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Primary Research Paper

Water quality of effluent-dominated ecosystems: ecotoxicological, hydrological, and management considerations

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Abstract

In arid and semi-arid regions of the southwestern United States and other parts of the world, flows of historically ephemeral streams are now perennially dominated by municipal and/or industrial effluent discharges, particularly in urbanized watersheds. Because effluent-dominated and dependent water bodies have previously received limited scientific study, we reviewed select contemporary topics associated with water quality of ephemeral streams receiving effluent flows. Our findings indicate that these ecosystems present numerous challenges to aquatic scientists and water resources managers, including: 1) appropriate ecosystems or upstream conditions used reference sites in biomonitoring are difficult to locate or do not exist; 2) water quality criteria, particularly for metals, are dramatically influenced by unique site-specific stream and land use conditions; 3) effluent-dominated streams represent worse-case scenarios for evaluating and predicting aquatic responses to emerging contaminants (e.g., pharmaceuticals and personal care products); 4) low-flow and drought conditions often preclude effective biomonitoring and water quality interpretation, or skew ambient assessment results; 5) chemical-physical water quality parameters (e.g., dissolved oxygen, conductivity, temperature) are dramatically altered by effluent and stormwater characteristics; and 6) beneficial reuse of reclaimed effluent waters potentially conflict with sustainability of ecological integrity. Subsequently, we recommend several water quality research priorities for effluent-dominated water bodies.

Abbreviations: 7Q2 – Minimum average 7-day flow with a 2 year recurrence interval; 7Q10 – Minimum average 7-day flow with a 10 year recurrence interval; BLM – Biotic Ligand Model; CWA – United States Clean Water Act; EE2 – 17α-ethinylestradiol; NPDES – National Pollutant Discharge Elimination System; PPCPs – Pharmaceuticals and Personal Care Products; SSRI – Selective Serotonin Reuptake Inhibitor; TMDL – Total Maximum Daily Load; USEPA – United States Environmental Protection Agency; VTG – Vitellogenin; WER – Water Effect Ratio; WET – Whole Effluent Toxicity; WLA – Wasteload Allocation; WQC – Water Quality Criteria; WQS – Water Quality Standards; WWTP – Wastewater Treatment Plant

Key words: instream flows, effluent dependent streams, whole effluent toxicity, beneficial reuse, arid ecosystems, urban ecosystems

Introduction

Streams in arid to semi-arid regions of the world often experience seasonal periods of extremely low flow conditions (Medeiros & Maltchik, 1999; Vidal-Abarca et al., 2001; McMahon & Finlayson, 2003; Oliva-Paterna et al., 2003). When municipal and industrial wastewater effluents are discharged to these ephemeral or intermittent streams, effluents may comprise the majority of stream flows (Taylor,

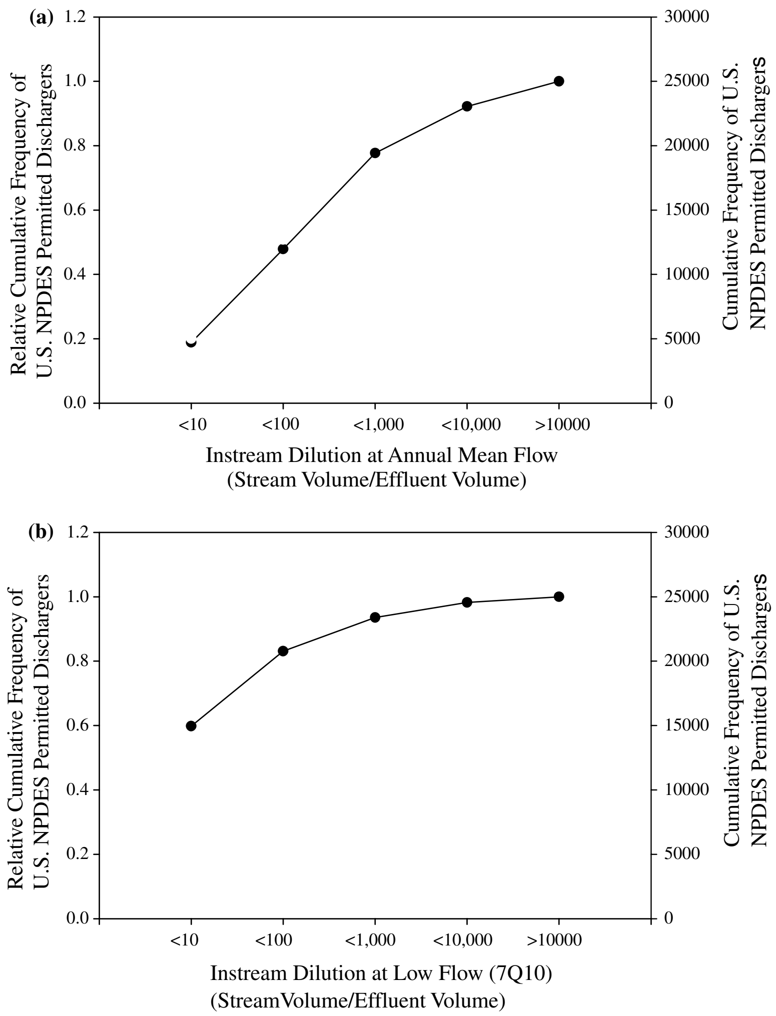

Figure 1. (a) Relative cumulative frequency and cumulative frequency distributions of instream dilution (stream volume/effluent volume) at annual mean flow of effluent dischargers permitted by the National Pollutant Discharge Elimination System (NPDES) Program, US. Environmental Protection Agency (data modified from USEPA, 1991a). (b) Relative cumulative frequency and cumulative frequency distributions of instream dilution (stream volume/effluent volume) at low flow conditions (7Q10) of effluent dischargers permitted by the National Pollutant Discharge Elimination System (NPDES) Program, US. Environmental Protection Agency (data modified from USEPA, 1991a).

2002; Brooks, 2002). In the United States, approximately 23% of regulated effluent releases enter streams receiving less than 10-fold instream dilution (Fig. 1a). During low flow conditions this percentage increases to 60% (Fig 1b). For example, stream flows in the Trinity River Basin, Texas, and the South Platte River Basin, Colorado, can be 90% or greater dominated by effluent flows (Dickson et al., 1996; Brooks, 2002). More specifically, 285 of 582 effluent discharges, a representative sample of the regulated major dischargers in the states of Texas, Oklahoma, New Mexico, Arkansas and Louisiana enter aquatic systems in which effluent comprised greater than 90% of instream flow (Fig. 2). In effluent dependent water bodies, instream flows are entirely dependent on effluent discharges.

Effluent-dominated and dependent streams, hereafter effluent-dominated streams, have unique water quality characteristics that, in most cases, are comparatively different from normal stream conditions upstream of the discharge or at regional reference sites (Taylor, 2002; Brooks et al., 2004).

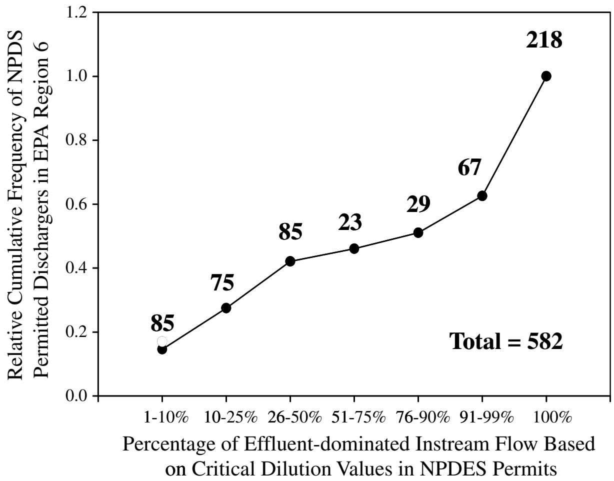

Figure 2. Relative cumulative frequency of percentages of instream flows influenced by effluent discharge, based on critical dilution permit limits, for a representative sample of major effluent discharges permitted by the National Pollutant Discharge Elimination System (NPDES) Program in U.S. Environmental Protection Agency Region 6 (Texas, Oklahoma, New Mexico, Arkansas, Louisiana).

Continuous flow augmentation of intermittent streams by effluent discharges can modify available habitat, temperature, dissolved oxygen regimes, nutrient and chemical constituent loadings, water quality, and instream toxicity. Such a continuous flow regime may decrease temporal and spatial variability of instream water quality and quantity, while simultaneously causing changes in riparian habitat form and function. Therefore, understanding the chemical, physical, and biological dynamics of these ephemeral or intermittent streams is critical for maintaining water quality and offers challenges in regulatory permitting, compliance, monitoring, water quality modeling, and total maximum daily load (TMDL) development in the United States.

Relative to most aquatic ecosystems and despite the potential impacts of effluent discharges on ephemeral or intermittent streams, water quality of effluent-dominated streams has received modest attention from aquatic scientists and other environmental researchers. Historically, effluent-dominated streams have been considered as little more than wastewater conduits, and this perception has likely influenced the lack of research to date. However, with increasing interest in understanding the ecosystem dynamics of urban environments (Grimm et al., 2000), effluent-dominated streams are now recognized as critical conduits for energy import and export in urbanized areas (Collins et al., 2000; Grimm et al., 2003). As demands for water increase, there is a need to find ways to augment water supplies and existing freshwater resources (Anjos, 1998). A projected doubling of human population in the state of Texas alone over the next 50 years will increase anthropocentric reliance on effluent-dominated water bodies, accentuating the importance of water quality maintenance concurrent with management of freshwater resources (Brooks, 2002).

To provide an overview of contemporary water quality issues pertinent to effluent-dominated streams, we reviewed a number of topics particularly relevant to those systems in the southwestern United States. Specifically, our review focused on contaminants of emerging concern, water quality criteria (WQC) and standards (WQS) issues including ecotoxicity testing, biomonitoring, low flow conditions, waste load allocation modeling and TMDLs, and resource management implications of beneficial reuse and instream flow protection policies.

Contaminants of emerging concern

Water quality of effluent-dominated streams may be affected by contaminants of emerging concern. Recently, pharmaceuticals and personal care products (PPCPs) have received unprecedented scientific attention as environmental contaminants (Daughton & Ternes, 1999; Daughton & Jones-Lepp, 2001; Kummerer, 2001a; Heberer, 2002;

Kolpin et al., 2002; Daughton, 2003). While personal care products such as surfactants have received previous investigation (Dorn et al., 1997; Ostroumov, 2002a, b), pharmaceuticals are often referred to as emerging contaminants because of the paucity of information on environmental pharmaceutical occurrence and the responses of aquatic organisms to therapeutic exposure (Brooks et al., 2003a). Such limited information and the presumption that pharmaceutical concentrations to which aquatic organisms are routinely exposed are relatively small ($< 1\ \mu g\ l^{-1}$) have precluded the development of acute and chronic national ambient WQC in the United States (Brooks et al., 2003b).

Pharmaceuticals primarily enter surface and ground waters from Concentrated Animal Feeding Operation runoff (USEPA, 2001) and from wastewater treatment plant (WWTP) effluent discharges. Boxall et al. (2004) and Koschorreck et al. (2002) recently reviewed pharmaceutical contaminants that enter aquatic systems from intensive agricultural activities. Compounds that have received recent study include the steroid trenbolone (Lange et al., 2002) and various antibiotics (Boxall et al., 2004). However, information on CAFOs inputs or impacts on effluent-dominated streams is limited. Effluents from conventional wastewater treatment serve as point source for these emerging contaminants because these systems do not completely remove pharmaceuticals from inflowing wastes (Heberer, 2002). Therapeutics are excreted as a combination of metabolites and parent compound; the proportion of metabolite to parent compound is related to the pharmacokinetic disposition of each drug (Daughton & Ternes, 1999). Although many pharmaceuticals are primarily excreted as metabolites, microbial activity in a WWTP may cleave conjugated metabolites, potentially resulting in reactivation to parent compounds prior to discharge to a receiving stream (Ternes, 2001).

Limited reports on PPCP occurrence in aquatic systems are associated with a lack of analytical methods for PPCP detection and quantitation in various aquatic matrices (e.g., water, sediment, tissue; Brooks et al., 2003a). Information that is available indicates widespread occurrence of pharmaceuticals, potentially extending wherever human populations excrete therapeutics (Stumpf et al., 1999; Kolpin et al., 2002). Concentrations of pharmaceuticals in effluent discharges and surface waters are generally detected from ng l^{-1} to low $\mu g\ l^{-1}$ levels (Kozak et al., 2001; Kummerer, 2001b; Ternes, 2001; Kolpin et al., 2002). However, most studies of PPCPs in aquatic systems have focused on effluents in developed countries (Ternes 1998; Stumpf et al., 1999; Heberer, 2002; Huggett et al., 2003a); far less information on PPCP loadings is available for countries with limited wastewater treatment infrastructure.

Although it is widely acknowledged that human exposure to environmental pharmaceuticals is below mammalian therapeutic levels (Schulman et al., 2002; Webb et al., 2003), responses of aquatic organisms and ecosystems to pharmaceuticals and their metabolites are largely unknown (Huggett et al., 2002; Brooks et al., 2003a, b; Richards et al., 2004). Unlike non-point aquatic pesticide exposures that may occur over short periods of time following rainfall events, potentially resulting in acute toxicity to aquatic organisms, lower-level pharmaceutical releases to effluent-dominated streams over longer time periods may subtly modulate and alter normal biochemical, physiological, reproductive, and ecological processes (Daughton & Ternes, 1999; Brooks et al., 2003a; Wilson et al., 2003). Therefore, biomarkers of exposure and effect that are specific to the mechanism of action for individual pharmaceutical classes should be developed for "non-target" aquatic biota (Daughton & Ternes, 1999; Brooks et al., 2003a, b). Specifically, vitellogenin (VTG), an egg-yolk precursor protein not normally present at detectable levels in male fish, is widely used to assess exposure of sexually mature males to estrogen pharmaceuticals or estrogenic effluents (Foran et al., 2003; Huggett et al., 2003b).

Exposure to synthetic estrogens in municipal effluents presents several potential consequences for aquatic organisms, the most severe of which is phenotypic sex reversal (Nimrod & Benson, 1998). Laboratory studies with roach (*Rutilus rutilus*) collected from effluent-influenced streams identified impairment of gonadal development, which resulted in intersexed fish (hermaphroditism) with reduced fertility (Jobling et al., 2002). A pharmaceutical that has received considerable study in such effluent discharges is the synthetic estrogen 17α-ethinylestradiol (EE2), a potent steroid commonly found in oral contraceptive formulations (Foran et al., 2003). Jobling et al. (1996) demonstrated that treatment with only 2 ng l^{-1} of EE2 induced VTG production and inhibited testicular growth in male rainbow trout (*Oncorhynchus mykiss*). In addition, following a complete life cycle study with fathead minnows (*Pimephales promelas*) Länge et al. (2001) reported a lowest observed adverse effect treatment level of 4 ng l^{-1} EE2. Desbrow et al. (1998) identified EE2 and endogenous estradiol and estrone as causative estrogens in United Kingdom rivers that are influenced by municipal effluent discharges. Further, Huggett et al. (2003b) and Brooks et al. (2003c) utilized an *in vitro* yeast estrogen screening assay, *in vivo* male Japanese medaka (*Oryzias latipes*) VTG induction, and a toxicity identification evaluation procedure with solid phase extraction and gas chromatography–mass spectrometry to identify steroid estrogens as primarily responsible for estrogenicity of an effluent-dominated stream in north central Texas, USA. Because EE2 and endogenous steroids are often detected in effluent discharges at such low ng l^{-1} levels that affect fish neuroendocrine function and reproduction, the potential impacts of EE2 and other steroids on water quality and biological processes is of particular concern in effluent-dominated streams (Brooks, 2002).

Relative to EE2, information on aquatic organism and/ or assemblage responses to other classes of PPCPs is not as available in peer-reviewed literature. Although standardized acute and short-term chronic ecotoxicity data, which establish concentration–response relationships for survival, growth and reproduction for a select group of organisms, are available for a limited number of compounds, studies on potential structural and functional responses of aquatic ecosystems to PPCPs are rare (Brooks et al., 2003a; Richards et al., 2004). For example, preliminary data indicates that exposure to the selective serotonin reuptake inhibitor (SSRI) fluoxetine, at environmentally relevant concentrations, modulates norepinephrine and dopamine levels in *O. latipes* brains (Brooks, et al., unpublished data). However, the relationships among such subtle neurochemical modulation by pharmaceuticals and potentially subsequent behavioral, physiological, biochemical, or ecological responses (e.g., competition, predation) are unknown.

Huggett et al. (2003c) recently proposed using mammalian pharmacological data to estimate and prioritize teleost responses to pharmaceutical insults. This approach is attractive as a screening model for therapeutics because: (1) most pharmaceutical mechanisms of action include enzyme/receptor systems, (2) many enzyme/receptor systems appear to be relatively conserved between humans and teleosts and (3) mammalian pharmacology information, including chronic carcinogenicity data, is gathered during pharmaceutical registration studies (Huggett et al., 2003c). Whereas teleosts and other fishes may have enzyme/receptor systems similar to mammals, such information for invertebrate and algal responses to pharmaceuticals is limited (Huggett et al., 2002; Hutchinson, 2002; Brooks et al., 2003a, b).

Even pharmaceuticals with highly specific biochemical mechanisms in vertebrates may exert toxicity through very different, largely unknown mechanisms in lower level organisms (Daughton & Ternes, 1999; Brooks et al., 2003a). For example, although the antidepressant fluoxetine exerts its therapeutic effect in humans by blocking serotonin reuptake at presynaptic nerve clefts, the green algae *Pseudokirchneriella subcapitata* was more sensitive to fluoxetine than the cladocerans *Ceriodaphnia dubia* and *Daphnia magna*, the amphipod, *Hyalella azteca*, the chironomid, *Chironomus tentans*, and the fathead minnow, *Pimephales promelas* (Brooks et al., 2003b). Fluoxetine and other SSRIs are reported to have antimicrobial properties (Munoz-Bellido et al., 2000), which suggests that fluoxetine toxicity to *P. subcapitata* was potentially exerted by efflux pump interference (Brooks et al., 2003b). Further, Wilson et al. (2003) recently observed structural changes in natural suspended and attached algal assemblages in laboratory bioassays following treatment with realistic effluent levels (ng l^{-1}) of triclosan, an antimicrobial agent, and ciprofloxacin, an antibiotic.

Effluent-dominated streams are suggested as "hot-spot" ecosystems for studying pharmaceutical and personal care products (PPCPs) because effluent-dominated streams receive little-to-no upstream dilution (Marsh et al., 2003; Brooks et al., 2003a, b). However, analytical methods for detection of pharmaceuticals in effluents, sediments and tissues are limited, and the responses of aquatic organisms and ecosystems to most pharmaceuticals are unknown. Further, the relationship between biomarkers based on specific pharmaceutical mechanisms of action, laboratory toxicity tests, and structural and functional responses to PPCPs has not been studied in effluent-dominated water bodies. Clearly, a characterization of PPCP occurrence and instream community responses to PPCPs in effluent-dominated streams requires further investigation.

Water quality criteria and standards in effluent dominated streams

Most water quality issues pertinent to effluent-dominated streams in the United States are related to problems applying national regulations, often intended to maintain ecological integrity or specific uses of aquatic resources, to effluent dependent systems. The US clean water act (CWA) requires that the US environmental protection agency (USEPA) develop ambient WQC, which are recommended and estimated concentrations of toxicants based on current scientific information. These WQC, if not exceeded, are considered protective for aquatic organisms and human health (USEPA, 1991a). Individual states and Indian tribes must subsequently adopt water quality standards (WQS), which are legal limits permitted by each state for specific aquatic systems and thought to be sufficient to protect water quality. Providing a foundation for a water quality based control program, also required by the CWA, WQS include four components: designated uses, antidegradation, policies on implementation, and WQC (USEPA, 1991a). Aquatic ecosystems are assigned specific use designations, which may include such classifications as water resources to support human consumption, agricultural use, or protection of aquatic life. An antidegradation policy is included as part of WQS to protect and maintain existing or attainable uses designated for a water body.

Specific water quality problems in effluent-dominated streams are often related to one or more components of WQS. Whole Effluent Toxicity (WET) tests are used through the national pollutant discharge elimination system (NPDES) program to biomonitor potential ecological impacts of industrial and municipal effluents (Grothe et al., 1996). This includes establishing low flow limits for an aquatic system receiving effluent discharge. Low flow conditions are calculated as the minimum average 7-day flow with a 2-year (7Q2) or 10-year (7Q10) recurrence interval. If, for example, under low flow conditions an effluent discharge volume is permitted to occupy 40% of the instream flow volume, WET biomonitoring tests must indicate that the effluent is not toxic when diluted with reconstituted laboratory water to 40% or lower (Grothe et al., 1996). However, because effluent dominated streams are often historically ephemeral systems, average minimum low flow volumes can near zero; therefore, as critical dilutions limits approach 100%, non-diluted effluent must not indicate adversely affected WET tests. The difficulty of developing appropriate WET and WQS limits for intermittent streams is compounded by the lack of hydrological data for most systems.

Another aspect of effluent-dominated streams that must be considered is whether the use of WET responses and biological assessments, intended to maintain water quality and instream biological integrity, are appropriate for streams in the arid and semi-arid southwestern US. WET tests rely on standard laboratory ecotoxicity testing with *P. subcapitata*, *C. dubia* and *P. promelas* (Grothe et al., 1996). WET tests are not designed to measure instream biological responses, may not protect all species, and do not account for contaminant bioaccumulation, mutagenicity, teratogenicity, or carcinogenicity (La Point & Waller, 2000). In addition, it should be noted that organisms used for WET biomonitoring are not necessarily extant flora and fauna of arid and semi-arid streams. However, WET test and other laboratory toxicity test responses, particularly *C. dubia* reproduction, are generally indicative of water quality and protective of instream responses to contaminant discharges in effluents (Dickson et al., 1992; La Point & Waller, 2000; Pascoe et al., 2000). Specifically, Dickson et al. (1996) established a weight-of-evidence relationship for using WET tests to predict ambient toxicity and instream macroinvertebrate and fish assemblage responses in the now effluent-dominated, formerly intermittent, Trinity River in north Texas, USA.

WQC, which include numeric toxicant concentrations and narrative components, are designed to protect designated use classifications of WQS (USEPA 1991a). Effluent-dominated streams present several problems for WQC of select contaminants of concern, including metals. Metal toxicity is inversely related to water hardness; as hardness increases, select metal toxicity decreases (Peng et al., 2002). WQC calculations for most metals include a correction for unique, site-specific hardness values. However, this can become problematic for arid and semi-arid streams in which water hardness concentrations exceed those used for metal WQC calculations (>400 mg l^{-1} as $CaCO_3$; Gensemer et al., 2002). Additionally, site-specific water chemistry parameters (e.g., chloride, sulfides, sulfates, dissolved organic matter) of an effluent or water upstream of a discharge site often differ from reconstituted laboratory water utilized in WET test dilutions (La Point et al., 1996). Sampling sites downstream from effluent discharges may exhibit greater biological integrity (e.g., richness, abundance, diversity) than upstream sites if additional habitat is created by the discharge or effluent constituents reduce the bioavailability of upstream toxicants (Eagleson et al., 1990; Brooks, 2002). For example, Clements et al. (1990) attributed higher copper toxicity to stream invertebrates in laboratory waters than in lotic mesocosms to higher total suspended solids and dissolved organic carbon in model streams. USEPA implemented water effect ratios (WER) to address such site-specific differences in water quality (USEPA, 1994). Often used for metal toxicants, a WER is a ratio of LC_{50}s from laboratory toxicity tests using stream water and reconstituted laboratory water for dilutions (USEPA, 1994).

Development of the biotic ligand model (BLM) in recent years has advanced site-specific hardness corrections and WER approaches for establishing acute WQC for metals. The potential utility of biotic ligand modeling, based on chemical equilibrium, is a quantitative characterization of site-specific water quality parameter influences on metal speciation and bioavailability to aquatic organisms (Paquin et al., 2002). The BLM can also predict an LA_{50}, defined as acute metal accumulation on the biotic ligand (e.g., metal–gill) required to produce 50% lethality, and an acute toxicity point estimate (EC_{50}) for standard WET test organisms (Di Toro et al., 2000). A specific application of the BLM relevant to effluent-dominated streams was performed by Gensemer et al. (2002) who utilized the BLM to predict speciation and acute toxicity of copper to *C. dubia* in very hard water, typical of select arid streams with unique ionic composition and varying alkalinities. Further, Brooks et al. (2004) employed outdoor lotic mesocosms and a BLM to demonstrate that water chemistry differences between reconstituted laboratory water and site-specific waters reduced cadmium bioavailability and acute toxicity to and benthic macroinvertebrate assemblages in effluent-dominated streams. In this study, a 48-hr EC_{50} for *C. dubia* exposed to cadmium in reconstituted laboratory water was calculated at 38.3 μg l^{-1} Cd, while the BLM predicted a markedly higher 48-hr EC_{50} value of 280 μg l^{-1} Cd for *C. dubia* in lotic mesocosms waters, accentuating the influence of water chemistry on metal bioavailability in effluent-dominated streams (Brooks et al., 2004).

Although BLM techniques have advanced the prediction of acute metal toxicity to cladocerans in effluent-dominated streams, future BLM research activities must focus on chronic responses of other aquatic organisms, including fish (McGeer et al., 2002). This is particularly important for heavy metals, which are not subject to biodegradation. Rather, metals continuously released in effluent discharges may ultimately partition to sediments, potentially stressing benthic and epi-benthic populations. For example, Brooks et al. (2004) found that although periphytic biomass and gastropod abundance were not reduced by a 15 μg l^{-1} Cd treatment level in effluent-dominated streams, the gastropod *Physa* sp. and periphyton accumulated Cd at the 15 μg l^{-1} Cd treatment level to concentrations two orders of magnitude higher than streams not treated with Cd. Brooks et al. (2004) suggested that even though water chemistry of effluent-dominated streams reduced Cd bioavailability and acute toxicity to *C. dubia*, longer term exposure to similar Cd concentrations may potentially lower the 15 μg l^{-1} Cd no adverse effect level.

Wasteload allocation and total maximum daily loads

Exemplifying the disparity of research and information for effluent-dominated streams is the development of wasteload allocations (WLAs), which are part of the TMDL process in the United States. TMDLs establish the maximum amount of a pollutant from point and non-point sources that a lake, river, stream, or estuary can receive and still maintain the ambient WQS of a particular state (USEPA, 1991a). Specifically, WLAs are used to determine the allowable waste loads from point source dischargers for compliance with WQS. WLAs are further used to define the impacts of point source pollution (USEPA, 1991b). Thus, WLA procedures require that the relationship between pollutant loads and the resulting water body responses be investigated.

A standard procedure is to apply a mathematical model to assist the determination of cause-effect relationships in aquatic ecosystems (Thomann & Mueller, 1987; USEPA, 1991a; USEPA, 1991b; Park & Uchrin, 1996). WLA methods have been developed for streams, rivers, lakes, and impoundments (Driscoll et al., 1983; Gilbert, 1987). Other methods for WLAs have been documented for alternative scenarios, such as fish farm wastes, a macrophyte growing impoundment system, and outfalls in an estuary (Kelly et al., 1996; Park & Uchrin, 1996; Smith & Purnama, 1999). Previous research also addressed the risks of WLA modeling and impacts of water quality modeling uncertainty on environmental management (Warwick & Roberts, 1992; Korfmacher, 1998). However, a minimal amount of research has been performed on the development of WLAs for effluent-dominated streams (Taylor, 2002).

Responding to rapid urbanization, a major emphasis in the United States is the construction of new wastewater treatment facilities and the upgrade of existing infrastructure. To meet this increasing demand on water resources, intermittent streams will continue to transport effluents. Assessing these future pollutant loadings requires that information be established on how intermittent streams are affected by effluent flows. A typical application of the TMDL process is to achieve reservoir WQS by developing WLAs for inflowing streams that are protective of such standards (Taylor, 2002). In many cases, the WLA will apply to a critical zone linking an inflowing stream and the backwaters of an impoundment. In this interface, a classic example is attainment of dissolved oxygen WQS in the stream and in the reservoir backwaters. The potential to cause non-attainment (or, violation) of dissolved oxygen WQS is dependent on loadings of oxygen demanding wastes, nutrient input, effluent and stream flow, environmental conditions of the receiving reservoir, and physical dynamics of the system. Additionally, biotic conditions of the receiving stream and reservoir can influence dissolved oxygen levels because algal productivity can cause drastic changes in concentrations. Intermittent streams create a challenge to this process, as the backwaters may be effluent-dominated with water quality conditions dependant on effluent quantity and quality (Taylor, 2002).

Another challenge to the WLA process for effluent dominated streams is the establishment of low flow conditions. Typically, WLA modeling, and chemical, ambient toxicity and bioassessment monitoring are conducted during low flow periods as defined by state and federal water quality regulations (USEPA, 1991b). The low flow condition is defined for most WLA decisions, such as the 7Q2 or 7Q10 (Thomann & Mueller, 1987). However, many ephemeral streams have little or no record of historical flow. In the absence of background flow data, the WLA process can be limited by a considerable amount of uncertainty, creating a contentious state between regulators and the regulated community (Taylor, 2002).

Natural variability of background stream water quality conditions presents yet another issue of particular interest to effluent-dominated streams. Whereas background water quality conditions upstream from an effluent discharge may result in violation of WQC, the effluent-dominated portion of the stream may ameliorate such conditions, facilitating attainment of WQC (CEPA, 2000). This can occur when the receiving stream carries a significant load of a constituent, such as oxygen demanding wastes. Likewise, stormwater runoff events are often significantly different from upstream conditions and produce detectable changes in reservoir backwaters for a period of days (Appel & Hudak, 2001; Taylor, 2002). Water quality conditions of effluent-dominated streams and backwaters may be less variable, thus making observations of water quality changes more pronounced. Application of WLA and TMDL procedures to effluent-dominated waters requires attention to impoundment stratification, biotic dynamics, and spatial gradients in water quality. Therefore, the typical approach of stream monitoring during low flow conditions and establishing a WLA may not be adequate to meet applicable WQS (Taylor, 2002).

Indirect reuse and instream flow management

Throughout the semi-arid and arid southwestern U. S., managing minimum stream and river flow to protect ecological integrity is becoming increasingly problematic, particularly in rapidly urbanizing areas with effluent-dominated ecosystems. Along smaller order intermittent streams, excessive diversions, drought, impoundment, development, and impacted ground and surface water recharge, increasingly become sources of aquatic resource impairment. These sources result in modifications of the temporal and spatial instream flow through watersheds, ultimately threatening estuaries and coastal aquatic ecosystems (Baron, 1995). Such modifications of lower order tributary flows are an endemic concern throughout major river basins in many arid and semi-arid regions of the world (Elhance, 1999). Instream flow offers numerous societal benefits, including enhanced water quality, aquatic and riparian wildlife habitats, as well as, providing for aesthetic values, enhanced groundwater recharge, land preservation, and the generation of hydroelectric power by providing increased flows to higher order rivers (Lilly, 1980; Davis, 1988; Kaiser & Binion, 1996; Colby, 2002; NRC, 2005).

Instream flow protection within river basins represents a potentially contentious geopolitical concern, particularly when watersheds are shared by multiple, competing political jurisdictions or water-user groups. For instance, diversion projects and waste water discharges within the Jordan, Tigris-Euphrates, and Nile international river basins have directly and indirectly influenced how riparian states respond to cooperative management strategies, as well as, determined the extent to which such watersheds are utilized for economic development and the enhancement of public services (Elhance, 1999). Similar management and geopolitical concerns are also applicable to many watersheds in the southwestern US, including the Rio Grande, Colorado, and Trinity river basins, and may function as limiting factors for effective, sustainable development of effluent-dominated systems.

Statutory protection for instream flow management historically and presently is a challenge faced by many western US states (Kaiser & Binion, 1996; Tarlock, 1978). In fact, in many states existing water law presents a barrier to providing for instream flow protection, and only recently have efforts been made to use new legal and economic strategies to seek cooperative solutions (Tarlock, 1999; Pitt, 2002). An excellent innovation is the Texas Water Bank, which functions as a brokerage institution under the authority of the Texas Water Development Board. Within this Bank, water rights can be "deposited" and then purchased or leased by other entities subject to certain restrictions to maintain, among other values, instream flow (DeLaughter, 2000). However, the Bank has never been funded for instream management purposes, and the full extent of such water marketing solutions to water scarcity has yet to be revealed. In many western states, surface water is allocated under the rule of "prior appropriation," which authorizes and establishes water rights based off historical acquisition and beneficial use (Baade, 1986; Dellapenna, 2000). Twelve of the fifteen major river basins in Texas, for instance, are already fully appropriated for uses other than instream flow protection (Jordan, 1995; NRC, 2005). It was not until 1985 that Texas gave statutory recognition protecting estuary inflow, while the status of instream flow remains unrecognized as a beneficial use, except for the requirement to review any new water permit only after an instream flow need assessment has been completed (TWCA, 1988a). Presently, to provide for instream flow for maintaining aquatic and riparian habitats would require the reallocation of water rights through cancellation or condemnation, both politically disadvantageous options (NRC, 1992).

Compounding this dilemma in effluent-dominated streams is an increasing trend for water right holders such as municipalities, municipal water districts, and river authorities, to recover effluent discharges for indirect beneficial reuse (Smith, 1993). Ensuring adequate water supply in western states is becoming an urgent and serious challenge (Glennon & Culp, 2002). Traditional strategies to meet increasing water demands through appropriation of more water and the construction of new surface drinking water reservoirs are either impossible, as in the case of fully appropriated river basins, or cost-prohibitive, particularly in relation to the expense of constructing infrastructure for conveying water from new sources. To address the rising costs of new infrastructure, increasing water resource scarcity, and intensifying competition for available water supplies, many aquatic resource planners and managers are interested in reusing treated wastewater for potable and non-potable uses. For indirect reuse, reclaimed water is discharged into surface waters, which may dilute and assimilate various pollutants, after which the effluent is recovered downstream to supplement, for instance, a municipality's drinking water supply.

This method of beneficial reuse is becoming increasingly popular as a cost-effective alternative in the western United States. All western states presently employ some form of water reuse, though no shared common definition of reuse is universally defined. Two stressors encouraging drought-prone states to invest in beneficial reuse are population and precipitation (Shattuck, 2002). As larger intermittent and perennial rivers are allocated, or in many instances, overallocated, reuse project managers are turning more to smaller ephemeral and effluent-dominated streams, historically used only for wastewater discharges. This stresses historically ephemeral ecosystems dependent on precipitation for flow, especially if large segments of the stream are located in highly populated, urbanized areas (Tarlock, 2000).

Most western states lack comprehensive water reuse legislation, with only California, Oregon, and Washington having adopted specific rule-making (Shattuck, 2002). As more appropriated waters are re-appropriated through indirect reuse, overall less return flow from WWTPs is discharged to receiving waters, potentially influencing the biological integrity of effluent-dominated streams. This return flow is then used downstream by water rights holders or granted as new water rights for beneficial reuse programs. In many effluent-dominated rivers, this effluent return flow constitutes the primary – and during summer or drought conditions – the only historical flows for downstream water users. Additionally, in effluent-dominated systems, effluent discharges constitute the only temporal and spatial flow to support instream aquatic organisms (Meyerhoff et al., 2002). Essentially, due to urbanization, over-allocation, and structural manipulation, many western lotic, riparian and estuarine ecosystems are now uniquely dependent on surplus flows from unused water rights. Drought conditions only intensify this dilemma, revealing the precarious situation water resource development has on existing aquatic ecosystem management when consideration of environmental protection is withheld from allocation decisions (Kaiser & Kelly, 1987). Since most western states' water law is embedded in the rule of prior appropriation, water diversions, including reuse flows, are closely monitored, but are difficult to regulate and manage specific to downstream, junior water rights, and specifically, for the preservation of instream flow (Shattuck, 2002).

To address the often competing interests of indirect reuse and instream flow management, most western states require some type of public review and consideration for original or new water right applications (Brownlee, 2002). These statutes vary greatly between states (Kaiser & Binion, 1996: 174, note 95). In Texas, as of 1985, the Texas Commission on Environmental Quality is required to assess the effects on bays, estuaries, existing instream uses, fish and wildlife habitat, and water quality before issuing a water permit (TWCA, 1988b). However, since many rivers were fully appropriated prior to 1985, such assessment provisions have had little benefit. As urbanization of rivers continue, with increasing populations, and escalating water demands, the debate over managing indirect reuse and instream flow will continue, while simultaneously influencing lotic, riparian, and estuarine ecosystems that are dependent upon effluent flows.

Conclusions

Here we reviewed a number of water quality issues that, based on our experiences, are particularly germane to effluent-dominated stream ecosystems. Challenges exist to developing appropriate methods for monitoring, modeling, managing, and regulating effluent-dominated streams, which necessitate an understanding of watershed level processes, with or without effluent flows. Specifically, advancement in remote monitoring of stream flows is needed to improve measures of effluent dominated stream hydrology during baseline and highly variable storm flow events, which often influence water quality variables. Spatial and temporal monitoring of water quality patterns within intermittent streams is needed to develop models by which the impact of effluent-dominated streams may be assessed. Historically, aquatic and terrestrial organisms within and around intermittent streams have adapted to ephemeral flow regimes. Therefore, it is critical that biotic community dynamics of effluent-dominated streams and associated riparian habitats be understood in light of such water quality monitoring.

A lack of understanding the dynamics of effluent-dominated streams, including those that flow to reservoirs, has created a void in methods suitable for evaluating the ecological integrity of these ecosystems (Taylor, 2002). Future research will also be needed to assess long term impacts of point and non-point source loadings from urbanized areas and how these loadings influence regulatory considerations such as development of site-specific WQC and TMDLs. Long-term, low level releases of PPCPs may subtly modulate instream structure and function (Daughton & Ternes, 1999; Brooks et al., 2003a; Wilson et al., 2003). Potential interaction effects of pharmaceuticals with different and similar mechanisms of action, and with other personal care products such as surfactants (Ostroumov, 2002a) also deserve future attention in effluent-dominated streams. Because of the continuous nature of effluent discharge, effluent-dominated streams are ideal ecosystems for studying aquatic organism responses to these "pseudo-persistent" emerging contaminants (Brooks et al., 2003a). Similarly, utility of the BLM to predict site-specific bioavailability and acute toxicity of metals to model organisms is particularly valuable in effluent-dominated streams (Brooks et al., 2004). However, future studies should evaluate how well BLM or other modeling approaches predict chronic responses of instream assemblages (Brooks, 2002).

Application of a watershed approach to the management of effluent-dominated streams may be specifically useful for beneficial reuses and instream flow protection. In particular, a watershed approach may improve our understanding of trends in water permitting, water recycling, and land use impacts of instream flow marketing. Likewise, it will assist communities with the development of management policies for rural to urban water use transfers, including interbasin transfers, in rapidly urbanizing areas with effluent-dominated streams. Clearly, human reliance on effluent-dominated ecosystems for water resources will increase over the next few decades in the United States, and further scientific and policy studies are required to develop effective management models for water quality and quantity in these water bodies.

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