-season measurements and likely overestimate dry-season conditions. Taken together, these factors suggest that the contribution of extreme events to annual sediment and phosphorus (P) loads is probably even higher than reported (Valkama and Ruth, 2017; Carpenter et al., 2018). While these calculations are not central to the primary hypothesis, they provide important context for highlighting the disproportionate role
425 of extreme events on sediment and nutrient loading.

Additional uncertainty is inherent to sediment tracing. Multiple tracer combinations often produced statistically valid yet conflicting source apportionment results. The consistent tracer selection (CTS) framework used here explicitly acknowledges this uncertainty, in contrast to traditional approaches that integrates all tracer passing conservative and discrimination tests (Latorre et al., 2021). Importantly, many alternative solutions still converged on similar dominant sources, differing primarily
430 in the relative magnitude of contributions. In addition, we applied clustering to all potential tracer outcomes and quantified statistical support for each cluster (Table S3). Herein lies the major strength of this study, where we integrate hysteresis analysis, sequential phosphorus extraction, and sediment tracing. This cross-validation among complementary methods allows for a more robust interpretation of SS and PP dynamics. This study is the first time sediment hysteresis analysis has been combined with quantitative source apportionment, mutually confirming the interpretation. For example, the observed dual SSC
435 and PPC peaks and figure-eight hysteresis pattern indicate sequential activation of distinct sediment sources, a finding corroborated by the sediment tracing results and fractional P distribution. This highlights the value of combining high-frequency sampling with process-based and elemental fractionation approaches in future studies of storm events.

Finally, the results underscore important implications for sampling and tracing strategies in dynamic catchments. While integrative sampling methods (e.g., sediment drapes, Philips tubes), low-frequency monitoring, or integrated unmixing using
440 all sediment, can provide reasonable time-averaged estimates of dominant sediment sources, they bias interpretations towards the most common hydrological situations, in this case alluvial contributions. As demonstrated here, such approaches can obscure the importance of short-lived dominant sources during extreme events in the overall sediment budget. Moreover, elemental fraction tracers provide a clear advantage over conventional tracing approaches by combining improved tracer



conservativeness with greater discriminatory power, resulting in more robust source attribution. Given the disproportionate influence of high-discharge events on sediment and nutrient export, future research should prioritise capturing and tracing sediment and phosphorus during these critical hot moments using appropriate tracers, and exercise caution when inferring overall sediment and phosphorus budgets from integrated or low-frequency datasets.

4.3 Implications for sediment budgets and management

Overall, this study highlights the critical role of extreme events as “hot moments” for sediment and phosphorus mobilisation, driving substantial downstream loading of phosphorus (Carpenter et al., 2018). In the 2024–2025 hydrological year, the *Cyclone Alfred* flood accounted for an estimated 57% of annual sediment yield and 65% of annual PP yield, values that are most likely conservative estimations. Source apportionment during these high-flow conditions reveals distinct temporal patterns and source dynamics. Alluvial material dominated sediment and PP contributions for most of the hydrograph but was supply-limited, resulting in only modest increases during the rising stage. In contrast, hillslope soils dominated for a short period around peak discharge yet contributed the largest share of sediment over the event and the hydrological year. In terms of phosphorus speciation, exchangeable (bioavailable) PP dominated both event-scale and annual budgets but was delivered in short pulses. Oxide-bound P derived from mobilised riverbank material prevailed during the early rising and late falling stages with distributed impacts throughout year in smaller events. It represents a less reactive fraction and is therefore less likely to drive immediate downstream ecological responses.

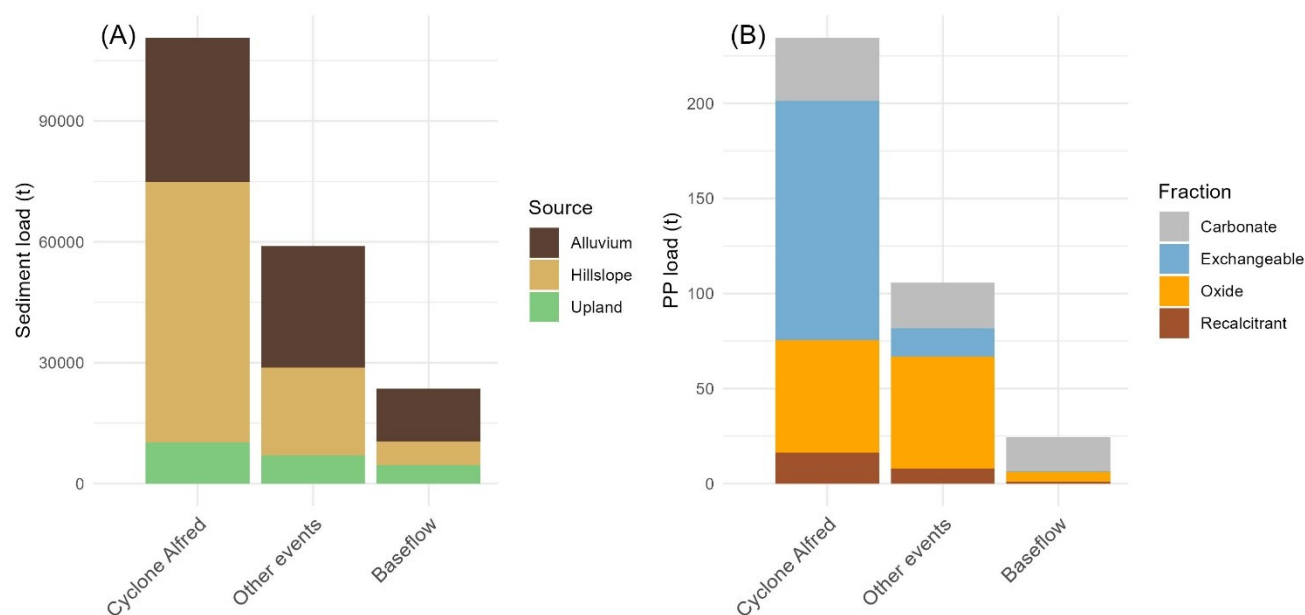


Figure 5: Cumulative importance of the *Cyclone Alfred* event compared to smaller storm events and baseflow to the 24-25 sediment budget with (A) importance of different sediment sources, and (B) PP budget with contribution of different fractions.



Our results from the Albert river demonstrate that hillslope erosion during the peak flow of *Cyclone Alfred* contributes more to total sediment export to Moreton Bay. Likewise, the dominance of highly bioavailable P during short, high-flow pulses accounts for over 65% of the *Cyclone Alfred* event PP load and more than 50% of the annual load. This episodic input of large bioavailable P loads is worrying since it increases the risk for eutrophication and algal blooms in downstream receiving waters, including Moreton Bay (Wulff et al., 2011). Catchment conditions can provide an explanation for these observations. In the Albert catchment, intermediate hillslope soils often contain dispersive subsoils overlain by more resistant topsoil layers (Figure S1). While there are no large gully complexes, recent large-scale urban development near Canungra has removed vegetation and topsoil across extensive areas, exposing highly erodible subsoils (Figure S7). Conversely, most croplands are located on alluvial black clay soils (Figure S1), which have high inherent aggregate stability and nutrient holding capacity, and are thus less susceptible to surface erosion and nutrient leaching (Webb and Dowling, 1990).

These findings add an additional dimension to our understanding and management of the drivers of increased sediment transport to Moreton Bay, which currently strongly emphasise riparian bank stabilisation (Olley et al., 2015; Wallbrink, 2004). These activities remain important since alluvium is the dominant source of sediment and PP under typical conditions and thus likely plays a key role in maintaining riverine water quality throughout the year. However, controlling the pulse losses of hillslope soils and exchangeable PP during extreme events will be a critical additional step for reducing the risk for siltation and algal blooms in Moreton Bay (Wulff et al., 2011). Given the likely increase in stochastic extreme rainfall events in the region due to the warming oceans (Tabari, 2020; Callaghan, 2023), this study demonstrates that management strategies based on typical hydrological conditions are insufficient to mitigate sediment and phosphorus export during extreme events (Zou et al., 2023; Bierozza et al., 2019). Moreover, there is a need for additional monitoring of soil loss and runoff from urban developments to quantify their role in driving hillslope sediment contributions (Forber et al., 2018; Lintern et al., 2020). Finally, it is critical to identify potential extreme rainfall triggered P point sources such as livestock effluent overflows, slurry storage failures, or urban sewerage overflows (Suchowska-Kisielewicz and Nowogóński, 2021; Vero and Doody, 2021).

5. Conclusion

This study confirmed the hypothesis that extreme flood events non-linearly activate different SS and PP sources as hydrological connectivity and sediment supply conditions evolve throughout a storm. High-frequency sampling during the 2025 *Cyclone Alfred* event revealed a pronounced figure-eight hysteresis in both SSC and PPC, reflecting sequential source activation. An initial first flush was dominated by alluvial bank material and oxide-bound P, followed by a transition towards hillslope-derived sediments and exchangeable (bioavailable) P as rainfall intensity, erosion rates, and catchment connectivity increased. Although alluvial sources dominated much of the hydrograph, hillslope material contributed the majority of event-scale sediment export despite being active for only a short period near peak discharge. Similarly, PP dynamics shifted from relatively stable oxide-bound forms to highly bioavailable exchangeable P during peak flow. The disproportionate increase in



exchangeable P suggests mobilisation pathways beyond sediment source shifts alone and points to additional dissolved or
495 point-source P inputs during the most extreme phase of the event. Consequently, *Cyclone Alfred* contributed an estimated 57%
of annual sediment export and 65% of annual PP export, demonstrating the dominant role of extreme floods in annual sediment
and nutrient budgets. From a management perspective, the findings show that while alluvial sources remain important under
typical conditions, short-lived hillslope sediment pulses and bioavailable phosphorus exports can exert a disproportionate
influence on annual loads and downstream water-quality risks.

500 Methodologically, this study demonstrates the value of integrating high-frequency event sampling, hysteresis analysis, and
sequential elemental fractionation for sediment tracing. The convergence of evidence from these complementary approaches
enabled more robust identification of sediment and phosphorus sources than could be achieved using the individual methods.
The results further highlight the potential of elemental fractions as tracers for improving source discrimination and suggest
that future development and application of this approach could provide an important advance for sediment tracing studies.

505 Future research should therefore extend monitoring and tracing of sediment and phosphorus to better capture extreme events,
improve attribution of hillslope sediment sources, and identify the origin of exchangeable P pulses, including potential
contributions from urban and agricultural point sources. As extreme rainfall events become more frequent and intense,
accounting for these episodic processes will be essential for protecting downstream receiving waters such as Moreton Bay.

Code and data availability

510 The data and R code for all data analysis and visualisation are available as an open-source dataset (Wynants et al., 2026).

Author contributions

MW contributed to: Conceptualisation, Data Curation, Formal analysis, Funding acquisition, Investigation, Methodology,
Project administration, Resources, Software, Supervision, Validation, Visualisation, and Writing (original draft preparation)

CV: Data Curation, Formal analysis, Investigation, Methodology, Validation, Visualisation, and Writing (original draft
515 preparation)

IL: Formal analysis, Methodology, Software, Visualisation, and Writing (review and editing)

HdB: Conceptualisation, Supervision, Writing (review and editing)

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WB: Conceptualisation, Data curation, Funding acquisition, Methodology, Project administration, Resources, Supervision,
520 and Writing (review and editing)

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(review and editing)



525 Competing interests

The authors declare that they have no conflict of interest.

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