### Title
Fate and transport in environmental quality




### Journal
Journal of Environmental Quality, 50(6)

### ISSN
0047-2425



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### Publication Date
2021-11-01

### DOI
10.1002/jeq2.20300

Peer reviewed

Published in final edited form as:
*J Environ Qual*. 2021 November ; 50(6): 1282–1289. doi:10.1002/jeq2.20300.

# Fate and transport in environmental quality

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CONFLICT OF INTEREST
The authors declare no conflict of interest.

## Abstract

Changes in pollutant concentrations in environmental media occur both from pollutant transport in water or air and from local processes, such as adsorption, degradation, precipitation, straining, and so on. The terms "fate and transport" and "transport and fate" reflect the coupling of moving with the carrier media and biogeochemical processes describing local transformations or interactions. The Journal of Environmental Quality (JEQ) was one of the first to publish papers on fate and transport (F&T). This paper is a minireview written to commemorate the 50th anniversary of JEQ and show how the research interests, methodology, and public attention have been reflected in fate and transport publications in JEQ during the last 40 years. We report the statistics showing how the representation of different pollutant groups in papers changed with time. Major focus areas have included the effect of solution composition on F&T and concurrent F&T, the role of organic matter, and the relative role of different F&T pathways. The role of temporal and spatial heterogeneity has been studied at different scales. The value of long-term F&T studies and developments in modeling as the F&T research approach was amply demonstrated. Fate and transport studies have been an essential part of conservation measure evaluation and comparison and ecological risk assessment. For 50 years, JEQ has delivered new insights, methods, and applications related to F&T science. The importance of its service to society is recognized, and we look forward to new generations of F&T researchers presenting their contributions in JEQ.

## 1 INTRODUCTION

Changes in contaminant concentrations in environmental media occur both due to transport in water or air and due to local processes, such as sorption, degradation, precipitation, or straining. The terms "fate and transport" and "transport and fate" reflect the tight coupling of contaminant movement with the carrier media and physical and biogeochemical processes controlling local transformations or interactions. Usage of these terms underscores the need and intent to characterize the results of such coupling. Fate and transport (F&T) first appeared in publications in 1964 (Horsak et al., 1964) and became actively used by the end of the 1970s. Fate and transport research reports have been omnipresent in the *Journal of Environmental Quality* (JEQ). This journal was the third after *Chemosphere* (Paris et al., 1978) and *Science* (Shnoor, 1981) journals to mention F&T and was the first journal to publish a paper on F&T in runoff (Lorber & Mulkey, 1982). This minireview shows how research interests, methodology, and public attention have been reflected in F&T publications in JEQ during the last 40 years.

For this review we selected papers listed in the SCOPUS database with the term "fate and transport" mentioned in the title, abstract, or keywords. We realize that many JEQ papers do not use the F&T term but de facto report F&T research. We assumed that our paper selection would allow an incomplete but representative view of F&T research as reflected by JEQ. Percentages of publications, including F&T terms for major contaminant groups, are shown in Figure 1, where the time periods used cover approximately equal numbers of papers. Pesticides initially dominated F&T publications in JEQ but encountered a steady decrease. In contrast, F&T of microorganisms—viruses, bacteria, and protozoa—was first mentioned rarely (Jin et al., 2000; Reneau et al., 1989) but recently became dominant. Microbial

F&T paper frequency of about 40% is comparable to that of nutrients and pharmaceuticals together.

Water was the dominant carrier of contaminants in the F&T studies referenced in Figure 1, with air as a carrier found only in 5% of papers. The F&T media in order of frequency of studies were soils > unsaturated zone > aquifers > runoff > streams > reservoirs or lakes. Fate and transport research was carried out at lateral scales of field, stream reach, and watershed and at vertical scales of soil horizon, soil profile, vadose zone, and aquifer. The largest number of citations received timely reviews on the F&T of emerging contaminants (Chee-Sanford et al., 2009; Lin et al., 2010).

## 2 MAJOR FOCUS AREAS

### 2.1 Solution composition and concurrent F&T

Studies showed suspended colloidal particles to be an important F&T factor. Colloids facilitated virus transport through porous media (Jin et al., 2000). Manure dramatically affected *Escherichia coli* attachment to soil (Guber et al., 2005). Complexation of chemical contaminants with bacteria was observed to control F&T in column experiments with cadmium (Li et al., 2019). And F&T in runoff was strongly affected by the attachment to suspended colloids for bacteria and a pesticide (Kennedy et al., 2001; Soupir et al., 2010).

Studying concurrent F&T of several substances appeared to be valuable, as in the research of the nitrate-inhibiting effect on selenate ($SeO_4$) reduction (Bailey et al., 2012) or phosphate effect on the adsorption–desorption kinetics of vanadium (Sun et al., 2019). In a uranium F&T study, acidic water created secondary precipitants that cemented quartz grains together and modified pore geometry in the center of the experimental column. This implied that wastes that leaked from buried tanks in the past likely did not migrate vertically but rather in the lateral pathways due to the precipitation of secondary precipitate phases (Um et al., 2005).

Another reason to consider concurrent F&T is that changes in the microbial community caused by the adaptation to contaminants affect the F&T of other solution components. This was the case, for example, when nitrate reduction occurred much sooner than perchlorate reduction in soils that had not been previously exposed to perchlorate, but nitrate and perchlorate were simultaneously reduced in soils previously exposed to perchlorate (Tipton et al., 2003).

### 2.2 Role of organic matter

The presence of organic substances dissolved and/or suspended in solutions is often an essential factor affecting F&T of contaminants. However, the nature of organic material is of importance. The poultry litter-derived dissolved organic matter was not likely to enhance inorganic phosphorus (P) transport, contradicting the assumption that dissolved organic matter released from organic wastes increases plant-available P when organic amendments and fertilizer P are co-applied (Goyne et al., 2008).

Organic matter is a strong F&T factor affecting the ecological service of soil as a filter. Filipović et al. (2020) suggested that retention of a pharmaceutical carbamazepine in topsoil was enhanced by increasing soil organic carbon. Rich in carbon, biochar was found to be an efficient amendment to prevent hormone transport (Duncan et al., 2015; Mina et al., 2016). Injection of manure showed promise in reducing the potential for off-site losses of hormones from manure-amended soils (Mina et al., 2016). And organic-matter-rich riparian zone soils showed promise in mitigating losses of urea from neighboring fields (Fisher et al., 2016). Tang et al. (2011) noted that carbonaceous adsorbents not only function as a superb sink for organic contaminants but also allow them to be slowly degraded while being trapped.

### Core Ideas

- JEQ was one of the first journals to accept the “fate and transport” terminology.
- Representation of different pollutant groups in papers changed with time.
- The role of temporal and spatial heterogeneity was studied at different scales.
- The value of long-term studies and modeling as the research approach was amply demonstrated.
- Fate and transport studies have been an essential part of conservation measure evaluation.

### 2.3 Relative role of different F&T pathways

The relative role of different F&T pathways has been a recurrent subject of studies (Chendorain et al., 1998). At the field scale, different pathways were dominant for different microorganism groups (Rieke et al., 2018). Rieke and colleagues found that surface water *Enterobacter* concentrations were influenced mainly by artificial drainage, whereas *Clostridium sensu stricto* was primarily transported to surface waters by runoff events. Gilfillan et al. (2018) noted distinct ecological drivers of impairment depending on the fecal indicator organism used in their work. *Escherichia coli* survival was driven by increased hardness and heterotrophic activity, whereas bacteriophage detection was inhibited by high levels of coliforms in sediment. Both indicators were influenced by organic matter and P limitation. The form in which contaminants moved was the important F&T pathway role factor. For example, particulate P losses were greater than dissolved P losses in the study of Brendel et al. (2019). These authors noted that “understanding relationships between flow, precipitation, transport pathway, and P fraction at the catchment scale is needed for effective conservation practice implementation” (p. 117).

## 3 SCALES AND HETEROGENEITY

### 3.1 Spatial and temporal heterogeneity

The role of pore spaces on the mobility of soil water was recognized in early F&T studies. Preferential flow occurring in soil columns was well described using a two-region, mobile–immobile water model, as in the study of bentazon F&T by Gaston et al. (1996) or atrazine F&T in fractured till (Helmke et al., 2005). The two-region model provided satisfactory results for pharmaceutical F&T (Casey et al., 2005; Fan et al., 2007). When flow was facilitated primarily via macropore channeling and actinide was present in the form of oxide particles, the relatively short residence time precluded a continuous interaction between the soil and the flowing water, which minimized the movement of pollutant in the soil (Litaor et al., 1996). In field-scale studies, the hydraulic conductivity of paddy soils, and consequently, heterogeneity of the velocity field, substantially influenced pesticide fate (Miao et al., 2003).

Layering strongly affected F&T of soil constituents because of its potential to increase biodegradation or slow the transport rate (Hansen et al., 2011). Hansen and colleagues concluded that quantifying coupled hydrologic–biogeochemical processes occurring at small-scale soil interfaces is critical to accurately describing and predicting chemical changes at the larger system scale. Studies of nitrate and pesticide F&T in fractured till suggested that aquifers and surface waters associated with thin, fractured till units may be vulnerable to contamination. Yet these materials may protect deeper aquifers due to increased residence time (Helmke et al., 2005). The controlling role of the residence time in virus F&T was clearly demonstrated in a study using sand-packed columns (Sasidharan et al., 2018).

Temporal heterogeneity could result in estimates of F&T different from that expected based on average values. For example, frequent, small storms had the potential to result in extreme losses of contaminants (Brendel et al., 2019). Accounting for time-scale dependence in F&T drivers improves F&T forecasts.

### 3.2 Land use and land cover

Land use and land cover (LULC) was shown to affect F&T at field and watershed scales. Kalin et al. (2010) successfully included LULC in the list of artificial neural networks' inputs to predict water quality in unmonitored watersheds. Gregory et al. (2019) showed that LULC differences could significantly affect background pollutant load transport during runoff events. Differences in root systems of species have affected the F&T of herbicides (Lin et al., 2003). M. Kim et al. (2018) suggested measures to improve our understanding of the impacts of land use change on fecal indicator bacteria in tropical watersheds. Trends in microbial water quality can be driven by land use modifications, including those caused by climate change.

### 3.3 Long-term studies

Long-term observations provided insights in possible changes in F&T pathways, processes, and parameters with time. Changes in degradation rates of organic contaminants were observed as the microbial adaptation occurred (Krutz et al, 2008, 2010). Phylogenetic analyses indicated that antibiotic resistance genes have evolved, although some genes have been maintained in bacteria since before the modern antibiotic era (Chee-Sanford et al., 2009). Biosorption was shown to play a role in contaminant transport and to change as microbial populations evolved (Qu et al., 2008). Phillips et al. (2006) provided an example of uranium (U) contamination of interbedded shale and sandstone, where the acidic U-enriched groundwater weathered away calcite veins, resulting in greater porosity, higher hydraulic conductivity, and higher U contamination. The importance of long-term studies of slowly occurring F&T can hardly be overestimated.

Long-term studies have also been instrumental for evaluating transport rates in the vadose zone. Boyle (1989) noted that because chlorinated aromatic hydrocarbons were rare in the environment until a few decades ago, they provide a unique opportunity to study the evolution of multistep catabolic pathways for the degradation of compounds with novel chemical structures. A relationship between groundwater age and the frequency of pesticide detection in the U.S. Midwest showed that pre-1953 water is less likely to contain pesticides because it tends to predate the use of pesticides (Kolpin et al., 1995). Research of pesticide occurrence in groundwater in southern Georgia found a limited number of wells with increases in pesticide concentrations and suggested that groundwater sources of these compounds were not increasing in concentration over the 12-yr time span (Dalton et al., 2008).

## 4 MODELING IN F&T RESEARCH

Modeling appears to be an indispensable methodology for studying F&T and integrating results of different studies. More than 30% of F&T papers in JEQ included modeling. Popular models such as CREAMS, RZWQM, SWAT, LEACHM, HYDRUS1D, and HYDRUS2/3D, as well as ad hoc developed models, were used. Whereas mechanistic models dominated the fine scales, empirical models (based on multisite and multiyear observations) demonstrated, to the surprise of authors, strong performances at coarser scales, such as in the case of phosphorus F&T at the watershed scale (Kleinman et al., 2017). Averaging over time the fine-scale dynamics of F&T controls, such as precipitation, could become an impeding factor for mechanistic model applications (Truman et al., 2007). Case studies of mechanistic models at the watershed scale were also reported. For example, Larose et al. (2007) concluded that the model is an effective tool for capturing the dynamics of streamflow and atrazine concentrations in a large-scale agricultural watershed in the midwestern United States. Safaie et al. (2020) demonstrated that the coliphage F&T model for lakes could be used to test hypotheses about potential sources and their behavior and for predictive modeling.

Substantial improvements in watershed-scale models arose from better conceptualization of transport mechanisms, such as for P (Collick et al., 2016; White et al., 2014) and *E. coli* (Hall et al., 2014; Liao et al., 2015). At this scale, models appear to be fairly complex; how much complexity is required in models was a question posed and addressed by Liao et al. (2015). The mismatch between parameters measured in batch experiments and estimated from model calibration has been observed by several authors, for example, Dontsova et al. (2006). Bradford et al. (2014) noted that many model parameters have to be optimized to simulate a diversity of observed transport, retention, and survival behavior even at the laboratory scale. These authors concluded that improved theory and models are needed to predict the fate of microorganisms in natural subsurface systems that are highly dynamic and heterogeneous.

Modeling was especially beneficial when more than one pathway was involved in F&T, as in the case of simultaneous transport of 1,3-dichloropropen in both liquid and gaseous phases (Wang et al., 2000). A modeling study with multiple scenarios was found to be a useful instrument to evaluate the effect of climate change on F&T in waste management systems

(Morales et al., 2015). Kalin et al. (2010) reported the first application of machine learning to estimate water quality across watersheds. These studies show that modeling is a valuable research methodology for F&T resulting from complex interactions.

## 5 APPLICATIONS: CONSERVATION AND REMEDIATION MEASURES

Fate and transport studies are an essential part of evaluating and comparing conservation measures (Fisher et al., 2016) as well as ecological risk assessment. Examples in JEQ encompass various topic areas, from risks related to septic tanks (Reneau et al., 1989) and sustainability studies of long-term land application of Class B biosolids (Pepper et al., 2008) to the comparison of managing F&T and input reduction as pollution prevention strategies (Ator et al., 2020). Controlling fate processes can improve best management practices (Kulesza et al., 2016; Mina et al., 2016). Vidon et al. (2019) advocated F&T research to improve our understanding of how riparian water and air quality functions have been affected by various practices, including stream restoration, subsurface drainage, two-stage ditches, beaver dam analogues, denitrification bioreactors and permeable reactive barriers, artificial wetlands, and short-rotation forestry crops. Environmental quality management usually relies on F&T control.

## 6 CONCLUSION

Fate and transport of contaminants is an essential component of environmental evolution affecting human and ecosystem health and resilience. The role of F&T research continues to grow, as does the complexity and amount of contaminants released. For 50 years, JEQ has delivered new insights, methods, and applications related to F&T science. The importance of its service to society is recognized, and as editors, we encourage new generations of F&T researchers to present their contributions to JEQ. We anticipate that JEQ will continue to publish F&T papers exploring new experimental techniques, cross-disciplinary approaches, novel modeling tools, artificial intelligence applications, and other innovative advances in the environmental science of our changing world.

## ACKNOWLEDGMENTS

The views expressed in this article are those of the authors and do not necessarily reflect the views or policies of the U.S. Environmental Protection Agency.

## Abbreviations

| | |
|---|---|
| **F&T** | fate and transport |
| **LULC** | land use and land cover |

## REFERENCES

Ator SW, Blomquist JD, Webber JS, & Chanat JG (2020). Factors driving nutrient trends in streams of the Chesapeake Bay watershed. Journal of Environmental Quality, 49(4), 812–834. 10.1002/jeq2.20101 [PubMed: 33016477]

Bailey RT, Hunter WJ, & Gates TK (2012). The influence of nitrate on selenium in irrigated agricultural groundwater systems. Journal of Environmental Quality, 41(3), 783–792. 10.2134/jeq2011.0311 [PubMed: 22565259]

Boyle M (1989). The environmental microbiology of chlorinated aromatic decomposition. Journal of Environmental Quality, 18(4), 395–402. 10.2134/jeq1989.00472425001800040001x

Bradford SA, Wang Y, Kim H, Torkzaban S, & Šimůnek J (2014). Modeling microorganism transport and survival in the subsurface. Journal of Environmental Quality, 43(2), 421–440. 10.2134/jeq2013.05.0212 [PubMed: 25602644]

Brendel CE, Soupir ML, Long LAM, Helmers MJ, Ikenberry CD, & Kaleita AL (2019). Catchment-scale phosphorus export through surface and drainage pathways. Journal of Environmental Quality, 48(1), 117–126. 10.2134/jeq2018.07.0265 [PubMed: 30640359]

Casey FXM, Šimůnek J, Lee J, Larsen GL, & Hakk H (2005). Sorption, mobility, and transformation of estrogenic hormones in natural soil. Journal of Environmental Quality, 34(4), 1372–1379. 10.2134/jeq2004.0290 [PubMed: 15998860]

Chendorain M, Yates M, & Villegas F (1998). The fate and transport of viruses through surface water constructed wetlands. Journal of Environmental Quality, 27, 1451–1458. 10.2134/jeq1998.00472425002700060022x

Chee-Sanford JC, Mackie RI, Koike S, Krapac IG, Lin YF, Yannarell AC, Maxwell S, & Aminov RII (2009). Fate and transport of antibiotic residues and antibiotic resistance genes following land application of manure waste. Journal of Environmental Quality, 38(3), 1086–1108. 10.2134/jeq2008.0128 [PubMed: 19398507]

Collick AS, Veith TL, Fuka DR, Kleinman PJ, Buda AR, Weld JL, Bryant RB, Vadas PA, White MJ, Harmel RD, & Easton ZM (2016). Improved simulation of edaphic and manure phosphorus loss in SWAT. Journal of Environmental Quality, 45(4), 1215–1225. 10.2134/jeq2015.03.0135 [PubMed: 27380069]

Dalton MS, & Frick EA (2008). Fate and transport of pesticides in the ground water systems of southwest Georgia, 1993–2005. Journal of Environmental Quality, 37(SUPPL. (5),), S264–S272. 10.2134/jeq2007.0163 [PubMed: 18765772]

Dontsova KM, Yost SL, Šimunek J, Pennington JC, & Williford CW (2006). Dissolution and transport of TNT, RDX, and composition B in saturated soil columns. Journal of Environmental Quality, 35(6), 2043–2054. 10.2134/jeq2006.0007 [PubMed: 17071873]

Duncan LA, Tyner JS, Buchanan JR, Hawkins SA, & Lee J (2015). Fate and transport of 17β-estradiol beneath animal waste holding ponds. Journal of Environmental Quality, 44(3), 982–988. 10.2134/jeq2014.08.0353 [PubMed: 26024278]

Fan Z, Casey FXM, Hakk H, & Larsen GL (2007). Discerning and modeling the fate and transport of testosterone in undisturbed soil. Journal of Environmental Quality, 36(3), 864–873. 10.2134/jeq2006.0451 [PubMed: 17485718]

Filipović L, Filipović V, Walker CW, Williams C, Preisendanz HE, & Watson JE (2020). Modeling carbamazepine transport in wastewater-irrigated soil under different land uses. Journal of Environmental Quality, 49(4), 1011–1019. 10.1002/jeq2.20074 [PubMed: 33016487]

Fisher KA, Meisinger JJ, & James BR (2016). Urea hydrolysis rate in soil toposequences as influenced by pH, carbon, nitrogen, and soluble metals. Journal of Environmental Quality, 45(1), 349–359. 10.2134/jeq2015.05.0228 [PubMed: 26828191]

Gaston LA, & Locke MA (1996). Bentazon mobility through intact, unsaturated columns of conventional- and no-till Dundee soil. Journal of Environmental Quality, 25(6), 1350–1356. 10.2134/jeq1996.00472425002500060026x

Gilfillan D, Hall K, Joyner TA, & Scheuerman P (2018). Canonical variable selection for ecological modeling of fecal indicators. Journal of Environmental Quality, 47(5), 974–984. 10.2134/jeq2017.12.0474 [PubMed: 30272784]

Goyne KW, Jun H-J, Anderson SH, & Motavalli PP (2008). Phosphorus and nitrogen sorption to soils in the presence of poultry litter-derived dissolved organic matter. Journal of Environmental Quality, 37(1), 154–163. 10.2134/jeq2007.0141 [PubMed: 18178888]

Gregory LF, Harmel RD, Karthikeyan R, Wagner KL, Gentry TJ, & Aitkenhead-Peterson JA (2019). Elucidating the effects of land cover and usage on background *Escherichia coli* sources in edge-of-field runoff. Journal of Environmental Quality, 48(6), 1800–1808. 10.2134/jeq2019.02.0051

Guber AK, Shelton DR, & Pachepsky YA (2005). Effect of manure on *Escherichia coli* attachment to soil. Journal of Environmental Quality, 34(6), 2086–2090. 10.2134/jeq2005.0039 [PubMed: 16221829]

Hall KK, Evanshen BG, Maier KJ, & Scheuerman PR (2014). Application of multivariate statistical methodology to model factors influencing fate and transport of fecal pollution in surface waters. Journal of Environmental Quality, 43(1), 358–370. 10.2134/jeq2013.05.0190 [PubMed: 25602570]

Hansen DJ, McGuire JT, & Mohanty BP (2011). Enhanced biogeochemical cycling and subsequent reduction of hydraulic conductivity associated with soil-layer interfaces in the vadose zone. Journal of Environmental Quality, 40(6), 1941–1954. 10.2134/jeq2011.0112 [PubMed: 22031578]

Helmke MF, Simpkins WW, & Horton R (2005). Ground water quality: Fracture-controlled nitrate and atrazine transport in four Iowa till units. Journal of Environmental Quality, 34(1), 227–236. 10.2134/jeq2005.0227 [PubMed: 15647553]

Horsak RD, Philip PB, Hamilton MC, & Thomas BFB (1964). Pesticides. In Environmental forensics: Contaminant specific guide. (pp. 143–165). Academic Press.

Jin Y, Pratt E, & Yates MV (2000). Effect of mineral colloids on virus transport through saturated sand columns. Journal of Environmental Quality, 29(2), 532–539. 10.2134/jeq2000.00472425002900020022x

Kalin L, Isik S, Schoonover JE, & Lockaby BG (2010). Predicting water quality in unmonitored watersheds using artificial neural networks. Journal of Environmental Quality, 39(4), 1429–1440. 10.2134/jeq2009.0441 [PubMed: 20830930]

Kennedy IR, Sánchez-Bayo F, Kimber SW, Hugo L, & Ahmad N (2001). Off-site movement of endosulfan from irrigated cotton in New South Wales. Journal of Environmental Quality, 30(3), 683–696. 10.2134/jeq2001.303683x [PubMed: 11401258]

Kim K, Whelan G, Molina M, Parmar R, Wolfe K, Galvin M, Duda P, Zepp R, Kinzelman JL, Kleinheinz GT, & Borchardt MA (2018). Using integrated environmental modeling to assess sources of microbial contamination in mixed-use watersheds. Journal of Environmental Quality, 47(5), 1103–1114. 10.2134/jeq2018.02.0071 [PubMed: 30272785]

Kim M, Boithias L, Cho KH, Sengtaheuanghoung O, & Ribolzi O (2018). Modeling the impact of land use change on basin-scale transfer of fecal indicator bacteria: SWAT model performance. Journal of Environmental Quality, 47(5), 1115–1122. 10.2134/jeq2017.11.0456 [PubMed: 30272793]

Kleinman PJA, Sharpley AN, Buda AR, Easton ZM, Lory JA, Osmond DL, Radcliffe DE, Nelson NO, Veith TL, & Doody DG (2017). The promise, practice, and state of planning tools to assess site vulnerability to runoff phosphorus loss. Journal of Environmental Quality, 46(6), 1243–1249. 10.2134/jeq2017.10.0395 [PubMed: 29293848]

Kolpin DW, Goolsby DA, & Thurman EM (1995). Pesticides in near-surface aquifers: An assessment using highly sensitive analytical methods and tritium. Journal of Environmental Quality, 24(6), 1125–1132. 10.2134/jeq1995.00472425002400060011x

Krutz LJ, Shaner DL, Accinelli C, Zablotowicz RM, & Henry WB (2008). Atrazine dissipation in s-triazine-adapted and nonadapted soil from Colorado and Mississippi: Implications of enhanced degradation on atrazine fate and transport parameters. Journal of Environmental Quality, 37(3), 848–857. 10.2134/jeq2007.0448 [PubMed: 18453406]

Krutz LJ, Shaner DL, & Zablotowicz RM (2010). Enhanced degradation and soil depth effects on the fate of atrazine and major metabolites in Colorado and Mississippi soils. Journal of Environmental Quality, 39(4), 1369–1377. 10.2134/jeq2009.0197 [PubMed: 20830925]

Kulesza SB, Maguire RO, Xia K, Cushman J, Knowlton K, & Ray P (2016). Manure injection affects the fate of pirlimycin in surface runoff and soil. Journal of Environmental Quality, 45(2), 511–518. 10.2134/jeq2015.06.0266 [PubMed: 27065398]

Larose M, Heathman GC, Norton LD, & Engel B (2007). Hydrologic and atrazine simulation of the Cedar Creek watershed using the SWAT model. Journal of Environmental Quality, 36(2), 521–531. 10.2134/jeq2006.0154 [PubMed: 17332256]

Li R, Zhang Z, Li S, Tang Y, Wei C, & Chen G (2019). Cadmium–bacteria complexation and subsequent bacteria-facilitated cadmium transport in saturated porous media. Journal of Environmental Quality, 48(5), 1524–1533. 10.2134/jeq2018.10.0369 [PubMed: 31589704]

Liao H, Krometis LA, Kline K, & Hession WC (2015). Long-term impacts of bacteria–sediment interactions in watershed-scale microbial fate and transport modeling. Journal of Environmental Quality, 44(5), 1483–1490. 10.2134/jeq2015.03.0169 [PubMed: 26436265]

Lin CH, Lerch RN, Garrett HE, Johnson WG, Jordan D, & George MF (2003). Bioremediation and biodegradation: The effect of five forage species on transport and transformation of atrazine and isoxaflutole (balance) in lysimeter leachate. Journal of Environmental Quality, 32(6), 1992–2000. 10.2134/jeq2003.1992 [PubMed: 14674520]

Lin D, Tian X, Wu F, & Xing B (2010). Fate and transport of engineered nanomaterials in the environment. Journal of Environmental Quality, 39(6), 1896–1908. 10.2134/jeq2009.0423 [PubMed: 21284287]

Litaor MI, Barth GR, & Zika EM (1996). Fate and transport of plutonium-239 + 240 and americium-241 in the soil of Rocky Flats, Colorado. Journal of Environmental Quality, 25(4), 671–683. 10.2134/jeq1996.00472425002500040006x

Lorber MN, & Mulkey LA (1982). An evaluation of three pesticide runoff loading models. Journal of Environmental Quality, 11(3), 519–529. 10.2134/jeq1982.00472425001100030038x

Miao Z, Cheplick MJ, Williams MW, Trevisan M, Padovani L, Gennari M, Ferrero A, Vidotto F, & Capri E (2003). Simulating pesticide leaching and runoff in rice paddies with the RICEWQ-VADOFT model. Journal of Environmental Quality, 32(6), 2189–2199. 10.2134/jeq2003.2189 [PubMed: 14674541]

Mina O, Gall HE, Saporito LS, & Kleinman PJA (2016). Estrogen transport in surface runoff from agricultural fields treated with two application methods of dairy manure. Journal of Environmental Quality, 45(6), 2007–2015. 10.2134/jeq2016.05.0173 [PubMed: 27898780]

Morales I, Amador JA, & Boving T (2015). Bacteria transport in a soil-based wastewater treatment system under simulated operational and climate change conditions. Journal of Environmental Quality, 44(5), 1459–1472. 10.2134/jeq2014.12.0547 [PubMed: 26436263]

Paris DF, Steen WC, & Baughman GL (1978). Role of physico-chemical properties of Aroclors 1016 and 1242 in determining their fate and transport in aquatic environments. Chemosphere, 7(4), 319–325. 10.1016/0045-6535(78)90130-3

Pepper IL, Zerzghi H, Brooks JP, & Gerba CP (2008). Sustainability of land application of class B biosolids. Journal of Environmental Quality, 37(Suppl. 5), S58–S67. 10.2134/jeq2007.0321 [PubMed: 18765778]

Phillips DH, Watson DB, Roh Y, Mehlhorn TL, Moon JM, & Jardine PM (2006). Distribution of uranium contamination in weathered fractured saprolite/shale and ground water. Journal of Environmental Quality, 35(5), 1715–1730. 10.2134/jeq2005.0124 [PubMed: 16899743]

Qu X, Xiao L, & Zhu D (2008). Site-specific adsorption of 1,3-dinitrobenzene to bacterial surfaces: A mechanism of $n$-$\pi$ electron-donor-acceptor interactions. Journal of Environmental Quality, 37(3), 824–829. 10.2134/jeq2007.0236 [PubMed: 18453403]

Reneau RB Jr, Hagedorn C, & Degen MJ (1989). Fate and transport of biological and inorganic contaminants from on-site disposal of domestic wastewater. Journal of Environmental Quality, 18(2), 135–144. 10.2134/jeq1989.00472425001800020001x

Rieke EL, Moorman TB, Soupir ML, Yang F, & Howe A (2018). Assessing pathogen presence in an intensively tile drained, agricultural watershed. Journal of Environmental Quality, 47(5), 1033–1041. 10.2134/jeq2017.12.0500 [PubMed: 30272801]

Safaie A, Weiskerger CJ, Nguyen TD, Acrey B, Zepp RG, Molina M, Pachepsky Y, & Phanikumar MS (2020). Modeling the photoinactivation and transport of somatic and F-specific coliphages at a great lakes beach. Journal of Environmental Quality, 49(6), 1612–1623. 10.1002/jeq2.20153 [PubMed: 33150652]

Sasidharan S, Bradford SA, Šimunek J, & Torkzaban S (2018). Minimizing virus transport in porous media by optimizing solid phase inactivation. Journal of Environmental Quality, 47(5), 1058–1067. 10.2134/jeq2018.01.0027 [PubMed: 30272798]

Schnoor JL (1981). Fate and transport of dieldrin in Coralville reservoir: Residues in fish and water following a pesticide ban. Science, 211(4484), 840–842. 10.1126/science.211.4484.840 [PubMed: 17740400]

Soupir ML, Mostaghimi S, & Dillaha T (2010). Attachment of *Escherichia coli* and enterococci to particles in runoff. Journal of Environmental Quality, 39(3), 1019–1027. 10.2134/jeq2009.0296 [PubMed: 20400597]

Sun W, Li X, Padilla J, Elbana TA, & Selim HM (2019). The influence of phosphate on the adsorption–desorption kinetics of vanadium in an acidic soil. Journal of Environmental Quality, 48(3), 686–693. 10.2134/jeq2018.08.0316 [PubMed: 31180437]

Tang H, Zhu D, Li T, Kong H, & Chen W (2011). Reductive dechlorination of activated carbon-adsorbed trichloroethylene by zero-valent iron: Carbon as electron shuttle. Journal of Environmental Quality, 40(6), 1878–1885. 10.2134/jeq2011.0185 [PubMed: 22031571]

Tipton DK, Rolston DE, & Scow KM (2003). Bioremediation and biodegradation: Transport and biodegradation of perchlorate in soils. Journal of Environmental Quality, 32(1), 40–46. 10.2134/jeq2003.4000 [PubMed: 12549540]

Truman CC, Strickland TC, Potter TL, Franklin DH, Bosch DD, & Bednarz CW (2007). Variable rainfall intensity and tillage effects on runoff, sediment, and carbon losses from a loamy sand under simulated rainfall. Journal of Environmental Quality, 36(5), 1495–1502. 10.2134/jeq2006.0018 [PubMed: 17766829]

Um W, Serne RJ, Yabusaki SB, & Owen AT (2005). Enhanced radionuclide immobilization and flow path modifications by dissolution and secondary precipitates. Journal of Environmental Quality, 34(4), 1404–1414. 10.2134/jeq2004.0395 [PubMed: 15998863]

Vidon PG, Welsh MK, & Hassanzadeh YT (2019). Twenty years of riparian zone research (1997–2017): Where to next? Journal of Environmental Quality, 48(2), 248–260. 10.2134/jeq2018.01.0009 [PubMed: 30951128]

Wang D, Knuteson JA, & Yates SR (2000). Two-dimensional model simulation of 1,3-dichloropropene volatilization and transport in a field soil. Journal of Environmental Quality, 29(2), 639–644. 10.2134/jeq2000.00472425002900020035x

White MJ, Storm DE, Mittelstet A, Busteed PR, Haggard BE, & Rossi C (2014). Development and testing of an in-stream phosphorus cycling model for the soil and water assessment tool. Journal of Environmental Quality, 43(1), 215–223. 10.2134/jeq2011.0348 [PubMed: 25602554]

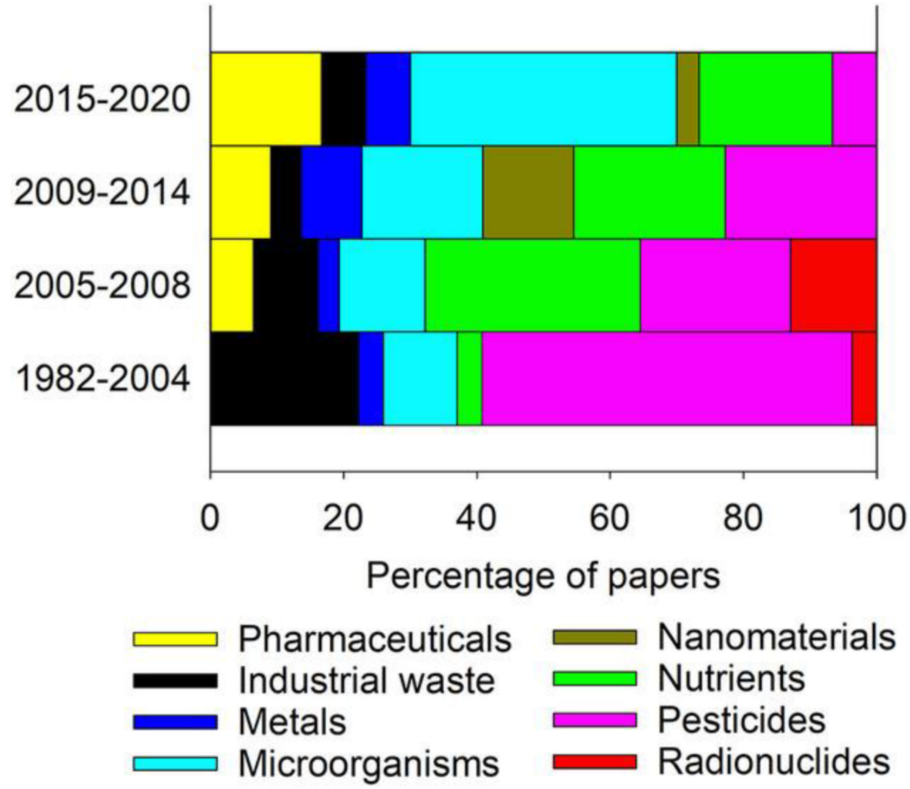


**FIGURE 1.**

Frequency of fate and transport papers for major pollutant groups