GRADISTAT in environmental sciences: a sampled review of the 21 years of the program application in environmental sciences

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Abstract: The study of sediment dynamics using grain size parameters is well established in sedimentology and earth sciences. To help the wide-ranging needs of researchers in the fields of earth and depositional sciences, Blott and Pye (2001) wrote a GRADISTAT program that is integrated into a Microsoft Excel spreadsheet. This study reviewed 66 scientific articles principally found in ScienceDirect. Sampled research papers are categorised into six general groups and summarised in terms of the most environmental themes addressed. The themes covered in this paper are: the understanding of land-sea interactions and processes; sediment contaminations and pollution; impacts of sediment variables and transportation on macrofauna, vegetation and habitat; microplastics; soil genesis and movement; and, palaeontology. The ubiquitous nature of this application has shown it applied in many parts of the world. The GRADISTAT will continue to be a relevant environmental advance that is essential in classifying sediments in depositional environments.

Keywords: depositional environment; grain size distributions; GSDs; grain size parameters; textural characteristics.

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Biographical notes: Temitope D. Timothy Oyedotun is an internationally recognised environmental researcher and university tutor. For the last 16 years, after the award of his first degree, he has acquired and developed interests in diverse academic and research fields of geography – principally in water resources management, river dynamics, fluvial geomorphology, quantitative and spatial analyses, geographic information systems (GIS), and of recent, estuarine/coastal systems morphodynamics (coastal geomorphology). Years of international academic exposure and training have developed in him a culture of discipline with an ethic of academic entrepreneurship and great scholarship performance. He is currently an Associate Professor (reader), lecturer and researcher in the Department of Geography and Dean of Faculty of Earth and Environmental Sciences (FEES), University of Guyana, Southern America.

1 Introduction

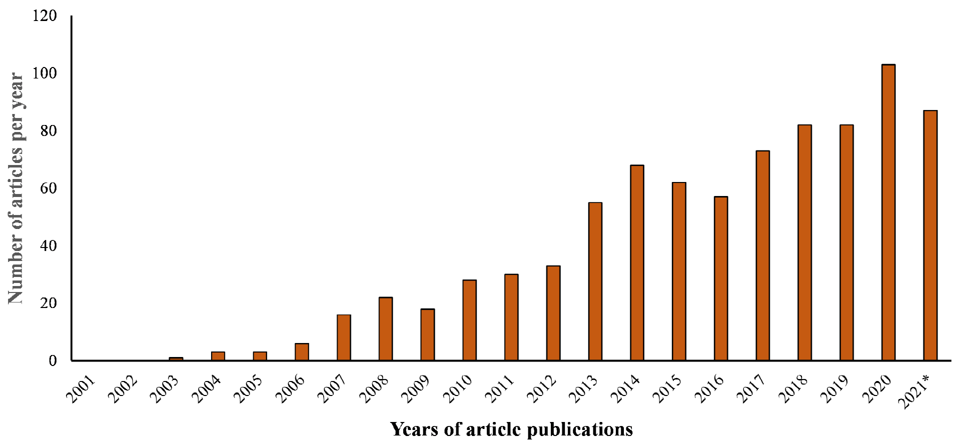
The study of sediment dynamics using grain size parameters has been well established as a routine in sedimentology and Earth sciences (e.g., Folk and Ward, 1957; Friedman, 1961; Ashley, 1978; Donohue et al., 2003; Francke et al., 2013; Fan et al., 2015; Flemming, 2007; McLaren, 1981; McLaren et al., 2007; Nugroho and Putra, 2017; Oyedotun, 2020; Oyedotun et al., 2012, 2013; Bhattacharya and Chatterjee, 2021). Many methods have been developed and extensively used to understand, describe, quantify and compare the depositional and sedimentary environments (McLaren et al., 2007; Roberson and Weltje, 2014; Fan et al., 2015; Azidane et al., 2021). Examples of which include grain size distributions (GSDs) summation and statistics (Katra and Yizhaq, 2017), principal component analysis (PCA) (e.g., Garzón et al., 2016; Katra and Yizhaq, 2017; Palazón and Navas, 2017; Flood et al., 2015; Tiecher et al., 2015; Oyedotun, 2020), and development of a series of log-ratio transformation practices (e.g., Aitchison, 1982) among others. To help the wide-ranging needs of researchers in sedimentology, geomorphology and other fields of Earth sciences in the depositional environment, Blott and Pye (2001) wrote a GRADISTAT program that is integrated into a Microsoft Excel spreadsheet with the calculation of which is based on Folk and Ward (1957) and moment methods (e.g., geometric method of moments, logarithmic method of moments). With the aid of Microsoft Visual Basic on which the program is written, the program could generate both tabular and graphic outputs. The program is imbued with the capacity to generate data on particle size distribution and classes, and to calculate some statistics such as mean, mode, standard deviation, kurtosis, skewness, etc., arithmetically, geometrically (in metric units) and logarithmically (in phi units).

From 28 September 2001, when the paper on GRADISTAT was first published as a Technical Communication by Blott and Pye (2001) in *Earth Surface Processes and Landforms* until the time of this writing, there have been 1,962 citations to the paper and the application/program [total number of citations indicated at Blott and Pye (2001)], out of which 829 are academic research or work published by journals hosted by ScienceDirect. These citations are evidence that the program is meeting the needs of wide-ranging researchers within the field of sedimentology, geomorphology and wider Earth sciences working in the depositional environment. Approaching the 20th anniversary of the publication of this program, this paper aims at summarising and synthesising the key GSD and other sedimentary issues in depositional environments that have been addressed in published research work with the aid of the GRADISTAT program.

2 GRADISTAT in ScienceDirect

This study considered relevant peer-reviewed publications and references in ScienceDirect data with a focus on studies that used GRADISTAT as one of the methods of investigations in the research reported in the articles. Within the ScienceDirect database, 829 published research works used the GRADISTAT program in one of the methodologies utilised as of 4 August 2021, and these covered 18 years, from 2003 when the first paper that made use of the program was published to the time of this writing 4 August 2021. What is noted is the increasing trend in the number of articles published using the program in their methodologies. From 2003 when only one article used the method, there has been a steady growth in the number of articles in the ScienceDirect database using GRADISTAT in the studies being reported with the highest number of the articles published in 2020 (at 103) (see Figure 1). Of these 829 articles, 8.7% of them were published as open access, 0.4% as open archive while 91% appeared in journals requiring subscriptions (Figure 2). The ScienceDirect database provides the materials for the analyses and reviews reported here, and Figure 1 uses bar charts to display the distribution of the articles over time. Only English-language journals and articles were included in this evaluation and review.

Figure 1 Number of articles published annually using GRADISTAT in ScienceDirect database (see online version for colours)



Note: As of 4 August 2021.

Figure 2 Article access type (see online version for colours)

In the literature review database, research articles are the most that utilised the program at 95.8% (n = 794), followed by short communications at 2.1% (n = 17) review articles at 1.1% (n = 9), book chapters at 0.5% (n = 4), data articles at 0.4% (n = 3) and others at 0.2% (n = 2), respectively. The examples of 660 of the articles that published in high impact factor journals, totalled 98.363 impact factors (Table 1) with the highest number of publications in *Marine Geology* (78), followed by *Geomorphology* (61), *Quaternary Science Reviews* (50), *Quaternary International* (56), *Estuarine, Coastal and Shelf Science* (54), among the 25 of those journals (see Table 1 for these examples). One can speculate the variety of findings reported in these journals. The categorisation of subject areas (and there are overlaps too) of the publications by ScienceDirect database indicated that 55.1% of these are found within the *Earth and Planetary Sciences*, 19.3% within *Agricultural and Biological Sciences*, 15.9% for *Environmental Sciences*, *Social Sciences* at 5.9%, *Engineering* at 1.5%, *Arts and Humanities* (which are all within the field of archaeological sciences) at 0.7%, *Material Science* at 0.7%, *Veterinary Science* and *Veterinary Medicine* at 0.5% and *Energy* at 0.5%, respectively (Figure 4). As this study is interested in the application of GRADISTAT within the field of environmental sciences, the review presented here is concentrated on the articles published within this subject area. This paper reviewed 66 of the articles published in the field of environmental sciences.

Table 1 High impact factor journals where some of the articles are published

S/N	*Publication title/journal*	*Number of publications*	*Percentage (%)*	*Impact factors*
1	*Marine Geology*	78	11.8	3.548
2	*Geomorphology*	61	9.2	4.139
3	*Quaternary Science Reviews*	59	8.9	4.112
4	*Quaternary International*	56	8.5	2.13
5	*Estuarine, Coastal and Shelf Science*	54	8.2	2.929
6	*Sedimentary Geology*	46	7.0	3.397
7	*Marine Pollution Bulletin*	43	6.5	5.553
8	*Science of The Total Environment*	32	4.8	7.963
9	*Palaeogeography, Palaeoclimatology, Palaeoecology*	29	4.4	3.318
10	*CATENA*	26	3.9	5.198
11	*Journal of Volcanology and Geothermal Research*	23	3.5	2.789
12	*Continental Shelf Research*	21	3.2	2.391
13	*Journal of South American Earth Sciences*	19	2.9	2.093
14	*Global and Planetary Change*	13	2.0	5.114
15	*Marine Environmental Research*	13	2.0	3.13
16	*Aeolian Research*	13	2.0	3.336
17	*Ocean & Coastal Management*	12	1.8	3.284
18	*Journal of Experimental Marine Biology and Ecology*	9	1.4	2.171
19	*Journal of Sea Research*	9	1.4	2.108
20	*Marine and Petroleum Geology*	9	1.4	4.348
21	*Environmental Pollution*	9	1.4	8.071
22	*Journal of Asian Earth Sciences*	7	1.1	3.449
23	*Quaternary Research*	7	1.1	2.72
24	*Geoderma*	6	0.9	6.114
25	*Ecological Indicators*	6	0.9	4.958
		660	100	*98.363*

Figure 3 Types of publications that used the GRADISTAT program (see online version for colours)

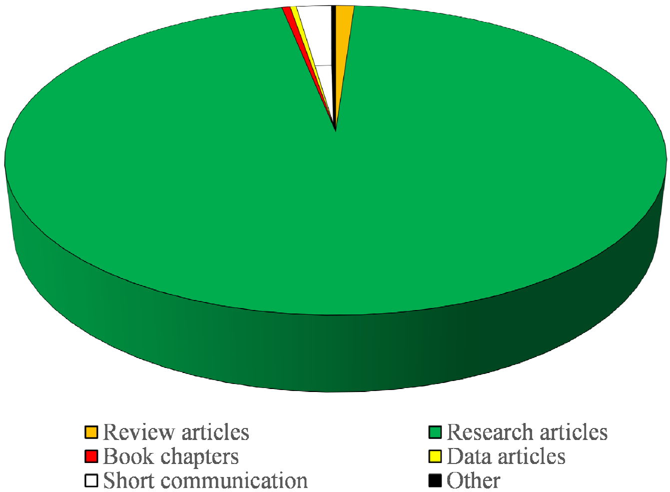
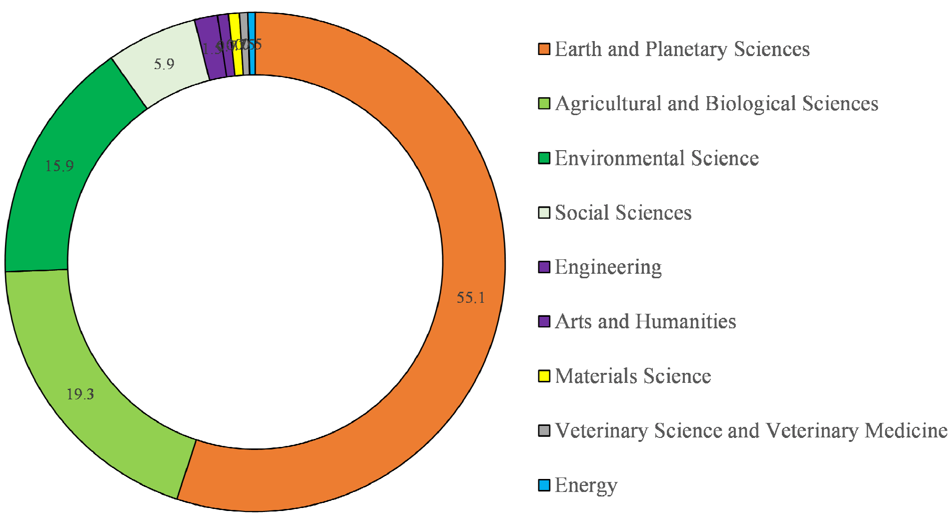


Figure 4 Subject areas which are the focus of most of the publications that utilised GRADISTAT (see online version for colours)



3 Thematic groups of issues in environmental sciences addressed by GRADISTAT

This study reviewed 66 scientific articles principally found in ScienceDirect. Research papers were categorised into six general groups and summarised in terms of the most substantial works on environmental themes addressed in these most relevant works. The first group of these environmental issues refers to studies of how GRADISTAT is used in understanding land-sea interactions or the environmental processes within the theme. After reviewing and discussing this, this paper also described other environmental categories that the sampled studies which utilised GRADISTAT based on the major themes of the published works, and these could be summarised as: in sediment contaminations and pollution, on the impacts of sediment variables and transportation on macrofauna, vegetation and habitat, microplastics, soil genesis and movement, and palaeontology. This grouping is on different studies but the grouped environmental themes adequately summarised the main topics covered in each group in which the application of GRADISTAT made useful contributions in the study (Table 2). Although some of the findings utilised more than one method in the study or fall into more than one group category, this review only focused on the contributions made by GRADISTAT in the sampled studies.

3.1 Land-sea interactions

Many developments and activities converge at the coast, where land and sea interact. This is also an area with unique landforms as they are exposed to diverse actions of tides, waves, oceanic and atmospheric processes as well as anthropogenic interventions (Stanchev et al., 2018; Arulbalaji et al., 2021; Azidane et al., 2021). The several driving processes and competing interest in this environment contributes to the dynamics of the landforms and changes in the depositional situation of this environment. Continuous and constant monitoring of these strategic land-sea interactions is essential in the understanding of the spatio-temporal morphodynamics that this zone is subjected to year by year. Several studies using GRADISTAT have proved its efficiency in the understanding of various processes, compositions, distributions, distinctions, attributes, and characteristics in the depositional environment of this zone.

The utilisation of GRADISTAT has varied applications in addressing the land-sea interactions issues as demonstrated by examples of various studies reviewed in this paper. The understanding and tracing of sediments sources, which are critical for understanding and planning for aquatic ecosystems in addition to the determination of the sediments in permanent interaction, are enabled by GRADISTAT (Ghsoub et al., 2020). Sediment composition, as determined by the application of the GRADISTAT program, in addition to the 2D and 3D morphology of the beach area, is also vital in the study of the influence of land-sea interaction on beach slope and monsoonal influences in causing rip current formations and hazards (Hamsan and Ramli, 2021). This application of the program is also vital in examining the differences of textural sedimentary facies at the land-sea interaction (e.g., Mohtar et al., 2017), in understanding the role play by regional rainfall in the supply of sediments (Alcántara-Carrió et al., 2018), for modelling of parameters of sediments (Abanades et al., 2018), the distribution of organic carbon within the depositional-sedimentary environment (Gao et al., 2021) and trend in seasonal variation of the conformity or lack of conformity driving by the land-sea interaction (Dora et al., 2012). These sampled studies range from the concentrated focus on the estuarine environment (e.g., Ghsoub et al., 2020), coastal beaches (e.g., Hamsan and Ramli, 2021), the intersection of the fluvial-coastal-marine environment (e.g., Mohtar et al., 2017), to the entire coastal area (e.g., Alcántara-Carrió et al., 2018; Abanades et al., 2018; Dora et al., 2012; Gao et al., 2021).

3.2 Sediment contaminations and pollution

The matter of contamination and pollution by metals and other substances are attracting constant attention in research and publications worldwide. These constant attentions are in various environments, ranging from marine (e.g., Agah et al., 2016; Ghrefat et al., 2018; Liu et al., 2018; Tu et al., 2018; Sadeghi et al., 2019; Saleh, 2021) to riverine/fluvial (e.g., Ahmad et al., 2020; Singh et al., 2020; Usman et al., 2021) environments. The apparent industrial and other anthropogenic activities in addition to natural processes such as weathering of crustal or other hazardous materials, acidic rainfall inputs, etc. are responsible for the introduction of contaminants and pollutants to the natural environment. Many of these contaminants and pollutants are biodegradable and have the potential to accumulate in sediment environments. Sediments are known for their ability to accommodate and accumulate contaminants and many pollutants, thereby remaining the main sink for these substances (Elias et al., 2018; Zhang et al., 2019).

Sediment analysis is a vital tool for, and means by which, assessment of contaminant in the natural environment could be ascertained (Diop et al., 2015). The GRADISTAT program, in the last 21 years, has played some important roles in this assessment. With the application of the program, Yi and Sung (2015) was able to examine the influence of soil texture and particle size in understanding the difficulties in the restoration of ecological properties of sediments after they might have been contaminated. Similarly, with the analyses of grain size parameters which was aided by GRADISTAT, Chiappetta et al. (2016) while investigating the sources of sediment contamination in an estuarine environment, was able to observe that some physicochemical properties (e.g., Eh) have the least negative value as the potential contamination sources. Mine tailings are found in sediments at Doce River Estuary in Brazil, as evidence of contamination and the analyses were made possible, in part, by the evaluation of the sediment grain size parameters which were observed to be changing by the sediment contaminated by mining (Sá et al., 2021). Furthermore, with the aid of the GRADISTAT program, Kovač et al. (2018), Li et al. (2018), Robichaud et al. (2019) and Aksentov et al. (2021) and observed that grain size parameters are very vital in the accumulation of contaminants and pollutants in sediments in their studies in Solvenia, China, Canada and Siberia, respectively.

However, the study by Vauclin et al. (2021) tends to caution against generalising the grain size parameters as the confounding factor in contaminant retention in depositional environments. With the application of the GRADISTAT program, Vauclin et al. (2021) were able to observe that with the uniformity of sediment GSD in the vertical core, the retention of contaminant is not dependent on the sediment size parameters. In another study that utilised GRADISTAT, the correlation between site-specific sediment grain sizes and their available organic matter are keys in the bioavailability of sediment contaminants, as observed by Pini et al. (2015). The calculation of grain size parameters using GRADISTAT by Cordeiro et al. (2021) enabled the study to indicate the predominance of silt size type and their variation between the assessed periods, which was able to show that the natural variability of weathering processes, the transportation of sedimentary materials and the deposition of these materials are the key for the predominant contamination of some metals (e.g., Al, Ba, Fe, etc.).

3.3 Impact of sediment variables and transport on macro-fauna, vegetation and habitat

The impact of sediment movements on vegetation, macro-fauna (e.g., benthic species and communities), habitats and diverse ecosystems is part of the focus of some of the papers sampled for this review. GRADISTAT was applied in examining, determining the patterns of, and the relationship between grain size parameter and the fauna community structure (Witmer et al., 2018; Amao et al., 2019; Bertocci et al., 2019; Cabral et al., 2020; Callaway et al., 2020; Greene et al., 2020), the influence of particle size statistics on sediment gradient and vegetation (Connolly et al., 2016; Ha et al., 2018), the relationship between physical datasets (sediment particle sizes) and nearshore habitat (Dean et al., 2013; Bessa et al., 2013; Barik et al., 2014; Jonah et al., 2015; Degli et al. 2021), and on invertebrate assemblages (Witmer et al., 2019; Pryor et al., 2020), among others.

Many factors threaten the survival of biodiversity globally, the eutrophication of surface water and high concentration of phosphorus is considered as among the most significant causes (Crocker et al., 2021). With GRADISTAT, Crocker et al. (2021) evaluated the correlation between the sediment particle sizes and coefficient of phosphorus and observed a lack of significant correlations coefficient for the phosphorus and percent of mud. Similarly, with the aid of GRADISTAT, Degli et al. (2021) observed that the diversities in organisms are a result of seasonality and not based on sediment grain sizes. Fairuz-Fozi et al. (2018), on the other hand, observed that mangrove horseshoe crab thrive where different sizes of sediment mix. Davies et al. (2009) noticed that the *Sabellaria spinulosa* worm thrive well by utilising the lower mean of sediment particle sizes, and the GRADISTAT program was employed for further analyses in the study. The loss on ignition for the organic matter content with the sediment particle size distribution was examined by Barillé et al. (2011) in their investigation of spectra response of benthic diatoms. They observed distinction on the reflectance of sediments based on sediment sizes and properties, with its effect on benthic diatoms biomass variation.

Variations were observed in meiofaunal assemblages and sediment grain size characteristics which were determined by GRADISTAT (Bertocci et al., 2019). Spatial variations played a significant role in the observed differences by Bertocci et al. (2019). This is also similar to the findings by Yu et al. (2019) where spatial dynamics and distribution of diatom assemblages are significantly influenced by the grain size dynamics determined by the application program under review. Apart from the diatom assemblages and biomass variation, GRADISTAT was also instrumental in the classification of the riverbed and its influence on riverine vegetation and habitat (Félix et al., 2020) or the erodibility effects on vegetation (Ha et al., 2018).

Table 2 The grouping of sampled reviewed studies by the particular subject or theme addressed with the aid of GRADISTAT, country of the study, a brief description of the theme addressed and the environmental system studied

Environmental theme	*Study/reference*	*Country of study*	*Particular focus addressed with GRADISTAT*	*Environmental system studied*
Land-sea interactions	Ghsoub et al. (2020)	Lebanon	Understanding of dynamic processes at the interface of estuarine and coastal environments using grain size and sediments compositions.	Estuarine environment
	Hamsan and Ramli (2021)	Malaysia	Morphology of 2D and 3D of beaches are influenced by beach slope and sediment composition.	Coastal beaches
	Mohtar et al. (2017)	Malaysia	No distinction between the fluvial and marine sediment distribution and sizes in terms of pattern, but there was a slight difference in terms of textural facies.	Coastal marine and riverine/fluvial environment
	Alcántara-Carrió et al. (2018)	Brazil	With the aid of GRADISTAT, it was observed that the regional rainfall plays a prominent role in the supply of sediment that is of coarse and medium silt texture, while storm waves drive the sediment that is of fine and/or very fine sizes that are supplied in suspension.	Coastal environment
	Abanades et al. (2018)	Spain	GRADISTAT was used in determining the sedimentary attributes that were used in modelling coastal processes for the wave farm.	Coastal environment
	Gao et al. (2021)	China	The organic carbon distribution's pattern was observed to be opposite to the conventional land to sea transition pattern as deduced from sediment grain-size analyses and other analyses in the study. Anthropogenic impacts on organic carbon sources and their transportation within the sedimentary environment are noted to be responsible for the observed pattern.	Coastal environment
	Dora et al. (2012)	India	Non-uniformity of beach's textural characteristics and morphodynamics suggest no significant correlation in the beach morpho-sedimentary variables. Lack of significant trend in seasonal variation of sediment's grain size and textural parameters was noted to be as a result of the presence of islands that obstruct the waves during the seasonal monsoon. The textural characteristics, aided by the GRADISTAT also indicated that the variation in the sediment grain size parameters would depend on the extreme change in the hydrodynamics.	Coastal environment
Sediment contaminations and pollution	Yi and Sung (2015)	South Korea	Soil texture and particle size were observed to show more uniformity, with their ecological properties not improved completely even after the removal of metals from contaminated soils. Adverse changes in physicochemical properties, however, affect the ecological properties.	Onshore former military sites
	Chiappetta et al. (2016)	Brazil	Analyses of grain size parameters of the sediments suggest the sites with predominant silt and sand content have the least negative physicochemical properties (e.g., Eh) value in the investigation of the potential contamination sources.	Estuarine environment/bay
	Sá et al. (2021)	Brazil	Sediment grain size parameters are changed as a result of mine tailings influence.	River estuary environment
	Kovač et al. (2018)	Slovenia	The grain size characteristics are key in the accumulation, adsorption and mobility of metla(oids)	Saltmarsh (coastal) environment
	Robichaud et al. (2019)	Canada	The GRADISTAT was used in the textural description consideration of the process of remediation of petroleum contaminated soils.	Controlled experimental site

Table 2 The grouping of sampled reviewed studies by the particular subject or theme addressed with the aid of GRADISTAT, country of the study, a brief description of the theme addressed and the environmental system studied (continued)

Environmental theme	*Study/reference*	*Country of study*	*Particular focus addressed with GRADISTAT*	*Environmental system studied*
Sediment contaminations and pollution	Aksentov et al. (2021)	Siberia	The sedimentary facies, determined by their textural parameters and sizes, were noted to influence mercury accumulation.	Oceanic environment
	Li et al. (2018)	China	The fractions of sediment grain size showed a relative response to flood events with a resultant increase of pollutants at coarser sand materials.	Lake environment
	Vauclin et al. (2021)	France	With the uniformity of grain size distribution, the grain size parameters were observed not to be a confounding factor in terms of the vertical trends of brominated flame retardants contamination of the sedimentary cores sampled for the study.	Fluvial (riverine) environment
	Pini et al. (2015)	UK	The metal bioavailability in the sampled sediments was observed to show a correlation between site-specific sediment grain size and organic matter.	Coastal environment
	Cordeiro et al. (2021)	Brazil	Grain size parameters are also vital in the understanding of the weathering processes and the contamination of sediments	Coastal environment
Impact of sediment variables and transport on macrofaunal, vegetation and habitat	Witmer et al. (2018)	USA	Sediment transport and sand transfer influence localised plant disturbances and the macrofaunal community structure.	Lake sub-tidal environment or system
	Connolly et al. (2016)	Australia	The availability of the coarse particulate organic matter and sediments play important role in the richness of invertebrates. Sampling sites standardisation by their sediment sizes was used in the identification of the impacts of invertebrate and riparian vegetation diversity.	Streams
	Amao et al. (2019)	Saudi Arabia	Grain size distribution and dominant sediment types are also vital in living benthic foraminiferal species adaptation and their relationships with potentially toxic elements (PTEs).	Offshore environment
	Cabral et al. (2020)	Portugal	Assessment of non-indigenous species (NIS) at benthic communities using a clam dredge, several water and sediment parameters of which GRADISTAT was used in calculating sediment parameters.	Estuarine environment
	Dean et al. (2013)	USA	The influence of sediment sizes on dominant nearshore hardbottom habitat.	Riverine environment
	Pryor et al. (2020)	Australia	Grain size distribution of marine sediments is associated with variation in invertebrate assemblages.	Marine environment
	Callaway et al. (2020)	UK	Sediment sizes and distribution significantly influence the microbenthic infauna community and their amounts. The variation is in conjunction with wave characteristics and waves climate.	Urbanised coastal environment
	Bessa et al. (2013)	Portugal	Despite the different sampling sites, habitats in the two sites are similar with grain size distribution properties investigated.	Coastal environment – beach
	Crocker et al. (2021)	UK	Lack of variance in particle size of the sediments show the lack of significant correlations coefficient of phosphorus for the percent of mud.	Inland wetland
	Jonah et al. (2015)	Ghana	The grain size of sediments did not correlate with the predominantly medium size sediments of the samples sites and the ghost crab burrow density.	Beach environment
	Barik et al. (2014)	India	Medium size sand, moderately sorted or well-sorted and platikurtic/leptokurtic sediments are some of the parameters observed as important and favourable environmental cues for nesting by sea turtles.	River mouth

Table 2 The grouping of sampled reviewed studies by the particular subject or theme addressed with the aid of GRADISTAT, country of the study, a brief description of the theme addressed and the environmental system studied (continued)

Environmental theme	*Study/reference*	*Country of study*	*Particular focus addressed with GRADISTAT*	*Environmental system studied*
Impact of sediment variables and transport on macrofaunal, vegetation and habitat	Degli et al. (2021)	Uruguay	Despite the contrasting sediment morphodynamics of the sampling sites at the Uruguayan beach, the arthropod diversity was not observed at the different beaches but the dunes. Organisms distribution was linked to the seasonality and not sediment grain size distributions.	Coastal environment
	Fairuz-Fozi et al. (2018)	Malaysia	*C. rotundicauda* was observed to thrive in areas where the mixing of sand, silt and clay was noted in the mangrove environment.	Mangrove environment
	Davies et al. (2009)		With the aid of GRADISTAT, the particle sizes of sediment were determined in the laboratory study of the fraction of sediment sizes that the *Sabellaria spinulosa* worm preferred.	Controlled laboratory environment
	Greene et al. (2020)	USA	The sorting and sizes of sediment grain sizes were observed to be important in the development of sand lance and also for benthic habitation of the 'upper tropic level species', e.g., forage fish, birds and mammals.	Coastal environment
	Barillé et al. (2011)	France	The construction of sediment reflectance spectra was of importance in the understanding of benthic diatom biomass variations as influenced by water content, grain sizes, mineralogy, organic matter, among other variables.	Fluvial environment (bay)
	Bertocci et al. (2019)	Italy	The grain size of sediment was considered with the biochemical composition of organic matter, meiofauna abundance, meiofaunal diversity, and its assemblage composition and abundance. The statistical parameters of the grain sizes were determined by GRADISTAT and the correlations of the different variables were considered.	Coastal environment
	Yu et al. (2019)	China	The spatial dynamics and distribution of diatom assemblages are greatly influenced by grain sizes of sediments in addition to the water depth and temperature.	Lake (lacustrine) environment
	Witmer et al. (2019)	USA	The differences in macroinvertebrates among the two beaches are a result of differences in their sediment disturbances, of which grain size parameters play a prominent role.	Coastal (beach) environment
	Félix et al. (2020)	Portugal	GRADISTAT was used to classify the riverbed and the coverage area of the instream.	Fluvial (riverine) environment
	Ha et al. (2018)	South Korea	The textural parameters are very instrumental in the understanding of the inverse relationship between the mass erodibility of the sampled cohesive sediments and the applied shear stress, in addition to the effects of vegetation and faecal pellets observed.	Coastal environment
Microplastics	Pagter et al. (2018)	Ireland	Sediment sorting and grain size parameters have impacts on the variation of subtidal sediment based on location and anthropogenic influences.	Coastal bay
	Kedzierski et al. (2016)	France	Development of a new microplastics classification based on grain size statistical and sedimentological parameters.	Marine environment
	Urban-Malinga et al. (2020)	Poland	Microplastic contamination of urban beaches is not related to grain size and does not differ significantly from those of national parks.	Sea
	Alves and Figueiredo (2019)	Brazil	No difference in microplastic concentration was observed with the differences in grain size of the sediments sampled for analysis	Marine environment

Table 2 The grouping of sampled reviewed studies by the particular subject or theme addressed with the aid of GRADISTAT, country of the study, a brief description of the theme addressed and the environmental system studied (continued)

Environmental theme	*Study/reference*	*Country of study*	*Particular focus addressed with GRADISTAT*	*Environmental system studied*
Microplastics	Tsukada et al. (2021)	Brazil	The coarseness of the sediment encourages the deposition of microplastics and the amount of deposition in the sampled area.	Beach environment
	Courtene-Jones et al. (2020)	Scotland, UK	The sediments of the sampled environment were geometrically classified, and the grain size parameter was observed of sandy silt and which remained consistent all through the sedimentary core sampled for the study. The porosity of the sediment and the microplastic accumulation and abundance were observed to be positively related.	Rockall trough (oceanic environment)
	Crew et al. (2020)	Canada	Sedimentary textural properties, in addition to other variables like sources and environmental filters, greatly influenced the distribution of microplastics across the St. Lawrence River bed sampled for the study.	Fluvial (riverine) environment
	Sekudewicz et al. (2021)	Poland	Grain sizes of sediment and the existence of organic matter greatly influence the efficiency of microplastic extraction from sediments.	Fluvial (riverine) environment
	Sadeghi et al. (2018)	Iran	Mining and the intensity of mining activities are noted to have affected the grain size distribution of suspended sediments.	Fluvial (riverine) environment
Soil genesis and movement	Al-Hemoud et al. (2020)	Kuwait	Using the grain size parameters in the understanding of the genesis and transportation of severe sand and dust storm.	Arid environment – dunes
	Andrews et al. (2021)	Iceland	The analyses of grain size parameters f the sedimentary core show their links and correlation with orbital forcing.	Oceanic environment
	Blanco-Chao et al. (2020)	Spain	Sediment sizes ranging from medium to coarse sands that are moderately sorted contributes to the progradation from the mainland and the morphodynamics of the studied spits.	
	George et al. (2019)	India	The grain size distribution and textural activities play a crucial role in sediment transport and influence the wave regime of the study site.	Coastal environment
	Mobilia et al. (2021)	New Zealand	Sediment particles in the internal of deep-sea ecosystems sponges were observed to be larger than those used for the experiment when the grain size parameters were considered using GRADISTAT.	Laboratory experiment of deep-sea samples
	Kheirfam and Sadeghi (2017)	Iran	The seasonal discharge conditions and grain size parameters influence bedload sediment transportation and dynamics.	Watershed environment
	Wang and Leigh (2015)	USA	Chronological characterisation of sedimentation rates suggests that sediment grain size parameters are influenced by the anthropogenic signatures, where the pre-settlement and post-sediment attributes reflect human activities.	River valley
	Job et al. (2020)	Australia	With the aid of GRADISTAT, the study presented the first grain-sized normalised values for cobalt Co and vanadium in the region.	Lake (lacustrine) Environment
	Shah et al. (2021)	Australia	GRADISTAT was used in the characterisation of sieved and final collected sediment as one fraction in the biosynthesis and functional analysis of the pristine estuarine sediments studied, among other analyses.	Estuarine environment
	Nascimento et al. (2017)	Brazil	The grain size was noted and verified to influence the distribution of organic matter and polycyclic hydrocarbons of the estuarine surface sediments in the evaluation of their origin and movement.	River-estuarine-coastal environment

3.4 Microplastics

Microplastics are ever-present anthropogenic substances and contaminants that are increasingly being detected in every ecosystem (Hale et al., 2020), be it coastal (De-la-Torre et al., 2020; Dong et al., 2021; Garcés-Ordónéz et al., 2021), estuary and beaches (Browne, 2015; Zhang et al., 2021), fluvial and riverine environment (Eerkes-Medrano et al., 2015; Lebreton et al., 2017; Crew et al., 2020; Villegas et al., 2021), continental sediments (Martin et al., 2017, 2020; Turner et al., 2019; Luoto et al., 2019; Xue et al., 2020; Padervand et al., 2020), islands (Alfaro-Nuñez et al., 2021; Jones et al., 2021) or in the ocean (Brandon et al., 2019; van Sebille et al., 2019). The matter of microplastic in any environment is of major concern because it remains a harmful anthropogenic substance that is practically difficult and impracticable to clean up, especially in complex environmental systems like depositional/sedimentary environments (Padervand et al., 2020).

GRADISTAT program was also applied for various investigations of the ubiquitous nature of microplastics in the environment. With the aid of the application, Pagter et al. (2018) observed that sediment grain size parameters like sorting have substantial impacts on the variation of microplastics in the subtidal sediments, which are amplified by the location of the sediments samples and the influence of other anthropogenic activities. However, Urban-Malinga et al. (2020), did not find any relationship between the microplastics contamination of beach sediments based on sizes especially when compared with sediments from other national parks. Similar to the observation of Alves and Figueiredo (2019), Tsukada et al. (2021) found that the coarseness of sediments, observed by the GRADISTAT application, encourages the deposition and the number of microplastics in their study area.

Other forms of application of GRADISTAT involve the utilisation of the program in microplastic and/or sedimentary classification. For example, Kedzierski et al. (2016) utilised the application in their development of new microplastic applications that are based on sediments particle sizes and depositional parameters. Courtene-Jones et al. (2020) geometrically classified the sediments, and the grain size parameters obtained with GRADISTAT, aided the classification carried out in the study. Apart from the application on microplastic and sedimentary classifications, the software was also utilised in evaluating the distribution of microplastics across the river bed (Crew et al., 2020), mining areas (Sadeghi et al., 2018), and the consideration of utilising grain size variables to possibly extract microplastics from sediments (Sekudewicz et al., 2021).

3.5 Soil genesis and movement

Soil conceptualised as the "natural, three-dimensional body of the Earth's surface" [Singer, (2015), p.3] has parameters and properties that made pedologists describe its origin and movement. With the aid of GRADISTAT, Al-Hemoud et al. (2020) examined the genesis and transportation of sands and dust during a severe storm in Kuwait. In another environment, Andrews et al. (2021) showed there are links between the sedimentary core and orbital forcing, and these are reflected in the grain size parameters analysed by GRADISTAT. GSDs and textural attributes of the sediments were found to play important role in the transport of sediment (George et al., 2019), progradation of spits from the mainland (Blanco-Chao et al., 2020), bedload sediment dynamics and transportation (Kheirfam and Sadeghi, 2017), and chronological characterisation of sedimentation rates (Wang and Leigh, 2015).

Furthermore, the consideration of size attributes of sediment particles was observed to influence the deep-sea ecosystem sponges (Mobilia et al., 2021), the sediment transport processes that shaped the geochemical signatures of estuarine sediments and the intensity of metal release (Job et al., 2020), the functional characterisation and biosynthesisation of pristine estuarine sediments (Shah et al., 2021), and the evaluation of the origin, distribution and movement of organic matter and polycyclic hydrocarbons on the estuarine sediment (Nascimento et al., 2017).

3.6 Palaeontology

To understand contemporary life, it is essential to study and understand life's evolutionary past. The GRADISTAT program was also utilised in a couple of studies aimed at understanding the Earth's evolutionary past. Liu et al. (2021) used the application to analyse grain size parameters of the sediments, and in addition to physico-chemical properties of the sediment, show the evolutionary changes of sediments from the lacustrine state to the marshy wetland and eventually to peatland. Over a large catchment area, surface runoff, as a non-glacial process, was observed to change the grain size of sediments which made Huang et al. (2016) unable to use silt as a proxy to interpret glacial activities. However, with the aid of GRADISTAT, other sedimentary variables could be used by the authors and it was observed that variation exists in the general distribution of samples along with the evolutionary core as demonstrated in the differences in sediment sizes in calk a BP (Huang et al., 2016). In a semi-arid lake basin, Cheng et al. (2020) found that sediment sorting determined by the application of the bulk grain size showed similar variation that was used as a proxy for wind intensity.

Other studies that examined textural attributes of sediments in understanding the evolution of the landforms and contemporary environments include Sánchez Goñi et al. (2016), Xu et al. (2019), Lindhorst et al. (2019), Yang et al. (2020), Kuosmanen et al. (2020), among others. The common theme of these sample studies is that the application of GRADISTAT software enabled the authors to examine the textural sizes of the sediments and how they reflect the past glacial advance (e.g., Xu et al., 2019), the changing climatic conditions (e.g., Yang et al., 2020), changing erosional regimes (e.g., Kuosmanen et al., 2020) the morphodynamic Aeolian movement of sediment materials and depositions (e.g., Han et al., 2015; Lindhorst et al., 2019), and/or of transition between geologic eras (e.g., Sánchez Goñi et al., 2016).

4 Summary and concluding remarks

As at the time of the writing of this article, there were 1,962 citations of the Blott and Pye's (2001) published Technical Communication on GRADISTAT, and 829 studies published in *ScienceDirect* which utilised the application as part of their methodologies. These citations are evidence that the program is meeting the needs of wide-ranging researchers within the field of sedimentology, geomorphology and wider Earth sciences working in the depositional environment. The 66 of the application of the program with a focus on environmental sciences sampled for this review showed that varied studies could be grouped under at least six environmental parameters and issues addressed by the application. These are discussed in this review under the subsections: land-sea interactions, sediment contamination and pollution, impacts of sediment variables and sediment transport on macrofauna, vegetation and habitat, microplastics, soil genesis and movement, and palaeontology.

The ubiquitous nature of this application has shown it applied for studies in various environmental systems. The environmental systems which the sampled studies reviewed here focused on are from estuarine environment, coastal beaches, coastal-marine and riverine environment, onshore control sites, bays, river-estuary environment, saltmarsh, lacustrine/lake environment, streams, offshore systems, inland wetland, river mouth, controlled laboratory environment, mangrove systems, river valley, peatland, arid and dune system, among others. Similarly, in the last 20 years of the development of the program, it has been applied in several study sites covering many countries of the world, and in almost all of the world's continents. Indeed, in the last 20 years of the development of GRADISTAT software by Blott and Pye (2001), its usefulness has been tremendous in many fields, of which environmental sciences, especially the for sedimentary or depositional environments, have not been an exception. The GRADISTAT will continue to be a relevant environmental advance that is an "essential tool in classifying sedimentary environment" [Blott and Pye, (2001), p.1237].

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