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REVIEW

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Release of treated effluent into streams: A global review of ecological impacts with a consideration of its potential use for environmental flows

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Abstract

1. Worldwide, the addition of treated wastewater (i.e. effluent) to streams is becoming more common as urban populations grow and developing countries increase their use of wastewater treatment plants. Release of treated effluent can impair water quality and ecological communities, but also could help restore flow and maintain aquatic habitat in water-stressed regions. To assess this range of potential outcomes, we conducted a global review of studies from effluent-fed streams to examine the impacts of effluent on water quality and aquatic and riparian biota.
2. We identified 147 quantitative studies of effluent-fed streams, most of which were from the U.S.A. and Europe. Over 85% of the studies identified water quality as a primary study focus, including basic physical and chemical parameters, as well as trace organic contaminants. Nearly 60% of the studies had at least some focus on aquatic or riparian biota, primarily fish, aquatic invertebrates, and basal resources (e.g. algae).
3. Effluent inputs generally impaired water quality near discharge points, mainly through increased water temperature, nutrients, and concentrations of trace organic contaminants, but also via decreased dissolved oxygen levels. The majority of ecological studies found that basal resources, aquatic invertebrates, and fish were negatively affected in a variety of ways (e.g. biodiversity losses, replacement of sensitive with tolerant species). However, several studies showed the importance of effluent in providing environmental flows to streams that had been dewatered by anthropogenic water withdrawals, especially in semi-arid and arid regions.
4. Knowledge gaps identified include the abiotic impacts of effluent, such as changes in channel morphology and hydrology (e.g. how nutrient-rich and warmer effluent affects infiltration rates or interactions with groundwater), the effects of effluent on plants and vertebrates (e.g. amphibians, birds), and the impact of effluent-induced perennialisation on naturally intermittent or ephemeral streams.
5. Although effluent-fed streams often exhibit signs of ecological impairment, there is great potential for these systems to serve as refuges of aquatic biodiversity

and corridors of ecological connectivity when wastewater treatment standards are high, especially in semi-arid and arid regions where natural streams have been dewatered.

KEYWORDS

aquatic invertebrates, contaminants, fish, primary producers, stream ecology, urban ecology, wastewater treatment

1 | INTRODUCTION

Streams are among the most altered ecosystems in the world, and for almost 2 centuries, large-scale human use of streams has resulted in poor water quality and ecological degradation in these systems (Vörösmarty et al., 2010). While great strides have been made to improve and restore stream water quality and habitat, there are still many concerns, including the disposal of treated wastewater (Vaughan & Ormerod, 2012). Before the second half of the 20th century, raw sewage was typically dumped directly into waterways, relying on dilution and natural purification processes to treat wastewater (Spellman & Drinan, 2001). Currently, environmental laws in many countries require wastewater treatment plants to enhance these natural purification processes (e.g. nutrient uptake, increasing dissolved oxygen, and decreasing biological oxygen demand), but treatment standards and technology vary widely across the globe (Angelakis & Snyder, 2015; Libralato, Ghirardini, & Avezzù, 2012). The end uses of this treated *effluent* include agricultural irrigation (Toze, 2006), urban irrigation (Fabregat, Mas, Candela, & Josa, 2002), aquaculture (Umble & Ketchum, 1997), groundwater recharge (Fournier, Keller, Geyer, & Frew, 2016), direct potable reuse (Leverenz, Tchobanoglous, & Asano, 2011), and direct discharge into streams or oceans (Brooks, Riley, & Taylor, 2006; McEneff, Barron, Kelleher, Paull, & Quinn, 2014).

Streams receiving effluent are called *effluent-fed*, but specific terminologies have emerged to define the ratio of effluent-to-natural

FIGURE 1 Examples of effluent-fed streams: (a) Rio de Flag, Arizona, U.S.A.; (b) Fountain Creek, Colorado, U.S.A.; (c) Los Angeles River, California, U.S.A.; (d) Rio San Miguel, Spain; (e) Boulder Creek, Colorado, U.S.A.; (f) Salt River, Arizona, U.S.A.. Photo credits: Michael Bogan (a, c, e), Bonita Bogan (b), Nuria Cid (d), Hamdhani (f) [Colour figure can be viewed at wileyonlinelibrary.com]

streamflow, including *effluent-dependent* (100% effluent during baseflow: Du, Haddad, Scott, Chambliss, & Brooks, 2015), *effluent-dominated* (>50% effluent: Boyle & Fraleigh, 2003) and *effluent-impacted* (<50% effluent: Schultz et al., 2010). Effluent-fed streams exist worldwide, range from small to large in size, and can be found in many different climate zones and geographic settings (Figure 1). As the world's population continues to grow (Lutz & KC, 2010), the development of new wastewater treatment plants will be crucial and the discharge of effluent into streams will increase. Despite this growing trend, the impacts of effluent on receiving streams are still relatively poorly understood and probably include a complex mixture of ecosystem subsidies and stressors (Aristi et al., 2015; Grantham, Cañedo-Argüelles, Perrée, Rieradevall, & Prat, 2012).

Issues in effluent-fed streams have been partly considered under the broader *urban stream syndrome*, whose symptoms include altered hydrographs, elevated concentrations of nutrients and contaminants, and reduced biotic richness with increased dominance of tolerant species (Violin et al., 2011; Walsh et al., 2005). However, many effluent-fed streams occur outside of urban areas. Water quality in effluent-fed streams has received the most research attention to date, including a previous review of water quality in effluent-dominated streams (Brooks et al., 2006). Water quality changes noted include elevated temperatures (Boyle & Fraleigh, 2003; Canobbio, Mezzanotte, Sanfilippo, & Benvenuto, 2009) and nutrient levels, such as nitrate (Chen, Nam, Westerhoff, Krasner, & Amy, 2009; Hur et al., 2007), ammonium/ammonia (Boyle & Fraleigh, 2003; Gafny, Goren, & Gasith, 2000), and phosphate (Birge, Black, Short, & Westerman, 1989; Chen et al., 2009). Reaches downstream of effluent outfalls are also frequently characterised by depleted dissolved oxygen levels (Birge et al., 1989; Matamoros & Rodríguez, 2017). Despite the fact that technologies used to purify sewage have improved (Lüddeke et al., 2015; Oturan & Aaron, 2014; Stalter, Magdeburg, Quednow, Botzat, & Oehlmann, 2013; Watkinson, Murby, & Costanzo, 2007), unregulated novel pollutants originating from chemical products in modern society pose new concerns (Barber, Loyo-Rosales, Rice, Minarik, & Oskouie, 2015; Noguera-Oviedo & Aga, 2016). These novel contaminants include endocrine disruptors (Barber et al., 2015; Dong et al., 2015) and pharmaceuticals (Grabicova et al., 2017; Mandaric, Mor, Sabater, & Petrovic, 2018). The relative impacts of water quality issues and novel contaminants also vary with the ratio of effluent volume to receiving streamflow. Effluent-dominated streams represent *worst-case scenarios* for evaluating the impacts of emerging contaminants on stream ecosystems (Brooks et al., 2006).

Although water quality issues are fairly well studied in effluent-fed streams, we still do not have a comprehensive understanding of the broader ecological impacts of effluent. Streams support a wide variety of taxa at different trophic levels, from microbes and primary producers to fish and aquatic mammals; taxa may not respond uniformly to effluent. For example, Murdock, Roelke, and Gelwick (2004) reported that addition of effluent affected primary production, with periphyton biomass being elevated near effluent outfalls. Other studies have reported increased abundances of invertebrates below effluent outfalls (Boyle & Fraleigh, 2003), but lower fish species diversity (Diamond, Hall, Pattie, & Gruber, 1994). Recent studies also have found high levels of pharmaceuticals in fish tissues collected from effluent-fed reaches (Grabicova et al., 2017; Schultz et al., 2010). Even with the highest level of wastewater treatment, effluent discharge may still have a negative effect on water quality (Brown, Snow, Hunt, & Bartelt-Hunt, 2015) and aquatic and riparian biota (Grabicova et al., 2015; Halaburka et al., 2013; Richmond et al., 2018), suggesting the need for a global review of the ecology of effluent-fed streams.

Although effluent can have negative impacts on receiving streams, it may also serve to enhance baseflow or restore flows to streams that have dried due to climate change or anthropogenic water withdrawals (Halaburka et al., 2013; Luthy, Sedlak, Plumlee, Austin, & Resh, 2015). Research suggests that by 2050, up to 79% of catchments affected by groundwater pumping will have reached or surpassed the ecological limits of streamflow (de Graaf, Gleeson, Beek, Sutanudjaja, & Bierkens, 2019). Furthermore, intensified droughts predicted by climate-change models in many regions (e.g. Seager et al., 2007) may deplete local aquifers and cause streams to transition from perennial to intermittent flow regimes. If treatment processes are advanced (e.g. tertiary level), then effluent could be an important source of environmental flows in drying streams, especially in semi-arid and arid regions (Bischel et al., 2013; Luthy et al., 2015; Martí, Riera, & Sabater, 2009).

Here, we critically review published papers about effluent-fed streams to summarise water quality issues and ecological impacts of effluent. This is the first global review of the impacts of effluent on receiving stream ecosystems. Brooks et al. (2006) reviewed water quality issues in effluent-fed streams in arid and semi-arid regions; we build upon their work by including studies from mesic countries (e.g. Britain, Denmark, Japan) and the large number of papers that have been published in the last decade. We used data from all reviewed studies to quantify and describe several factors, including geographical distribution, study concern, percent of effluent input, methodology used, water quality issues, and ecological impacts of effluent. We also identify research gaps that deserve further attention and provide management recommendations.

2 | METHODS

We used Web of Science (www.webofknowledge.com) to search for publications from 1864 up to 29 January 2018, using the keywords "effluent dominated river(s)" and "effluent dominated stream(s)". We specifically targeted effluent-dominated streams because they are most likely to demonstrate ecological impacts (Brooks et al., 2006), but the search identified effluent-fed streams with a wide range of effluent-to-receiving stream flow ratios (see Results). The initial search resulted in 242 papers; we then read through all 242 abstracts to exclude publications that were not related to effluent and streams. For example, studies conducted in lakes or wetlands were excluded. Similarly, studies that solely focused on treatment processes or the effluent itself, without any relation to receiving streams, were also excluded. Moreover, studies on ecological impacts in streams that

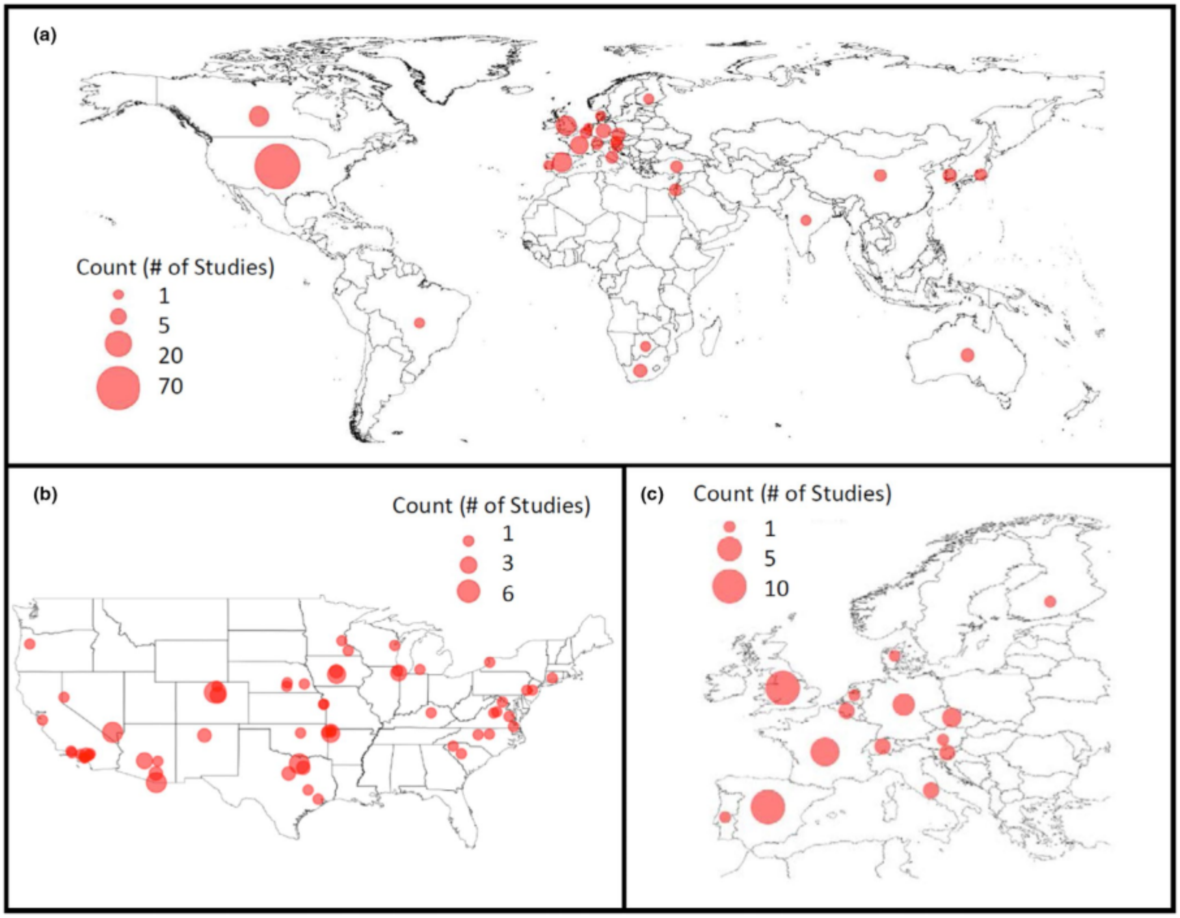

FIGURE 2 Distribution of effluent-fed stream studies (a) globally, (b) in the U.S.A., and (c) in Europe from selected 147 studies available via Web of Science and published prior to January 2018. A complete list of studies and their exact locations is found in the Table S1 [Colour figure can be viewed at wileyonlinelibrary.com]

only received untreated sewage were also excluded from this review. We acknowledge that with our search criteria, there is potential to miss published papers that focus on streams with small amounts of effluent inputs. Our search criteria also excluded purely descriptive studies with limited or no statistical analyses—this may have limited the geographic scope of our review by excluding qualitative studies from developing nations. However, our refining process still resulted in a total of 147 papers (Table S1) being included.

First, we categorised all 147 papers by their specific topics, including *study concern*, *study design*, *proportion of effluent in the receiving stream*, *geographic scope*, and *taxonomic concern*. For *study concern*, we classified papers into one or more of the following nine primary concerns: infiltration, influent source, wastewater treatment process, basic water quality, trace organic contaminants (TrOCs), stream morphology, flow management, sediment, and/or aquatic ecology. For *study design*, we distinguished whether the study was conducted (1) only downstream of effluent discharge, (2) in reaches upstream and downstream of effluent discharge, or (3) in effluent-fed reaches and a reference stream. Using data provided by the authors (when reported), we also identified the proportion of the effluent in the stream as effluent-dominated (>50%) or effluent-influenced (<50%). For *geographic scope*, we classified which country the studies occurred in and whether they were conducted in single versus multiple stream systems. Finally, for *taxonomic concern*, we determined if papers focused on one of the following major stream or riparian taxa: basal resources (e.g. algae, bacteria, biofilm), aquatic invertebrates, fish, amphibians and reptiles, birds, and macrophytes (including riparian vegetation).

For most taxonomic groups, there were insufficient studies ($n \leq 3$) reporting the same biological metrics at a comparable scale, so a meta-analysis approach was not possible. However, several metrics of aquatic invertebrate assemblages (e.g. density and species richness) were reported frequently enough across studies that we calculated average responses for these metrics across studies to make broader generalisations. Because no synthesis of the taxonomic groups affected by treated effluent in streams has been previously done, we consider our work to be a baseline review to identify those main concerns. More complex ecological topics, such as food webs, ecological networks and functional processes, are beyond the scope of this work but should be considered for future endeavors.

3 | RESULTS

3.1 | Geographic, study focus, and temporal trends

Studies of effluent-fed stream were concentrated in the U.S.A. (49%) and Europe (33%), with fewer studies from Canada (7%), Asia (5%), Africa (3%), Australia (2%), and South America (1%; Figure 2a). Within the U.S.A. (Figure 2b), the Southwest and Midwest regions received considerable research attention (28 and 23%, respectively), with fewer studies in the Rocky Mountain (17%), southeast (14%), West Coast (11%), and northeast regions (7%). Within Europe, studies were most common in western Europe (Figure 2c), including the U.K. and Spain (21% each), France (15%), and Germany (8%).

Across the 147 reviewed studies, 52 studies clearly defined the percentage of treated effluent contribution in the studied streams. Within those studies, 35 studies were from effluent-dominated streams, six were from streams with >25–50% effluent, and 11 were from streams with effluent contributions ranging from 1 to 25%. The remaining studies could not be classified due to lack of information regarding the amount of treated effluent in the receiving stream system; however, each study identified effluent contribution as being significant enough to cause ecological impacts.

Over 85% of the studies identified water quality as a major focus, including basic physical and chemical parameters, as well as TrOCs such as endocrine-disruptors and pharmaceuticals (Figure 3a). Very few studies focused on sediment quality, water treatment, infiltration, influent source (e.g. agricultural, municipal, industrial), or stream morphology. With regard to sampling design, the majority of studies either compared upstream and downstream reaches or had sampling sites along a gradient below effluent discharge points (i.e. more than two sampling sites longitudinally; Figure 3b). Only *c.* 10% of studies compared conditions in effluent-fed streams versus reference streams.

The earliest studies occurred in the 1970s and focused on basic water quality (Figure 4). Beginning in the 1990s, studies on TrOCs emerged, and their number increased dramatically in the 2000s. The number of TrOCs studies from 2010–2017 suggests that by the end of 2010s, TrOCs will replace basic water quality as the primary research focus in effluent-fed streams.

3.2 | Water quality factors

We identified specific parameters in basic physical, chemical, and biological water quality (e.g. temperature, dissolved oxygen, pH, alkalinity, nutrients), as well as TrOCs, and summarised the patterns reported for these factors (Table 1). In general, effluent-fed streams were characterised by elevated water temperature, conductivity, alkalinity, nitrate, ammonia, ammonium, phosphate, and heavy metals. In contrast, dissolved oxygen levels were generally low adjacent to effluent outfall points. In terms of biological water quality parameters, effluent discharge usually did not result in higher in-stream levels of the pathogen *Escherichia coli*. For example, relatively low concentrations of *E. coli* were found in treated effluent that discharged into a stream in an urbanised catchment in Houston, Texas (U.S.A.) with a geometric mean of 5 MPN/dl as compared to 394 MPN/dl according to the Texas Water

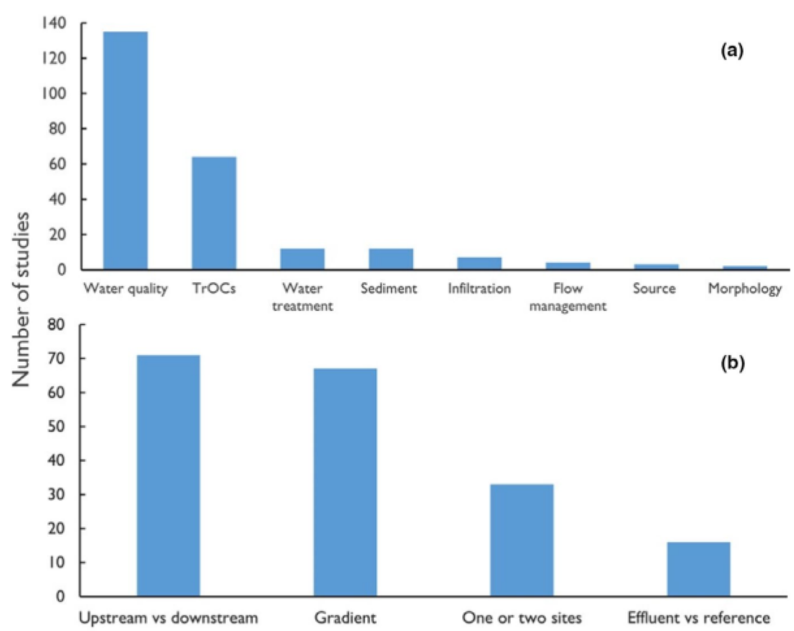

FIGURE 3 Study concerns (a) and sampling designs (b) from selected 147 studies of effluent-fed streams published prior to January 2018. TrOCs, trace organic contaminants [Colour figure can be viewed at wileyonlinelibrary.com]

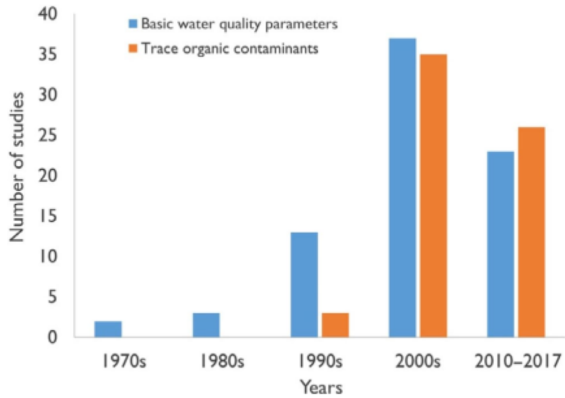

FIGURE 4 Trends through time in water quality study concerns from selected 147 studies of effluent-fed streams published prior to January 2018 [Colour figure can be viewed at wileyonlinelibrary.com]

Quality Standards (Petersen, Rifai, Suarez, & Stein, 2005). Studies generally identified non-point sources as being more important. Larger populations of antibiotic-resistant coliform bacteria were found downstream of effluent discharge as compared to upstream (Akiyama & Savin, 2010). Trace organic contaminants, specifically endocrine-disruptors, pharmaceuticals, and pesticides/biocides, were commonly found in reaches near effluent outfalls (Buxton & Kolpin, 2005; Dong et al., 2015; Mandaric et al., 2018; Munz et al., 2017).

3.3 | Ecological impacts of effluent

Eighty-seven of the 147 reviewed studies focused on the ecological impacts of effluent on one or more taxonomic groups (Figure 5). The earliest study we found concerned the dominance of dipteran invertebrates (e.g. Chironomidae) in an effluent-fed stream near the city of Wolverhampton, U.K. (Gower & Buckland, 1978). We did not find any studies on riparian vegetation and macrophytes until the 2000s, when Spänhoff et al. (2007) studied the fate of riparian leaves in a stream receiving effluent in Germany. From 1970s to present, the number of studies in all groups expanded; however, studies of riparian vegetation and macrophytes lag greatly behind other taxonomic groups (Figure 5). We found only one study focusing on birds; it examined birds that feed on fish from an effluent-dominated stream in Japan (Tanoue et al., 2014). We also found one study focusing on an insectivorous bat (Kalcounis-Rueppell, Payne, Huff, & Boyko, 2007). We found no studies with a quantitative focus on amphibians or reptiles.

3.4 | Basal resources

We reviewed 20 studies focusing on basal resources (algae, bacteria, and biofilm communities). Algal biomass and abundance generally increased with effluent inputs. In an effluent-dominated stream in Texas (U.S.A.), periphyton biomass was highest near effluent inputs and exhibited a general decrease downstream (Murdock et al., 2004). Algal taxa were dominated by Bacillariophyceae and algal growth on PVC plates reached nuisance levels (>100 mg chlorophyll-*a*/m^2) in a 6-day period. Similarly, algal biomass in German rivers was up to 8× higher in effluent-impacted reaches than in reference reaches (Gücker, Brauns, & Pusch, 2006). Finally, total algal abundance increased with effluent inputs in two of three U.K. streams; however, the taxon richness of algae remained similar (Oliveira & Goulder, 2006). Bacillariophyceae was the dominant group and comprised >90% of the community in one of the streams. In contrast to these examples, algal biomass decreased in some Canadian effluent-fed streams with high ammonium concentrations (Waiser, Tumber, & Holm, 2011).

Bacterial taxon richness changed in response to effluent inputs, but the direction of these changes was not consistent across studies. Effluent discharge near Chicago (U.S.A.) significantly reduced bacterial richness in the receiving stream (Drury, Rosi-Marshall, & Kelly, 2013). However, in an Australian stream, highest bacterial diversity was observed just downstream from the effluent outfall, and decreased further downstream (Wakelin, Colloff, & Kookana, 2008). Different types of effluent (e.g. tannery, clothing factory, button factory) were associated with distinct bacterial taxa in China, such as *Betaproteobacteria*, suggesting that the source of effluent must be taken into account when determining ecological impacts (Lu & Lu, 2014).

Nutrient loading from effluent often altered stream ecosystem function. This loading often exceeded assimilation rates by primary producers. Diel gross primary productivity in an effluent-fed river in Iowa (U.S.A.) was approximately two times greater than that reported for other streams in the region (Crumpton & Isenhart, 1987). In an effluent-dependent stream in California (U.S.A.), mean nitrate uptake decreased by over 50% from day to night (Kent, Belitz, & Burton, 2005). Nitrate uptake for the 24-hr study was approximately 11 mg NO_3-N/L/day, but CO_2 depletion during the afternoon decreased nitrate assimilation rates. Even in streams that are not effluent-dominated, small amounts of effluent input can still decrease nutrient uptake efficiencies (Gücker et al., 2006).

Finally, complex relationships have been identified between algae or microbes and pharmaceuticals present in effluent. In Texas (U.S.A.), triclocarban, triclosan, methyl-triclosan, and diphenhydramine bioaccumulated in stream-dwelling algae (Coogan, Edziyie, Point, & Venables, 2007; Du et al., 2015). Varying impacts have been reported for antibiotics and antimicrobial pharmaceuticals on algal biomass by taxa, but in one instance, total algal biomass increased 120% when ciprofloxacin was present in effluent (Wilson, Smith, deNoyelles, & Larive, 2003). In Spain, antibiotic resistance of enterobacteria and *Aeromonas* downstream of effluent outfalls increased by 20 and 40%, respectively, when compared to reference reaches (Goni-Urriza et al., 2000).

3.5 | Aquatic invertebrates

Of the 31 studies we reviewed that focused on invertebrate communities, 25 (81%) compared communities upstream and downstream

TABLE 1 Water quality issues gathered from effluent-fed river studies

Water quality	Parameters	Trend	References
Physical properties	Temperature	Higher water temperatures close to the effluent outfall and decreasing temperatures downstream	Birge et al. (1989), Boyle and Fraleigh (2003), Kinouchi, Yagi, and Miyamoto (2007) and Canobbio et al. (2009)
	Suspended solid and turbidity	Relatively stable downstream of effluent outfall	Gafny et al. (2000)
Chemical properties	pH	Relatively stable (ranged from circumneutral to slightly basic) along gradients downstream of effluent outfall	Chen et al. (2009), Prat, Rieradevall, Barata, and Munné (2013) and Matamoros and Rodríguez (2017)
	Dissolved oxygen (DO)	Lower DO immediately below effluent outfall, higher DO as flow moves downstream	Birge et al. (1989), Boyle and Fraleigh (2003) and Matamoros and Rodríguez (2017)
	Electric conductivity	Higher electric conductivity at effluent outfall, and then remaining relatively stable along downstream gradient and across seasons	Chen et al. (2009), Prat et al. (2013) and Matamoros and Rodríguez (2017)
	Alkalinity	Higher alkalinity near effluent outfall, but then decreasing values further downstream from outfall	Birge et al. (1989) and Boyle and Fraleigh (2003)
	Nitrate	Higher nitrate near the effluent outfall, lower nitrate as flow moves downstream. Nitrate attenuation was detected, and this was influenced by chemical, biological and physical (dilution) processes, in some cases, nitrate increased as flow moved downstream due to evaporation and low or no dilution	Hur et al. (2007) and Chen et al. (2009)
	Ammonia	Higher ammonia near effluent outfall, but lower values again as flow moves downstream	Gafny et al. (2000) and Boyle and Fraleigh (2003)
	Ammonium	Higher ammonium near effluent outfall, lower as flow moves downstream	Chen et al. (2009)
	Phosphate	Higher phosphate near the effluent outfall, lower phosphate as flow moves downstream	Birge et al. (1989) and Chen et al. (2009)
	Heavy metals	Elevated heavy metal concentrations near effluent outfall from treatment facilities receiving industrial waste	Begum and Harikrishna (2008), Kara, Kara, Bayram, and Gündüz (2017) and Munz et al. (2017)
Biological property	Bacteria (*Escherichia coli*)	Relatively low concentrations of *E. coli* contributed from treated effluent outfall. Nonpoint source loads were the primary source of bacteria loading	Petersen et al. (2005)
	Antibiotic-resistant coliform bacteria	Higher populations of antibiotic-resistant coliform bacteria in reaches downstream of effluent outfall as compared to those upstream	Akiyama and Savin (2010)
Trace organic contaminants	Endocrine-disruptors (EDCs)	Undetected or very low levels upstream of effluent outfall, but detected, and often in high levels, at sites below effluent outfall. Some EDCs attenuated to undetectable concentrations within 11 km	Sengupta et al. (2014), Dong et al. (2015) and Barber et al. (2015)
	Pharmaceuticals	Undetected or very low values upstream of effluent outfall, and frequently higher at sites below effluent outfall. Pharmaceutical attenuation during stream transport was detected. Some active compounds can decrease almost 4-fold within 30 km distance from effluent outfall	Ternes (1998), Fono, Kolodziej, and Sedlak (2006), Ramirez, Mottaleb, Brooks, and Chambliss (2007), Sengupta et al. (2014), Brown et al. (2015), Dong et al. (2015), Grabicova et al. (2017) and Mandaric et al. (2018)
	Biocides	Elevated concentrations about 2-fold of biocide compounds found downstream of effluent outfall	Munz et al. (2017)

of effluent inputs, with eight (26%) also examining community changes along gradients downstream from wastewater treatment plants. Although metrics varied widely by study, most reported changes in at least one or more of the following metrics: taxon richness, diversity, density, abundance, and/or community composition. Detailed reporting of these metrics allowed us to calculate global mean effects of effluent for several metrics.

Overall taxon richness, and the richness of sensitive Ephemeroptera, Plecoptera, and Trichoptera (EPT) taxa, were consistently and negatively affected by effluent, but other factors exhibited

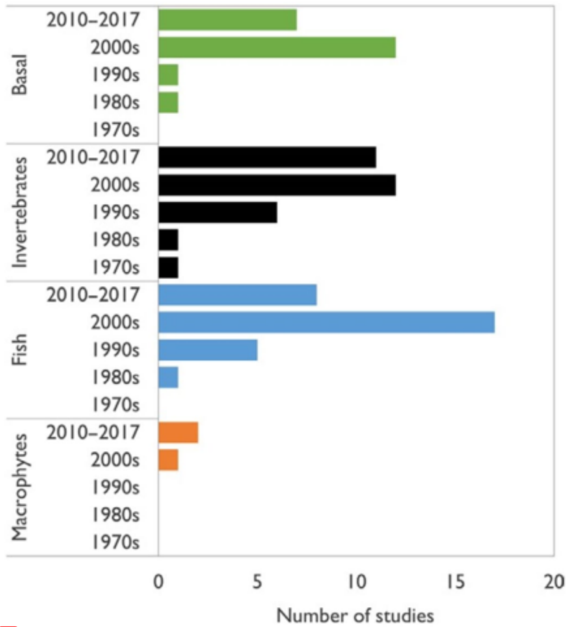

FIGURE 5 Trends through time by taxonomic group for studies from effluent-fed streams published prior to January 2018. The Basal (i.e. basal resources) category includes studies of algae, bacteria, and biofilm. Note that the final decade (2010s) is incomplete and only contains papers published up to 1 January 2018, so the final number of studies for this decade is expected to be larger in each category [Colour figure can be viewed at wileyonlinelibrary.com]

much more variability. Overall taxon richness declined by nearly 50% in effluent-fed reaches (mean change ± 1 *SD*: −46.9 ± 23.0%, *n* = 13 studies), with only a single study reporting equal richness values above and below effluent outfalls (Gücker et al., 2006). Of the 16 studies that reported EPT abundances or richness values, 94% observed a decline in EPT taxa below effluent outfalls, and 50% observed a complete loss of EPT taxa in effluent-fed reaches. Broadscale patterns were less clear with Shannon's diversity index. Although diversity tended to be lower in effluent-fed reaches, there was significant variation across studies (mean change ± 1 *SD*: −23.4 ± 50.9%, *n* = 7 studies). In fact, the addition of effluent was associated with increased diversity values in Arizona (U.S.A.) and Germany (Boyle & Fraleigh, 2003; Spänhoff et al., 2007). The majority of studies reported large increases in invertebrate abundance and/or density downstream of effluent outfalls, but again, the variability was also quite large (mean change ± 1 *SD*: +404 ± 837%, *n* = 9 studies). For example, abundances did not change, or were lower, below three treatment plants in the eastern U.S.A. (Diamond et al., 1994; Nedeau, Merritt, & Kaufman, 2003) and Germany (Spänhoff et al., 2007).

Although some univariate metrics were somewhat equivocal across studies, clear and consistent changes in community composition were observed downstream of effluent outfalls. EPT taxa were quite sensitive to the addition of treated effluent in streams. Similar levels of EPT richness and abundance upstream and downstream of effluent outfalls were only observed from a single study in Germany (Gücker et al., 2006), whereas all other studies reported large-scale reductions or complete loss of these taxa. Tolerant midges (Chironomidae, Diptera) and oligochaetes dominated community composition in most effluent-fed streams, often comprising 90–99% of the total abundance of invertebrates. Although most studies did not identify midges beyond family or subfamily, one study reported a shift in composition: *Polypedilum* dominated upstream of effluent outfalls and *Chironomus* dominated downstream (Gower & Buckland, 1978). Hydropsychid caddisflies were often abundant in effluent-fed streams, with 35% of studies reporting this family in the top three taxa. Other commonly reported taxa in effluent-fed reaches were nematodes, flatworms, leeches, gastropods (e.g. *Ferrissia*, Physidae, *Potamopyrgus*), amphipods, ostracods, and isopods. Community recovery was noted with significant distance downstream of outfalls (20–40 km) or with substantial upgrades of treatment plants to improve effluent quality.

3.6 | Fish

Across the 31 studies that focused on fish, 45% compared communities upstream and downstream of effluent outfalls and 21% examined community changes along longitudinal gradients downstream from outfalls. Twenty-nine percent of studies compared communities in effluent-fed streams with those from reference streams, and 8% only examined communities from one or two sampling sites below effluent outfalls.

Nearly all studies on the taxonomic diversity, richness, or abundance of fish reported negative effects of effluent. Fish diversity in one U.S.A. stream was sharply depressed, with no fish species found in the site closest to the outfall and only 69% survival rates for fish observed 15 km downstream of the outfall (Birge et al., 1989). Lower fish richness was also observed in an effluent-fed stream near Tel Aviv (Israel), but fish biomass was higher than in a nearby undisturbed stream (Gafny et al., 2000). Four studies reported a shift in species composition from intolerant to more tolerant taxa in sites downstream of outfalls. In South Korea, >90% of fish in one effluent-fed stream were characterised as tolerant, compared to <20% in a reference stream (Ra, Kim, Chang, & An, 2007) and similar patterns were reported in the U.S.A. (Porter & Janz, 2003). Nearly complete losses of top predator fishes also have been reported in effluent-fed streams (Porter & Janz, 2003; Ra et al., 2007).

All studies focusing on fish and TrOCs reported higher concentrations of those compounds in fish tissues of effluent-fed streams compared to those from reference streams. For example, pharmaceuticals at concentrations of 0.05–2.5 ng/g were detected in the brain tissue of white suckers in streams with 75–80% effluent loads, but none were detected in fish from reaches upstream of effluent outfalls (Schultz et al., 2010). Detectable levels of pharmaceuticals, such as fluoxetine and sertraline, were still found in white suckers *c.*

8 km downstream from effluent outfalls, but at lower concentrations than near the outfall (Schultz et al., 2010). Brown trout have also been found with considerable levels of pharmaceuticals, probably due to high concentrations of these chemicals in their invertebrate prey (Schultz et al., 2010). Pharmaceuticals were also detected in fish-eating birds that were sampled from an effluent-dominated stream in Japan (Tanoue et al., 2014).

Elevated pharmaceutical concentrations have also been blamed for causing sex abnormality in fish, with higher proportions of female and intersex fish being observed in effluent-fed streams. For example, in several U.S.A. streams, Woodling, Lopez, Maldonado, Norris, and Vajda (2006) documented that 83% of white suckers were female in reaches with 77% effluent input, compared to only 45% female in reaches upstream of effluent outfalls. This apparent feminisation of fish was even stronger in reaches with >90% effluent input, in which no male white suckers were observed (80% female, 20% intersex). This tendency was in line with a study of roach in Danish streams, which documented a higher prevalence of intersex roach below effluent outfalls than in upstream reaches (Bjerregaard, Korsgaard, & Bjerregaard, 2006).

4 | DISCUSSION

The addition of effluent alters both water quality and ecological communities in receiving streams. Water quality impairment near effluent outfalls included increased water temperatures, nutrients, and concentrations of TrOCs, as well as decreased dissolved oxygen levels. Through our review, we found that most ecological research focused on primary producers, aquatic invertebrates, and fish. In the following sections, we: (1) highlight water quality issues that lead to ecological impacts; (2) identify knowledge gaps and avenues for future research; and (3) provide recommendations to improve ecological function in effluent-fed streams.

4.1 | Water quality trends and ecological implications

Elevated temperatures below effluent outfalls cause numerous ecological impacts. For example, elevated temperatures increase primary producer growth rates and biomass (Murdock et al., 2004), even when the taxonomic richness is unaffected (Oliveira & Goulder, 2006). Warmer water, in combination with higher nutrients levels, can also lead to eutrophication in effluent-fed streams (Moss et al., 2011). Many aquatic animals (e.g. fish, invertebrates) are adapted to specific temperature ranges (Carveth, Widmer, & Bonar, 2006; Eliason et al., 2011), so increased temperatures may exclude sensitive taxa from effluent-fed reaches. For example, the Greenside Darter (*Etheostoma blennioides*) was eliminated by high temperatures in an effluent-fed Canadian stream and replaced by heat-tolerant fish (Brown et al., 2011). Fortunately, many studies show that temperatures gradually decline in reaches downstream from effluent outfalls due to the increasing influence of air temperature or groundwater (Boyle & Fraleigh, 2003; Canobbio et al., 2009).

Dissolved oxygen levels in effluent-fed streams often fall below the levels that many lotic organisms require to survive (Birge et al., 1989). Causes of reduced dissolved oxygen levels vary across systems, but include increased temperatures and eutrophication from nutrient loading that in turn, can increase biological oxygen demand (e.g. Birge et al., 1989; Boyle & Fraleigh, 2003; Brooks et al., 2006). Invertebrate taxa that require high oxygen levels, such as mayflies and stoneflies, are frequently absent below effluent outfalls and are replaced by tolerant worms and true flies. True flies in the genus *Chironomus* tolerate low oxygen conditions by using a type of haemoglobin (Lencioni, Bernabo, Vanin, Muro, & Beltramini, 2008), and several species of worm can survive for long periods in anaerobic conditions (Martins, Stephan, & Alves, 2008). Sensitive taxa may not reappear in effluent-fed reaches until many kilometres downstream of effluent outfalls, where dissolved oxygen levels begin to recover.

In addition to these basic water quality parameters, high nutrient levels in effluent-fed streams can lead to increased algal biomass and water turbidity, and decreased dissolved oxygen concentrations (e.g. Boyle & Fraleigh, 2003; Chen et al., 2009; Gafny et al., 2000). These changes can cause increased fish mortality and blooms of toxic phytoplankton (Carey & Migliaccio, 2009). High ammonia concentrations (e.g. >2 mg/L for chronic exposure and >17 mg/L for acute exposure: US EPA, 2013) are particularly influential, reducing growth rates and reproductive success or causing direct mortality in aquatic invertebrates and fish (Constable et al., 2003). Low species richness of fishes in effluent-fed reaches is often due to ammonia toxicity (Gafny et al., 2000; Ra et al., 2007; Yeom, Lee, Kang, Seo, & Lee, 2007). Furthermore, fish that are intolerant of ammonia may disperse away from effluent-fed reaches to avoid toxicity (Ra et al., 2007; Yeom et al., 2007).

Effluent-fed streams frequently exhibit high concentrations of TrOCs, which can significantly affect stream ecosystems (Dong et al., 2015). Despite improved wastewater treatment technologies, many TrOCs pass through treatment and persist in streams to varying degrees (Buxton & Kolpin, 2005). For example, pharmaceuticals accumulate in primary producers (Coogan et al., 2007; Du et al., 2015), invertebrates (Grabicova et al., 2015; Munz et al., 2017) and fish (Brooks et al., 2005; Schultz et al., 2010; Tanoue et al., 2014). Invertebrates may uptake pharmaceuticals directly through the water, while uptake in fish occurs via the prey they eat (Du et al., 2015; Grabicova et al., 2015). Exposure to TrOCs in the aquatic environment may result in bioaccumulation (Du et al., 2015) and biomagnification (Du et al., 2014). TrOCs caused changes in fish at cellular, organ, organismal, and community levels (Porter & Janz, 2003). Steroidal oestrogens led to feminisation of male fish, resulting in more female and intersex fish in populations (Jobling et al., 2002; Vajda et al., 2008; Woodling et al., 2006). Fortunately, some TrOCs (e.g. tonalide, fluoxetine, iopromide, sucralose, and perfluorooctanesulfonic acid) are attenuated immediately downstream of effluent outfalls, probably due to biodegradation and photolysis, thus reducing their impacts to aquatic communities (Dong et al., 2015).

4.2 | Knowledge gaps in effluent-fed streams

Streams receiving effluent have received considerable scientific attention in recent years, but significant knowledge gaps remain and >80% of published studies come from the U.S.A. and Europe. Many abiotic factors are little studied in effluent-fed streams. For example, how does nutrient-rich and warmer effluent affect infiltration rates and interactions with groundwater (see Treese, Meixner, & Hogan, 2009)? Similarly, how do effluent inputs alter sediment dynamics in downstream reaches? Together, benthic sediment and surface-groundwater interactions are crucial in determining biological communities within hyporheic zones and how they interact with benthic communities (Lawrence et al., 2013). Additionally, effluent inputs can alter flow regimes including perennialisation of intermittent or ephemeral streams (e.g. Brooks et al., 2006) and cause high diurnal fluctuations in flow where little natural baseflow is present (Halaburka et al., 2013). The ecological impacts of these effluent-altered flow regimes have not been studied. Finally, novel contaminants, such as microplastics (e.g. McCormick et al., 2016), continue to be discovered in effluent-fed streams and are deserving of further study.

The vast majority of biological studies in effluent-fed streams focused on basal resources, aquatic invertebrates, and fish. Surprisingly, we did not find any studies focusing on other aquatic animals, such as amphibians and reptiles. This lack of studies is not due to a lack of these taxa in effluent-fed streams. In fact, endangered amphibians and reptiles, such as California red-legged frogs (*Rana draytonii*) and San Francisco garter snakes (*Thamnophis sirtalis tetrataenia*) occur in effluent-dominated streams in California (Luthy et al., 2015). In Arizona, we have observed multiple amphibian and reptile species along the effluent-dominated Santa Cruz River, including toads (*Incilius alvarius*), turtles (*Kinosternon sonoriense*), and garter snakes (*Thamnophis marcianus*). Interestingly, these observations in California and Arizona also come from streams that would be dry during baseflow conditions in the absence of effluent inputs (i.e. they have been perennialised by effluent). These patterns suggest that studies of effluent-fed streams should be expanded to include aquatic and riparian vertebrates, and that these systems could serve as aquatic biodiversity refuges in arid regions where much natural stream habitat has been lost (Bischel et al., 2013).

Despite the potential benefits of using effluent as a source of environmental flows, caution should be exercised when considering its use in naturally intermittent or ephemeral streams (Chiu, Leigh, Mazor, Cid, & Resh, 2017). These systems are often regarded as *secondary ecosystems* relative to perennial streams (Acuña, Hunter, & Ruhí, 2017), but their resident aquatic and riparian biota are often adapted to survive cycles of drying (Leigh et al., 2016). Anthropogenic perennialisation due to effluent addition may facilitate the invasion of non-native species lacking adaptations to drying, leading to negative effects on native biota (Chiu et al., 2017). Future studies should carefully evaluate the impacts of adding effluent to naturally intermittent or ephemeral systems.

4.3 | Management recommendations for effluent-fed streams

Based on our review, we propose the following management recommendations. First, whenever possible, wastewater should be treated to the tertiary level before being released into rivers. In a recent study, Peschke, Capowiez, Köhler, Wurm, and Triebskorn (2019) reported that macroinvertebrate communities downstream of an effluent outfall in Germany improved, and were no longer different from those upstream of the outfall, after the wastewater treatment plant was upgraded. Second, to optimise ecological function and ecosystem services, water quality monitoring should be conducted along longitudinal gradients in effluent-fed streams. Monitoring effluent water quality in treatment plants prior to discharge into streams is insufficient because many complex chemical and ecological processes can happen in receiving streams, including synergistic toxicity effects (Cedergreen, 2014). Also, single-point sampling near an effluent outfall may skew perception towards negative impacts, considering water quality can improve dramatically with distance downstream. Third, improved mapping and discharge measurements of effluent-fed streams over larger spatial and temporal scales are needed. Many studies did not include, or did not have access to, critical information about the relative percentage of effluent-to-receiving stream flow, nor how it varied by season. Larger scale mapping of effluent-fed stream networks also would help in identifying non-point sources of pollution downstream of effluent outfalls. This information is important because these sources may counteract the natural remediation of contaminants below outfalls.

Improved mapping efforts would also enhance public awareness of effluent-fed streams, which could have multiple benefits. With awareness of these systems, the public may be more likely to support conservation efforts that promote aquatic biodiversity (e.g. minimum in-stream flow requirements). Additionally, this knowledge may encourage the public to reduce household pollutant loads and change behaviours regarding the disposal of pharmaceuticals, so that less of these compounds enter wastewater treatment plants. Improved understanding of effluent-fed streams could also help provide motivation for managers and the public to better protect these systems. Previous studies of effluent-fed systems have identified a variety of societal benefits: educational and cultural opportunities (Luthy et al., 2015), groundwater recharge (Treese et al., 2009), land preservation and hydroelectric power (Brooks et al., 2006), aesthetic appeal and recreation (Asano, Burton, Leverenz, Tsuchihashi, & Tchobanoglous, 2007), and increased property values and tax revenue (Bischel et al., 2013).

We hope that our review will encourage further study of these unique and expanding ecosystems. With careful study and management, effluent-fed streams could become important sources of aquatic biodiversity as natural streams dry up due to climate change or are dammed and diverted for anthropogenic use.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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