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AN SAB REPORT: EVALUATION OF THE BLACKSTONE RIVER INITIATIVE

PREPARED BY THE ECOLOGICAL PROCESSES AND EFFECTS COMMITTEE

September 11, 1998

EPA-SAB-EPEC-98-011

Honorable Carol M. Browner
Administrator
U.S. Environmental Protection Agency
401 M Street, S.W.
Washington, DC 20460

Subject: Evaluation of the Blackstone River Initiative

Dear Ms. Browner:

At the request of Region I Administrator John DeVillars, the Ecological Processes and Effects Committee (EPEC) of the EPA Science Advisory Board (SAB) met on March 24-25, 1998 in Boston, MA to review the Blackstone River Initiative (BRI). The BRI is an inter-agency, inter-state project to monitor and model water and sediment quality in the Blackstone River in Massachusetts and Rhode Island. The river is an important natural resource that has experienced the effects of industrial and sewage treatment plant effluents, runoff from urbanized areas, and damming for hydropower. The river has also been identified as a major source of metals and nutrients to Narragansett Bay. Although the SAB rarely conducts regional reviews, the BRI presented an opportunity for the Committee to assist a Regional office with peer review and to encourage Regional adoption of integrated watershed assessment approaches.

The BRI study was designed to assess the influence of wet weather flows on baseline water quality conditions in the Blackstone River. This was accomplished with field monitoring to assess conditions during storm events and during dry weather (base flow) conditions, and modeling of dissolved oxygen, suspended solids, and metals. The BRI also included toxicity bioassays using effluent and sediment samples and some limited biological assessments with fish and macroinvertebrate species. In addition, a more detailed study of water column and sediment contaminants was conducted for one of the impoundments along the river (Rice City Pond) in order to develop possible remedial actions.

The overall charge to the EPEC Committee was to assess whether the BRI study design and implementation met the project objectives to determine current water quality in the Blackstone River under wet and dry flow conditions, assess the relative contribution of pollutant loadings from point- and nonpoint-sources in the Blackstone watershed, and forecast annual pollutant loading rates.

The Committee's comments on the BRI fall into two categories. First, and foremost, the Committee commends Region I and the other BRI participants for initiating the study. Despite the limitations noted in the SAB report, the Committee believes that the BRI study represents a significant advance for the Agency as an initial attempt to integrate multi-agency, multi-scale, and multi-environmental stressor considerations. The Committee also noted that the contribution of volunteer and in-kind services was impressive, and the BRI's accomplishments far surpass the dollars expended by the EPA.

There were, however, a number of deficiencies noted by the Committee in the BRI study. While many of these shortcomings appear to be due to budgetary limitations, they nonetheless affect the conclusions that can be drawn from the project. One important issue was the insufficiency of wet flow events to characterize adequately the range of wet flow conditions that occur on annual and decadal time scales. The BRI study does not offer a solid basis to estimate total annual pollutant loadings into Narragansett Bay. The Committee noted several deficiencies of the BRI study in the use of models to predict water quality parameters. The Committee also noted the emphasis on chemical characteristics of the water, rather than the needed broader look at the ecological condition of the river and the watershed. The Committee's report describes important areas where the current BRI report can be improved and enhanced.

The second set of comments and recommendations highlight the benefits to be gained from a second phase of the BRI that takes a truly watershed focus. Although the Region did not present firm plans to continue and broaden the BRI, the Committee strongly recommends that a new phase of the study be initiated. Components of a recommended next phase are described in some detail, and include incorporation of the ecological risk assessment framework, limited additional monitoring, inclusion of biological information and land-use/land-cover data for the watershed, use of Geographic Information System (GIS) analysis of the data, and the use of more appropriate existing models for watershed-level analysis.

Emphasis by the Committee on a subsequent phase of the BRI reflects the Committee's view that the current BRI results will not provide an adequate scientific basis for some of the management decisions that are under consideration for the Blackstone River-Narragansett Bay system. For example, load allocation decisions will require an improved understanding of the relative contributions of point and non-point sources within the watershed; selection of remedial options for the river (including possible removal of some of the dams) will require a better understanding of the cycling of metals and other contaminants within the impoundments, as well as watershed sources of such contaminants; and management decisions to control nutrient loadings to Narragansett Bay would be improved by a more rigorous approach to forecasting pollutant loads from the Blackstone River to the Bay.

The Committee, therefore, strongly urges the Agency to build on the BRI study, and the inter-agency and government/academic partnerships it fostered, as a case study example of an attempt to do true watershed management. The next phase of the BRI would entail working with the partners to bring the scientific tools to bear on a broader set of management options, looking well beyond simple chemical management to additional stressors, using multiple endpoints at the watershed and landscape levels. Agency support for an expanded BRI program would be consistent with and supportive of the EPA's increasing focus on community-based environmental protection (CBEP) and watershed management approaches. In fact, although the recommendations for future work contained in this report are cast in terms of the BRI, many of the sampling, analysis, and modeling issues apply equally well to assessments in other watersheds.

We hope these comments will be useful to you in your efforts to increase the Agency's emphasis on integrated watershed management, and to Region I in gaining the maximum benefit from the BRI project. We look forward to your response.

Sincerely,

Joan M. Daisey

Dr. Joan M. Daisey, Chair
Science Advisory Board

Mark A. Harwell

Dr. Mark A. Harwell, Chair
Ecological Processes and
Effects Committee
Science Advisory Board

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ABSTRACT

At the request of Region I Administrator John DeVillars, the Ecological Processes and Effects Committee (EPEC) of the EPA Science Advisory Board (SAB) met on March 24-25, 1998 in Boston, MA to review the Blackstone River Initiative (BRI). The BRI is an inter-agency, inter-state project to monitor and model water and sediment quality in the Blackstone River in Massachusetts and Rhode Island. The river is an important natural resource that has experienced the effects of industrial and sewage treatment plant effluents, runoff from urbanized areas, and damming for hydropower. The river has also been identified as a major source of metals and nutrients to Narragansett Bay. Although the SAB rarely conducts regional reviews, the BRI presented an opportunity for the Committee to assist a Regional office with peer review and to encourage Regional adoption of integrated watershed assessment approaches.

The BRI study was designed to assess the influence of wet weather flows on baseline water quality conditions in the Blackstone River. This was accomplished with field monitoring to assess conditions during storm events and during dry weather (base flow) conditions, and modeling of dissolved oxygen, suspended solids, and metals. The BRI also included toxicity bioassays using effluent and sediment samples and some limited biological assessments with fish and macroinvertebrate species. In addition, a more detailed study of water column and sediment contaminants was conducted for one of the impoundments along the river (Rice City Pond) in order to develop possible remedial actions.

The Committee concluded that the BRI study represents a significant advance for the Agency as an initial attempt to integrate multi-agency, multi-scale, and multi-environmental stressor considerations. The effort to characterize both “dry” and “wet” conditions was important in showing that different processes govern pollution input, transport, and fate in this system during different weather patterns. This has important implications, for example, for management of the system and for the calculation of loadings to Narragansett Bay. However, the Committee noted a number of deficiencies in the study that, while apparently due to budgetary limitations, limit the conclusions that can be drawn from the study. The Committee, therefore, strongly urges Region I and the other participants in the BRI to initiate a subsequent phase of the project to take the needed broader look at the ecological condition of the river and the watershed. Recommended components of a subsequent phase of the BRI include incorporation of the ecological risk assessment framework, limited additional monitoring, inclusion of biological information and land-use/land-cover data for the watershed, use of Geographic Information System (GIS) analysis of the data, and the use of more appropriate existing models for watershed-level analysis.

KEYWORDS: watershed assessment; dissolved oxygen; nutrients; metals

U.S. ENVIRONMENTAL PROTECTION AGENCY
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Review of the Blackstone River Initiative
March 24 - 25, 1998

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1. EXECUTIVE SUMMARY

At the request of Region I Administrator John DeVillars, the Ecological Processes and Effects Committee (EPEC) of the EPA Science Advisory Board (SAB) met on March 24-25, 1998 in Boston, MA to review the Blackstone River Initiative (BRI). The BRI is an inter-agency, inter-state project, organized by EPA at the request of the Massachusetts Department of Environmental Protection and the Rhode Island Department of Environmental Management, to monitor and model water and sediment quality in the Blackstone River in Massachusetts and Rhode Island. The river is an important natural resource that has experienced the effects of industrial and sewage treatment plant effluents, runoff from urbanized areas, and damming for hydropower. The river has also been identified as a major source of metals and nutrients to Narragansett Bay. Although the SAB rarely conducts regional reviews, the BRI presented an opportunity for the Committee to assist a Regional office with peer review and to encourage Regional adoption of integrated watershed assessment approaches.

The BRI study was designed to assess the influence of wet weather flows on baseline water quality conditions. Three storm events were sampled (in September and November 1992, and October 1993), and this information was used in combination with surveys of dry weather (base flow) conditions (conducted in July, August, and October 1991). Water and sediment quality parameters measured included dissolved oxygen (DO), chlorophyll *a*, chloride, pH, biochemical oxygen demand (BOD), nutrients (ammonia, nitrate, and orthophosphate), and trace metals (Cd, Cr, Cu, Pb, and Ni). The QUAL2E model was used to model DO dynamics, and the Pawtoxic model, which is based on TOXIWASP, was used to simulate total suspended solids (TSS) and metals. Toxicity bioassays were performed using effluent and sediment samples and some limited biological assessments were performed with fish and macroinvertebrate species. In addition, a more detailed study of water column and sediment contaminants was conducted for one of the impoundments along the river (Rice City Pond) in order to develop possible remedial actions.

The charge to the EPEC Committee was to assess whether the BRI study design and implementation met the project objectives to determine current water quality in the Blackstone River under wet and dry flow conditions, to assess the relative contribution of pollutant loadings from point- and nonpoint-sources in the Blackstone watershed, and to forecast annual pollutant loading rates. Additional specific questions were asked of the Committee concerning the approaches used in the BRI for describing dissolved oxygen, modeling metals and suspended solids, defining aquatic life criteria violations,

identifying hot spots in the river, estimating annual loading rates into Narragansett Bay, and making available the database to the scientific community and the public.

The Committee commends EPA Region I and other participants in the BRI for initiating the study. The project is important for a number of reasons: it looks at the river as a whole, rather than studying segments in isolation within political boundaries; it begins to relate water quality conditions within the river to watershed contributions to loadings (e.g., wet weather loadings); and it demonstrates cooperation among multiple federal, state, and local organizations, which is a major accomplishment. The research provides significant insights into the influence of wet weather conditions, an issue that is important in this and other regions. The contribution of volunteer and in-kind services was impressive, and the BRI's accomplishments far surpass the dollars expended by EPA. The participants are also highly commended for their efforts to bring the report to completion, and to disseminate the findings and data.

There were, however, a number of deficiencies noted by the Committee in the BRI study. While many of these shortcomings appear to be due to budgetary limitations, they nonetheless affect the conclusions that can be drawn from the project. One important issue was the insufficiency of wet flow events to characterize adequately the range of wet flow conditions that occur on annual and decadal time scales. The BRI study does not offer a solid basis to estimate total annual pollutant loadings into Narragansett Bay. The Committee noted several deficiencies of the BRI study in the use of models to predict water quality parameters. The Committee also noted the emphasis on chemical characteristics of the water, rather than the needed broader look at the ecological condition of the river and the watershed. Coupling the BRI data base with a spatially explicit (GIS-based) watershed-scale land-use data base is essential to identify sources of stressors to the river system. The Committee also commented on the benefits of integrating the BRI study into the EPA ecological risk assessment framework, which include consideration of a broader set of stressors to the watershed-river-estuary system and articulation of specific ecological characteristics of the system to be protected.

As a result of these deficiencies, the Committee concludes that the BRI study at this point is not sufficient to form the basis for some of the management decisions raised in the charge questions concerning the Blackstone River and, especially, its influence on the Narragansett Bay ecosystem. For example, important decisions are expected to be made concerning the management of the numerous impoundments along the Blackstone River, affecting river habitat as well as water quality parameters such as DO and metals, yet the BRI study does not provide the type of information needed to evaluate the efficacy of impoundment management options (e.g., data on water and sediment quality and dynamics with the impoundments). Similarly, there are insufficient data to distinguish nonpoint- from point-source contributions under various parts of an annual hydrograph.

Despite these limitations, the Committee believes that the BRI study was a significant advance for the Agency because of its integration of multi-agency, multi-scale, multi-stressor considerations. As a result, the Committee strongly urges the Agency to build upon the BRI study, and the inter-agency and government/academic partnerships it fostered, as a case study example of an attempt to do true watershed management. The next phase of the BRI would entail working with the partners to bring the scientific tools to bear on a broader set of management options, looking well beyond simple chemical management to additional stressors, using multiple endpoints at the watershed and landscape levels. Agency support for an expanded BRI program would be consistent with and supportive of the EPA's increasing focus on community-based environmental protection (CBEP) and watershed management approaches.

Specific elements in of a subsequent phase of the BRI would include development and use of an integrated, GIS-based data base of monitoring, landuse, modeling, and other types of information. It should include development of watershed-scale water runoff models, coupled to continuous monitoring of outputs from the Blackstone River to Narragansett Bay. Biological considerations should be integrated with the current focus on engineering solutions. EPA and the states should focus on developing the quantitative tools and supporting database to allow effective characterization of the consequences of potential management options.

The BRI should also be expanded to include the full set of relevant chemical, biological and physical stressors, including metals, nutrients, organics, and habitat alteration. Assessment and management of the Blackstone River system in a broader context will be enhanced by the application of an ecological risk assessment framework. The ecorisk framework explicitly identifies stress regimes, ranks stressors, identifies ecosystem at-risk, identifies specific ecological endpoints for each ecosystem, makes explicit ecological/environmental goals, incorporates sensitivity analyses for data and analytical uncertainties, and supports a report card construct to evaluate the efficacy of management decisions and identify corrections to improve the health of the environment. Such an approach constitutes the next generation of ways to improve the environment. The BRI is an ideal point-of-departure for Region I and the Agency for watershed management and as a demonstration project for implementation of ecorisk assessment in different watersheds and in different regions.

In summary, EPA support for a subsequent phase of the BRI would allow more informed consideration of management and remediation options for the Blackstone River, both from the perspective of water and sediment quality within the river, as well as the river's contributions of nutrients and contaminants to Narragansett Bay. Although the recommendations for future work contained in this report are cast in terms of the BRI, many of the same sampling, analysis, and modeling issues apply to assessments in other watersheds.

And finally, the findings of the BRI should be disseminated in the region by the Agency and other participants in the project to increase public understanding of the environmental condition of the Blackstone River. For example, the National Park Service should incorporate information about environmental degradation of the River into its educational materials so as to inform current and future generations about the long-term environmental consequences of taking a river for granted.

2. BACKGROUND AND CHARGE

2.1 Background

At the request of Region I Administrator John DeVillars, the Ecological Processes and Effects Committee (EPEC) of the EPA Science Advisory Board (SAB) met on March 24-25, 1998 in Boston, MA to review the Blackstone River Initiative (BRI). The BRI is an inter-agency, inter-state project, organized by EPA at the request of the Massachusetts Department of Environmental Protection and the Rhode Island Department of Environmental Management, to monitor and model water and sediment quality in the Blackstone River in Massachusetts and Rhode Island. The river is an important natural resource that has experienced the effects of industrial and sewage treatment plant effluents, runoff from urbanized areas, and damming for hydropower. The river has also been identified as a major source of metals and nutrients to Narragansett Bay. Although the SAB rarely conducts regional reviews, the BRI presented an opportunity for the Committee to assist a Regional office with peer review and to encourage Regional adoption of integrated watershed assessment approaches.

The BRI study was designed to assess the influence of wet weather flows on baseline water quality conditions. Three storm events were sampled (in September and November 1992, and October 1993), and this information was used in combination with surveys of dry weather (base flow) conditions (conducted in July, August, and October 1991). Water and sediment quality parameters measured included dissolved oxygen (DO), chlorophyll *a*, chloride, pH, biochemical oxygen demand (BOD), nutrients (ammonia, nitrate, and orthophosphate), and trace metals (Cd, Cr, Cu, Pb, and Ni). The QUAL2E model was used to model DO dynamics, and the Pawtoxic model, which is based on TOXIWASP, was used to simulate total suspended solids (TSS) and metals. Toxicity bioassays were performed using effluent and sediment samples, and some limited biological assessments were performed with fish and macroinvertebrate species. In addition, a more detailed study of water column and sediment contaminants was conducted for one of the impoundments along the river (Rice City Pond) in order to develop possible remedial actions.

Although EPA Region I provided funding for the BRI, accomplishment of the study required active participation by MA and RI agencies in the field sampling and analyses and the cooperation of a number of industrial and municipal facilities along the river.

2.2 Charge to the Committee

The Charge to the Committee requested review of the final report from the Blackstone River Initiative, which describes the wet and dry weather monitoring efforts, application of fate-and-transport models, and determination of annual pollutant loading rates. The overall charge was to assess the study design and implementation with regard to meeting the project objectives, which were to: determine the current water quality of the Blackstone River under both wet and dry weather conditions; assess the relative contribution of pollutant loadings from point and nonpoint sources in the watershed; and forecast annual pollutant loading rates.

More specifically, the Committee was asked to consider the following:

a) Please comment on the approach used to describe the fate of dissolved oxygen in the Blackstone River. Are the procedures used to calibrate and validate the dissolved oxygen model appropriate? *(See Section 6.1)*

b) A basic, mathematical model was used to describe the fate of suspended solids and trace metals in the Blackstone River. Please comment on this approach. The dry weather trace metal data were also used to define aquatic life criteria violations. Please comment on this approach and its relevance to ambient water toxicity. *(See Sections 6.2 and 5.1)*

c) The data from the Blackstone River Initiative were used to determine the relative importance between dry and wet weather pollutant loads and point and nonpoint sources of pollution. The analysis led to the identification of river reach pollutant hot spots. Please comment on whether this analysis appears appropriate. *(See Section 7)*

d) A procedure was followed to combine the dry weather modeling and dry and wet weather data analysis to estimate annual loading rates to Narragansett Bay by the Blackstone River. Is the application of this procedure appropriate and is the methodology transferable to other watersheds? *(See Sections 8 and 9)*

e) The Blackstone River Initiative has generated a substantial data base of information for a moderately sized watershed. What is the utility of this data base on CD-ROM as a resource for other applications? *(See Section 10)*

The Committee's overall assessment of the BRI, as well as answers to the specific charge questions, is contained in the following sections.

3. GENERAL COMMENTS

3.1 Overview

The Committee commends EPA Region I and other participants in the BRI for initiating the study. The project is important for a number of reasons: it looks at the river as a whole, rather than studying segments in isolation within political boundaries; it begins to relate water quality conditions within the river to watershed contributions to loadings (e.g., wet weather loadings); and it demonstrates cooperation among multiple federal, state, and local organizations, which is a major accomplishment. The research provides significant insights into the influence of wet weather conditions, an issue that is important in this and other regions. The contribution of volunteer and in-kind services was impressive, and the BRI's accomplishments far surpass the dollars expended by EPA. The participants are also highly commended for their efforts to bring the report to completion, and to disseminate the findings and data.

To maximize the utility of the BRI, the Committee urges the Agency and other participants in the project to build on the current work by initiating a new phase of the BRI that takes a truly watershed perspective, for example by incorporating the ecological risk assessment framework, expanding the assessment to include watershed indicators such as landuse and landcover in a Geographic Information System (GIS) context, increasing the consideration of biological information, and initiating limited additional monitoring (e.g., in impoundments and at the downstream end of the river). EPA support of a subsequent phase of the BRI would allow more informed consideration of management and remediation options for the Blackstone River, both from the perspective of water and sediment quality within the river, as well as the river's contributions of nutrients and contaminants to Narragansett Bay. Greater detail is provided on these, and other suggested improvements, in the sections that follow.

With regard to the completion of the current BRI report, which describes activities to date, the Committee urges that this be done expeditiously and that in so doing the authors attend to numerous editorial corrections associated with the text and figures, and provide a thorough edit. Examples include the need to revise the use of color in data figures so that the color gradients correspond to the gradients of the depicted parameters and are sufficiently different to distinguish between parameter values; all figures should include error bars; and some figure legends need to be corrected. Specific examples of needed corrections are noted in subsequent sections of our report. In addition, the Executive Summary is too long, yet fails to emphasize some key points (such as the finding that water quality criteria violations and toxicity are occurring during storm events, which is not mentioned until p. 39 of the Executive Summary), and implications of the findings to possible management and remediation approaches.

Although the Committee realizes that new data collection and modeling efforts are unlikely prior to completion of the current BRI report, we urge the project participants to take full advantage of existing data to characterize the Blackstone River watershed. As noted in subsequent sections, this should include application of the ecological risk assessment framework to organize the existing data, incorporation of existing biological information, and discussion of existing local, long-term climatological data for the watershed, as well as additional calibration of the QUAL2E model. Further, the BRI report should acknowledge the limitations of the study results in some respects, e.g., the failure of the modeling to adequately predict water column metal concentrations and the uncertainty in the estimates of annual loading rates to Narragansett Bay.

3.2 Use of Ecological Risk Assessment Guidelines

The Blackstone River Initiative is an important example of how water quality problems should be addressed from a whole river perspective. While we recognize that the BRI field data were collected five to seven years ago, the interim years have seen the formalization of an ecological risk assessment framework within the Agency. With the publication of the *Guidelines for Ecological Risk Assessment* (U.S. EPA, 1998), EPA has provided a conceptual template for the conduct of ecological risk (ecorisk) assessments that has direct application to the BRI. Even at this stage of the project, the ecorisk paradigm can be used to organize the existing BRI data, and the Committee recommends that this be done. This approach will help significantly to identify the strengths and weaknesses of the data base, where additional data are needed, and the type of data. The ecorisk guidelines will also be an important guide for the next stage, i.e., the selection of effective management approaches to reduce risks and thus improve overall water and sediment quality within the Blackstone River watershed.

Technology transfer and public support and appreciation for the BRI would also be enhanced if the project were presented in the context of an ecological risk assessment. This assessment would identify the societal values to be protected in the Narragansett Bay, the Blackstone River, and the contributing watershed. Identification of ecological endpoints of interest in Narragansett Bay, for example, would give perspective to the importance of the chemical stressors monitored in the BRI and facilitate selection of key stressor variables to continue to monitor at the river outflow to the Bay in a recommended future phase of the study. The conceptual model of the full watershed-river-estuary system, necessary for the risk assessment, would emphasize the linkage of these sub-systems, place more emphasis on habitat issues, and provide a convenient framework for presenting research results and management recommendations.

3.3 Water Quality Management and Remedial Options

The Committee was concerned that the BRI report devotes only a few pages to the implications of the BRI data for water quality management and possible sediment and water quality remedial actions. Despite the limitations noted in our report, these data are the most detailed information available on the water and sediment quality of the Blackstone River. Thus, we strongly urge that the report provide a more detailed discussion of the relevant management questions and remedial options, while acknowledging that, in some cases, the evaluation of management options will require additional field work (e.g., sampling within the impoundments in order to assess the impacts on water quality of dam removal — see Section 4.1).

3.4 Integrating Biology and Ecology into the BRI

It is clear that the BRI has effectively gathered a strong coalition of federal and state agency scientists and university researchers to address the water quality issues of the system under dry and wet season flow conditions. This coalition, however, is dominated by civil engineers and physical modelers. The Committee recommends that a similar effort be initiated to assemble expertise to address biological issues in the study and that the total expanded group be integrated in order to mount a truly interdisciplinary effort. An important source of expertise for the BRI would be regional university researchers in ecology, both in the short run to help with interpretation of existing data on invertebrates, fish, whole organism toxicity, and algal chlorophyll, and in the longer term to plan future phases of the work.

The Committee recommends that the level of biological information incorporated in the analyses of both dry and wet season conditions be increased. A significant effort could be made in this regard in the current report using data already available on invertebrates and fish, as described below. For recommended future studies, biological measures should be included throughout as an integral part of the BRI. A promising approach, based on studies of other rivers worldwide (Cushing et al., 1995), would be to focus on benthic macroinvertebrates, benthic algal chlorophyll, benthic algal community composition, and fish populations. The invertebrate samples should emphasize habitat differences by reach and focus on general taxonomic diversity (richness) and community functional organization. Perhaps the most useful approach would be to organize the taxonomic information resolved at a general level by functional groups related to habitat and/or nutritional resource requirement.

Some examples of the use of macroinvertebrate data to indicate water quality conditions would be to:

a) graph general diversity indicators such as taxa richness or mayfly, stonefly, caddisfly (*Ephemeroptera, Plecoptera, Trichoptera* — ept) index as a function of DO, ammonia, metals, etc.; and

b) plot ratios of functional groups vs. environmental parameters to indicate ecosystem attributes: for example, the ratio of periphyton scrapers and aquatic macrophyte shredders to filtering collectors, gathering collectors, and coarse-particle detrital shredders is an indicator of the importance of benthic primary production that could be compared to water column chlorophyll measurements and would provide insight into the origin of the water column chlorophyll (Merritt and Cummins, 1996).

Extraction of chlorophyll from cores of surficial sediments and general taxonomic characterization of algal communities (e.g., filamentous vs. non-filamentous, diatoms, green algae, bluegreen algae) would provide useful data for future correlation with dry and wet season flows and associated water quality parameters. Using existing data, plots of all chlorophyll samples, regardless of flow, against the corresponding flow data would indicate by a direct relationship that the primary source of the chlorophyll was benthic.

Although it requires more specialized equipment and labor-intensive collection efforts, fish sampling provides important ecological information that integrates across trophic levels. For example, functional analyses would provide insight into habitat condition by comparing water column vs. benthic forms or air breather plus low DO-tolerant forms to non-air breather plus low DO-intolerant forms.

3.5 Public Education about the Blackstone River

The findings of the BRI should be disseminated in the region to increase public understanding of the environmental condition of the Blackstone River. The Committee was concerned that the educational materials circulated at the review meeting by the National Park Service, describing the Blackstone River Valley National Heritage Corridor, failed to mention the impacts of human activities on the river system. The long-term use of the Blackstone River for hydropower and urban and industrial discharges has left a legacy of severe environmental degradation. The National Park Service should incorporate information about this environmental degradation into its educational materials so as to inform current and future generations about the long-term environmental consequences of taking a river for granted.

4. FIELD STUDY DESIGN AND SAMPLING ISSUES

4.1 Spatial and Temporal Variability

Spatially, the coastal zone is a complex mosaic of interacting ecosystems from watersheds and rivers to estuaries and the coastal ocean. Aquatic ecosystems within this mosaic also exhibit significant variability on short time scales (hours-days) relative to terrestrial and oceanic ecosystems. Nutrient enrichment and contaminant loadings were once thought to be a local problem with little system-wide significance, and attempts to regulate loadings focused on reducing point source discharges from sewage treatment plants. It is now clear that diffuse inputs (surface runoff and groundwater discharge from a variety of sources, including fertilizers, animal wastes, acid rain, forest-disturbance, and waste disposal sites) are significant and often account for most material inputs to coastal river-estuarine systems. The rates and pathways of diffuse inputs reflect the interactive effects of a variety of factors that include the physical-chemical characteristics of the chemicals and patterns of land-cover, land-use, and precipitation over the drainage basin. Consequently, diffuse inputs tend to occur episodically (pulsed) in response to rainfall events. Although such inputs may occur over short periods, they have system-wide effects and are often sufficiently large to be reflected in seasonal and interannual variations in nutrient loading and ecosystem-level expressions of nutrient loading. In this regard, the general scarcity of observations of sufficient duration, spatial extent, and resolution to capture the transient effects of storms and to resolve trends from variability is a major impediment to the goals of predicting environmental changes and their consequences in coastal systems.

The Blackstone River Initiative (BRI) was an attempt to address this problem in terms of loadings to the river, changes in water quality and biotoxicity within the river, and exports to Narragansett Bay. The BRI encompasses four major, and laudable, goals: a) to document the effects of rainfall on point and diffuse (including sediment sources within the river) loads of nitrogen, phosphorus and trace metals to the river; b) to determine the effects of these loads on water quality and biotoxicity; c) to quantify annual exports to Narragansett Bay; and d) to determine how loads to the river are related to exports to the Bay. To achieve these goals, two monitoring tactics were used, one for dry weather (assumed to define steady-state, baseline conditions) and one for wet weather (nonsteady-state responses to rainfall events). The success of these tactics depends on how well spatial and temporal patterns of variability were quantified and on how representative the three rainfall events monitored are of the spectrum of rainfall events experienced by the drainage basin on interannual time scales. It should be emphasized at this point that, given the level of funding (which was clearly insufficient), the BRI team did a remarkable job in their efforts to address these problems.

The **spatial** aspect of this problem includes rainfall (the forcing function), patterns of land-cover and land-use in the drainage basin, patterns of export from land to water, and variation along the axis of the river. The study did a fine job capturing spatial patterns of rainfall for the storms measured and demonstrating that both rainfall pattern and total rainfall must be considered in terms of all four goals. This was true even though point-source inputs are generally greater than diffuse inputs for the Blackstone River. However, a quantitative evaluation of the effects of rainfall on loads should include an analysis of how land-cover and land-use in the drainage basin modulate the relationships between rainfall and loads, a clear spatial distinction between point and diffuse sources, and an analysis of the potential significance of groundwater discharge along the course of the Blackstone River itself (at least to rule out groundwater inflows as a significant factor; e.g., is it possible that the increase in nitrate loading observed between Stations 8 and 12 in Fig. 4-21 was associated with groundwater discharge as wetland grasses die back in the Fall?). This expanded analysis would be an important component of a future phase of the BRI.

More importantly, the measurement program likely did not capture significant changes along the axis associated with the impoundments, where reductions in flow velocity and increases in water residence time should be reflected in higher concentrations of chlorophyll, lower dissolved oxygen, and greater sedimentation rates. Impoundments may also be more susceptible to resuspension events.

Sampling within the impoundments is crucial to an understanding of the behavior of oxygen, nutrients, and metals in the system. The dams reduce water velocity, allowing sediments and the contaminants associated with them to deposit. The dissolved oxygen content of the water in the impoundments is expected to diminish as a consequence of the reduced degree of reaeration of the water. Furthermore, the oxygen concentration of the water near the sediment-water interface may be depleted as a result of sediment oxygen demand. Careful sampling of the water column is needed to evaluate the actual oxygen regime. Below the dam, the oxygen levels would be higher, and would tend to be saturated as a result of the reaeration of the water as it passes over the spillway. This reaeration is demonstrated by the data obtained in the study.

The additional sampling is important not only in terms of documenting patterns in water quality and sediment contaminants, but also in terms of model validation (e.g., the model generates impoundment effects that that cannot be verified by the data because samples were not collected from the impoundments). The dynamic interaction of nutrients, trace metals, and dissolved oxygen must be understood to allow proper management of the system. For example, removal of dams could have major impacts on the water quality. An appropriate analysis of the effects of such a modification is necessary prior to such an undertaking.

The **temporal** dimension was also undersampled and should be expanded in future BRI studies. No data were collected during winter when biological activity is at its annual minimum and relationships between loads from the drainage basin and exports to Narragansett Bay should be least complex. Also there were no spring samples. In addition, it is not clear that samples were collected with sufficient temporal resolution to resolve the effects of rainfall on loads from the drainage basin from the effects of increased turbulent flow on resuspension of in situ sediments. Finally, there is the important question of how representative the three rainfall events monitored are of the spectrum of rainfall events (in terms of rate and cumulative precipitation) that the drainage basis is subjected to on decadal time scales. This becomes important when one considers the nonlinear nature of load-rainfall relationships, a reality that will significantly affect the accuracy of calculated annual exports to the Bay and of any attempt to extrapolate beyond the range of conditions monitored for the BRI, e.g., to calculate loads with known certainty for a larger rainfall event based on statistical relationships between loading and rainfall derived from these data. The current BRI report should discuss the representativeness of the three rainfall events measured in relation to existing local, long-term climatological data.

A necessary first step in the process of change detection and prediction is to develop observational tools that provide both areal coverage and resolution in time over sufficiently long periods to capture the full range of variability in both inputs and responses. To these ends, the selective use of in situ technologies is recommended that employ high frequency measurements and, ideally, real time telemetry. Key variables such as flow, temperature, dissolved oxygen, chlorophyll, and nutrient concentrations should be measured at selected locations. For the Blackstone River-Narragansett Bay system, the single most important location would be near the mouth of the Blackstone River upstream of tidal influences. The Committee recommends, therefore, that the Agency employ a continuous monitoring station at that location as part of an expanded BRI.

4.2 Additional Important Parameters

The addition of several important parameters to the field program and sample analyses is recommended for future BRI efforts in order to improve the dry and wet season condition assessments and the model results:

a) **light attenuation**: Data on light attenuation could be expected, with a few nutrient-controlled exceptions, to correlate well with benthic algal biomass, as measured by sediment chlorophyll concentrations. Because the Blackstone River is shallow, an actual sensor (e.g., LICOR underwater PAR sensor) to record profiles of light extinction would be required rather than the approximation measured with a Secchi disc. The impoundments might be of sufficient depth seasonally to use Secchi disc readings, but for comparability light sensor attenuation profiles should be measured. Since the emphasis in the BRI is on chlorophyll-containing organisms (rather than, for example, on photic responses in animals), the sensor used should measure photosynthetically active radiation (PAR) rather than some broader spectral range. Light attenuation is dependent on turbidity and, primarily, dissolved organic matter, both of which can be measured directly, but the measure of PAR would be integrative and most directly related to photosynthesis.

b) **dissolved organic matter**: In most cases, dissolved organic matter, measured as dissolved organic carbon, would be an appropriate index of color and would be of significant use in evaluating the precipitation of heavy metals through the formation of complexes.

c) **acid volatile sulfide**: Further sampling of the sediment to determine the ratio of simultaneously extracted metals to acid volatile sulfide (SEM/AVS) is also needed (Allen et al., 1993). This is particularly important to establish the likelihood that metals would be released from the sediments to the overlying water. AVS is formed in the sediments when sulfate is the terminal electron acceptor in the oxidation of organic matter. Care must be taken in sediment sampling that the sulfide is not oxidized. Previous sediment sampling for the determination of toxicity may have oxidized sulfides during the homogenization process.

d) **total phosphorus**: Total phosphorus concentrations (rather than just dissolved phosphorus) should be measured for water samples to provide an additional check point for the phosphorus mass balance in the QUAL2E model.

e) **long-term BOD**: Long-term BOD tests of the wastewater treatment plant effluents and receiving water samples are needed to generate the ratio of $CBOD_u$ to $CBOD_5$ for these samples. Note that the model calculates $CBOD_u$ to indicate the ultimate potential of oxygen consumption in the water column. Receiving water $CBOD_u$ values are needed to compare with the model results. In addition, the regulatory staff use $CBOD_5$ in NPDES (National Pollutant Discharge Elimination System) permits. The ratio of $CBOD_u$ to $CBOD_5$ is therefore needed to develop the wasteloads based on the QUAL2E model results. (For further details, see Appendix A).

5. ASSESSING TOXICITY

5.1 Aquatic Life Criteria Violations

Charge Question: The dry weather trace metal data were also used to define aquatic life criteria violations. Please comment on this approach and its relevance to ambient water toxicity.

The use of water quality criteria (WQC) values in comparison with ambient water concentrations of soluble metals provides the basis for a screening-level assessment of the potential for metals to cause effects in the Blackstone River. However, it is important to remember that water quality criteria are intended to be protective and not predictive. There are numerous examples in the literature of concentrations of metals in surface waters that exceed the ambient WQC yet do not appear to be toxic (see, for example, Hall et al., 1997). The primary reason for this is the fact that the WQC are derived from “clean” water laboratory studies and do not consider the effect on toxicity of suspended solids, dissolved organic matter, or pH. The fraction of total dissolved metal that acts as a toxicant is determined by the speciation of the metal under ambient conditions.

The lack of toxicity in some of the surface water and sediment bioassays may be attributed to low bioavailability of metals. The primary binding ligands in surface water are dissolved organic carbon and suspended solids, and in sediments are sulfides, mineral oxides, and organic carbon. It is also important to note that a lack of toxicity in a given bioassay may or may not be indicative of the effects on the ecosystem.

For a subsequent phase of the BRI, the Committee recommends that the chlorine, ammonia, and metals data be co-mapped with infaunal benthic invertebrate data and with in-stream bioassay data by river mile to allow for a comparison of the various stressors and responses. Assessment of in situ biota from sites where metal violations and toxicity are observed would supply the missing information for a triad test including chemistry, bioassay, and biota. It is also recommended that Toxicity Identification Evaluation (TIE) procedures (U.S. EPA, 1991; Rand, 1995) be employed to identify the source(s) of toxicity, when noted, in surface water and sediment samples. The state-of-the-art of these procedures has advanced to the point that the tests are routine and fairly inexpensive. These data taken together should provide a much better assessment of the cause-and-effect relationship between pollutants and potential effects in the river. Particular attention should be paid to the ammonia levels (and pH) in surface water and sediment pore water samples; ammonia is highly soluble and its toxicity is not reduced by sorption. Additionally, it should be pointed out that diazinon (used to control grubs in lawns) is a common contaminant that is responsible for toxicity to daphnids following storm events and the associated run-off from residential yards.

5.2 Toxicity Testing

Although the Charge to the Committee did not specifically refer to the toxicity testing portion of the BRI, the Committee felt that this component of the study had produced some important findings that should be given greater emphasis in the final report. For example, the study found that sediments are highly toxic in the river and that water column violations occur sporadically during base flow and consistently during storm flow conditions.

The discussion in the BRI report of the toxicity work provides less detail than that given for the water quality and modeling portions of the study, and should be strengthened. Further information should be provided on both the test methods and the data analyses. For example, any sediment or water chemistry measures (such as pH, chloride, NH_4, sulfide, or grain size) that were taken during toxicity tests should be given. A clear list of which parameters were measured and a data table showing concentrations should be present for each experiment. Further, some of the test data that are included in the report are difficult to interpret. For example, on p. 4-79, in the *Ceriodaphnia* data table, it is difficult to see how the results from Station 9 are significant while those from Station 14 are not. Control data should be presented in this table.

The discussion of wet weather toxicity test results (p. 7-40) states that the samples contained levels of residual chlorine (from wastewater treatment) that were “orders of magnitude greater than the EPA ambient water quality criteria.” For this reason, the authors report that samples were dechlorinated prior to toxicity testing to “preclude the masking effects of chlorine toxicity and to test whether other constituents were toxic.” The Committee had some concern with this approach, since toxicity from this residual chlorine should be measured and in situ biota should be assessed to determine if they are suffering episodic events as a result of wastewater treatment plant discharges.

As with other sections of the BRI report, the toxicity section of Chapter 4 needs a thorough edit. The discussion of control sites for whole sediment toxicity tests is very difficult to follow. For example, the report should say why Lexington and Concord pond sediments were eventually chosen for controls; site names should be consistent with those used in the water quality section of the report (or at least provide a map for the new site names); and errors in units and in defining pore water vs. whole sediment, which occur throughout the section, should be addressed.

6. MODELING ISSUES

6.1 Dissolved Oxygen Modeling

Charge Question: Please comment on the approach used to describe the fate of dissolved oxygen in the Blackstone River. Are the procedures used to calibrate and validate the dissolved oxygen model appropriate?

The fate of dissolved oxygen (DO) in the river was described using the QUAL2E model and data from three water quality surveys. In evaluating the modeling effort, it is necessary to consider both the adequacy of the data supporting the modeling and the derivation of coefficient and parameter values for use in the model. Three dry weather water quality surveys were conducted in 1991, with river flows (at Woonsocket, RI) ranging from 137 cfs to 625 cfs. Although there are 15 stations in the main stem of the river, samples from pools behind the dams were not taken. The model predicts that dissolved oxygen levels in the pools tend to drop (because of sediment oxygen demand) and then are raised by dam reaeration. Data collected from the pools behind the dams would have substantiated the model results for dissolved oxygen. Further, the wet weather field work only covers three storms with precipitation close to 1 inch, far short of any sizable storms, thereby missing much information on the effects on DO of different weather conditions. In general, however, the BRI field program has provided sufficient data to support the dry weather modeling analysis.

The QUAL2E model used for the BRI study is a one-dimensional, steady-state model specifically suited for modeling BOD/DO in rivers and streams (see Brown and Barnwell, 1985). It has been supported by the EPA for almost two decades and has been successfully applied to numerous river and stream water quality modeling studies throughout the country. An important feature of the model for application to the Blackstone River is its ability to consider dam reaeration, as there are a number of small dams along the river in the study area and their effect on the dissolved oxygen budget must be accounted for in the analysis. While more advanced models such as the Water Quality Analysis Simulation Program (WASP) (Ambrose et al., 1993) are now available, the Committee found that the QUAL2E framework was adequate to describe the fate of dissolved oxygen in the Blackstone River under dry weather steady-state conditions. However, additional model calibration is recommended to fine tune the model so that it can be used to predict, with confidence, the water quality under other flow conditions during dry weather. Modifying several model kinetic coefficients and constants (e.g., algal settling velocity, non-algal light extinction coefficient, and nutrient half-saturation constants) will improve the match between the model results and the field data and this should be done prior to finalizing the current BRI report.

In addition, to calibrate the DO model, all parameter values for each river reach were sequentially estimated from measurements, with the exception of the algal growth and respiration rates. The growth rate parameter was tuned for each reach to achieve a good match between modeled DO and measured DO for the entire river. The quality of the match was judged by visual comparison of the plots of modeled and observed DO. The Committee recommends instead that a formal measure of goodness-of-fit, such as the root mean square (RMS) of the difference between observed and measured DO, be calculated and presented in the BRI report.

Calibration was performed for the entire river using two of the available data sets (July and October, 1991). To validate the DO model, a simulation of the entire river was compared to a third data set (August 1991). The resulting figures for DO, Fig.s 5-33 (July) and 5-34 (October), would seem to be satisfactory, but not so Fig. 5-35 (August). However, as pointed out during the review meeting by one member of the review panel, this figure may be in error, since plotting the results from the CD-ROM yields better results for August (see Appendix A). This figure should be revised and re-done for the final report. In general, Fig 5-35 (as is) shows relatively constant DO data across the river, whereas the model shows a more dynamic trace.

Since the modeled river reaches are independent of each other except for the boundary condition, one could think of matches of measured and modeled DO by reach to be another way of validating the model. This could increase the number of validation points and open up the possibility for statistical analysis. Using this approach, failure to match observed and modeled DO for a reach during calibration can be considered as failure to validate, and could lead to investigations of why the model fails to explain DO in that reach. This approach may lead to useful insights about the river dynamics in that reach.

A more detailed discussion of QUAL2E model calibration and verification issues is contained in Appendix A to this report.

6.2 TSS and Metals Modeling

Charge Question: A basic, mathematical model was used to describe the fate of suspended solids and trace metals in the Blackstone River. Please comment on this approach. The dry weather trace metal data were also used to define aquatic life criteria violations. Please comment on this approach and its *relevance to ambient water toxicity.*

The modeling framework, TOXIWASP (a module of WASP), used to simulate suspended solids and metals represents a straightforward approach. Model results mimic the spatial trends of concentrations under dry weather conditions. However, additional model calibration in conjunction with model sensitivity runs of partition coefficients of metals and settling velocity of suspended solids is recommended as these two parameters are the most important tuning knobs in the model.

6.2.1 Total Suspended Solids

Total suspended solids (TSS) within each river reach was modeled as exponential decay or increase, based on empirical relationships between flow and TSS within each reach. Data from the BRI and previous surveys were used to calculate the coefficients for the decay equation. Because only abiotic TSS was considered as a function of stream velocity, a correction for biotic TSS was made, using the relationship between chlorophyll *a* and volatile suspended solids (VSS) within each reach; an empirical regression coefficient relating chlorophyll *a* to VSS was calculated for each reach, and VSS was then subtracted from TSS to give abiotic TSS.

The Committee noted a potential problem with this approach, in that VSS, especially in effluent, is unlikely to be algae. The correlation between VSS and chlorophyll *a* in the dry weather data sets is fairly poor, especially in October. Although values for the regression coefficient and data showing the chlorophyll *a*:VSS relationships were not shown in the report, they can be derived from the data on the CD-ROM. It appears that the model assumes that VSS is composed entirely of chlorophyll *a*, whereas in fact chlorophyll *a* is just a small, representative fraction of algal biomass. However, since VSS is generally a small fraction of TSS, the final model output is not strongly affected by this parameter.

The empirical decay coefficients varied substantially between the reaches that contain impoundments and those that do not. The overall predictions of TSS were fairly insensitive to these decay coefficients, however, presumably because of relatively rapid flow. The authors concluded that TSS modeling was adequate for the purposes of the current modeling effort. Despite the oversimplification and the potential error described above, the Committee generally agreed.

6.2.2 Metals

One objective of the BRI was to define “hot spots” in the river where metals and

TSS are high and where there are potential in-stream or external sources. The data collection alone did that for the conditions examined, except for the lack of data, as noted for other parameters, on metal and TSS levels within the impoundments. As previously discussed, the model and data collection do not reflect conditions during very high flows or winter flows, and therefore cannot be used to estimate accurately the metals load to Narragansett Bay.

Metal concentrations were modeled as functions of TSS, using partition coefficients (here called K_p). K_p in the model was varied as a function of flow, using partitioning data summarized by Kontaxis et al. (1982) from the older literature for TSS above 10 mg/L, plus Blackstone River data from the dry weather surveys. Only dry weather data were used because the model was designed for base flow conditions, and because K_p can vary between storm flow and base flow of the same magnitude. It might have been better to use Blackstone River data for high flow K_p's, although it appears that only total (and not dissolved) metals were measured during the storm events. In the TSS vs. K_p relationships used, K_p varies by less than one order-of-magnitude for most of the metals over the range of TSS observed. Dissolved metals were modeled based on TSS, particulate metal concentration, and K_p. The data collected were adequate to support the simple model used, with the exception that both dissolved and total metal concentrations might have been measured during storm events.

The metal model was calibrated using July and October dry weather data, and tested against the August data set. Model predictions were outside the error in the data for many of the metals in many of the reaches. Dissolved and total Cd and Ni were overpredicted; Cr was generally in agreement with the model; Cu was underpredicted, especially downstream of UBWPAD; and Pb was underpredicted, especially in the central river. A model incorporating resuspension and two point sources as the only major loading processes, and with K_p's derived partially from outside the system, appears to be too simple to predict metal concentrations in this complex system. System-specific partition coefficients (using Blackstone River wet weather K_p's for the higher TSS range) or newer inter-ecosystem estimates of K_p might improve the existing model.

In summary, the simple model used adequately described the net input of TSS within each reach but the model fit was less good for many of the metals examined. Both the simplicity of the model and the model parameterization probably contribute to this result. The Committee felt that settling and partitioning coefficients seemed inappropriate in some cases. For example, dissolved organic carbon could affect K_p, and hence model behavior. The model was constructed as an empirical combination of settling rates and solid/dissolved phase partitioning coefficients. Although some of these coefficients may not reflect the reality of individual processes, taken as a whole, the model and the empirical coefficients do a reasonably good job of representing TSS in the system. However, the model does not do an adequate job predicting many of the metals.

The Committee was concerned that the simple model used will not adequately inform management and remediation decisions for the Blackstone River because it does not describe the processing of TSS and metals within each reach, nor can it distinguish between internal and external sources of TSS and metals to each reach. Thus, as highlighted by the findings of wet weather toxicity, an important focus ofrecommended future studies would be more information and data, plus a more complex, non-steady state model, to describe adequately the fate-and-transport of metals in the river. Of particular interest and concern to the Committee is the interaction between the water column and bed sediments. A number of processes may affect this interaction, in addition to simple resuspension, which is the only process included in the current model. In constructing a Total Maximum Daily Load (TMDL) model for metals in the Blackstone River, it will be important to understand more fully how historically contaminated sediments and industrial sites are contributing to present day water column contamination. To do this, the geochemistry of those sediments must be studied in more detail, and fuller budgets need to be constructed for important reaches. Both the basic geochemistry of the sediments and the metal geochemistry need to be examined. For example, sediment toxicity appears to vary seasonally, suggesting ammonia or sulfide toxicity rather than metal toxicity. However, basic data on sediment sulfide and ammonium concentrations were either not collected, or were not presented in the BRI report. These data are needed to assess metal mobility from sediments.

There are two critical areas of the river where bed/water interactions appear to control metal concentrations in the water column. The first is downstream of UBWPAD, where loss of metals from the water column was of interest to the authors of the report, and where metal modeling failed. On p.6-28, the authors suggested that sedimentation is not the mechanism, because TSS and particulate metal concentrations did not increase as "dissolved" metals decrease. The Committee did not agree with that logic. Rapid sedimentation would mask this process. The authors of the BRI report also speculated that metals could be taken up by periphytic algae and bacteria into the slime layers on rocks. Some work was done to characterize the concentration of metals into these layers. However, the work done to date is not sufficient to elucidate the mechanism(s) whereby metals are lost from the river, and biotic uptake remains highly speculative. A mass balance for each metal of concern would need to be done in detail for at least one of these reaches, including concentrations in and fluxes to each phase in the system. The Committee felt that the importance of the slime layers as a loss mechanism should be downplayed, but agreed with the report's authors that the loss process would require further study.

The second area of the river where bed/water interactions are critical is in historical impoundments where lowered water levels have exposed bed sediments. These sediments are then subject to erosion during higher flows. The presence of these exposed beds and their impact on metals and TSS needs to be made clearer in the Executive Summary. The data are highly suggestive that historically contaminated bed sediments are the source of metals within reaches where these sediments occur. However, it should be made clear that the results are not definitive. As noted above, the data collection and modeling cannot distinguish between in situ and external sources of metals to each reach. The model cannot separate, for example, contributions from terrestrial runoff from contaminated plant sites from contaminated groundwater flow from resuspension of bed sediments.

7. DISTINGUISHING POINT FROM NONPOINT SOURCES

Charge Question: The data from the BRI were used to determine the relative importance between dry and wet weather pollutant loads and point and nonpoint sources of pollution. The analysis led to the identification of river reach pollutant hot spots. Please comment on whether this analysis appears appropriate.

The two largest point sources on the Blackstone River are the UBWPAD and Woonsocket wastewater treatment plants. The BRI point source load estimates accurately represent the characteristics of these two facilities. The UBWPAD plant, an advanced secondary facility with nitrification, dominated the ambient river flows in the July and August surveys by a margin of 3-to-1, and this ratio was about 1-to-1 in the October survey. Nitrification was not implemented at the Woonsocket plant in 1991, when the samples were taken. There is no nutrient removal at these plants. Future estimates of the point source loads can be obtained from the discharge monthly reports (DMR) submitted by the operators to the state regulatory agencies in Massachusetts and Rhode Island.

The wet weather sampling program provides sufficient data to estimate pollutant loads during the three storms surveyed, particularly from combined sewer overflows (CSOs). In general, the relative contribution of point and nonpoint loading rates during these storms is properly defined by the field surveys with the exception of a possible groundwater contribution, for which no data are available.

The ranking of reaches according to their relative contribution of a particular pollutant was helpful in terms of identifying “hot spots” for further study. In subsequent studies, mass balances should be calculated for each reach to show sources and fates of pollutants entering and leaving each reach. For example, a nutrient budget for each reach of the QUAL2E model should be constructed to itemize the point and nonpoint source loads during the dry weather conditions; the total loading rate for ammonium entering any given segment in the model should be balanced by the sum of the loading rate leaving the segment and the gain/loss of ammonium within that segment under the steady-state condition. Note that the WASP model has this feature of providing a mass balance summary for every segment of the model. While the QUAL2E model does not have this feature, one can still construct the budgets from the model output of QUAL2E.

The report distinguishes the two major point sources on the river, the UBWPAD and the Woonsocket WWTF, from other sources of pollution in the watershed. Although the data generally support the decision to separate these two sources from other inputs in the analysis, because they clearly dominated the loadings for most pollutants at low flows, the report should clearly state that they are not the only point sources. There are numerous small municipal and industrial discharges that were grouped inappropriately into the “nonpoint sources” category. This is an unconventional and misleading use of the term, and should be changed in the report to “other sources.” Nonpoint sources conventionally include those sources whose contributions cannot be traced back to an outfall pipe.

The analysis of “nonpoint sources” did not distinguish between pollutants derived from sediments (e.g., resuspension of particulates and movement of dissolved pollutants from the sediments back into the water column) and pollutants that are new nonpoint source contributions from the watershed (e.g., from diffuse surface water runoff). This distinction is important for management purposes because the techniques for reducing these two sources of pollutants are quite different. Further, the Committee notes that a significant portion of the metal loads ascribed to resuspension of in-stream sediments in certain reaches may be derived from current point source discharges. For example, the abrupt loss of mass loads of dissolved and total cadmium, nickel, and copper just downstream of the UBWPAD suggests a local sink, hypothesized by the authors to be sediments or attached organisms. The substantial load increases in these constituents in the reaches just downstream during storm events certainly suggests remobilization of these metals. For this reason, when determining responsibility for load reductions in a management scenario, it is important to recognize that some of the resuspended load is a delayed point-source contribution, rather than a true nonpoint-source contribution.

The BRI study makes a very important contribution by clearly demonstrating the increased loads and toxicity during wet weather conditions. However, the study did not use a model for the wet weather conditions, which could have served as counterpart to the dry weather modeling effort. Further, diffuse pollutant contributions, including runoff from agriculture, silviculture, or natural forests in the watershed, were not specifically examined in the study. This, coupled with the inability of the analysis to distinguish between new nonpoint-source loads and resuspension of contaminants in the river, limits the utility of the BRI to inform the selection of management approaches. Future nonpoint-source work in a subsequent phase of the BRI should consider the entire watershed, not just the river channel. A recommended approach is to use GIS land-use information in conjunction with a watershed model to identify the location of nonpoint source “hot spots”. This approach would also aid future development of tools such as a Spatial Decision Support System that could be used to evaluate potential management scenarios.

A watershed hydrological model capable of modeling runoff and pollutant loads from storm events, when coupled to GIS for terrestrial analysis, should be very helpful to distinguish point- from nonpoint-source pollution. It would also be helpful to test loads that would result from various combinations of storm frequency and duration. The watershed model would be used to generate nonpoint loads to be used as input for the river water quality model. Several EPA-supported models could be used for the watershed modeling in future BRI studies; for example, the Hydrology Simulation Program-FORTRAN (HSPF) is a comprehensive watershed level model that also includes fate-and-transport in stream channels. Other possibilities are the Storm Water Management Model (SWMM) in the highly urbanized area at the headwaters of the Blackstone River, and the Soil and Water Assessment Tool (SWAT) for rural areas. For the river water quality model, another EPA-supported model like the Water Quality Analysis Simulation Program (WASP) could handle the dynamics of storm transients. (Information on these models is available at the following URL addresses: for SWMM, see www.epa.gov/earth100/records/swmm.html; for WASP, see www.epa.gov/earth100/records/wasp.html; for SWAT, developed by the USDA Agricultural Research Service, see www.brc.tamus.edu/swat/).

8. ANNUAL LOADING ESTIMATES

Charge Question: A procedure was followed to combine the dry weather modeling and dry and wet weather data analysis to estimate annual loading rates to Narragansett Bay by the Blackstone River. Is the application of this procedure appropriate and is the methodology transferable to other watersheds?

The approach used in the BRI to forecast annual pollutant loading rates from the Blackstone River is not adequate. The procedure to combine dry weather with wet weather loading rates would not reflect the nonlinear nature of the wet weather loads. In addition, the wet weather data collected from the three storms fall far short of quantifying loading rates during large storms. To verify the annual load predictions, data from at least one station at the downstream end of the study area must be available to validate the calculation. Such a data base does not exist at the present time and would be an important contribution of a next phase of the BRI.

Several limitations of the study that diminish the ability to predict annual pollutant loadings are described below:

a) There is a lack of sufficient data on storm events at the higher magnitude-lower frequency portion of the spectrum of storms. It is clear that annual loading into Narragansett Bay must include phenomena that occur on decadal time frames. That would include storms such as major Northeasters as well as tropical storms and hurricanes. Hurricane Bob is clearly a case in point, in which a massive quantity of precipitation led to extraordinary storm water runoff, sediment resuspension, and movement of materials from the landscape into and through the river system. Experience in river systems shows that such rare but intense events can dominate loading inputs to estuaries, especially for the movement of pollutants that may be bound to sediment and other particulates. Consequently, extrapolating annual pollutant loads into Narragansett Bay based on typical, medium-scale precipitation events such as the three storms in the BRI study is simply inadequate and may severely underestimate annual pollutant loading rates.

b) The BRI study only examined wet and dry weather conditions in the summer. This means that the processes and rates of materials fluxes occurring under normal winter low flow, wet weather flow, winter storm, and snow melt conditions are not captured by the BRI-based estimates. As one example of the problem this causes, consider that nitrogen inputs differ considerably in the winter, both because the human-engineered system for nitrification is turned off during the winter (thereby allowing ammonia inputs rather than nitrates) and because the natural denitrification processes are suppressed in the winter. Another example is the pulse of material fluxes that would be expected to occur following melt of major snow events. The contributions from such winter-based loadings are simply unknown from the BRI study.

c) Another critical issue is understanding the frequency distribution of precipitation events. These data are available from NOAA and other sources and are essential in order to characterize how representative are the three storms events measured in BRI. This information is essential in order to know how far these data can be extrapolated and therefore how well annual loading could be calculated.

d) Superimposing the weather loads based on the data from the three storms on the dry weather loads neglects the nonlinear nature of the wet weather characteristics. It is highly questionable that such a procedure will have predictive capability. As a first step, the river flow rates, e.g., at the USGS gaging station at Woonsocket, should be predicted and verified with the data. Yet, there is no such modeling effort in the BRI study. Further, water quality at that station must be predicted and verified with the data. It is understood that water quality data are not collected at the Woonsocket station.

If follow-up studies are initiated in a subsequent phase of the BRI to determine loading rates, the Committee recommends the following approach:

a) A **watershed model** (e.g., HSPF) is needed to provide time-variable loads (flow and concentrations) from the watershed to the river during the entire year.

b) A **time-variable receiving water model** is needed to simulate the water quality in the Blackstone River following the receipt of the watershed loads and point source loads during the dry and wet weather conditions throughout the year. Therefore, the model must be run for at least one full year.

The BRI report suggests that the QUAL2E modeling framework be modified for continuous simulations. It should be pointed out that the QUAL2E model is designed for steady-state calculations. The WASP model, which is also supported by the EPA, should be used for this modeling analysis. Several plots of model results vs. data from the time-variable (whole-year) simulations of the Upper Mississippi River and Lake Pepin are appended to our report (Appendix B) to show a successful application of the

WASP model. (Note that the dry weather data from the BRI study are adequate for the WASP model application, but the wet weather data are insufficient.) This suggested approach simply calls for continuous simulations of the watershed and receiving water for the whole year, regardless dry or wet conditions.

c) To support such a modeling effort, a **field monitoring program** for the watershed and the receiving water must be carried out on a continuous basis; this is needed to improve predictions of loading to the river, as well as to improve estimates of loads from the river to the Bay.

The Committee strongly recommends that, in a subsequent phase of the BRI, continuous monitoring of water quality data be conducted at the Pawtucket dam, at the head of tide. The USGS and other organizations operate continuous, flow-weighted samplers at many gaging stations in the U.S. These samplers can be modified to take "clean" metal samples, and/or to preserve nutrient samples through time. A continuous monitoring station likely would be the most efficient way to provide accurate Narragansett Bay loading data for TMDL calculations and for Narragansett Bay modeling efforts. Since very high flow events may load many years worth of some components, it is critical to capture these events.

The monitoring station should collect samples for metals, nutrients, basic water chemistry, and potential organic contaminants, along with flow. Such a data base could provide direct measurements of loading inputs into Narragansett Bay, both of great utility in analyses of total loading inputs and in calibration and validation of watershed models. Well calibrated and validated models would be extremely valuable in estimating the consequences of potential watershed management options (e.g., some of the options under consideration by the Corps of Engineers with respect to loading inputs of metals, nutrients and organics into Narragansett Bay.)

9. TRANSFERABILITY TO OTHER WATERSHEDS

Charge Question: Is the application of this procedure [to estimate annual loading rates] appropriate and is the methodology transferable to other watersheds?

For the reasons discussed in the previous section, the Committee does not recommend that other watersheds use the specific methodology developed for the BRI for translating dry and wet weather data into annual loads. With respect to the overall study, however, many attributes of the BRI may profitably be used in other areas.

Clearly, the effort to characterize both "dry" and "wet" conditions showed that different processes govern pollution input, transport, and fate in this system during different weather patterns, and the annual load calculations will be more accurate as a result of including at least some wet weather data. Based on this experience, it is reasonable to assume that other watersheds, particularly those in which current or historic sediment contamination is significant, would benefit from similar weather-related characterizations. Further development of the BRI data base to incorporate results of winter and very high flow events, combined with use of a model designed to handle these inputs, would provide additional insight useful to other regions, as well. In order to maximize the utility of the current results, the Committee recommends that the "lessons learned" during BRI program design and implementation (e.g., the need to sample both above and below the small dams and the advisability of notifying local police of night-time sampling activities) be assembled in a single location in the document for easy reference.

Similarly, the whole river analysis initiated in the BRI is commendable and would be appropriately transferred to other regions. The results obtained to date demonstrate that in-stream habitat quality in the Blackstone River is dominated by several types of sources whose relative effects change under different weather patterns. Understanding these relationships improves the ability to design a management program that optimizes habitat improvements.

While the BRI's focus on selected chemical stressors is a reasonable approach for determining pollution control responsibilities, it is not the most effective way to assess restoration opportunities for the watershed. In this regard, the BRI is not a good template for other regions. During the review, it was apparent that other ecological issues face the watershed, ranging from the preservation interest of the National

Heritage Corridor to the need for more wetland habitat. Under similar circumstances, other regions might well be advised to adopt a broader, less constrained objective such as improving the overall ecological integrity of the watershed. The resulting study design would include, but not be limited to, chemical pollutants.

10. THE BRI DATA BASE AS A RESOURCE

Charge Question: The Blackstone River Initiative has generated a substantial data base of information for a moderately sized watershed. What is the utility of this data base on CD-ROM as a resource for other applications?

The effort made by the participants in the BRI to make their data available in digital form must be applauded. This is a very good idea and worth noting as exemplary. These data will be useful for teaching (e.g., for water quality modeling classes), for validation of other models, for public information, and for other applications. The format of the data limits its utility, however, since a particular software application is needed to access the CD-ROM files. Using generic ASCII text files would make the data more accessible. The figures would be more useful as *.gif files linked to an html document in order to be accessible through a web browser. The entire CD-ROM would be more useful if its contents could be accessed via a web browser. This would allow enhanced accessibility online via the web and also as a CD by using the browser in local mode. Future continuous monitoring data, recommended by the Committee in Section 8, should also be made available on the web.

11. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

The Committee strongly urges the Agency to build upon the BRI study, and the inter-agency and government/academic partnerships it fostered, as a case study example of an attempt to do true watershed management. The next phase of the BRI would entail working with the partners to bring the scientific tools to bear on a broader set of management options, looking well beyond simple chemical management to additional stressors, using multiple endpoints at the watershed and landscape levels. Agency support for an expanded BRI program would be consistent with and supportive of the EPA's increasing emphasis on community-based environmental protection (CBEP) and watershed management approaches.

Specific elements in a subsequent phase would include development and use of an integrated, GIS-based data base of monitoring, landuse, modeling, and other types of information. It should include development of watershed-scale water runoff models, coupled to continuous monitoring of outputs from the Blackstone River to Narragansett Bay. Biological considerations should be integrated with the current focus on engineering solutions. EPA and the states should focus on developing the quantitative tools and supporting database to allow effective characterization of the consequences of potential management options.

The BRI should also be expanded to include the full set of relevant chemical, biological and physical stressors, including metals, nutrients, organics, and habitat alteration. Assessment and management of the Blackstone River system in a broader context will be enhanced by the application of an ecological risk assessment framework. The ecorisk framework explicitly identifies stress regimes, ranks stressors, identifies ecosystem at-risk, identifies specific ecological endpoints for each ecosystem, makes explicit ecological/environmental goals, incorporates sensitivity analyses for data and analytical uncertainties, and supports a report card construct to evaluate the efficacy of management decisions and identify corrections to improve the health of the environment. Such an approach constitutes the next generation of ways to improve the environment. The BRI is an ideal point-of-departure for Region I and the Agency for watershed management and as a demonstration project for implementation of ecorisk assessment in different watersheds and in different regions.

Since a primary focus of the BRI was to identify sources and loads to the River with a view towards improving the Blackstone River and Narragansett Bay with respect to pollution and with respect to establishing a TMDL for the watershed, some fine-tuning of the data set is recommended for future studies:

a) Analysis of sediments behind dams for the purpose of assessing sediment contaminant redistribution during storm events;

b) Inclusion of biological measures, such as information on benthic invertebrates, benthic algal chlorophyll, benthic algal community composition, and fish populations;

c) Data collection to assess contaminant and nutrient loads during the winter and spring months, in addition to the sampling during summer low flow and storm events;

d) Use of the WASP model to assist in the overall assessment of contaminant and nutrient transport, including the calculation of mass balance by reach for metals and nutrients;

e) Implementation of TIE procedures as part of the analysis of storm events to assist in the identification of the contaminant(s) responsible for toxicity during the storm events; and

f) Use of a Geographic Information System (GIS) format, which would provide a very useful approach for presenting the toxicity, contaminant, infaunal and fish data in a combined manner across the watershed.

An additional research and land management issue identified during the review meeting related to the presumed failure of natural processes to re-vegetate historically impounded areas along the Blackstone River that are now drained. The value of revegetation could include: sediment stabilization, phytoremediation, and habitat enhancement (the Blackstone River corridor is a major flyway). The first step in the investigation of this situation would be a determination of the limiting factors for plant establishment and growth (e.g., chemical toxicity, soil physical conditions, microclimate, and/or lack of seed sources/vectors). This would be followed by field efforts to alter soil conditions and/or field establishment of selected vegetative types.

In summary, EPA support for a recommended additional phase of the BRI would allow more informed consideration of management and remediations options for the Blackstone River, both from the perspective of water and sediment quality within the river, as well as the river's contributions of nutrients and contaminants to Narragansett Bay. Although the recommendations for future work contained in this report are cast in terms of the BRI, many of the same sampling, analysis, and modeling issues apply to assessments in other watersheds.

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APPENDIX A: Further Discussion of DO Model Calibration and Verification

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Water Quality Data to Support the Modeling Work

As noted by Wright et al. (1998), the BOD samples of the river were not filtered to separate the algae in suspension. Since there is appreciable algal biomass in the river, it is important to separate algae from the dissolved organics in the water column as diurnal fluctuations of DO have been observed at locations along the river. Algae impacts on BOD deoxygenation rates occur wherever high concentration of chlorophyll *a* or significant diurnal DO fluctuations occur. In general, 10 μg/L of chlorophyll *a* will increase the $CBOD_u$ concentration by 1 mg/L above that without algae. Algal respiration and decay in the BOD bottle can cause higher measured CBOD values and thus higher K rates (in the laboratory) compared to samples without algae.

Further, long-term BOD tests of the effluents and of receiving water samples were not included in the study. Since the model calculates $CBOD_u$ to indicate the ultimate potential of oxygen consumption in the water column and the regulatory staff use $CBOD_5$ in the wasteload allocations and in issuing discharge permits, it is important to have an accurate relationship between $CBOD_u$ and $CBOD_5$ for the effluents.

The laboratory protocol to quantify $CBOD_u$ of wastewaters has improved significantly in recent years. One of the difficulties in the laboratory analysis has been nitrification suppression. Often, anomalous results of CBOD analysis have been reported in which $CBOD_u$ exceeds BOD_u values, and the CBOD vs. time curve does not follow first-order kinetics. One possible source of errors is the nitrification inhibitor used in the laboratory analysis. In many cases, inhibitor degraders are present in the wastewater and water samples. The potential for biodegradation casts doubt on the integrity of results obtained when a certain inhibitor is used in a long-term BOD test. The current practice of determining $CBOD_u$ does not call for the use of nitrification inhibitors. Instead, the total amount of oxygen consumption is recorded along with concurrent measurements of ammonium, nitrite, and nitrate concentrations, ensuring an accurate mass balance of the nitrogen components. The CBOD is then derived by subtracting the amount of oxygen used in the nitrification process from the measured total oxygen consumption (Lung, 1998).

The UBWPAD facility has nitrification in its operation. It is expected that nitrifying bacteria are present in the effluent. Thus, it is essential that the above procedure be followed to determine accurately $CBOD_u$ concentrations in the effluent. Since the long-term CBOD test is a time-consuming effort, it is not recommended that this test be conducted for every receiving water sample. Samples from only select stations may be used to provide a check on the $CBOD_u$ to $CBOD_5$ ratio for the ambient water.

Three dry weather water quality surveys were conducted in July, August, and October of 1991. While most of the water quality parameters were measured in the field and laboratory, total phosphorus concentrations were not measured from the samples. Only dissolved phosphorus levels were measured. Measuring total phosphorus in the lab is a routine practice and should have been included in the study. These data would provide an additional check point for the phosphorus mass balance in the model.

Data Analysis

Water quality data collected from the three surveys play a key role in the modeling work. For example, BOD data are used independently to derive the in-stream deoxygenation rate, K_d. However, the plot of CBOD loading rate (in log scale) vs. travel time shows increasing CBOD loads in the downstream direction (Table A.35.1) instead of the downward trend as normally expected. This upward trend is because the unfiltered BOD samples include algal biomass. This problem clearly indicates that samples should be filtered and the filtered CBOD results should be used to develop the K_d rate. Without this independent derivation of the K_d, one has to obtain the K_d rate through model calibration, thereby generating additional uncertainty with the modeling analysis. An example of an independent derivation of the deoxygenation rate is shown in Figure 1 of this Appendix for the Upper Mississippi River (Lung and Larson, 1995).

Model Calibration and Verification

Since the water quality constituents are interrelated, it is useful to display them on a same page to show their interactions. Figures 2 to 4 of this Appendix show the original model results (Wright, 1998) vs. data for the three surveys: July, August, and October 1991. The water quality constituents presented are: chloride, CBOD (unfiltered), TKN, ammonium, nitrite/nitrate, orthophosphate, chlorophyll *a*, and dissolved oxygen. Model results show both the unfiltered and filtered CBOD concentrations. The model-calculated unfiltered $CBOD_5$ concentrations (as shown in solid lines) should be compared with the data (unfiltered samples).

A closer examination of the model input data file has raised a number of questions:

1. Algal settling velocity is zero in the first 10 reaches of the model and is 1.0 ft/day in the rest of the river. What is the justification for varying settling velocities? The zero settling velocity in the first 10 reaches (approximately from River Mile 45.8 to River Mile 27.8) tends to keep all the algae in suspension, while the 1.0 ft/day settling velocity tends to lose much algal biomass from the water column. A uniform settling velocity should have been used. Further, a settling velocity of 1.0 ft/day seems to be high (EPA, 1995). Thus, a uniform settling velocity of 0.25 ft/day is recommended.

2. The non-algal light extinction coefficient, K_e , used in the model is 0.01 ft^{-1}, which is very small. For example, a typical light extinction coefficient (without algal self-shading effect) in many riverine systems is between 0.1 ft^{-1} and 0.4 ft^{-1}. A K_e value of 0.2 ft^{-1} is recommended for the Blackstone River.

3. Nutrient half-saturation constants (Michaelis) of nitrogen and phosphorus used in the model are 0.25 mg/L and 0.05 mg/L, respectively. They are about one order-of-magnitude higher than they should be (EPA, 1995). Using such high values tends to overly limit algal growth in the water column, i.e., causing a false alarm of nutrient limitations. More reasonable values should be 0.025 mg/L and 0.002 mg/L for nitrogen and phosphorus, respectively.

4. The remineralization rate of organic phosphorus of 0.35 day^{-1} is much too high, causing rapid nutrient recycling in the water column. On the other hand, the organic phosphorus settling rate of 0.05 day^{-1} is too low. A more reasonable remineralization rate of 0.05 day^{-1} is recommended, and an organic phosphorus settling rate of 0.25 day^{-1} should be used.

5. Finally, a lower chlorophyll *a* to algal biomass ratio of 2 μg/mg should be used, indicating that 0.2% of the dry weight is chlorophyll *a*, consistent with values reported in the literature.

After incorporating these changes in all three model runs: July, August, and October, the revised results are shown in Figures 5 to 7 of this Appendix. Compared with the original model calibration results, the revised model results match the data better for almost all water quality constituents. Note that these changes are just a beginning. Additional model runs should be conducted to fine tune the model until a unique set of kinetic coefficients reproduce the water quality data from the three surveys.

Model Calibration Procedure

The calibration procedure presented in the report by Wright et al. (1998) does not appear to be adequate to calibrate the model fully, as seen in Figures 2 to 4 of this Appendix. A brief summary of steps to fine tune the model is outlined as follows to further improve model calibrations.

1. Perform independent estimates of the exogenous variables such as river flows, mass transport patterns, and boundary conditions, and environmental conditions should first be derived from the data to minimize uncertainties. However, light intensity, turbidity, or Secchi depths were not measured to assign accurately the light extinction coefficient.

2. Independently develop and derive as many kinetic coefficients as possible using the available data. One example is quantifying the deoxygenation coefficient, K_d from the CBOD data. Unfortunately, data deficiency prevented such an exercise for the Blackstone River.

3. Consult literature for coefficients that cannot be derived from the available data. Examples are algal growth rate, respiration rate, nutrient half-saturation constants, etc. In this situation, experience in water quality modeling is required to assign reasonable coefficient values.

4. Conduct model sensitivity runs and component analyses to quantify the relative importance of the coefficients to the dissolved oxygen budget as well as the algal-nutrient dynamics in the water column.

It should be pointed out that model calibrations are not intended to "curve fit" the data. Rather, the calibrated coefficients are obtained through a series of model sensitivity runs with reasonable and narrow ranges of their values derived from the literature and other modeling studies. In model calibrations, adjusting the kinetic coefficients and constants (within their narrow ranges) to improve the calibration of a certain water quality constituent(s) often results in adverse outcomes for matching other water quality constituents. These are the constraints in the model calibration process which will eventually lead to the development of that unique set of model coefficients.

Quantitative Measures of Goodness of Fit

A qualitative evaluation of the success of the model calibration in a study can be made by inspection of the agreement between the calculated temporal distributions and the data (see Figures 2 to 7 of this Appendix). For the Blackstone River modeling study, some statistical comparisons may provide additional understanding of model credibility. Statistical techniques have been proposed as quantitative measures of comparison (Thomann, 1980), although the interpretation of these results may be ambiguous and should, therefore, be used with caution. In this study, difficulty arises as depth-averaged water quality constituent concentrations calculated by the model are compared to grab samples at a single depth in the water column at the sampling location. Assuming the data from all locations are characterized by the same bias throughout the river system, the results of statistical analyses may provide a basis for relative comparisons between various locations for steady-state model simulations.

Thomann (1980) suggested a number of statistical analyses between observed and computed values for water quality modeling: (a) regression analyses, (b) relative error, (c) comparison of means, and (d) root mean square error. Each of these measures displays model credibility from different statistical viewpoints. Some are apparently useful for diagnostic purposes, while others appear to be directly of value in succinctly describing model verification and calibration status.

It is recommended that the root mean square error measure be used to quantify the goodness of fit between the model results and field data. The root mean square error is evaluated as follows:

$$r=\left[\frac{\sum (x_i - C_i)^2}{N}\right]^{0.5}$$

where

r = root mean square error
x_i = model results
C_i = field data
N = number of data points

Root mean square (rms) errors are statistically well-behaved and provide a direct measure of model errors. For this study, the rms errors should be calculated over the entire study area at single locations with field data.

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APPENDIX B: Comparison of WASP Model Results to Field Data for Upper Mississippi River