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A Long-Term, Multitrophic Level Study to Assess Pulp and Paper Mill Effluent Effects on Aquatic Communities in Four US Receiving Waters: Background and Status

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Special Series

EDITOR'S NOTE:

This is 1 of 8 papers reporting on the findings of an ongoing study conducted by the National Council for Air and Stream Improvement (NCASI) to understand the relationship between pulp and paper mill effluents and ecological conditions in 4 receiving streams in the United States. The data reported in this Special Series were collected between 1998 and 2006.

ABSTRACT

An industry-funded, long-term, receiving water study was initiated in 1998/1999 to address questions about the potential effects of pulp and paper mill effluent discharges on US receiving waters. Although the study continues, the knowledge gained to date provides an opportunity to reflect on the study development process, its progress, and its outcomes. As a backdrop to a series of articles in this special issue describing study results, this article describes the process by which study information objectives were identified as well as the process by which the experimental design was developed. A review of past literature and research identified gaps in long-term population/community data about effluent effects and that, consequently, emerged as a primary information objective. The selected streams for study included 1) Codorus Creek (Pennsylvania, USA), 2) Leaf River (Mississippi, USA), 3) McKenzie River (Oregon, USA), and 4) Willamette River (Oregon) represent a blend of mill process types, coldwater and warmwater stream types, and a range of effluent concentrations. Measurements included numbers of periphyton, macroinvertebrate, and fish communities; the assessment of water and effluent quality; laboratory bioassays; and fish full–life-cycle assays. Information objectives included addressing natural variability and, consequently, the study included long-term temporal (>10 y) and watershed-scale spatial frameworks. Regional-scale ecological risk assessments were performed for each site that aided in placing each site in an ecological and regulatory context. An adaptive-management process is described that allowed for modifications over time as a result of lessons learned as the study progressed. Results from the initial 7 to 8 y of monitoring, as described in the series of articles in this special issue, provide a unique data set with respect to addressing point-source pulp and paper mill effluent discharge concerns and may serve as a template for others to use in developing monitoring or management programs to assess or address water quality conditions or concerns.

Keywords: Pulp/paper mill effluent periphyton Macroinvertebrate Fish water quality Long-term monitoring Environmental management

INTRODUCTION

The pulp and paper industry is continually challenged by the public and regulatory agencies to address a variety of environmental responsibilities related to effluent discharges while, at the same time, meeting the need to remain economically viable by limiting unnecessary expenditures. The information needs necessary to meet environmental responsibilities are varied and complex and change over time in response to new research findings, emerging issues, and regulatory mandates. Before the implementation of effluent secondary treatment during the 1970s, concerns focused on oxygen consumption and obvious effects on biota linked to overall contaminate load (Owens 1991; Dubé et al. 2008). In the 1980s and 1990s, the focus shifted to chlorine-containing compounds and changes in biota exposed to mill effluents based on more sensitive indicators and detected by even more sophisticated methodologies (Owens 1991). The regulatory limits imposed on the industry followed these trends as witnessed by the Effluent Guidelines Cluster Rules in the United States (US Environmental Protection Agency [USE-

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PA] 2006) and revised Pulp and Paper Effluent Regulations in Canada (Environment Canada 1992). These regulations required the industry to make in-plant process changes as well as to install new secondary treatment facilities where none existed and to improve secondary treatment performance at existing facilities. These developments have positioned the pulp and paper industry to a point of compliance with respect to some of the most stringent regulatory requirements as well as substantial improvements in effluent quality.

The attention now shifts to decisions concerning the requirements of future environmental strategies. An important environmental goal for the industry with respect to effluent discharges is the long-term sustainability of aquatic communities and populations. This would be best addressed proactively by the industry, based on detailed scientific assessments using the most comprehensive environmental impact assessment tools/methods. The aim of such assessment is to gather information about the current status of aquatic populations/communities in relation to mill effluents and thereby assess the outcome of the changes implemented thus far and provide a foundation for future environment strategies. There has seldom been the opportunity for the industry to serve as an industry/science stakeholder in addressing developing regulatory approaches or in evaluating their environmental benefit once implemented. For example, changing regulatory priorities have, within the United States and internationally, never allowed time for confirmation of population/community level ecological significance of the short-term indicators of such effects that are used in regulatory programs, as encouraged by Owens (1991), Munkittrick and Sandström (2003), and others.

LONG-TERM RECEIVING WATER STUDY OVERVIEW

This article and others in this special issue relate to a long-term receiving water study (LTRWS) initiated in 1998 by the US pulp and paper industry in 4 effluent-receiving waters. The LTRWS is an integrated study; although the primary focus is at the aquatic population/community level, evaluations also used other biotic and abiotic assessment tools to identify and interpret possible effluent-related effects. It was also the intent at the beginning that, although the study was designed specifically to address questions about point-source effluent effects, it would be conducted at an expanded watershed spatial scale and at a multiple-year temporal scale. These expanded scales were chosen to better understand how potential effluent effects might be influenced by natural upstream/downstream changes, changes from season to season or from year to year, and changes in the human use of the watershed.

Although the study is funded by the forest products industry through membership in the National Council for Air and Stream Improvement (NCASI), a nonprofit research organization, it is not directed by the industry but rather by a panel of academic and industry research scientists. This background article focuses on the process through which the study information objectives and experimental design were developed and how the study is managed.

As a pulp- and paper-industry–based, voluntary initiative, the process by which the LTRWS was developed may be unique in the United States and elsewhere and, consequently, may be of interest to others. The developed set of biotic/abiotic monitoring parameters provided an initial, interpretive framework for documenting ecosystem conditions and assessing effluent effects. Using an adaptive management process, the methods were altered to refine and optimize monitoring elements over time. In some instances, measurements found to be of little value were discontinued or modified. Measurements found to be needed were added to the protocols.

Active research and rich literature exist related to effects, or indicators of effects, based on individual effluent-exposed organisms or field-based assessments. However, far fewer studies exist addressing whether short-term changes in individual pulp mill effluent-exposed fish or other aquatic community representatives equate to changes at the population or community level. Although subtle, actual or potential effects of an effluent on an individual organism may represent important technical and societal questions in their own right, they should be addressed as such and not as a priori evidence of population/community level effects. An example from a fish research perspective would be to ask whether short-term changes in reproductive markers (e.g., steroids, gonadal somatic indices, external sexual characteristics) for an individual species should be considered as evidence of altered reproductive capacity or sustainability for this species, or further, as evidence of impairment for the broader community of fish. Although this article and the majority of those in this series emphasize the importance of assessing effluent effects over an extended, temporal and spatial framework at the community and population level, there is no argument implied that short-term or other assessment tools are not also important. If an argument is to be made, it is that both long-term ecosystem, as well as short-term bioassessment, approaches are of value and that the strongest platform from which environmental protection concerns can be addressed is one that encompasses and embraces both types of data.

STUDY DEVELOPMENT AND INFORMATION OBJECTIVES

Perspective on effluent effects and ecologically relevant assessment endpoints

The LTRWS has benefited from several unique features. First, the study was not based on a regulatory requirement and, consequently, was free of specific mandates with respect to methodologies or to a requirement to generate quick answers. It also evolved without cause–effect hypotheses with respect to the effluent effects questions being addressed and, consequently, allowed flexibility in modifying existing or adding new monitoring parameters of interest. Second, industry commitment to the importance of long-term data in addressing effluent effects questions provided an unusual level of assurance for continued, requisite, stable funding. The flexibility in experimental design also allowed expansion of the spatial scope of the study to include a sufficient number of upstream/downstream monitoring locations to provide for an interpretation of potential effluent effects within the context of other anthropogenic or natural water quality influences.

Historical issues and approaches—Questions of effluent effects

Various approaches are available for assessing pulp and paper mill effluent-receiving water effects. Environmental assessments are sometimes classified by biological organization level in the progression: Community → population → whole organism → suborganism → molecular measurements, with each approach having advantages and disadvantages. The ultimate goal of most effluent-related environmental protection strategies is to preserve the integrity of the aquatic biota at the population/community level. Hence, the population/community approaches offer advantages in providing direct measurements at this organization level. However, these approaches are rarely undertaken because of costs and perceived complexities, and they also pose interpretation challenges because of likely interactions of large numbers of noneffluent-related environmental variables. Short-term bioassessments, at the organism and suborganism level, are more common because they can require less-complex study designs and less effort, but they create new questions about the significance of the findings in relation to populations and communities. Adams (2002) values lower organizational levels (e.g., biomarkers) but only if they are correlated and calibrated against higher-level organizational responses. The importance of addressing ecological integrity by assessing, or at least understanding, potential effects at the population/community level was stressed in the reviews by Owens (1991) and Hall and Miner (1997) as was the need for integrated studies leveraging the advantages of a variety of short-term and long-term, as well as organizational level, approaches. Munkittrick and Sandström (2003) also addressed this concern, noting that there has been a trend away from community and population level assessments toward lower levels of organization but that this can lead to controversy because relationships between these approaches have seldom been clarified.

In addition to organizational-level distinctions, approaches can also be partitioned according to whether they are field or laboratory based. Toxicity (bioassay) and many suborganism level tests are commonly carried out in the laboratory, whereas all population/community-based and some individual organism studies are carried out in effluent-receiving waters. This distinction can add another level of debate/controversy because laboratory tests are designed to minimize test-condition variables that may be important ecosystem drivers in effluent-receiving waters. Some assessment approaches that are carried out in the field use a set of organism- or suborganism-level metrics (e.g., condition factor, liver somatic index, gonadal somatic index) applied to a selected sentinel species to address population/community organizational concerns (Gibbons and Munkittrick 1994). The need for an integrated study design that incorporates both laboratory and field measurements has been supported by Owens (1991) and by Hall and Miner (1997). Munkittrick and Sandström (2003), however, emphasized that there should be strong evidence of field effects before investigations are extended to the laboratory.

Although addressing potential effects at the population/community level has been recognized as important, few such studies have actually been conducted in relation to pulp and paper mill effluents. At the time of the Owens (1991) review, the only multiple organizational-level study (benthic community, fish population, and perch biochemical measurements) had been in the Gulf of Bothnia (Baltic Sea) with an untreated, molecular, chlorine-based, bleached kraft mill effluent at Norrsundet, Sweden. More recently, Hall (1996) provided a review of 6 North American integrated monitoring studies and 2 large-scale outdoor experimental streams studies that included population/community level measurements in receiving waters. Kovacs et al. (2002) reported on a fish assessment carried out on the St. Francois River in Quebec, Canada, where an index of biotic integrity (IBI), based on measurements for 3 species, was compared with measurements of single sentinel species based on a fish health assessment index and measurements of mixed function oxidase (MFO) and plasma steroid levels. Van den Heuvel (2004) reported on only 1 community-based study underway at the time of his 2003 review of fish health studies.

The few studies comparing population/community and lower organizational-level measurements have been directed primarily at fish rather than the broader aquatic community. Exceptions are studies carried out with outdoor experimental streams exposed to bleached kraft mill effluent that included periphyton, macroinvertebrate, and warmwater (NCASI 1983) or coldwater fish communities (Hall et al. 1991; Haley et al. 1995). Although these experimental stream studies attempted to mimic the structure and function of natural streams, they were substantially simplified in comparison to the variability and complexity of natural streams. Another exception is the Environmental Effects Monitoring (EEM) program in Canada (Lowell et al. 2005), where fish health indicators for selected sentinel species in mill effluent-receiving waters are assessed in conjunction with measurements of benthic community abundance and taxa richness.

Past pulp and paper effluent studies have largely focused on single effluent-specific effects without consideration for effluent effects within a watershed or watershed management context. The LTRWS and associated regional-scale ecological risk assessment (Landis and Thomas 2009) provide an example of the value of combining both assessment approaches. The watershed risk assessment provides for the identification of stakeholder-valued water quality attributes and an identification of natural as well as human-related factors that may alter these. The expanded spatial scale of water quality and biological monitoring in the LTRWS provides support for the risk assessment, and the risk assessment, conversely, helps place the mill effluent discharge into a watershed context as it relates to stakeholder values and watershed management needs.

Current effluent effects issues and research status

The status of effluent-related effects until the beginning of the 1990s was summarized in the review by Owens (1991). Since then, the international interest in pulp and paper mill effluent effects has been significant as evidenced by a series of international fate and effects conferences, the first of which occurred more than 15 y ago (Södergren 1991). More than 100 peer-reviewed articles related to effluent biological effects have resulted from these conferences alone, including Servos et al. (1996), Stuthridge et al. (2003), and Borton et al. (2004). A series of more recent reviews included McMaster et al. (2006) on field studies and mechanistic research; Parrott et al. (2006) on the development and application of fish bioassays; and Hewitt et al. (2006, 2008) on the sources and characteristics of bioactive substances in mill effluents, especially in relation to fish reproduction, all with a focus on Canadian research. A review of case studies on pulp and paper mill effluents has also been provided by Dubé et al. (2008).

Much of the early research in this period related to the application of biomarkers, including MFO system induction, as indicators of effluent exposure and effect and whether this was related to mill processes or effluent treatment type. Although the use of biomarkers was prevalent, at the same time, questions arose about their relevance and significance. For example, the application of MFO induction as an indicator of effect, rather than simply one of exposure, was questioned in the research of Swanson et al. (1996) and others. Many of the fate and effects conferences addressed questions about the role of chlorinated organic compounds in effluents and their potential effects on aquatic organisms and whether sum parameters (e.g., absorbable organically bound halogens, extractable organic halogens, extractable organic chlorine) were useful indicators of effect for application in regulatory programs. Mill process changes, driven by market and regulatory mandates, resulted in significant reductions in effluents of chlorinated organic compounds before some of the chlorinated organics effects questions were fully investigated. These changes also took place during a period in which in some countries (e.g., Canada) secondary treatment of effluent was being implemented for the first time. The resulting action of 2 significant modifications (effluent treatment and the implementation of nonchlorine bleaching processes) created difficulty in identifying which, if either, was responsible for improved effluent quality as measured by biomarkers, bioassays, or other assessment tools (Munkittrick and Sandström 2003).

The receiving waters at 65 mill sites monitored in the Canadian EEM program have indicated a general pattern of nutrient enrichment, based on national patterns observed in studies involving benthic invertebrate communities and sentinel fish (Lowell 2005). In the case of invertebrates, enrichment was evidenced by a pattern of increased abundance with some effect on taxon richness. In the case of fish, the national pattern for effluent-exposed fish was larger liver, faster growth rate, and greater condition factor. Sentinel fish species observations were accompanied by a common pattern of downstream increases in benthic invertebrates supporting the expression of an effluent-related enrichment effect. Although the findings for both fish and invertebrates were described as a function of enrichment, reduced fish gonad size was additionally considered an indication of energy diversion away from reproduction and, consequently, an expression of metabolic disruption. Continued recent research has indicated that effluent reproductive effects indicators as observed in the Canadian EEM may be unrelated to mill process type, the level of effluent treatment, or other process-related variables but may more likely be due to a common causative agent or agents inherent in wood or a wood breakdown products (Dubé et al. 2008; Hewitt et al. 2008). Current fish reproduction research also includes laboratory-based partial and full life-cycle tests with selected fish species including those reported by Borton et al. (2009). Questions remain, however, about the parameters used for assessing reproductive effects in the wild or in the laboratory because many are generally short-term in nature and lack sufficient depth or context to address long-term population or community sustainability questions.

Ultimately, sustainability questions should be addressed through long-term measurements of effluent-exposed aquatic communities and populations for their continued viability and diversity. As noted, there is a paucity of long-term data of this type for fish and even less for periphyton and macroinvertebrate communities. Although timelines for environmental protection directives may not always allow for decisions to be made based on long-term or community-based data, this does not lessen the need for these data in addressing long-term environmental protection needs and priorities. For example, increasing attention paid to watershed-level ecological assessment and management ultimately requires a better understanding of aquatic organism health as expressed by long-term community diversity, structure, and stability measurements not only based on point source discharges but also on a variety of other land and water use activities. This focus also emphasizes the need to better understand water quality not only from a fish health perspective but also from a broader food web and trophic structure perspective. The recent development of nutrient criteria approaches in the United States, for example, points to the need for information not just in terms of nutrient concentrations and nutrient sources as they relate to primary production but also to the understanding of any resulting linkage between these conditions and alterations in trophic structure and function as measured in macroinvertebrate and fish communities.

LTRWS concept and study development

Development of the LTRWS began in 1995, with the formation of an industry task group (TG) to identify relevant information needs. The resulting scope and framework information objectives included 1) determining the environmental compatibility of mill effluents and corresponding margins of safety against adverse impacts, 2) documenting improvements in environmental quality as contaminant waste loads are reduced, 3) providing an early indication of any important adverse impacts related to mill effluents, and 4) extending the framework for interpreting new and subtle measures of aquatic organism and ecosystem health (Hall and Miner 1997). Also identified was the need to better understand the extent of variability (spatial and temporal) in mill effluent-receiving waters so that the significance of biological, physical, or chemical changes as they relate to mill effluent discharges could be more accurately interpreted. From this standpoint there was a consensus that the study be long term ($>$10 y) in nature and include a gradient of sample locations above and below the mill effluent discharges. Other recommendations included the need to include mills using both bleached (which may discharge trace amounts of chlorine-containing organics) and unbleached mill processes and receiving waters representing both coldwater and warmwater aquatic communities. The TG recommended an upstream/downstream study approach, viewing it unlikely that multiple paired-watershed approach opportunities could be found in the United States. The TG suggested 4 study streams as a goal, expecting that this would provide adequate representation of desired mill process categories, geography, and stream types. There was TG consensus that, once industry information needs were identified, further development and experimental design should be delegated to those with scientific expertise in aquatic biology and ecotoxicology.

Following TG scoping work, NCASI staff began screening for possible study sites that would meet the information objectives. The screening process included eliminating sites with confounding variables that might detract from the ability to detect or interpret mill effluent effects. Some site exclusion factors included the presence of dams that would create slack water or blockage to fish passage or the presence of other major mill or nonmill industrial or municipal discharges that might alter or influence water quality. More than 100 US receiving-water locations were identified initially but then

Table 1. Long-Term Receiving Water Study streams, mill types, and study parameters

Study stream	Location	Start date	Mill type	Stream (km)	Sample sites[a]	% Mean effluent concentration[b]	Receiving water type
Codorus Creek	Pennsylvania	1998	Bleached kraft	44	2/4	32.4	Coldwater upstream Warmwater downstream
Leaf River	Mississippi	1999	Bleached kraft	55	2/4	2.0	Warmwater
McKenzie River	Oregon	1998	Unbleached kraft + recovered fiber	31	2/3	0.5	Coldwater
Willamette River	Oregon	1998	Bleached kraft + recovered fiber	46	3/3	0.2	Coldwater

[a] Sample sites = the number of stations above/below the mill discharge.
[b] Mean effluent = percentage v/v after complete mixing.

reduced to 25 locations based on either positive or negative attributes plus an additional criterion that the focus be on freshwater ecosystems rather than marine or estuarine. Reconnaissance visits were made to some streams considered of high study potential. An industry Site Selection Committee (SSC) met 3 times in 1997 and reached a consensus on 3 initial study streams: Codorus Creek in Pennsylvania, USA, and the McKenzie and the Willamette rivers in Oregon, USA (Table 1). Codorus Creek is a small effluent-dominated stream and consequently met the margin of safety scope and framework study objective. The mills on Codorus Creek and the Willamette River both anticipated process changes, which met another study objective. The McKenzie River mill provided the desired addition of an unbleached mill along with a synergy in working with 2 rivers in the same watershed. The 3 locations also provided representation of both cold and warmwater stream types.

In 1998, at the conclusion of the site selection process, a 6-member science advisory panel (SAP) was formed by NCASI, consisting of representatives from academia ($n = 3$) and industry ($n = 3$) with professional experience in conducting river biological surveys and ecological assessments. The SAP typically met twice yearly and functioned as external LTRWS science stakeholders, helping to assure question focus and data quality, as well as providing a peer review of study findings, conclusions, and publications. The SAP also provided substantial input and critique in formulating field monitoring methods during the initial years of the study. The SAP members were reimbursed for travel and accommodations expenses associated with meeting attendance as well as a $500 honorarium for each meeting.

The LTRWS included an adaptive management approach. This approach provided for knowledge-based modifications to the study over time. As a long-term study, it was desired that methods once tested and adopted not be changed but also that the study be flexible so that as it progressed, sampling elements providing redundant or nonuseful information could be discontinued or new protocols added if new data needs were identified. Adaptive management was intended to optimize environmental information data acquisition based on the most efficient application of resources. It also was assumed that there would be some stream-specific method differences based on hydrology, morphology, or habitat factors unique, or of particular importance to, 1 or more of the study streams.

The LTRWS began monitoring with draft procedures on the 3 initial streams in 1998. Experience with monitoring protocols was the focus of discussion during initial SAP meetings, which also included the participation of guest experts in periphyton, invertebrates, and fish communities and assessments as well as in the statistical analysis of environmental data. The most complicated protocol changes were for periphyton, where methods evolved from rock surface subsamples to whole rocks. Most monitoring methods changes were, however, minor and were refined and resolved within the initial year of study.

During the initial year of monitoring, work continued toward identifying a large southern river as a 4th stream. Although the lower reaches of Codorus Creek classify as warmwater, its small size (mean flow 1.8 m^3/s) was atypical of more southern US warmwater receiving waters. The SSC, in conjunction with the SAP, concurred with the NCASI recommendation that the Leaf River, Mississippi, USA, be selected as the 4th study stream (Table 1). Monitoring began on the Leaf River in 1999.

EXPERIMENTAL DESIGN

Integrated study parameters

The LTRWS uses an integrated experimental design involving in-stream monitoring along with parallel laboratory assays for effluent chemical and biological quality (Table 2). In-stream biology focuses on population- and community-level measurements, except for fish, where individual fish are also assessed for length and weight, condition factor, and the presence of external anomalies. Habitat and chemical parameters are included, so the effects of these variables on biology may be assessed, as well as those of effluent-related parameters. Effluent is assessed for biological (i.e., bioassay) as well as chemical properties. Monitoring frequency ranges from monthly (in-stream chemical) to quarterly (effluent characterization and in-stream biology) to every 4 y (bed morphology).

Defining—What is the question?—One important aspect of experimental design was the recognition that there are 2 related types of questions relative to biological conditions: 1) is there a difference? and 2) if there is a difference, is there an impact on the receiving water? The type 1 question (is there a difference?) could be addressed by a variety of methods, including those of a short-term nature (e.g., bioassay) or at lower levels of biological organization (e.g., biomarker). Field assessments based on type 1 questions may also be carried out at the population/community level but without sufficient temporal or spatial scope to address broader-relevancy

Table 2. Primary in-stream measurements and effluent characterization parameters applied in the Long-Term Receiving Water Study

In-stream measurements			Effluent characterization	
Biological	**Habitat**	**Chemical**	**Biological**	**Chemical**[a]
Fish	Bed morphology	Color	Chronic bioassay	Alkalinity
Population/community metrics	Current velocity	Conductivity	*Ceriodaphnia dubia*	BOD
Weight/length	Photo record	Hardness	*Pimephales promelas*	COD
Condition factor	Riparian zone	Metals	*Selenastrum capricornutum*	Color
External anomalies	Solar radiation	Nutrients		Conductivity
	Substrate	pH	Full life cycle	Hardness
Macroinvertebrate	Temperature	—	*P. promelas*	Metals
Population/community metrics	Turbidity	—	—	Nutrients
Biomass	—	—	—	Resin/fatty acids Tannin/lignin
Periphyton	—	—	—	TOC
Population/community metrics	—	—	—	TSS
Chlorophyll	—	—	—	—

[a] BOD = biological oxygen demand; COD = chemical oxygen demand; TOC = total organic carbon; TSS = total suspended solids.

questions (i.e., single point in time or single upstream/downstream sample sites). The overarching objective in the LTRWS was to select monitoring parameters that were sensitive but were also relevant to addressing the type 2 question, which relates directly to whether aquatic communities are stable and sustainable at the at the population/community level. It was recognized that type 1 questions could be addressed through potentially sensitive laboratory or short-term indicators of effect but that they would, in turn, require type 2 question validation with respect to their relevance and reliability in addressing the long-term conditions of various algal, macroinvertebrate, and fish populations/communities. Consequently, the LTRWS focused, wherever possible, on addressing the type 2 question directly through appropriate field measurements. Periphyton and benthic macroinvertebrates (BMIs), for example, were sampled from natural substrates, even though artificial substrates would have minimized variability. Also, a regimen of multiple seasonal and annual samples was incorporated to address temporal variability, and a gradient of multiple sample sites was employed to address spatial variability. A focus on type 2 questions also served as a filter when new questions arose or in considering modifications to methods. For example, discussions took place related to whether fish tissue samples should be taken for chemical analysis or autopsy for the determination of organ condition or morphometry. In both instances, the decision was that it was of greater importance to direct resources toward population/community assessment and type 2 questions. This was in part due to the reality of finite resources and in part to an expression of adaptive management, where type 1 questions and approaches could be pursued later if effects were identified at the population/community level.

Study management, structure, and funding

The LTRWS may be unique in the United States and internationally with respect to its having a long-term, industry funding commitment, with a structure that provided for industry-defined information needs, and then, the development of an independent science-based experimental design to address those information needs. Following TG development of industry scope and framework objectives, a draft experimental design, was developed by NCASI aquatic biology staff and was then reviewed by the SAP. Questions raised by the SAP were, in most cases, resolved through study design modifications. There were only a few exceptions where those modifications would have exceeded the available resources.

The NCASI staff met with the SAP twice yearly, beginning in 1998, for the purpose of reviewing experimental design and study progress. In addition, NCASI staff met 2 to 3 times annually with an industry TG responsible for reviewing LTRWS progress and budget requirements as well as other elements of a broader aquatic biology program. The industry TG purview did not extend to decisions related to experimental design issues or to review or judgment about study conclusions or how they were communicated with respect to publications or conferences. The NCASI also provided periodic reviews of LTRWS progress and findings to the environmental staffs of the 4 host mills.

Funding for the LTRWS was provided through a portion of the association dues from the NCASI member companies. For most years, expenses for carrying out field work on the 4 streams were approximately US$100000, not including an associated staff allocation of 3 field technicians (full time), a senior research biologist (full time), and a program manager (part time). The NCASI field technicians carried out most sampling but worked in conjunction with paid contractors in some cases. One example was the Leaf River, where monthly water quality samples were collected by a contractor, and a state agency provided boat and staff for electrofishing. Another exception was the collection of fish during the initial 3 y of monitoring on Codorus Creek and the McKenzie and Willamette rivers, which was carried out under a research agreement with Western Washington University (L. Bodensteiner, Huxley College of the Environment, Bellingham, WA, USA). This agreement allowed for a more detailed initial seasonal assessment of fish populations and the training of NCASI staff in boat and backpack electrofishing skills. It also provided for the completion of Relative Risk Assessments for these same streams (Landis and Thomas 2009).

Methods for in-stream measurements used in the LTRWS, including quality assurance/quality control (QA/QC) are described by NCASI (2008) as well as for corresponding laboratory procedures (NCASI 2005). Water quality measurement and QA/QC generally followed those of American Public Health Association (APHA 2000) or NCASI (1986, 1997, 2000). Bioassay methods followed those of USEPA (2002). Written procedures and QA/QC practices were also required of contractors associated with the study. Data entry QA/QC included an independent cross-check by a NCASI staff member before data were archived in either Microsoft Excel or Microsoft Access database formats. The NCASI technical bulletins referenced in this article or other articles in this series, including data compendia, are available on the public side of the NCASI Web site (www.ncasi.org).

RESULTS AND DISCUSSION

Results from the initial 8 y of the LTRWS are presented in the series of articles in this issue. Although the study continues, it was felt that sufficient time and effort have been expended to communicate the results to date. The characteristics of the watersheds, mills and mill effluents, sample sites, water quality, and habitat parameters are reported by Hall, Ragsdale, et al. (2009). A series of articles by Flinders, Minshall, Hall, et al. (2009); Flinders, Minshall, Ragsdale, et al. (2009); and Flinders, Ragsdale, and Hall (2009) describe upstream/downstream patterns for periphyton, macroinvertebrate, and fish communities and their relationship to effluent or other water quality parameters. The results of laboratory fathead minnow (*Pimephales promelas*) full life-cycle studies with the 4 effluents are described by Borton et al. (2009) and represent an additional approach to assessing fish reproduction effects beyond those measured directly through long-term, in-stream community assessment. Finally, a compilation and overview of the lessons learned from the initial years of the LTRWS are presented by Hall, Fisher, et al. (2009).

Beyond the lessons learned with respect to questions about potential effluent effects, the LTRWS development process provided useful insights that others might wish to consider in developing similar studies. These insights included the importance of addressing effluent effects questions from a watershed spatial scale and a multiyear temporal scale and the provision for an adaptive management approach.

Watershed spatial scale

The inclusion of multiple sample sites above and below each mill discharge was initially included in the LTRWS, based on a concern that simple upstream/downstream sample comparisons might potentially be expressions of in-stream habitat variability unrelated to the effluent discharges. As reported by Hall, Ragsdale, et al. (2009), there were, in fact, significant biologically important upstream/downstream habitat changes identified for some of the LTRWS rivers that might have otherwise been confused with effluent effects. Examples included current velocity differences immediately above and below the discharge on the McKenzie River and differences in incident light above and below the discharges on Codorus Creek and the Willamette River. Codorus Creek also provided an example of marked upstream/downstream habitat change with the area upstream in the vicinity of the mill having a rich riparian habitat, which degraded to riparian-poor flood-control channelization downstream. The expanded watershed spatial scale also allowed the identification of tributaries as important nutrient contributors to the study streams.

Application of the LTRWS at a watershed scale also fits well with a shift in the United States toward watershed-based regulatory programs. Examples include total maximum daily load (TMDL) programs targeting the achievement of biocriteria, temperature, dissolved oxygen, organics, metals, nutrients, or other parameter levels that are consistent with established or proposed water quality standards. From an industry perspective, TMDLs provide an example of the need to better understand potential effluent effects within the context of the broader watershed. Experience with nutrients, for example, indicates that, for these 4 streams, the mill discharges contribute little or no measurable in-stream nutrient signal, contrasting with strong signals from adjacent agriculture-influenced tributary streams (Hall, Ragsdale, et al. 2009). It would be desirable when addressing nutrients or other water quality conditions that watershed management and regulatory efforts be prioritized according to the relative importance of various point or nonpoint sources within the watershed.

Multiyear temporal scale

Long-term ecological research studies, although rare, are necessary for identifying nonequilibrium or nonlinear characteristics, and although the need is clear, most ecological research does not extend beyond traditional 2- to 3-y grant periods (Hobbie et al. 2003). Without a long-term temporal context (or a large spatial scale), short-term ecological findings can be difficult to interpret. The LTRWS included, as a design element, what was envisioned as sufficient time to address temporal variability (>10 y).

Data from the initial 4 to 5 y of the LTRWS were used for assessing potential minimum temporal variability-based timelines for the study streams (Thomas 2005). The approach included a consideration for the relevant life span of small- and large-bodied fish, the desired statistical power, and the use of the annual hydrograph as a measure of system abiotic variability. Codorus Creek provided the shortest minimum study timeline driven by moderate abiotic variability. At the LTRWS sample frequency (2–4 times/y), the timeline for expressing differences was 2 y and 12 y, respectively, for short-lived, small-bodied fish and for long-lived, large-bodied fish. The primary driving factor for study duration on Codorus Creek was the reproductive life span of respective small-bodied and large-bodied fish rather than abiotic factors. Larger abiotic variability on the Leaf River extended the large-bodied fish timeline to >16 y. The McKenzie and Willamette rivers with low abiotic variability had intermediate time line values of 7 and 8.5 y, respectively, for small-bodied fish and 15 y (both rivers) for large-bodied fish. Although not analyzed by Thomas (2005), the shorter relevant life span for periphyton (days or weeks) and macroinvertebrate (months) communities might allow for much shorter study timelines. This analysis emphasizes the value of long-term ecological assessment in identifying effect drivers and variability, that there is an essential relationship between study duration and effect size, and that this may be site specific.

One objective of the LTRWS was to evaluate the effects of mill process changes on effluent quality and whether these resulted in measurable improvements in receiving-water quality. The timeline assessment by Thomas (2005) suggests that it may be necessary to reset the study duration clock if the same level of environmental assessment certainty is desired following mill process changes or, similarly, for changes that reflect significant nonmill-related disturbances in the watershed.

As addressed by Hobbie et al. (2003), an advantage of a long-term study is the opportunity to identify response and recovery from natural disturbances. The availability of long-term data may help to avoid misjudgments about current environmental conditions, including the extent to which they have been impacted by anthropogenic activity. The initial 8 y of the LTRWS illustrated the value of a long-term study in capturing potentially significant natural disturbance events. Significant drought conditions occurred for each of the 4 streams during the study period, including historic low flow on the Leaf River and near-record low flows on the McKenzie and the Willamette rivers. The study also spanned a period during which water quality on the Leaf River was influenced by Hurricanes Rita and Katrina. The availability of a data set before and after these and other natural events provides an opportunity to better understand disturbance/recovery processes.

Adaptive management

An adaptive management policy provided for monitoring protocol changes over the course of the study. Method modifications were based primarily on initial-experience protocols, site-specific considerations, and an assessment of accumulated data. As a long-term study, it was considered important that effort expenditure be optimized with a provision to add, delete, or modify monitoring elements where needed. The opportunity to apply an adaptive management approach was considered an advantage in the LTRWS because there were no requirements to follow a rigid study protocol, which may occur under regulatory-based or litigation-based monitoring programs. The development of initial field methods included the application of standard field protocols, many based on USEPA rapid bioassessment protocols (RBP) (USEPA 1999) for wadeable streams and rivers. Resulting modifications were based on initial success with these methods in the field, combined with consultation with the SAP and a group of guest experts in the fields of periphyton, macroinvertebrate, and fish sampling. Some protocol changes were a reflection that only 1 of the study streams (Codorus Creek) was wadeable and, therefore, not all the RBP approaches were directly applicable.

Examples of adaptive management include increased monitoring frequency (4 times/y) during the initial 3 y for Codorus Creek and the McKenzie and the Willamette rivers, followed by a reduction in frequency (2 times/y) once data were available to allow seasonal and annual variability to be assessed (NCASI 2002, 2003a, 2003b). A further reduction in monitoring to 1 time/y for Codorus Creek took place based on the variability/sample duration analysis of Thomas (2005). Another adaptive management example is the reduction of monthly water samples from 12 times/y to 6 times/y after 6 y of data were analyzed for seasonal and annual variability. Similarly, the frequency of chronic toxicity testing with *P. promelas* was reduced after 3 y because of a general lack of response at 100% v/v effluent, and tests with *Selenastrum capricornutum* were added when this testing ability became available. Biological sample method changes also took place based on initial experience, including a switch from Surber to Hess samplers to avoid the wash around of BMI samples for 3 streams (Codorus, McKenzie, and Willamette). For the Leaf River, Hester–Dendy multiplate samplers were used for BMI samples rather than native sand habitat to express greater potential BMI diversity. Another Leaf River modification was the development of a method for sampling periphyton chlorophyll *a* from native sand that followed a series of trials with several types of artificial substrates. Continued use of adaptive management will allow for the addition of new monitoring parameters where effects questions are raised within the existing study framework or to address new questions that might result in conjunction with future mill process changes or regulatory activities.

SUMMARY

The LTRWS provides an example of a research initiative addressing questions about single-industry effluent effects in receiving waters. The main goal of the pulp and paper industry in initiating this study was to obtain evidence as to the status of aquatic communities/populations in relation to mill effluents under current operating conditions and regulations. Study information could be used to learn about the effectiveness of current mill operating practices with respect to the aquatic environment and to provide the basis for future management decisions concerning environmental protection, if needed. Industry stakeholders contributed to a study scope and framework, which was subsequently implemented in 4 US receiving waters under the auspices of an academic–industry SAP with additional guidance from aquatic ecosystem experts. The resulting experimental design for this continuing study integrated both field and laboratory assessments as well as abiotic and biotic parameters. A population/community level monitoring approach was chosen for field assessment based on the desire for ecosystem sustainability to be the driving force for the formulation of environmental strategies. Assessments at lower levels of organization were also carried out in the laboratory. The study framework included a broad watershed spatial scale and a multiseason/multiyear temporal scale to provide for an interpretation of mill effluent signals within the context of natural variability. It also incorporated an adaptive management approach with flexibility to modify, delete, or add monitoring parameters over the duration of the study in an effort to optimize both resource expenditure and information generation. The temporal and spatial scale of the study allowed for a weight-of-evidence approach to be taken across the matrices of biological and physical/chemical parameters. Knowledge gained with respect to variability contributed to a data-based approach to defining suitable study duration, which varied according to relevant life span (e.g., small-bodied, short-lived fish vs large-bodied, long-lived fish).

Finally, a regional scale ecological risk assessment carried out for each river addressed effluent as well as other factors at a broader watershed scale.

CONCLUSION

The study provides an example of an approach to addressing water quality concerns and may serve as a model for other industries to follow. It provides a detailed framework for conducting watershed-based ecological assessments, which may be useful for others in addressing watershed concerns, management, or protection issues.

Details of study findings are provided in the series of LTRWS articles in this special issue. A detailed description of the study experimental design, including a description of study streams, sample sites, mills, and mill effluents is provided by Hall, Ragsdale, et al. (2009). Also described are water quality and habitat measures for the 4 streams as well as effluent chemical and biological characterization. Flinders, Minshall, Hall, et al. (2009a) describes periphyton spatial and temporal patterns above and below the mill discharges for the 4 streams based on chlorophyll *a* standing crop as well as macroinvertebrate community-structure metrics (Flinders, Minshall, Ragsdale, et al. 2009). Fish community-structure patterns are described by Flinders, Ragsdale, and Hall (2009c), and results are reported from laboratory-based, full life-cycle, reproductive effects tests by Borton et al. (2009).

The 13-y path to develop, implement, and carry out especially the initial years of the study provided an opportunity to reflect on what worked well, and not so well, in the LTRWS. These lessons learned are recounted in the last article of this series (Hall, Fisher, et al. 2009), along with an overview of findings related to pulp and paper mill effluent effects from the initial years of the study.

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