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HIDDEN POLLUTION IN IRRIGATION SYSTEMS: MICROPLASTICS IN SURFACE AND GROUNDWATER OF THE PAZHAYAR RIVER BASIN, SOUTH INDIA

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ABSTRACT

Microplastic (MP) contamination from anthropogenic sources has been repeatedly proposed as an environmental threat based on its possible ecological and human health impacts, due to its persistent nature. The research aimed to explore the occurrence, distribution, characteristics and polymer composition of microplastics at the groundwater and surface water level of Pazhayar River basin, Kanyakumari District. Fifty-two water samples (35 groundwater and 17 surface water) were collected and analyzed by means of wet peroxide oxidation, vacuum filtration, stereomicroscopy, and Fourier Transform Infrared (FTIR) spectroscopy. All locations where sampling was conducted contained detected microplastics, noting higher abundances in surface waters than groundwater — a record of anthropogenic signals. Morphologically, fibres predominated; and polypropylene (PP) and polyethylene (PE) were the dominant polymers detected. Higher microplastic levels were again reported for urbanized areas such as around Nagercoil and Suchindram, suggesting the impact of population density and effluent discharge. Our findings reveal the extent of microplastic pollution across coastal ecosystems in southern Tamil Nadu and indicate a pressing need for ongoing monitoring, enhanced plastic waste management measures and more efficient water resource protection strategies.

KEYWORD: Microplastic pollution; Freshwater ecosystems;Polymer characterization; Groundwater quality; Kanyakumari District.

1. INTRODUCTION

Microplastic pollution is a pervasive environmental issue that is found in global terrestrial and freshwater as well as marine ecosystems. Because of their small size (<5 mm), chemical stability, and ability to adsorb co-contaminants, microplastics can intrude into soil profiles, surface water bodies, and consume groundwater resources with potential threats towards aquatic biota[1,2], ecosystem services[1,3], and human exposure risk on drinking water contamination pathways.[4] The annual global production of plastics has crossed 400 million metric tons, and around 11 million metric tons are estimated to be disposed of into aquatic environments every year, leading to the generation of a substantial amount of MPs and NPs over time.[5,6] Their prevalence in environmental compartments necessitates the understanding of their fate, transport, and also biological impacts, especially for water resources used substantially for domestic and agricultural purposes.[7,8] In recent reports, the presence of microplastics has been determined in surface water bodies (rivers and lakes), sediments, wastewater effluents, and even drinking water sources after treatment across various geographical regions—Europe, North America, China, and South Asia, among others.[9-11] Polyethylene (PE), polypropylene (PP), polystyrene (PS), polyethylene terephthalate (PET), and polyacrylonitrile (PAN) constitute the most frequently reported prevalence of dominant polymer types, combined with fibrous and fragment morphologies from textiles, packaging, and urban runoff.[12,13] Analytical methods, density separation, filtration, stereo microscopy including µ-FTIR and Raman spectroscopy, and now SEM–EDS GS[14,15], have facilitated robust identification and quantification—although methodological variability continues to differ between studies If this were real life. Microplastic presence in rivers Pollutant identification, determination, and pollution features research studies in Indian riverine systems that have substantiated the occurrence of microplastics in significant rivers such as Ganga, Yamuna, Cauvery, and the coastal system of Tamil Nadu with quantities varying from tens to hundreds of particles per liter in surface waters.[9,10,16]

Although an increasing international interest in studies dealing with microplastic pollution in groundwater, especially for underdeveloped tropical and monsoon-prone regions and aggressive urbanization of coastal regions of South India, is limited and spatially sketched.[7,17,18] Surface water microplastics have previously been reported in some Indian rivers, but groundwater data are scarce, with only a few recent studies from Punjab, Maharashtra, and Kerala reporting low-to-moderate abundances without systematic source apportionment or detailed hydrogeological context.[17,19,20] Significant knowledge gaps remain regarding the seasonal variation, vertical transport processes through regolith and aquifer frameworks, polymer-specific leaching behavior, and influence of land use activities (plastic waste dumping/septic infiltration/agricultural mulching) on microplastic loadings within shallow aquifers.[7,8,21] Additionally, the interactivity of microplastics with co-occurring pollutants such as heavy metals in groundwater a mechanism already established to occur in Tamil Nadu coastal surface waters[22] is largely uninvestigated in subsurface systems.

The Pazhayar River basin in Nagercoil, Tamil Nadu, is a high-priority case study area given its hydrogeological setting, i.e., a shallow, unconfined coastal aquifer system in fractured crystalline rock-overlying alluvial sediments being abstracted under extreme pressure (>120% stage of development), has widespread disposal of plastic waste informally, and is affected by peri-monsoonal floods (mobilizing debris to the groundwater–surface water interfaces).[22,23] Further, more than 85% of the population in the vicinity is dependent on dug wells and borewells for domestic water intended for use as a source most of which are sited within 100 m from open waste dumps/sewage channels, flagging immediate alarms of direct exposure to liquid-filled microplastics.[18,24] These coastal aquifers in the region are also imperiled by saline intrusion and anthropogenic contamination, resulting in a composite of contamination status where microplastics might serve as vectors for toxic additives and adsorbed pollutants.[22,25] Therefore, characterizing the distribution of microplastics in these critical aquifers is important not only for regional water management but also to provide guidance on policies affecting plastic waste setting and drinking water quality standards in data-limited tropical systems.

Hence, this study intends to evaluate the prevalence, distribution in space and time, morphological variation, and polymer types of microplastics existing in surface water (river/ponds/canals) and groundwater (dug wells/borewells) in the Pazhayar River Basin, Nagercoil. Specific objectives include quantification of microplastic abundance (number of items/L, number of items/kg sediment) as a function of both wet and dry seasons; (ii) morphological characterization (size, shape, color, surface degradation features), using stereo and scanning electron microscopy; (iii) identification of polymer type using Fourier-transform infrared spectroscopy (μ-FTIR); (iv) determining the relationship between microplastic load observed in riverine systems and land use pattern, hydrochemical parameters (e.g., EC, NO_3^-, Cl^-, proximity to pollution sources); and (v) potential human health risk estimation based on exposure scenarios for ingestion involving toxicological threshold values for additives found within plastics such as phthalates, BPA, or PBDEs. This systematic approach will both fill in important knowledge gaps regarding the microplastic dynamic in under-researched tropical coastal aquifers and establish a new litter size data set that is crucial to sustainable management of South Indian groundwater resources.

2.0 Study Area and Methodology

The methodology used to monitor the level of microplastic pollution in the Pazhayar River basin adheres to widely adopted methods adopted for environmental microplastic studies with respect to sampling, pretreatment, and the novel analytical techniques. The study strictly followed the 0.45 µm cellulose nitrate membrane filter for microplastic extraction, considering its high strength retention and compatibility with spectroscopic methods from Ephemia.[26]

2.1 Study Area

It was carried out in the Pazhayar River basin between Perunchani Dam and Manakudi estuary up to Nagercoil, Kanyakumari District, Tamil Nadu, South India (Fig.1). It passes through varied land uses, including forests, horticultural lands, urban areas, and coastal plains, till it discharges into the Arabian Sea. In the study area, there is a tropical climate with distinct monsoonal rainfalls and substantial use of groundwater for domestic and agricultural water supply. These effects also appear to influence the riverine landscape of this basin (and in other places); consequently, evident depositional structures are observed in ARD, which could render it more susceptible to microplastic contamination and infiltration by means of both surface and groundwater.[21,23,24,27,28] The presence of microplastic pollution has also been widely reported in a range of riverine Indian systems, including the Kaveri[10], Thamirabarani, Adyar, and Cooum, all within Tamil Nadu[29], and Ganga and Yamuna[9], re-emphasizing the regional importance of these studies.

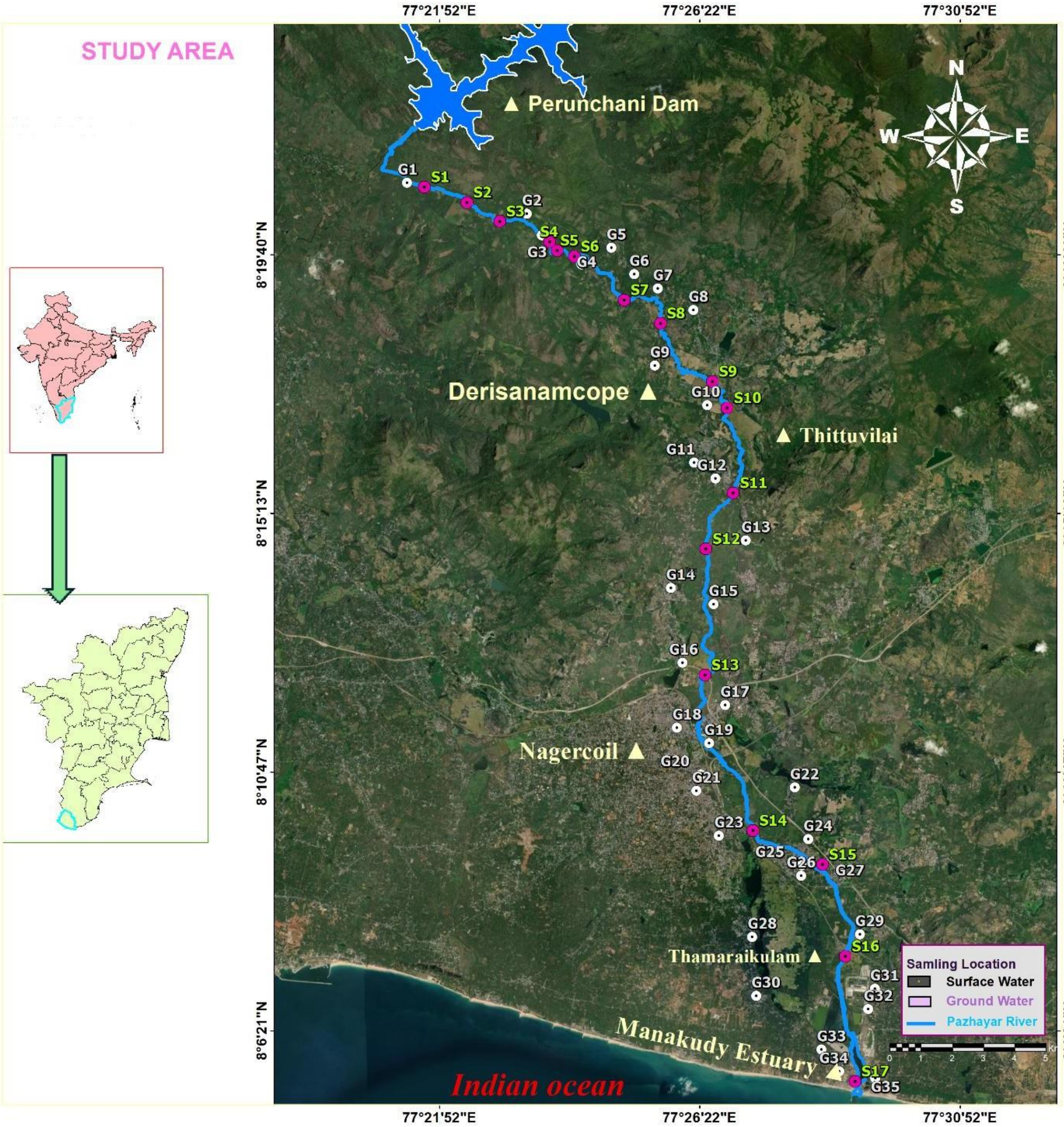

Fig. 1: Study area map of the Pazhayar River basin, Kanyakumari District, Tamil Nadu, India, showing the groundwater and surface-water sampling locations (G1–G35 & S1- S17).

2.2 Sample Collection

2.2.1 Surface Water Sampling

The present investigation was conducted in the vicinity of the Pazhayar River, Nagarcoil, and its environs in Kanyakumari District, Tamil Nadu, India. The studies were conducted in the upriver Moolayanai (Chellanthurithy) and downriver Manakudy estuaries, including both ground and surface water sampling sites. Geographically, the area is located in the range of latitudes 8.348121° N to 8.091448° N and longitudes 77.325560° E to 77.490114° E, with boundaries marked upstream near Moolayanai (coordinates: 8.348121° N, 77.355094° E) and downstream at Manakudy estuary (coordinates: 8.091448° N, 77.484115° E). In total, thirtyfive water samples were taken from groundwater and seventeen surface water samples along the river course and adjacent settlements such as Sulore, Arumanallurazhagiapandipuram, Boothapandi, Eracahakulam, Nagercoil, Theroor, Suchindram, Thamaraikulam, Parakkai, and Manakudy. The study region is a transition zone from the Western Ghats foothills in the upstream to the urban/semi-urban stretch at Nagercoil and from there to the coastal, alluvial estuary near Manakudy. Crystalline basement (Charnockite and Khondalite groups) rocks constitute the uplands, while fluvial alluvium occurs along the river course, and coastal sediments are found near the estuary. The Pazhayar River flows mainly in a northwesterly direction before draining into the Arabian Sea at Manakudy; the region is affected by both the Southwest and Northeast monsoons with a tropical wet-and-dry climate. A total of 17 surface water samples were collected from the Pazhayar River, which ranged between upstream to midstream and downstream sides starting from the Perunchani Dam to the Manakudi estuary. Sampling sites were selected to cover differences in hydrological and human impacts. Water samples were collected from a depth of about 10–20 cm below the water surface through pre-cleaned 1-liter glass bottles to avoid plastic contamination.[30] Samples were sealed, tagged, and transferred to the laboratory for analysis soon after sampling. Comparable procedures of surface water sampling have also been utilized in other river studies, for instance, in the Gaula River (India) and Zayandeh-rud River (Iran).[31,32] A total of 35 groundwater samples were collected from bore wells and open wells located throughout the Pazhayar River basin, ranging from the Perunchani Dam to the Manakudi estuary. All wells were purged 5–10 min before sampling to purge (flush) stagnant water and obtain good-quality representatives of groundwater. Samples of groundwater were preserved in pre-cleaned glass vials, closed, and transported under controlled temperature conditions to the laboratory for MP extraction and analysis. The importance of this knowledge for microplastic pathways into groundwater, especially in the vicinity of landfill areas or locations characterized by high anthropogenically influenced plastic consumption, is also illustrated in several other papers.[33-35]

2.3 Preparation for the Samples and Digestion of Organic Matter

WPO was used to eliminate organic matter that could lead to interference in the detection of microplastics in water samples after filtration. About 0.2 g of each sample (dry weight) was added in a measured volume to be digested with a gentlyheated solution at a constant temperature of all samples and treated with 30% hydrogenperoxide (H_2O_2). The treated samples were cooled, and then subsequent processing was performed. Wet peroxide oxidation is a widely used method for organic matter removal in microplastic analysis and has been applied in studies using different environmental matrices such as river water and sediments.[36-39] This is to allow samples to crystallize, which will render microplastic particles more visible and easier to correctly characterize—free from biological detritus.

2.4 Microplastic Extraction and Filtration

The organics from thesample were filtered upon digestion. Microplastic extraction The processed samples were filtered under vacuum through precombusted cellulose nitrate membrane filters with a pore size of 0.45µm (Whatman™ grade CN45, Cytiva, USA). These filters are selected according to the following specifications: collection efficiency >99.9% of particles ≥0.45 µm, low background contamination (untreated), and FTIR-analysis compatibility[26], Filters were inspected visually under a stereo microscope and washed with ultrapure water (18.2 MΩ·cm) before filtration to remove any loose fibers or particles remaining on the filter surface. Filtration was by means of sterilized, glass fritted funnels and shine-through filters that had been pre-cleaned using wash out with ultrapure water. The whole filtration system was washed with ultra-pure water then set 70% ethanol and dried in laminar air flow upon the next consecutive samples to preclude cross-contamination. The microplastic particles were then removed from the filters and air-dried in a class-100clean bench for 24 h to eliminate water content that may interfere with microscopy and spectroscopy analysis. This filtration regime matches the typical outlined isolation method for microplastics as advised by the Joint Research Centre (JRC) of the European Commission and used in key environmental monitoring works.

2.5 Appearance and Morphological Analysis of the Isolates

Stereomicroscope Dry filters were examined using a stereomicroscope to distinguish possible microplastic particles. The microplastic particles were characterized in terms of shape (fibers, fragments, films, and pellets), color, and size. Only particles with features suggestive of an anthropogenic nature (homogeneous color, lack of cellular structure, and characteristic fracture patterns) were subsequently examined. Visual characterization with a stereo microscope is often used as the first step of microplastic analysis to separate apparent microplastics and natural debris, as indicated in previous studies.[37,40]

2.6 Polymer Identification and Surface Morphology

We found the surface resin deposits that formed after etching reactions for two reasons: to use as a profile image to check PII and to see if they could be moved back to SiO_2 after removing silicide. Using a Thermo Fisher Nicolet Summit X FTIR Spectrometer from the Department of Geology at Periyar University Centre for Postgraduate and Research Studies in Dharmapuri, we looked at the polymer composition of microplastic particles. The given spectra were ascribed to certain polymer types (PE, PP, PS) according to their respective libraries. FTIR spectroscopy can find polymers and give different spectral features to different kinds of plastics.

2.7 Quality control and contamination

Strict quality control measures were taken when sampling and analyzing in the laboratory to minimize contamination. All the glassware and apparatus used were previously cleansed with distilled water. The experimenters conducting the measurement between trials wore a cotton lab coat, and nitrile gloves were added to reduce environmental fibre cross-contamination. Procedural blanks (ultra-pure water on which all the procedures had been carried out) were regularly performed in order to account for possible airborne or laboratory contamination. This process is essential in trace analysis to prevent background interferences that can result in the presence of trace levels of contaminants contributing to the error from an analytical outcome.[39] It has been well established that "radiation contamination," including airborne fibre and laboratory equipment contamination, needs to be avoided in microplastic research.[8]

2.8 Data Analysis

For both surface water and groundwater samples, the microplastic abundance was determined as the number of particles per liter (particle/L). Arc GIS and Statistical analysis used SPSS aimed at exploring spatial differences in concentrations between locations along the Pazhayar River section from Perunchani Dam to Manakudi estuary and between microplastic abundance of surface water and groundwater compartments. The most suitable statistical methods were selected according to the distribution of data and the objectives of analysis so that findings can be interpreted confidently. Such quantitative analysis is beneficial to the evaluation of pollution and source and transport processes of microplastics in the river basin.[11,41]

3. RESULT AND DISCUSSION

Microplastic (MP) contamination is a pervasive environmental issue, significantly impacting both groundwater and surface water resources, particularly in regions like Tamil Nadu, India. Studies have highlighted the widespread occurrence of MPs in various aquatic environments, emphasizing their hazardous characteristics and potential role as vectors for other pollutants, such as heavy metals.[22] The data provided for southern Tamil Nadu reveals a substantial presence of microplastics across all sampled groundwater (G1–G35) and surface water (S1–S17) sites, with a total of 323 microplastic particles identified (**Table 1**). This universal detection underscores the widespread nature of MP pollution in the region, extending even to areas perceived as relatively remote.

Table 1: Global evidence of microplastic contamination in aquatic environments: Sources, distribution, and reported concentrations.

Country/Regi on	Water Body Type	Location	Microplastic Concentrati on (with units)	Predomina nt Polymer Types & Morphologi es	Analytical Methods & Key Characteristics	Referen ce
Vietnam	Surface Water & Sediment	Mekong River Delta (Tien River)	Average 1290 ± 440 items/m³ in surface water; 1210 ± 860 items/kg (d.w.) in sediment 6	Fragments, fibers, pellets; Polyethylen e (PE), Polypropyle ne (PP), Polystyrene (PS) 6	Visual identification, F TIR spectroscopy; Inadequate wastewater treatment, agricultural, aquaculture waste 6	Kieu et al., 2023
Bangladesh	Surface Water, Sediment, Biota	Surma River	Significant MP pollution detected in water, sediment, fish, crustaceans, and bivalves 7	Fibers, fragments, films, pellets; Polyethylen e (PE), Polypropyle ne (PP) 7	Visual identification, FTIR spectroscopy; Deteriorating ecological health due to plastic waste emission 7	Jahan et al. 2024,
Bulgaria	Marine Sediment/Surf ace water	SW Black Sea coast	464.44 ± 272.50 MP·kg−1 dry sediment in urbanized areas 10	-	High pollution associated with urbanization 10	Bobche v et al., 2024
India	Surface Water	Chalaku dy River, Kerala	15.13 ± 4.13 – 170 ± 17.75 particles L−1 (mean: 55.81 ± 34 particles L−1) 11	-	Not specified in abstract	Manees h Kumar et al.,2023
Turkey	Surface Water	Van Bay, Van Lake	641,424 to 1,426,638 per km2 (2.35 to 5.09 MPs/m3 in water columns) 12	-	335 µm mesh manta trawl; Most frequently observed shapes: fiber, film, fragment, pellet 12	Atici et al., 2022
Global (Review)	Aquatic	Worldwi de	Concentrati ons vary		FTIR, Raman spectroscopy;	

	Environments	(freshwat er & marine)	widely (e.g., 0.00 to 19,000 MP particles/g	PE, PP, PS, PA, PVC, PET common 13	Challenges in standardization, widespread occurrence 1314	Harley-Nyang et al., 2023
			dry weight in sewage sludge) 13			
Europe (Meta-analysis)	Aquatic Environments (Marine & Freshwater)	Across Europe	Influenced by latitude, proximity to WWTPs, population density, mesh size 9	-	Meta-analysis of over 60 studies; methodological recommendation s for future research 9	Hartz et al., 2025

3.1 Microplastic Abundance and Distribution

The spatial distribution of color-specific microplastics collected from G1-G35 along a stretch of Pazhayar River extending from Perunchani Dam up to the Manakudy estuarine sector, Nagercoil district, Tamil Nadu (Fig. 2a-h & 3a- g & Table 2). The various colors observed along the sampling transect could originate from multiple sources that may still be hydrologically active, implying a gradual redistribution of Microplastics.[10] The only exception is the colorless and white particles, which were relatively rare in wetlands but were widely distributed mainly in the upstream and middle reaches.[11] Less abundant, brown and beige were present mainly at the upper station (Fig. 2a–d). The range of net eastward movement observed for red and yellow particles overlaps extensively (shown in orange on the left panel) with a greater difference in longitude seen for the full range of particle colors (Fig. 2e-f). Meanwhile, violet and green particles were observed sparsely but reached the estuarine zone (Fig. 2g-h). Indeed, the fact that for G18-G27 and G30-G35 we find many color classes indicates a possible pile-up in the downstream areas.[42,43] The surface water spatial distribution of microplastics in the Pazhayar River basin are colour-based distinctive and indicate regionally heterogeneous sources and transport pathways within the river continuum. Microplastics were in general favourably distributed with colourless microplastics being more charged, whilst white and black particles sufficiently grew higher concentrations post S8 varying especially along the middle stretch of the river (Fig. 3a–c). While blue microplastics were more abundantly found in the downstream reaches and high loading at S11–S12 and S17, red and yellow particles had extensive distributions but were enriched at S12 sites and down river locations (Fig. 3d–f). Violet microplastics were less common but detected at many sites, again with a significant finding near S15 and the lower reaches (Fig. 3g). The colour-specific distribution patterns observed constitute an important indication of localised anthropogenic inputs and hydrodynamic controls over microplastic accumulation at a river basin scale. This regionalism argues that the knowledge currently available on freshwater transport mechanisms and microplastic particle characteristics, flow dynamics, retention in sediments, catchment land inputs and permeability is sufficient to inform actual risks. A major novelty of this study is the colour-resolved spatial association between the occurrence of microplastics and river-and groundwater environments within a poorly studied tropical riverine ecosystem in the Pazhayar basin.

Table 2: Distribution of microplastic characteristics in groundwater and surface water of the Pazhayar River basin.

Pazhayar River Basin Surface and Ground water sample																											
				Colour Classification									Shape Classification					Size Classification			Poliymer Classificification						
S.NO	Code	Village / Location	Type of Sampls	White	Transparent	Black	Blue	Green	Red	Yellow	Violet	Total	Fibre	Fragment	Film	Foam	Pellet	Macro	Meso	Micro	PP	PE	PA	PS	PVC	PES	PET
G1	MOL	Moolayanai (Chellanthuraithy)	Ground water	0	2	0	0	0	0	1	0	3	2	0	1	0	0	0	0	3	2	0	0	0	0	0	1
G2	SUL	Sulore	Ground water	1	0	1	0	1	0	0	1	4	1	0	0	1	2	0	0	4	1	2	1	0	0	0	0
G3	PBS	Pazhayar Bridge, Sulore	Ground water	0	1	1	0	0	0	0	0	2	1	0	0	1	0	0	0	2	0	1	1	0	0	0	0
G4	ARM	Arumanallur	Ground water	0	1	1	0	0	1	0	0	3	2	0	0	1	0	0	0	3	1	2	0	0	0	0	0
G5	THA1	Thadikaran Konam 1	Ground water	0	1	0	1	0	0	0	1	3	2	0	0	1	0	0	0	3	0	0	1	0	0	0	2
G6	AZH	Azhagiapandipuram	Ground water	0	1	2	0	0	0	0	2	5	1	3	0	1	0	0	1	4	2	3	0	0	0	0	0
G7	THA2	Thadikaran Konam 2	Ground water	1	1	0	0	0	0	0	1	3	0	2	0	1	0	0	0	3	1	1	1	0	0	0	0
G8	KES	Kesavanputhoor	Ground water	0	2	1	0	0	0	0	1	4	2	2	0	0	0	0	0	4	1	2	1	0	0	0	0
G9	ANT	Anthirapuram	Ground water	2	0	1	0	0	0	0	0	3	0	0	1	0	2	0	0	3	0	2	1	0	0	0	0
G10	CHI	Chiramadam (Derisanamcope)	Ground water	1	2	0	0	0	0	0	1	4	0	2	1	1	0	0	1	3	0	0	1	0	0	2	1
G11	THI	Thittuvilai	Ground water	1	0	0	0	1	0	0	0	2	2	0	0	0	0	0	0	2	1	0	0	0	0	0	1
G12	BOO	Boothapandi	Ground water	0	0	1	0	0	0	0	0	1	1	0	0	0	0	0	0	1	1	0	0	0	0	0	0
G13	POO	Poolanguzhi	Ground water	0	0	0	0	0	0	0	1	1	0	0	0	1	0	0	0	1	0	0	0	0	0	0	1
G14	ERA	Eratchakulam	Ground water	0	0	1	1	0	0	0	1	3	2	0	0	1	0	0	0	3	0	1	0	0	0	0	2
G15	VNM	Veeranarayana Mangalam	Ground water	0	0	1	1	0	0	0	2	4	3	0	0	1	0	0	0	4	0	2	2	0	0	0	0
G16	GNN	Ganesh Nagar, Nagercoil	Ground water	0	2	0	2	0	0	0	0	4	0	2	1	0	1	0	0	4	2	0	2	0	0	0	0
G17	TKP	Theraikalputhoor	Ground water	1	0	1	0	0	0	0	0	2	1	0	0	0	1	0	0	2	0	0	0	0	0	1	1
G18	NAG	Nagercoil	Ground water	0	1	2	1	0	0	0	0	4	2	0	0	2	0	0	0	4	0	1	1	0	0	2	0
G19	KGR	Kothaigramam	Ground water	0	3	0	0	0	0	0	0	3	0	2	0	0	1	0	0	3	0	1	1	0	1	0	0
G20	VAD	Vadiveeswaram	Ground water	2	0	1	0	0	0	0	0	3	3	0	0	0	0	0	0	3	1	1	0	0	0	1	0
G21	KTR	Kottar	Ground water	0	2	0	1	0	0	0	0	3	2	0	0	1	0	0	0	3	1	0	0	0	0	0	2
G22	THR	Theroor	Ground water	0	1	3	0	1	0	0	1	6	2	2	0	2	0	0	1	5	2	0	2	0	0	1	1
G23	EDA	Edalakudi	Ground water	0	0	1	0	0	0	0	2	3	1	0	0	1	1	0	0	3	1	0	0	0	0	1	1
G24	SUA	Suchindram Akkarai	Ground water	2	1	1	1	0	0	0	0	5	2	1	1	0	1	0	0	5	2	0	2	0	0	1	0

G25	SST	Sannithi Street, Suchindram	Ground water		0	2	2	0	0	0	0	0	4		2	0	0	0	2		0	0	4		0	2	0	0	2	0	0
G26	SUC	Suchindram	Ground water		1	2	1	1	0	0	0	1	6		2	2	1	1	0		0	0	6		2	2	0	0	0	2	0
G27	VAZ	Vazhukamparai	Ground water		0	0	1	0	0	0	0	0	1		1	0	0	0	0		0	0	1		0	0	1	0	0	0	0
G28	PAR	Parakkai	Ground water		0	2	1	0	0	0	0	0	3		3	0	0	0	0		0	0	3		0	2	0	0	1	0	0
G29	TMN	Thamaraikulam North	Ground water		0	0	1	1	0	0	0	0	2		2	0	0	0	0		0	0	2		0	1	0	0	0	0	1
G30	TGP	Thengamputhur	Ground water		0	0	1	0	0	0	0	0	1		1	0	0	0	0		0	0	1		1	0	0	0	0	0	0
G31	SWM	Swamithoppu	Ground water		0	0	1	0	0	0	0	0	1		1	0	0	0	0		0	0	1		0	1	0	0	0	0	0
G32	SKV	Sasan Kovil Vilai	Ground water		1	2	0	0	2	0	0	0	5		3	1	0	1	0		0	1	4		2	0	3	0	0	0	0
G33	KPT	Keezha Puthalam	Ground water		1	2	0	2	0	0	0	0	5		2	2	0	0	1		0	0	5		0	1	2	0	0	2	0
G34	MMK	Mela Manakudy	Ground water		1	2	0	0	0	0	0	0	3		0	2	0	0	1		0	0	3		1	2	0	0	0	0	0
G35	KLM	Keelamaikudi	Ground water		0	0	2	0	0	0	0	2	4		4	0	0	0	0		0	0	4		0	3	0	0	0	0	1
S1	CHE	Chellanthuraithy	Surface water		2	2	2	1	1	0	0	0	8		4	2	0	1	1		0	1	7		2	3	0	0	3	0	0
S2	SUR	Surulacode	Surface water		1	2	0	1	0	0	0	2	6		3	0	0	2	1		0	0	6		1	1	0	2	0	0	2
S3	SLR	Sulore	Surface water		1	3	2	1	1	0	0	1	9		3	3	1	0	2		0	1	8		3	2	0	0	3	1	0
S4	SLB	Sulore Bridge	Surface water		2	0	2	0	0	0	0	2	6		4	1	0	0	1		0	0	6		1	1	0	0	0	2	2
S5	VEP	Veerapuli	Surface water		1	1	2	1	1	0	0	1	7		3	2	1	0	1		0	0	7		2	1	0	0	0	2	2
S6	GDN	Gandhi Nagar	Surface water		3	2	3	0	2	0	0	1	11		5	3	0	0	3		0	3	8		3	2	0	2	1	2	1
S7	VAN	Veeravanallur	Surface water		3	4	4	1	2	0	0	1	15		7	3	0	3	2		0	1	14		2	4	2	0	4	1	2
S8	PAL	Pallikondan Anicut	Surface water		2	3	2	0	0	0	0	2	9		5	3	0	0	1		0	1	8		3	1	0	0	0	4	1
S9	DER	Derisanamcope	Surface water		1	3	0	1	1	0	0	2	8		3	2	0	2	1		0	2	6		2	0	4	0	0	0	2
S10	MUD	Mudanganvilai	Surface water		1	2	2	1	0	0	0	2	8		3	2	0	2	1		0	0	8		0	2	0	0	0	3	3
S11	AND	Andithoppu	Surface water		3	4	2	0	2	1	0	3	15		7	4	2	0	2		0	1	14		1	2	3	2	0	3	4
S12	NTR	Nagercoil (Theroork Road)	Surface water		3	5	2	2	2	1	0	5	20		7	6	3	2	2		2	4	14		6	4	3	1	2	2	2
S13	PRB	Pazhayar Railway Bridge	Surface water		3	5	5	0	2	0	0	1	16		8	4	1	0	3		0	1	15		4	0	2	2	3	2	3
S14	SOB	Suchindram Old Bridge	Surface water		2	4	2	1	2	0	0	4	15		5	5	0	3	2		0	2	13		3	4	1	1	2	1	3
S15	PRM	Parampuram	Surface water		3	5	3	0	2	0	2	4	19		8	4	4	0	3		0	3	16		3	2	5	2	3	1	3
S16	TMK	North Thamaraikulam	Surface water		3	8	3	0	2	0	0	1	17		6	7	1	0	3		0	2	15		5	4	3	2	0	2	1

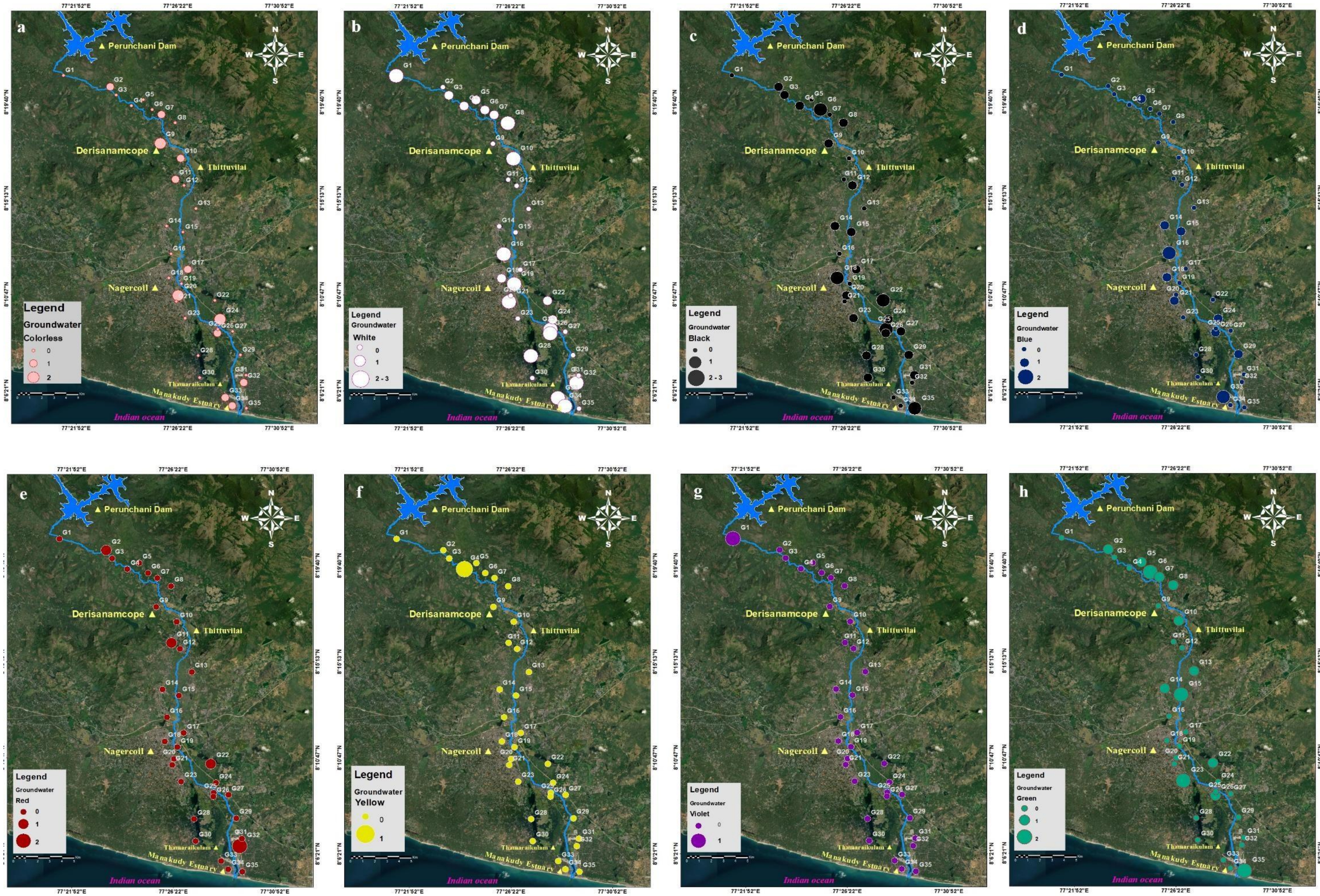

Fig. 2a-h: Spatial distribution of microplastics in Ground water of the Pazhayar River basin based on colour.

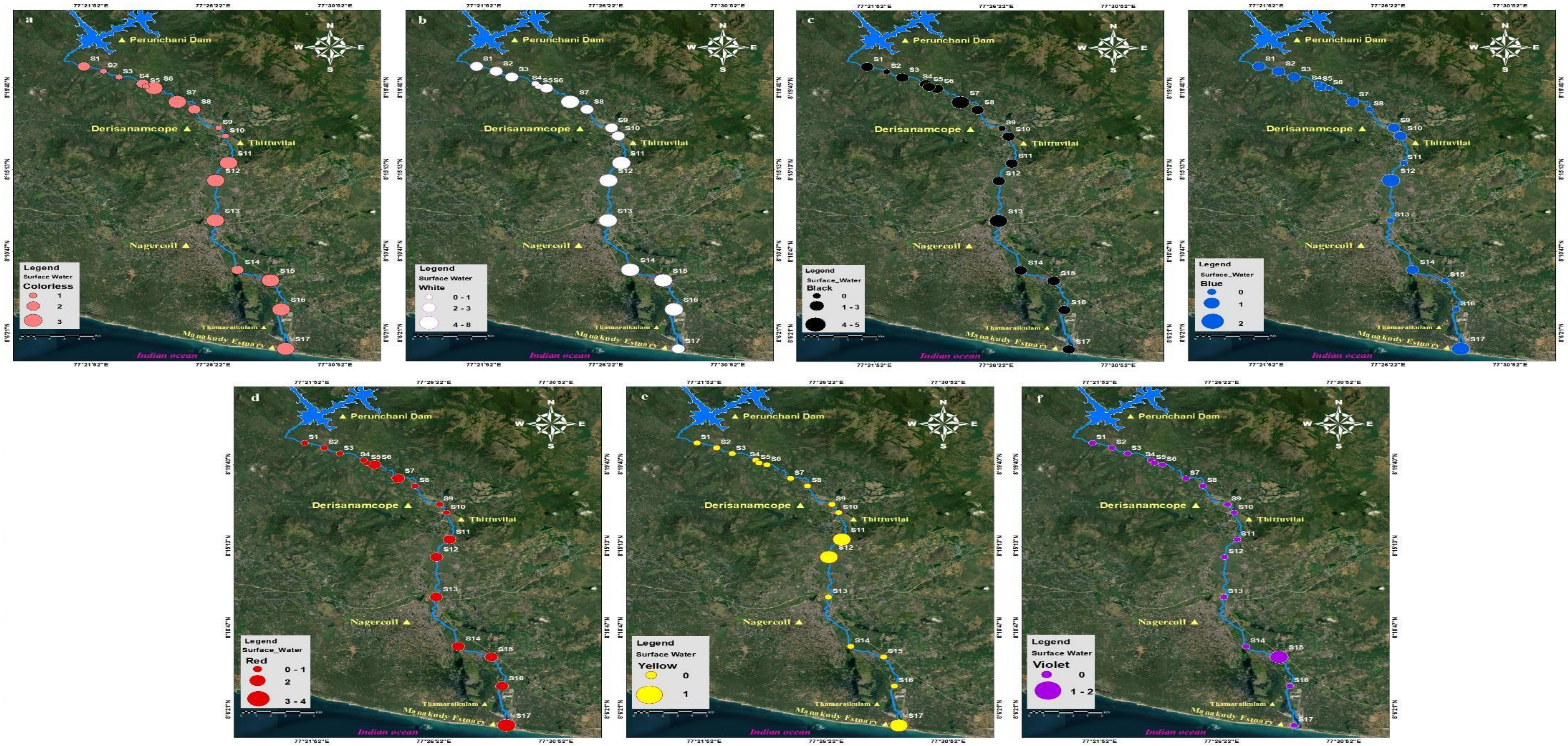

Fig. 3a-g: Spatial distribution of microplastics in surface water of the Pazhayar Rive.

Morphological Characteristics (Shapes)

Data is analysed for microplastic (MP) contamination from various groundwater and surface water sampling sites in Kanyakumari district, Tamil Nadu, India. In this study, MPs are classified into fibre, fragment, film, foam and pellet, providing a comprehensive overview of their occurrence and relative abundance (Fig. 4a–e)**.** In this context, microplastic contamination of groundwater and surface water has become a vital research area because their pollutants are released into the environment across the globe and may have ecological and human health effects.[44] Rivers, which are primary conduits for microplastic transport, have been found to incorporate large amounts of microplastics into benthic sediment and aquatic organisms[45], being adjacent water bodies to the worst affected coastal regions from sewage depollution, followed by infiltration in groundwater. Some regions, (for example karst area), have unique topography with rapid transport of surface water to underground areas with greater microplastic contamination capacity.[35] Interpretation of the table above indicates specific and different scenarios concerning the distribution of microplastics. Groundwater samples (G1–G35): Average total microplastic count per site is 2.8 particles. The maximum total count in groundwater was recorded at G35 (4 fibre particles) Kelamaikkudi, whereas the minimum total count (0) were observed in six sites viz; G7 Dhadikarankonam, G9 Anthirapuram, G27 Vazlukamparai, G30 Thengamputhur and G31 Swamitopur. Fibre microplastics run the show, making up 29 out of the 35 groundwater samples that were analysed. For instance, 2 fibre particles were found in G1 (Moolayanai) and G4 (Arumanallur), while the remaining locations gave 3 fibres including G15 (Veeranarayana Mangalam) (Fig. 4a)**.** Few numbers of fragment microplastics were also reported but samples collected from G6 (Azhagiapandipuram) and G8 (Kesavanputhoor) were 3 fragments and 2 fragments respectively (Fig. 4b)**.** Groundwater samples were mostly less contaminated with film, foam, and pellet types (Fig. 4c–e)**.** This is in line with the few other studies showing microplastics commonly exists in global freshwater systems (most often with more variation depending on local conditions and origins.[46] Microplastics in groundwater are scarce, a study from Shiraz aquifer, Iran detected concentrations between 0.1 and 1.3 MP L−17. Likewise, large abundances of microplastics have been found in groundwater in the Jiaodong Peninsula area of China.[46]

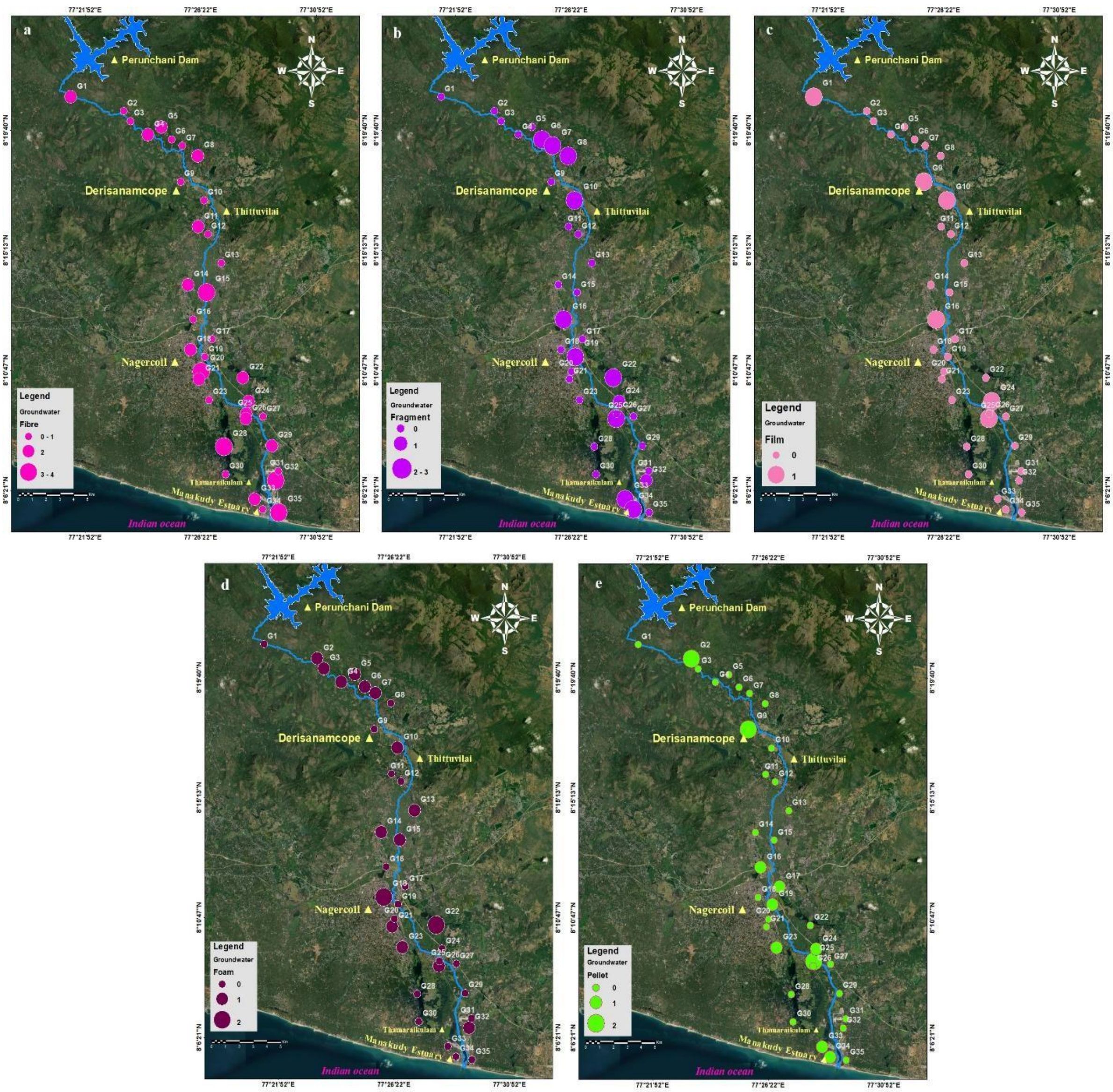

Fig. 4: The distribution of Total microplastics in the Pazhayar river basin, (a- e) distribution of microplastics based on Shape_Groundwater.

Microplastics Characterization the average total microplastic count per site in surface water samples (S1–S17) is higher than 4.3 particles. Among the category of total microplastic counts, S13 (Near Pazhayar Railway Bridge, Nagercoil), S15 (Parampuram) and S17 (Manakudy) recorded maximum of 8 particles. Similarly, fibre microplastics also represented the predominant morphology in surface water at both S7 (Veeravanallur) and S11 (Andithoppur), with 7 fibre particles (Fig. 3a). S17 (Manakudy) and S12 (Nagercoil) presence of 8 fragments of fragment microplastics in surface water followed by 6 fragments (Fig. 4b). It is interesting to note that film types were prominent at S15 (Parampuram) with 4 particles and S12 (Nagercoil) with 3 particles (Fig. 3c). In surface water, foam and pellet particles were found in larger amounts than groundwater, with S7 (Veeravanallur) having 3 foam particles (Fig. 4d) and S6 (Near Gandhi Nagar), S13 (Near Pazhayar Railway Bridge, Nagercoil), S15 (Parampuram), S16 (North Thamaraikulam), S17 (Manakudy) observing 3 pellet particles each (Fig. 4e)**.**The higher loading of microplastics in surface waters compared to groundwater is consistent with the role of rivers as main transport vectors for microplastic into surrounding environments prior to possible infiltration into groundwater.[47] Urban areas are the most critical microplastic sources in rivers, and could account for the measured contents.[4] In terms of locality, Nagercoil, Suchindram and Sulore that fall under urban or industrialized areas in the Kanyakumari district had a higher extent of microplastic contamination. S12 (Nagercoil), S13 (Nagercoil) and S14 (Suchindram), and which have higher abundance of microplastic occurrences.

Fig. 5: The distribution of Total microplastics in the Pazhayar river basin, (a-e) distribution of microplastics based on Shape_Sourface water.

Microplastic shape spatial distribution in Pazhayar River surface water extensively varied along the river course reflecting differential transport and accumulation processes. Fibres were abundant in the higher concentrations at S7–S8, S11–S12 and the more downstream S15–S17 reaches and mainly towards the estuary area (Fig. 5a). In the river water, more abundant fragments were observed at S12 and their abundances showed increasing trends toward lower reaches with a large amount of accumulation at S16–S17 (Fig. 5b). For mains, films were less abundant overall, but S11–S12 and S15 showed significant enrichment (Fig. 5c). Across the river, pellets were found in higher abundances around S9–S13 and S15-17 (Fig. 5d–e). In conclusion, the shoaling and subsequent catchment fixation of surface microplastics indicate that riverine transport, coupled with localized anthropogenic inputs and estuarine retention collectively drive the spatiotemporal disposition of microplastic shapes in the Pazhayar River system. This further indicates that anthropogenic factors such as population density and sewage input are associated to microplastic pollution. Additionally, land use types and sediment granulometry affect microplastic distributions along rivers.[48] The study demonstrates that microplastics can be found both in groundwater and surface water, revealing the widespread nature of polymer pollution and the need for more extensive monitoring and management strategies within this region. These results are of significance to define comprehensive water quality in the region as these water sources are essential for domestic/irrigational uses.[49]

3.2 Size Classification

The color of MP in groundwater (G1–G35) and surface water (S1–S17) collection points is represented according to the available data. Comparison of these sampled points indicates that microplastic pollution levels in Groundwater Sampling Points (GPWs) and Surface Water Sampling Points (SPWs) are quite different, with the latter much greater than the former (Fig 6a-b & 7a-b). The average groundwater (G1-G35) shows a very low count of microplastics on average, and the points such as G12 (Boothapandi), G13 (Poolanguzhi), G27 (Vazlu kamparai), G30 (Thengamputhur), and G31 (Swamitopur) showing only 1 particle in them make volumes skimmed through; other than these nearest numbers from each other in the sets, there are nothing but the same points. Both such points represent 1 plastic again of those. The colors of MP are most commonly violet (n=6) and translucent (n=8), but may be black, blue, green, or yellow (n=1–3). Red microplastics are an uncommon factor and were identified alone at station G4 (Arumanallur) (Fig 6a-b). This aligns with the broader concerns of groundwater contamination, which arise from multiple factors, such as industrialization and urbanization resulting in percolation and accumulation.[44] Microplastic contamination occurs more frequently than other forms of water pollution in surface water samples (S1–S17). There are between 6 and 21 particles at each site. There are 6 particles at S1/Chellanthurithy and S4/Sulore Bridge, and 21 particles at S17/Manakudi. The transparent microplastic is most common in the surface water. At most 8 can be there at S12 (Nagercoil). White, black, and green microplastics are also major. Another study conducted on the microplastic pollution in surface water bodies on the East Coast of India found that polyethylene (43%), polypropylene (42%), and polystyrene (15%) were the major polymers observed.[12]

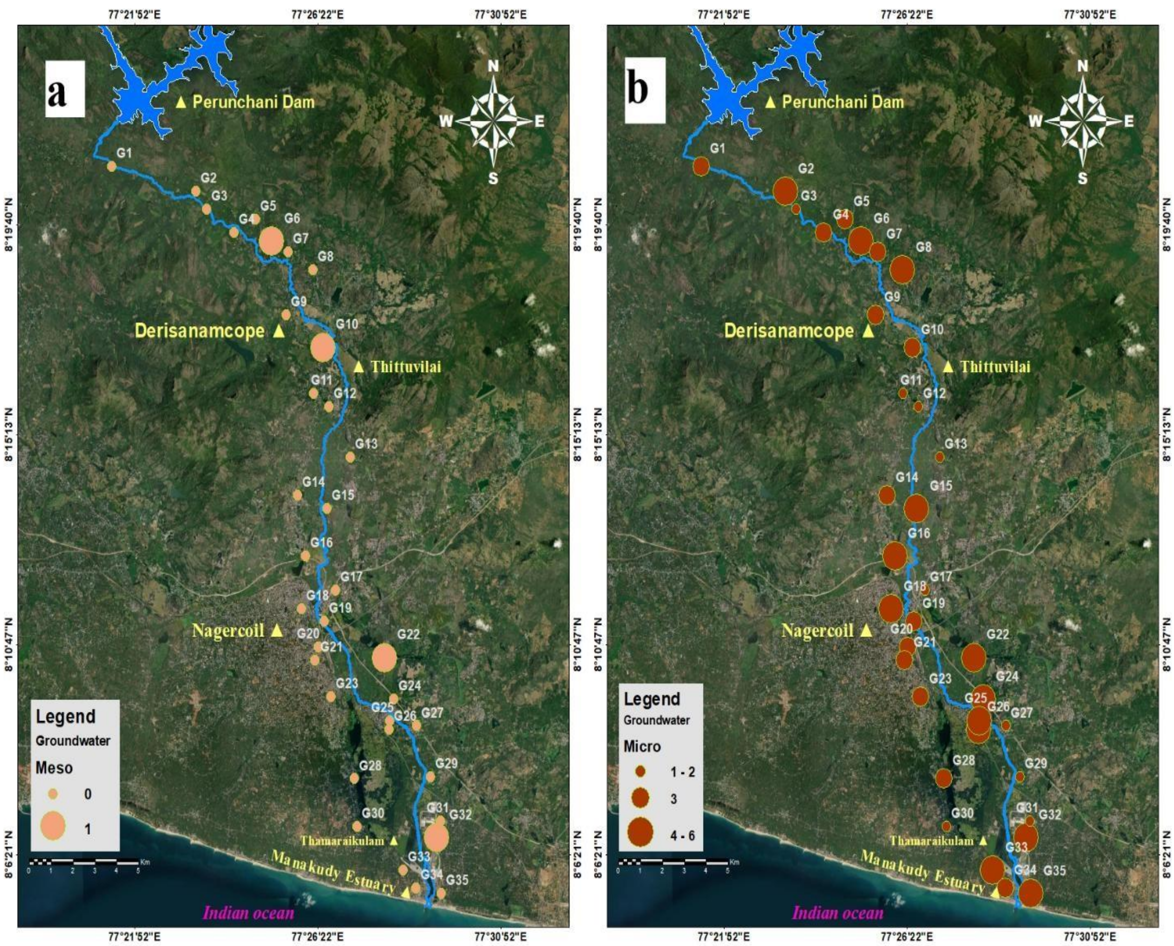

Fig. 6: The distribution of Total microplastics in the Pazhayar river basin, (a- b) distribution of microplastics based on Size_Ground water.

Spatial distribution of microplastics Spatially, Nagercoil, Suchindram and Thamarai Kulam are less concentrated with microplastics (Fig 7a-b). This suggests a significant influence from anthropogenic activities, consistent with what is observed at other sites where water pollution is intensified by urbanization and industrialization.[44] Microplastics, at least for Nordic countries, were collected from both industrial and local sources. Captured microplastic can be due to increased load in transport.[33] The transport of microplastics from riparian soils to groundwater indicates the complex contamination paths. They are in blues and greens of reds and yellows. The means of all pair values in surface water are 1, 2, 1, 0, 1, 0, 0, and 1 for each color. These results reveal the omnipresence and multiple implications of microplastic contamination in diverse water bodies throughout the Kanyakumari district.

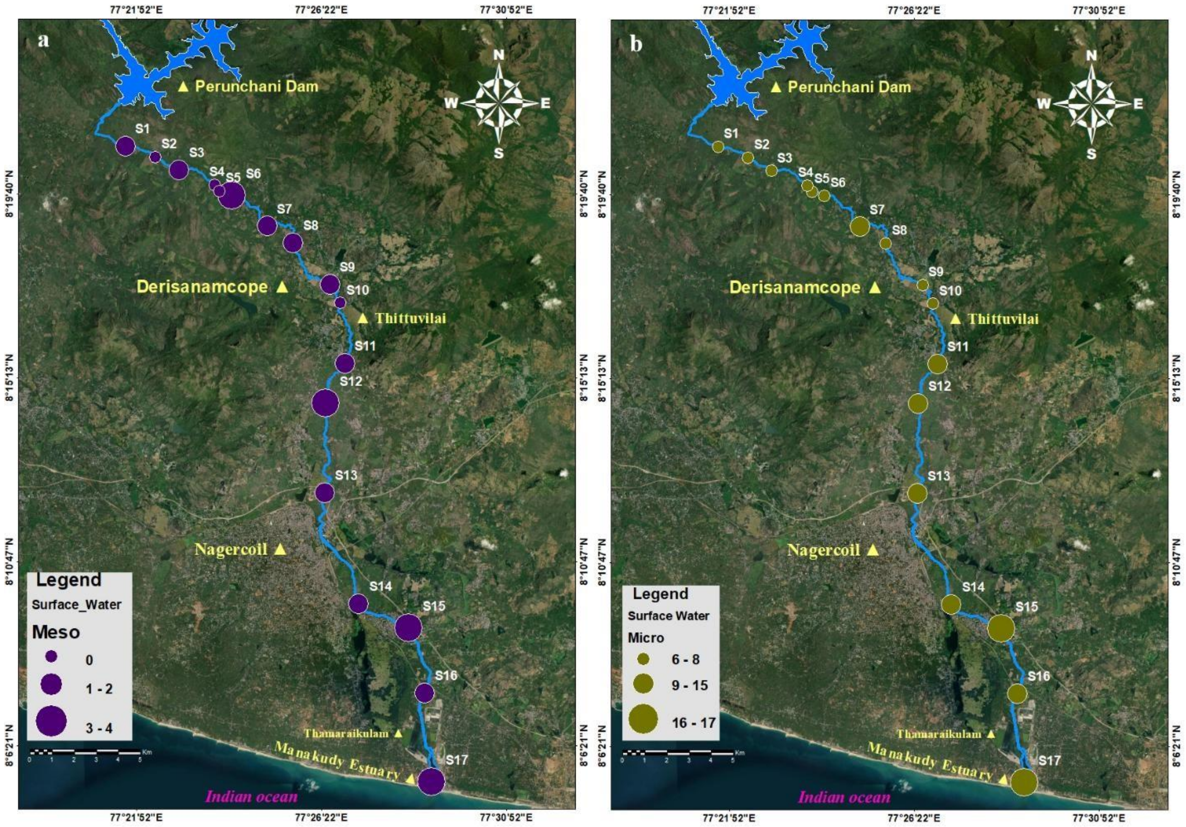

Fig. 7: Spatial distribution of total microplastics in the Pazhayar River basin based on size classification in surface water (a) mesoplastics and (b) microplastics.

3.3 Polymer Composition

The distribution of polymer-specific microplastics in the Pazhayar River basin is remarkably spatially heterogeneous, especially between groundwater and surface-water environments. In groundwater, most PP was distributed widely with significant accumulation at G28 (Parakkai), G31–G32 (Thamarai Kulam–Sasan Kovil) and G33 (Keezha Puthalam), but PE showed better enrichment towards the lower basin (e.g., G28, G33–G35), likely indicative of localised anthropogenic inputs (Figs. 8a–b). PA was scattered and more abundant at G14–G16 and G22–G26, while PVC was concentrated in the central-to-lower basin near sites G26–G28 and G34–G35 (Fig. 8c–d). Distinct enrichments of PES were observed at G11 (comparison D) and G18–G19 and G23–G27 (comparisons C, E), while PET was widely dispersed with high fragment counts associated with regions including from the 5' intergenic region upstream to the bar-shaped TE located at G4, peaks at G14 (comparisons A to B), and peak(s) centred at approximately coordinates in proximity of seven '3'-UTRs' within the boundary range of spade, comparison or alternate genes acute mustalic grouper complexes (figure comparison distributions). 8e–f). All together, the groundwater results show that accumulation of specific polymers is a function of the interaction between localised anthropogenic sources, subsurface transport processes and hydrogeological connectivity.

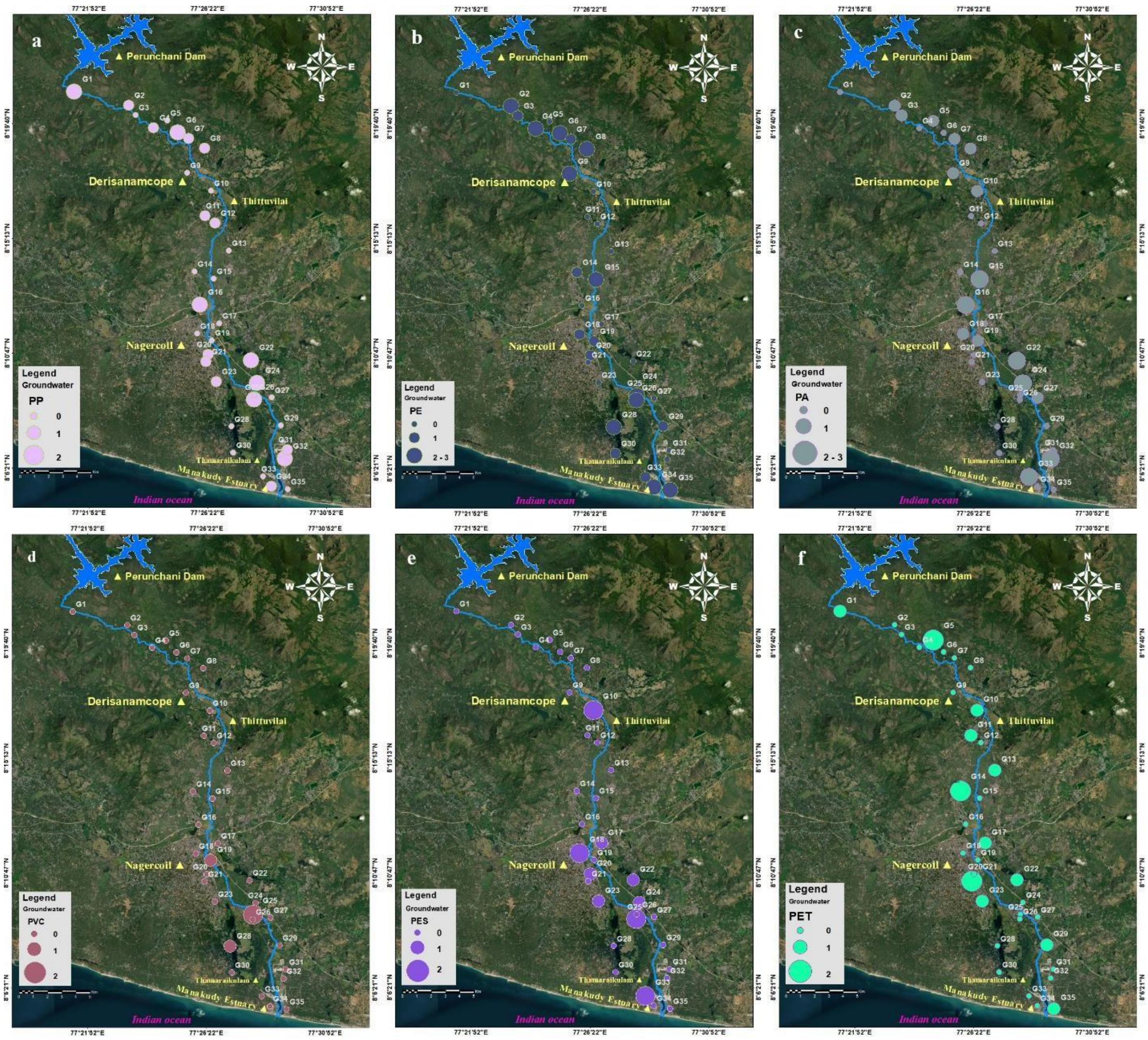

Fig. 8a-f: Spatial distribution of microplastic polymers in groundwater of the Pazhayar River basin.

In surface waters, we observed a 7-component longitudinal polymer-specific signature with many polymers concentrated more at downstream reaches. PP exhibited broad distribution but with a stronger concentration at S7, S9–S10, S12–S13 and S16–S17, while PE showed prominent enrichment from S7 through to the upstream of S12 and downstream of S14–S17 in proximal areas towards the estuarine sector (Fig. 9a–b). Concentrations of PA were more concentrated at S9–S10, S15 and S17, indicating a localised source along the middle and lower reaches, whereas PVC was again dispersed from S3–S7, S9 and S13–S16 (Fig. 9c–d). Both PES and PET were much less abundant at S5–S6, S8–S12 and S16–S17 (Fig. 9e–f). The net downstream enrichment, especially at S16–S17 (North Thamaraikulam–Manakudy), also indicates the active transport function of the Pazhayar River for polymer-specific microplastics, where upstream inputs undergo continuous redistribution and retention near lower river and estuarine zones. The interdependence of contrasting groundwater–surface-water patterns provides new evidence that the downriver fate and polymer composition of microplastics in the Pazhayar River basin are regulated simultaneously by hydrological connectivity, land-based anthropogenic inputs and downstream depositional processes.[45,46]

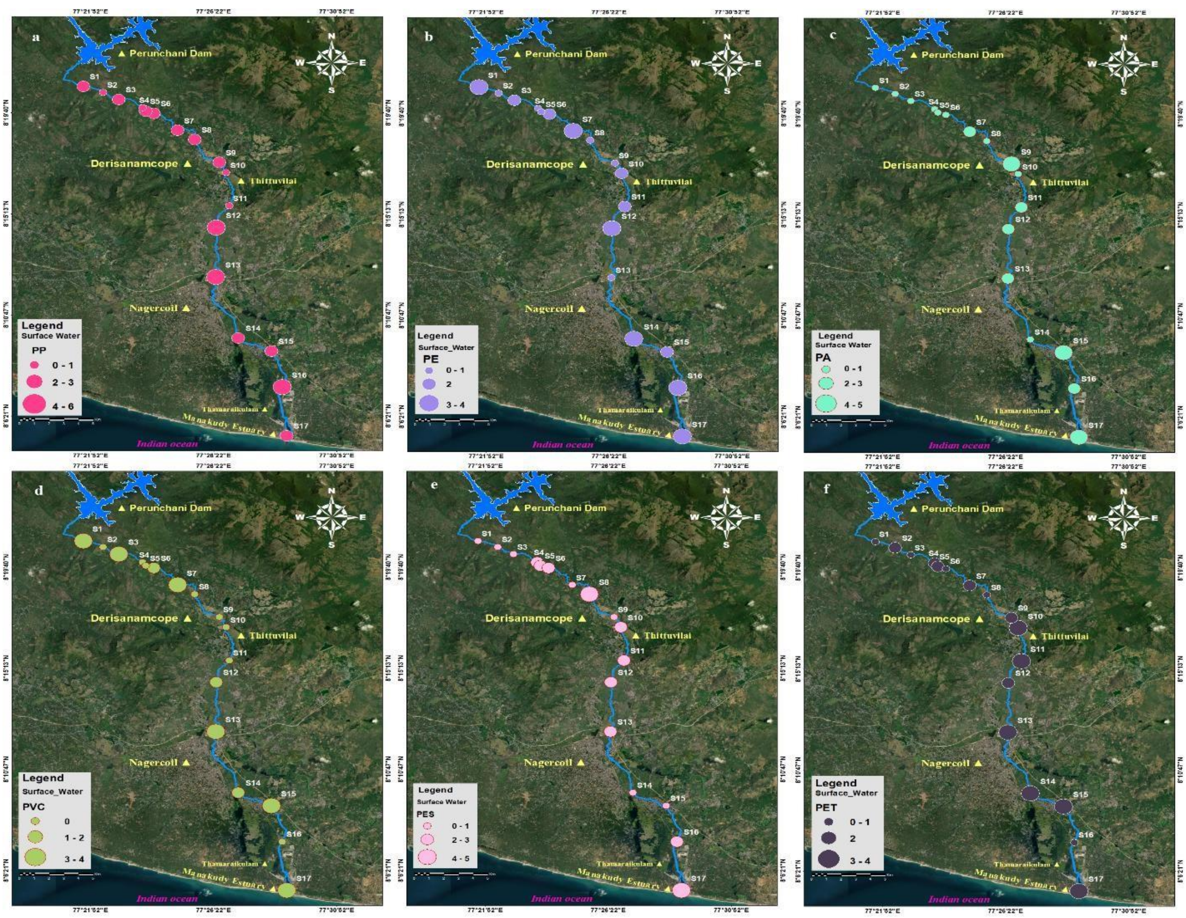

Fig. 9a-f: Spatial distribution of microplastic polymers in surface water of the Pazhayar River basin.

4. Conclusion and Future Directions

The present study is the first comprehensive study on microplastic pollution in freshwater and estuarine ecosystems, revealing a widespread issue of plastic pollution at tropical river basin levels—specifically that of the Pazhayar River basin, Kanyakumari District, Tamil Nadu. This study successfully recorded the occurrence, distribution, and properties of microplastics in 35 groundwater and 17 surface water sampling sites; over the entire study area there was significant contamination with a total of 323 identified microplastic particles. Fibrous microplastics were identified as the dominant morphological type in both water compartments, with higher levels of baseline contamination (4.3 particles per site) detected in surface waters than that found at groundwater sites (2.8 particles per site), supporting previous observations that rivers act as a major vector for the transport of microplastic pollution. Spatial heterogeneity in polymer- and color-specific distributions—wherein polypropylene and polyethylene were the most abundant polymers, respectively—weakly indicates localized anthropogenic inputs, urban runoff, and hydrodynamic controls on microplastic accumulation patterns. Urban areas like Nagercoil and Suchindram were found to be more contaminated, pointing out the importance of population density, sewage outlets, and industrial discharges as sources of microplastic pollution. Microplastic enrichment in the downstream sediment, especially at the Manakudy estuary, reflects the probable transport by river and retention in estuaries. These results have important implications for the management of water quality, as groundwater and surface water resources in this region are used both for domestic drinking purposes and because of their importance in agricultural irrigation. Conclusions and Relevance The study highlights the imperative for integrated monitoring programs, better waste management practices, and specific mitigation measures against microplastic pollution in tropical river basins. In addition, the pathways of contamination identified—from surface water infiltration to groundwater systems—highlight the interconnectivity of hydrological systems and the need for integrated strategies to shield water resources from emerging contaminants. Future studies need to evaluate the ecotoxicological and human health risks of long-term microplastic exposure in these important water sources.

CRediT authorship contribution statement

V. Kanagaraj: Methodology, Formal analysis, Data curation, Conceptualization.

G. Sangeetha: Investigation, Funding acquisition.

P. Amulraj: Investigation, Funding acquisition.

G.T. Niveditha: Software, Resources, Project administration, Methodology.

K. Sanjai Gandhi: Writing – review & editing, Writing – original draft, Supervision, Funding acquisition.

S. Krishnakumarm & **P.M. Velmurugan:** Writing – review & editing, Validation.

Declaration of competing interest

This is to certify that all authors have reviewed and approved the manuscript being submitted. We confirm that the article is the authors' original work and has neither been previously published nor is it under consideration for publication elsewhere.

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Data availability

Data will be made available on request.

REFERENCE

1. Rai, M., et al., *Microplastic pollution in terrestrial ecosystems and its interaction with other soil pollutants: a potential threat to soil ecosystem sustainability.* Resources, 2023; 12(6): 67.
2. Egbueri, J.C., et al., *Emerging microplastic threats to global water sustainability: reviewing polymer, morphology, and toxicity patterns across water matrices.* Water, Air, & Soil Pollution, 2026; 237(9): 511.
3. Rana, L., et al., *Unseen threats: the impact of emerging contaminants on surface and groundwater quality*, in *Surface Water and Groundwater Quality for Sustainable Utilization: Advanced Methods and Technology*, 2025; Springer. 309–331.
4. Liu, J. and L. Zheng, *Microplastic migration and transformation pathways and exposure health risks.* Environmental pollution, 2025; 368: 125700.
5. Lin, H.-T., et al., *Microplastics in Asian rivers: geographical distribution, most detected types, and inconsistency in methodologies.* Environmental Pollution, 2024; 349: 123985.
6. Nirmala, K., et al., *A critical review on recent research progress on microplastic*

pollutants in drinking water. Environmental Research, 2023; 222: 115312.

7. Sumam, S., S. Gautam, and P. Arulraj, *Understanding Microplastic Pollution in Groundwater: Pathways, Health Implications and Solutions.* Water Environment Research, 2025; 97(7): e70132.
8. Liu, S., et al., *Microplastics in groundwater: Environmental fate and possible interactions with coexisting contaminants.* Environmental Pollution, 2025; 372: 126026.
9. Gupta, P., et al., *A comprehensive assessment of macro and microplastics from Rivers Ganga and Yamuna: Unveiling the seasonal, spatial and risk factors.* Journal of Hazardous Materials, 2024; 469: 133926.
10. Pavithra, K., et al., *Microplastics in packaged water, community stored water, groundwater, and surface water in rivers of Tamil Nadu after the COVID-19 pandemic outbreak.* Journal of Environmental Management, 2024; 356: 120361.
11. Li, Y., et al., *Microplastic pollution in urban rivers within China's Danxia landforms: Spatial distribution characteristics, migration, and risk assessment.* Science of the Total Environment, 2024; 910: 168610.
12. Velmurugan, P., K. Vijayaprabhakaran, and P. Devika, *Baseline study on identification, characterization, distribution and abundance of microplastics in surface water from Ennore to Kovalam along the east coast of India.* Physics and Chemistry of the Earth, Parts a/b/c, 2023; 130: 103391.
13. Sundaram, B.P., et al., *An investigation on microplastics at wastewater confluence points in the southern coastal regions of Tamil Nadu, India.* Bulletin of Environmental Contamination and Toxicology, 2025; 114(1): 10.
14. Joshi, A., N. Akhtar, and A. Kumar, *Microplastics detection techniques*, in *Microplastics Pollution and its Remediation*, 2024; Springer, 25–53.
15. Li, Y., et al., *Unraveling Microplastics: Sources, Environment and Health Impacts, and Detection Techniques.* Environments, 2026; 13(3): 134.
16. Soundrapandian, P., *The Prevalence of Microplastics in Water and Sediment Collected from Vellar Estuary in South India.* UTTAR PRADESH JOURNAL OF ZOOLOGY, 2024; 45(23): 177–186.
17. Priya, K., et al., *Implications of solid waste dumps on the microplastic abundance in groundwater in Kollam, India.* Journal of Environmental management, 2023; 348: 119224.
18. Sangkham, S., et al., *Evidence of microplastics in groundwater: A growing risk for human health.* Groundwater for Sustainable Development, 2023; 23: 100981.

19. Valsan, G., et al., *Exploring the presence and distribution of microplastics in subterranean estuaries from southwest India.* Marine Pollution Bulletin, 2023; 190: 114820.
20. Patterson, J., et al., *Hydrochemical quality and microplastic levels of the groundwaters of Tuticorin, southeast coast of India.* Hydrogeology Journal, 2023; 31(1): 167–184.
21. Singh, S. and A. Bhagwat, *Microplastics: A potential threat to groundwater resources.* Groundwater for Sustainable Development, 2022; 19: 100852.
22. Selvam, S., et al., *Hazardous microplastic characteristics and its role as a vector of heavy metal in groundwater and surface water of coastal south India.* Journal of Hazardous Materials, 2021; 402: 123786.
23. Kumar, R. and P. Sharma, *Microplastics pollution pathways to groundwater in India.* Curr. Sci., 2021; 120: 249.
24. Natesan, U., et al., *Spatial distribution of microplastic concentration around landfill sites and its potential risk on groundwater.* Chemosphere, 2021; 277: 130263.
25. Zhang, T., et al., *Current status of microplastics pollution in the aquatic environment, interaction with other pollutants, and effects on aquatic organisms.* Environmental Science and Pollution Research, 2022; 29(12): 16830–16859.
26. Zea Cobos, A.G., et al., *Standardization of FTIR-Based Methodologies for Microplastics Detection in Drinking Water: A Meta-Analysis Indeed and Practical Approach.* Water, 2024; 16(22): 3170.
27. Severini, E., et al., *River–groundwater interaction and recharge effects on microplastics contamination of groundwater in confined alluvial aquifers.* Water, 2022; 14(12): 1913.
28. Khant, N.A. and H. Kim, *Review of current issues and management strategies of microplastics in groundwater environments.* Water, 2022; 14(7): 1020.
29. Ganie, Z.A., et al., *Assessment and accumulation of microplastics in the Indian riverine systems: Risk assessment and implications of translocation across the water-to-fish continuum.* Aquatic Toxicology, 2024; 272: 106944.
30. Priyanka, R. and B. Govindarajulu, *Transportation of microplastics from the rural area into the urban area of the Kosasthalaiyar River in the metropolitan city of Chennai.* Regional Studies in Marine Science, 2023; 66: 103151.
31. Rami, Y., et al., *Occurrence and characteristics of microplastics in surface water and sediment of Zayandeh-rud river, Iran.*, 2023.
32. Shifa, S., K. Sathish, and S. Saraswat, *Assessment of upstream and downstream surface water microplastic pollution in Lower Himalayan Gaula River, Uttarakhand, India.*

Bulletin of Environmental Contamination and Toxicology, 2025; 114(6): 85.
33. Gong, X., et al., *Microplastic pollution in the groundwater under a bedrock island in the South China sea.* Environmental Research, 2023; 239: 117277.
34. Loui, C., et al., *Polymer-specific transfer and retention of microplastics at the river–sediment–groundwater interface.* Water Research, 2025; 125018.
35. Shu, X., et al., *Spatial distribution characteristics and migration of microplastics in surface water, groundwater and sediment in karst areas: The case of Yulong River in Guilin, Southwest China.* Science of The Total Environment, 2023; 868: 161578.
36. Ditlhakanyane, B.C., et al., *Quantification of microplastics in Coptodon rendalli and surface waters of Dikgatlhong Dam, Botswana: the first baseline evidence.* Environmental Technology, 2025; 46(18): 3599–3609.
37. Dilshad, A., et al., *Microplastic pollution in the surface water and sediments from Kallar Kahar wetland, Pakistan: occurrence, distribution, and characterization by ATR-FTIR.* Environmental Monitoring and Assessment, 2022; 194(7): 511.
38. Ajegi, J.O., et al., *Preliminary investigation of the spatio-seasonal distribution of microplastics in the surface water of River Benue, North Central Nigeria.* Environmental Monitoring and Assessment, 2025; 197(6): 650.
39. Zheng, Y., et al., *Comparative study of three sampling methods for microplastics analysis in seawater.* Science of the Total Environment, 2021; 765: 144495.
40. Shikwambana, P., et al., *Microplastic concentrations in sediments and waters do not decrease in two rivers flowing through the Kruger National Park, South Africa.* Water, Air, & Soil Pollution, 2024; 235(10): 675.
41. Cheng, D., et al., *Migration characteristics of microplastics in riparian soils and groundwater.* Environmental Monitoring and Assessment, 2024; 196(9): 796.
42. Dey, S., et al., *Optical source apportionment of aqueous brown carbon (BrC) on a daytime and nighttime basis in the eastern Indo-Gangetic Plain (IGP) and insights from 13C and 15N isotopic signatures.* Science of the Total Environment, 2023; 894: 164872.
43. Kieu-Le, T.-C., et al., *Baseline concentration of microplastics in surface water and sediment of the northern branches of the Mekong River Delta, Vietnam.* Marine Pollution Bulletin, 2023; 187: 114605.
44. Selvaraj, A., S. Saravanan, and J.J. Jennifer, *Mamdani fuzzy based decision support system for prediction of groundwater quality: an application of soft computing in water resources.* Environmental Science and Pollution Research, 2020; 27(20): 25535–25552.
45. Purushothaman, A., N. Vishnudattan, and S. Nehala, *Utilization of waste plastic in the*

manufacturing of bricks along with quarry dust and manufactured sand. Indian Journal of Environmental Protection, 43(7): 648–652.

46. Velmurugan, P.á., K. Vijayaprabhakaran, and P. Devika, *Baseline study on identification, characterization, distribution and abundance of microplastics in surface water from Ennore to Kovalam along the east coast of India.* Physics and Chemistry of the Earth, Parts a/b/c, 2023; 130: 103391.