



(Review Article)

Transfer of Microplastics from River Systems to Underground Water Resources: Mechanisms, Impacts, and Research Needs

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ABSTRACT

This study investigated the ways that microplastics move from rivers to groundwater. Microplastics occur when large pieces of plastics break down. We have a number of daily uses for products made with microplastics. Microplastics last forever and travel through water, soil and rock to find their way into groundwater. There are several ways in which microplastics get into the groundwater. Microplastics can pass through small pores in the space between rocks and dirt. When the river banks become saturated with water and start to leak out they carry microplastics with them. Also, when underground water levels rise due to natural means, microplastics will be carried along too. Movement of microplastics is dependent upon the characteristics of the microplastic itself, the type of dirt/soil, how much water flows over the surface and other factors related to the environment around it. A major concern in studying this topic is to determine where microplastics are in groundwater, because if we don't know where they exist we cannot protect against them contaminating our aquifers. In addition to identifying areas of contamination, there are many challenges associated with collecting and analyzing sample data. Microplastics have negative impacts on both the ecosystems and human health and are now found in the world's groundwater. This review article identifies gaps in the scientific knowledge of how microplastics travel through groundwater and what happens to them once they are in the environment. It also emphasizes the need for researchers to collaborate together to develop standard practices (e.g. use of standardized sampling techniques, testing, and reporting) so that researchers can understand all aspects of microplastic pollution (sources, pathways, effects) and develop effective strategies to protect our water supply. As such, addressing microplastic pollution will help protect groundwater quality and preserve aquifer function as an essential provider of ecosystem functions and safe drinking water.

Keywords: Microplastics, River-aquifer interaction, Groundwater contamination, Microplastic transport.

1. INTRODUCTION

A. Background on Microplastics

The presence of microplastics in the environment has become a major issue due to the fact that they are less than 5 millimeters in diameter. The origin of microplastics is through the degradation of large plastics or by manufacturing industrial and consumer products. A wide variety of chemical formulations of these microplastic particles are present in both terrestrial and aquatic environments. Since microplastic particles are very small, they tend to persist in water and accumulate in sediment layers while being transported into other environmental components [2][3][4]. Microplastic particles can be generated from several source areas including: the breakage down of large plastic materials, wastewater treatment plants discharging into rivers, industrial processes utilizing microplastics, tire wear, synthetic textile fibers used in clothing and agricultural practices using plastics. Synthetic textile microplastics discharged into rivers also come from many different types of industrial sources. In addition to discharge from factories and industrial facilities that use tires, there is another source which includes the shedding of synthetic fiber material from garments and fabrics during washing. Rivers provide an important pathway that carries microplastics from land based activities to marine-based systems [5][6][7]. Many recent research studies have shown that once microplastic particles reach river systems, it is difficult to remove them from the system because many microplastics settle out on the bottom of rivers or move into deeper subsurface environments [8]. Because microplastic particles can absorb pollutants and toxins within the environment, when consumed by animals within food webs, those pollutants are transferred throughout the food chain. As such, microplastics pose a risk to ecosystems and human health [9][10][11]. Since microplastic particles persist in the environment and in ecosystems, it makes cleaning them up much more difficult and increases the potential for bioaccumulation to occur in realistic field conditions [12][13]. Understanding how microplastic particles move between surface water systems and groundwater systems is particularly important because many people obtain almost half of their drinking water from groundwater [14][15]. Once microplastic particles enter aquifer systems,

they can remain for extended periods of time. This persistence can result in pollution to the water quality in aquifer systems and damage to the health of ecosystems within those same systems [14][16].

B. Overview of River-to-Underground Water Transfer

The movement of water between rivers and aquifers occurs through several different natural processes including hyporheic exchange, bank filtration and groundwater recharge [17]. As a result of these processes, there can be an exchange of both soluble substances and particulate materials or pollutants that are present in surface waters with those in groundwater [18][19]. Factors that affect the migration of contaminants in these types of systems include the hydraulic gradient that exists from one layer to another; the degree of porosity in sediments; the size and shape of particles; and the rate at which water flows through each medium [20] [21].

This review aims to provide a summary of previous studies that identify the key processes and variables associated with the movement of microplastics from rivers into sub-surface (ground) water. The primary research question guiding this review was: What are the mechanisms describing how microplastic move from rivers to groundwaters, and what of the hydrologic, geologic, physico-chemical, and biologic variables affect the movement and retention of microplastics in subsurface aquifers? Figure 1 depicts some of the major processes involved in moving microplastics from rivers into groundwater using processes such as hyporheic exchange, bank filtration, and preferred flow through macropores and karst conduits. This review identifies the characteristics of microplastics related to their transport, impact on ecosystems, and provides an overview of the current gaps in research. This review will synthesize previous studies and provide guidance for both environmental monitoring programs, groundwater protection, and water resource management. (Figure 1.)

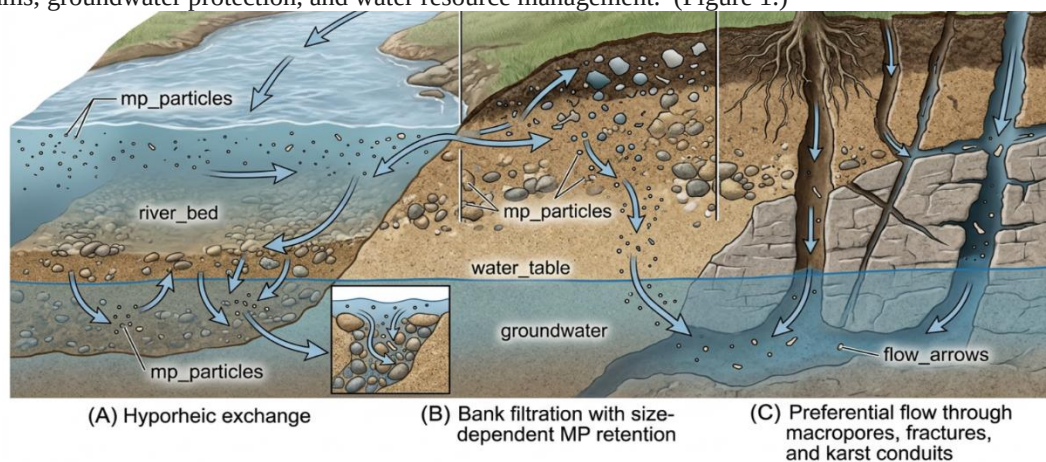


Figure 1. A conceptual model of the movement of microplastics from river systems to groundwater through (A) hyporheic exchange, (B) bank filtration, and (C) preferential flow through macropores and karst systems in real-world scenarios [22].

2. METHODOLOGY

A. Literature Search and Selection Criteria

A systematic review of existing literature was conducted across academic databases such as Scopus, Web of Science, Google Scholar, and ScienceDirect. These databases were chosen because they provide a wide range of research in environmental science and hydrology. The keywords used during the search were as follows:

“microplastics in rivers”
 “microplastics groundwater contamination”
 “hyporheic zone microplastic transport”
 “river-aquifer interaction contaminants”
 “microplastic filtration in sediments”

Boolean search strings included 'microplastics AND groundwater' and 'river transport AND microplastics infiltration'. Studies were included if they:

Investigated microplastics in freshwater or groundwater systems
 Examined transport mechanisms or environmental pathways
 Peer-reviewed journal articles from the years 2004 to 2025.

In contrast, studies which were conducted exclusively on marine systems with no links to freshwater systems, or studies which did not provide any empirical evidence or observations were excluded.

B. Data Extraction and Analysis

A preliminary corpus of 312 records was established through systematic electronic database searches and comprised 98 from Scopus, 87 from Web of Science, 79 from Google Scholar, and 48 from ScienceDirect. After removal of duplicates ($n = 64$), 248 records were screened by title and abstract. Of these, 143 were excluded as irrelevant to freshwater or groundwater microplastic transport. Because they did not meet the inclusion criteria, we excluded a further 31 full text articles (exclusively marine focus: $n = 19$; no empirical data: $n = 12$). Ultimately, 74 peer-reviewed articles formed the core evidence base for this systematic review. The relevant data extracted from the selected studies included:

- Measurements and composition of microplastics.
- Environmental distribution patterns are observable.

In addition, regarding transport means, the use of detection and analytical methods is essential.

The environmental effects were documented. Using a qualitative synthesis allowed for a comparison of the study results. All these processes clarified new directions of research, limits of knowledge, and recurring themes and the gaps in the research. (Figure 2.)

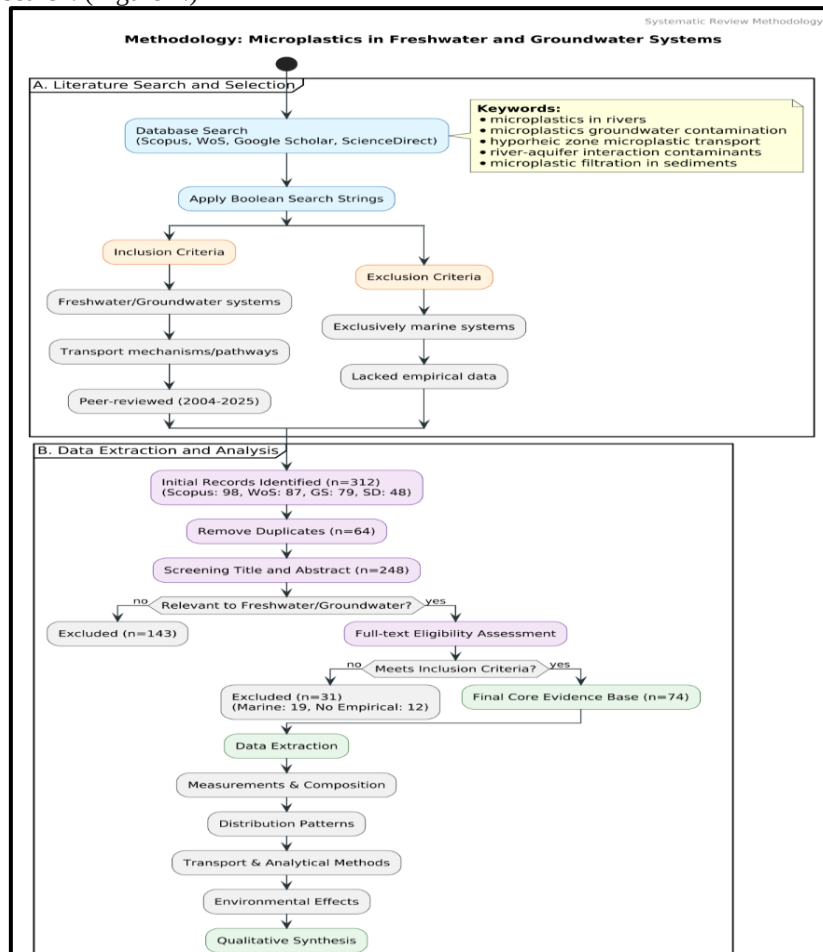


Figure 2. Systematic Review Methodology as per PRISMA.

3. PROPERTIES OF MICROPLASTICS

A. Physical and Chemical Properties of Microplastics

Fibres, film fragments, and microbeads have been reported in numerous river studies with respect to size and polymorphy [23], while fibre forms are also the most commonly reported shape type for all rivers studied [24].

- Polyethylene (PE)
- Polypropylene (PP)
- Polystyrene (PS)
- Polyethylene terephthalate (PET)

The polymers studied exhibit different densities, stabilities to chemicals, and degradation rates that consequently influence their transport mechanisms and environmental persistence [25][26][27]. The surface characteristics of microplastics support adsorption of a wide variety of contaminants such as heavy metals, pesticides, and POPs [28], therefore implying that they could be acting as carriers for pollutants in aqueous environments [29].

B. Transport Mechanisms in River Systems

Microplastic distribution in rivers primarily depends on hydrodynamic factors such as water flow, turbulent motion and flow direction. Hydrodynamic processes influence how quickly water flows through a river system (flow velocity) and how much water is flowing (discharge), which determines if microplastics remain suspended in the water or are deposited to the bottom of a river [30]. Sediment movement also plays an important role in the distribution of microplastics. When sediment is moved along a riverbed, it can either capture (sequester) or suspend existing microplastics. A major factor that promotes suspension of microplastics is when there is a large increase in river flow due to precipitation [31]. Additionally, the morphological characteristics of a river (i.e. the shape and size of the river's channel, the type of sediments present within the channel, and the vegetation growing from the river bank) will affect where microplastics tend to accumulate in space and over what time frames they may be released back into the river [32].

C. Interactions with Riverbed and Bank Materials

Microplastics could potentially get "stuck" in small spaces in fine grained sediments such as pore spaces/openings within those sediments. This process would reduce the ability of the sediment to move/transport [33]. Interactions between river bed sediments and microplastics include Adsorption, Aggregation, Filtration. Microplastics can accumulate in fine grain sediments' pore space and create an obstruction for them to move [34]. Aggregation is a phenomenon where microplastics attach themselves to organic matter, minerals and/or microbial biofilm, and it increases the weight/density of the particle(s) and influences how they settle [35]. Changes to surface properties of microplastics and increased adhesion between the sediment and microplastics (i.e. through biologic means i.e. through microbial colonization), can change the way microplastics are transported [36].

4. TRANSFER PATHWAYS FROM RIVER TO UNDERGROUND WATER

A. Hyporheic Exchange Processes

The hyporheic zone is the area beneath a river bed and adjacent to a river bed where surface water and groundwater interact. It serves as a critical interface between these two types of waters with respect to controlling biogeochemical exchange processes [37][38]. Surface water can move through porous sediments within the hyporheic zone creating pathways for particle movement. [38][39][21]. Once microplastic enters the hyporheic zone they may either remain in the hyporheic zone temporarily or migrate downward through the sediment depending upon the sediment's porosity, the rate at which the water moves through the sediment, and the size of the microplastic [21][38][39]. Retention Mechanisms: In addition to physical filtration and adsorption of the microplastic onto the sediment grains, when "breakthrough" occurs, an increase in flow rates results in both an increase in shear stress and a decrease in residence time resulting in mobilization of previously sequestered material [38] [40].

B. Groundwater Recharge and Bank Filtration

Replenishment of groundwaters occur when water from surface waters flows through porous soils that are then filtered as they flow down through layers of aquifer sediments. Bank filtration systems installed with the support of many local government agencies have improved the quality of drinking water [41] because these systems utilize the natural filtering characteristics of the soil and sediment layers as the water infiltrated through them. Conversely, microplastics less than or equal to 100 µm in size can be carried across permeable substrates such as aquifer sediments and into underlying aquifers [42].

C. Preferential Flow Paths and Karst Systems

The pathways for "preferential" or "rapid" water movement in soils and sediments include all forms of macro-pore movement (such as fractures, plant roots), which will move microplastic at a rate greater than the average pore space within the soil/sediment matrix [43]. Due to the unique hydrogeological characteristics of Karst aquifers, contaminants are transported with little filtering through both surface and subsurface voids created by dissolution of soluble rocks such as Limestone [44]. Many studies have demonstrated the rapidity of contaminant transport through Karst Systems, suggesting that Microplastic migration would occur rapidly [45].

5. FACTORS INFLUENCING MICROPLASTIC TRANSFER

A. Hydrogeological Factors

Physical properties of an aquifer—such as its porosity, permeability, and particle size—are significant in terms of determining the migration, filtering, trapping, and retaining of microplastics in groundwater [46]. The directionality and velocity of moving particles—and therefore the potential for microplastics to migrate toward a body of water—is directly related to various levels of hydraulic pressure that exist within the aquifer, as well as the volume of water that moves through it. Large gradients in hydraulic pressure may contribute to increased amounts of microplastics entering the groundwater system, thereby increasing the likelihood of contamination [47]. Geochemical properties such as pH and ionic concentration play a substantial role in determining how particles interact with one another and/or with solid phases present in the subsurface. Further, geochemical processes affecting microplastics will be determined by their individual properties [48]. Specifically, particle size, density, and shape/geometry are critical parameters. For example, smaller diameter particles/fibers exhibit greater mobility than larger diameter particles during passage through a porous medium [49]. Furthermore, progressive environmental degradation of microplastics due to time-related changes (aging) lead to modifications in both surface morphologies and surface chemistries. Such changes increase the propensity for aggregation/clustering with other sediment particles or adhesion to existing sediments, which increases the likelihood of long-term accumulation [50]. Additionally, the electrostatic charge on microplastic surfaces and their hydrophobic nature also contribute to their association/adhesion to soils/sediment particles and organic matter [51].

B. Microplastic Characteristics

The movement of microplastic is greatly affected by its particle size, density and shape. Smaller fiber and particles are able to move through pore spaces and channels within a filter material and sediment than larger ones. Many studies have shown this [50]. As weathered and aged microplastics undergo changes in surface chemistry and topography, they can aggregate to other sediments [52], or be adsorbed onto sediment. The interaction between microplastics and soil particles/organic matter are greatly dependent on their hydrophobic properties and charge distribution.

C. Environmental and Anthropogenic Factors

Environmental conditions combined with environmental impacts caused by human activity can be a major influence on this issue. Microplastic particles are moved through an area when seasonal fluctuations in water levels cause flooding which resuspends sediment and increases the amount of sediment moving within the stream [53]. Intense rain and flooding causes surface runoff and soil disturbances that allow microplastics to move and enter underground aquifers [54]. Land uses including urbanization, agricultural and waste management practices contribute to the significant amount of microplastics entering waterways [55].

6. DETECTION AND QUANTIFICATION METHODS

A. Sampling Techniques

Microplastic sampling typically occurs through netting, filtering, or collecting bulk water in rivers. Sampling sediment is generally done with a corer or grab sampler. Grab samplers were used to sample sediments by K. Zhang et al. [56] and Wu et al. [110]. Nkosi et al. [76] found similar results. However, Panno et al. [79] stated that specialized wells or pump systems are required to collect representative ground-water samples and to minimize contamination. A nationwide survey of microplastic presence in water-treatment systems was conducted by Park et al. [80]. The high degree of spatial variability of microplastics makes it difficult to obtain an adequate number of samples to accurately represent their distribution in the environment.

B. Analytical Methods

The use of microscopic inspection as an initial method for visually determining the type of particle is generally followed by the application of analytical methods to accurately identify the chemicals composing such particles. The results of such analyses provide greater accuracy than those obtained through visual classification. [59] Fourier Transform Infrared Spectroscopy (FTIR) and Raman Spectroscopy are also commonly applied methods for polymer identification. [60] Finally, additional advanced analytical techniques, including Pyrolysis Gas Chromatography Mass Spectrometry (PyGC/MS), in which polymers undergo thermal degradation resulting in the fragmentation of each component for separation and detection, permit the quantitative analysis of different polymer species. [61]

C. Quality Assurance and Control

The first concern with the research is the risk of contamination as it relates to both the sampling procedure and the analytical techniques used in analysing samples. Quality is at a premium for researchers, so they will take every precaution available to them. Many researchers are using cotton lab coats, filtered air, and procedural blanks to help prevent some of the errors that could arise from sample collection and analysis. [62] In addition to preventing contamination when collecting and analysing samples, ensuring the quality of the results is also critical. This is especially true since quality assurance/quality control procedures are such an important part of the overall research design. [63]

7. ENVIRONMENTAL AND HEALTH IMPLICATIONS

A. Ecological Impacts

Microplastics, along with chemicals that may accompany them, can pose risks for marine and freshwater ecosystems. The physical contact that occurs when organisms ingest microplastics, create an obstruction from ingesting other substances due to the microplastic(s) being present, and/or absorb chemical contaminants associated with microplastics can cause harm to those organisms. Since microplastics can accumulate within food chains they may ultimately affect organisms further up in the food chain [64]. This could result in reduced reproduction success, slowed development, and increased mortality rates among impacted species [65]. Additionally, microplastics also have the ability to carry harmful pollutants and pathogens and therefore increase the toxicities of both [10]. The accumulation of microplastics in sediments or water can also disrupt the ecosystem health of soil systems according to research conducted by Xu et al. [111], and Chia et al. [21]. Presently scientists continue to study the long-term impacts that microplastic exposures will have upon ecosystems while simultaneously conducting studies regarding the effects of microplastics on the diversity of organisms found in ecosystems.

B. Human Health Concerns

Additionally, exposure to microplastics via consumption of drinking water, ingestion of food, or inhalation may have adverse impacts upon human health [67]. Although the long term health implications due to exposure to microplastics has not been thoroughly researched, it is believed by many scientists that this type of exposure will lead to an increase in inflammation as well as increased exposure to toxins and chemicals [68]. The first studies have shown that microplastic particles may be absorbed into the body after being ingested and then travel to other parts of the body including other organs and produce a variety of system wide negative effects [69]. As stated by Hong and Kim [70], some of these additives and contaminants become stuck to microplastics which will likely make them even more toxic than they would be if they were present alone. Further research is needed in order to determine what the long range health risk for humans is when consuming microplastics over a prolonged period of time.

C. Water Resource Management Implications

Microplastics present a persistent challenge for treating potable water due to the likelihood of smaller size fractions being able to pass through typical filtration systems [71]. Researchers have investigated advanced methods of filtration including membrane filtration and activated carbon adsorption as means to improve the removal efficiency of microplastics [72]. However, both options typically increase operating cost and energy consumption [73]. Combining multiple technologies could potentially provide more effective ways to address microplastic contamination in source waters [74], such as coagulation/filtration/membrane based technologies. Better protection of groundwaters will require better monitoring and control.

8. DISCUSSION

Microplastics can move through river water to the groundwater system, and these contaminants may get there through many different routes. There are at least three major routes of microplastic movement, according to the reviewed literature. These include: hyporheic exchange; bank filtration; and preferential flow through macropores and karst conduit systems. While researchers have examined individual routes separately, careful examination of these studies reveals both considerable differences among the relative efficiencies of these routes and the different environments in which they operate under normal conditions. Drummond et al. [29] and Stride et al. [99] demonstrated that the hyporheic zone stores microplastics and transfers them downstream in streams, especially with respect to fibers and small pieces. Conversely, Panno et al. [79] found that karst aquifers quickly transport microplastics almost entirely without attenuation and indicate a direct hydraulic connection between micro-environments and macro-environments, where the concentration of microplastics in deep wells is similar to the concentration of microplastics in nearby surface waters. This indicates that alluvial aquifers attenuate naturally significantly less than karst systems, and therefore influence risk assessment for groundwater contamination in areas composed of limestone. Severini et al. [96] and La Cecilia et al. [58] indicated that although bank filtration removes a large percentage of the larger microplastics ($>100\text{ }\mu\text{m}$) from wastewater, it is consistently able to bypass the natural barriers for the removal of the smaller microplastic particles and fibers. Laboratory column experiments conducted by Khant and Kim [53], and reviewed here, also illustrate size dependent retentive efficiencies. A further problem is that bank filtration systems used throughout Europe and Asia for the production of potable water offer limited protection against microplastic contamination; especially with regard to the smaller microplastics that are more likely to accumulate in organisms. Due to methodological heterogeneity, comparisons of microplastic concentrations across studies are difficult. Concentration values of microplastics in groundwater vary widely depending upon sample preparation, analytical detection method, and particle size criteria for the determination of a minimum particle size [78]; such variation limits the ability to integrate results from multiple studies. Additionally, because of variability in reporting, researchers should utilize consistent and standardized methodologies when conducting research on microplastic contamination. Optical methods utilized in several studies [79] clearly identify much smaller particles, as well as a greater variety of polymers, than do studies using only optical microscopy; therefore, optical methods grossly underestimate levels of contamination. Seasonal variations in water cycling and flood pulse events have been identified as the dominant environmental/human factor responsible for increased movement of microplastics through increased flow rates, mobilizing previously deposited material, and creating pathways for sub-surface infiltration [80] of contaminated sediments into soil and groundwater. This finding is consistent with more general theories of contaminant transport; for microplastics it implies that input occurs episodically through runoff due to storms, snow melt, or sediment resuspension and is therefore likely to be missed by conventional long-term monitoring efforts during periods of low flow. Therefore, future monitoring plans should explicitly include sampling during and immediately after storm events to ensure capture of peak transport episodes. Although the field has developed substantially structurally over recent years, it remains limited by an incomplete methodology and insufficient numbers of long term field-based studies, particularly in realistic settings. Longitudinal field based studies examining microplastic contamination in surface waters, hyporheic zones, vadose zones and saturated aquifers in an integrated catchment setting are critically required. Moreover, without such studies, we will continue to fail to understand accurately how widespread microplastic contamination is in groundwater and what changes are expected with continued climate change and plastic usage.

9. KNOWLEDGE GAPS AND FUTURE RESEARCH DIRECTIONS

A. Existing Constraints

Although there is much being learned about the way in which microplastics move from rivers into ground water (qualitatively) very little has been studied as it relates to transporting microplastics through the soil (quantitatively). In addition, little research exists regarding the long term effects of microplastics on the environment and their ultimate degradation path. Table 1 provides a comparison of microplastic concentration levels, common polymers identified and techniques used to detect microplastics from some of the major studies referenced throughout this paper, all related to field environments. Therefore, future research efforts may want to address the following:

- Standardized sampling methods development
- Monitoring underground water systems as an entity
- The need for interdisciplinary study including hydrology, chemistry and environmental science

B. Emerging Research Areas

Current research is centered around developing new ways to detect nanoplastic, utilizing tracers to better understand how they move through the environment and to develop a greater understanding of microplastics' distribution within it by way of hydrologic models.

C. Recommendations for Future Studies

Future research will be focused on the following key areas:

- Development of standardized methods for detecting and measuring microplastics across all field and laboratory settings
- A further examination of groundwater systems
- Encourage an inter-disciplinary approach that combines the disciplines of hydrology, chemistry and environmental science. (Table 1.)

Table 1: Comparative Summary of Key Microplastic Studies in River-Groundwater Systems.

Study	Environment	MP Concentration	Dominant Polymer	Detection Method	Key Finding
Panno et al. (2019)	Karst groundwater, Illinois, USA	6.4–93.3 particles/L	PE, PP, PS	FTIR, optical microscopy	MPs present in all karst groundwater samples; rapid transport with minimal filtration
Severini et al. (2022)	Confined alluvial aquifer, Italy	0.5–14 particles/L	PET, PE	Raman spectroscopy, optical microscopy	MPs <100 µm bypass bank filtration; river–GW interaction drives contamination
Drummond et al. (2022)	Hyporheic zone, multiple rivers, USA	Up to 1,500 particles/kg sediment	Polyester (fibers), PE	FTIR spectroscopy	Hyporheic zone acts as long-term sink; accumulation increases downstream
Chia et al. (2021)	Soil and groundwater, global review	0.7–7 particles/L (GW)	PE, PP, PET	Optical microscopy, ATR-FTIR	MPs widespread in global groundwater; soil macropores key transport route
La Cecilia et al. (2023)	Bank filtration / managed aquifer recharge, Switzerland	Removal >70% for particles >300 µm	Mixed (PP, PE, PET)	Py-GC/MS, FTIR imaging	Smaller fragments persist after filtration; Py-GC/MS detects sub-100 µm particles missed by optical methods
Koelmans et al. (2019)	Drinking water / freshwater, global review	0.0007–31.4 particles/L	PE, PP (variable)	Various (optical, FTIR, Raman)	High inter-study variability; data quality criteria essential for comparison

PE = Polyethylene; PP = Polypropylene; PS = Polystyrene; PET = Polyethylene terephthalate; FTIR = Fourier-transform infrared spectroscopy; Py-GC/MS = Pyrolysis–gas chromatography–mass spectrometry; MP = Microplastic; GW = Groundwater; ATR = Attenuated total reflectance.

10. CONCLUSION

Microplastic particles have been found migrating into subsurface aquifer systems through both direct and indirect means such as hyporheic exchange, bank filtration and the process of groundwater recharge. These movements are also dependent on the physical/chemical properties of the microplastic itself, the sediment it encounters during its journey; the amount of flow in the system and finally the degree of human activity contributing to the presence of these pollutants within the groundwater environment. Therefore, there exists a great risk that microplastics may be present in drinking water around the world, with potential impacts on ecosystems and access to clean drinking

water. To effectively address this global concern, researchers need to work together, as well as develop better methods of managing our environment so that we can ultimately stop producing waste plastics.

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