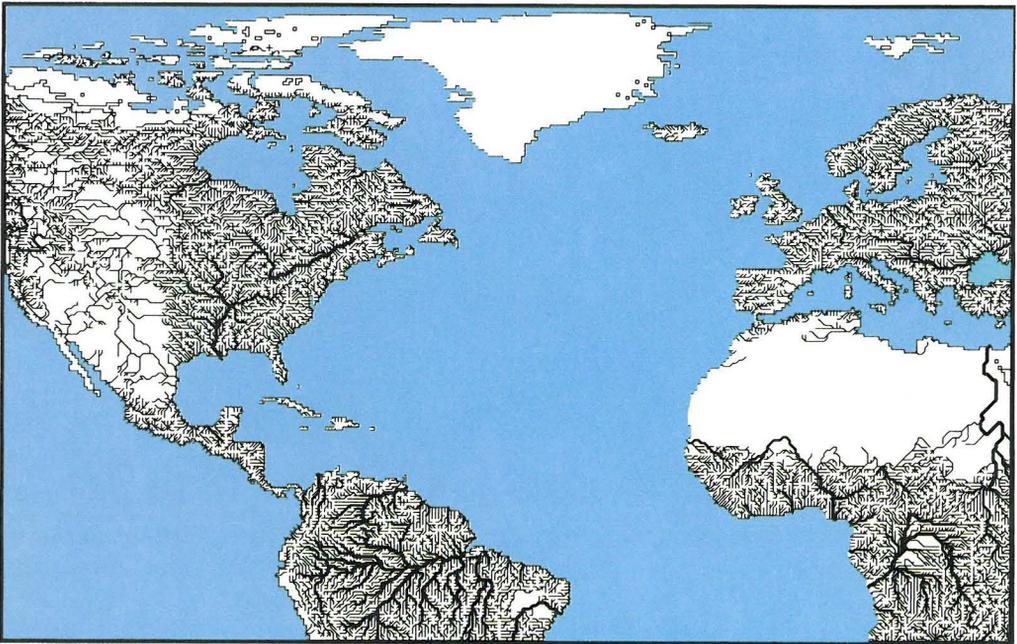


# IGBP REPORT 39

International Geosphere–Biosphere Programme (IGBP)



## Modelling the Transport and Transformation of Terrestrial Materials to Freshwater and Coastal Ecosystems

### Workshop Report

The International Geosphere-Biosphere Programme: A Study of Global Change (IGBP) of the International Council of Scientific Unions (ICSU)  
Stockholm, Sweden

# IGBP REPORT 39

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## **Modelling the Transport and Transformation of Terrestrial Materials to Freshwater and Coastal Ecosystems**

### **Workshop Report**

#### **Recommendations for IGBP Inter-Programme Element Collaboration**

Edited by:

C.J. Vörösmarty (BAHC)

R. Wasson (PAGES)

J. Richey (LOICZ)

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## Workshop Report

IGBP Workshop Reports do not necessarily reflect the science programme approved by the Scientific Committee (SC-IGBP). IGBP approved science is described in the Programme Element Science Plans and Implementation Plans.

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Cover Illustration: Portion of a global river network database at 50 km spatial resolution. The use of this and several other biophysical data sets in models of land-to-ocean biogeochemical fluxes is discussed in this report. Image courtesy of C. Vörösmarty and B. Fekete, University of New Hampshire, USA.

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## Executive Summary

Human disturbance of the water cycle is a global phenomenon affecting both river discharge and the transport and processing of sediments, carbon, and nutrients in aquatic ecosystems. This has led to significant changes in the transport of constituents from terrestrial biomes to the oceans with poorly known impacts on global biogeochemistry. Despite its enormous importance to human society, a relatively neglected element of the global change question concerns linkages between the continental land mass, river systems, and the coastal/nearshore environment. An IGBP modelling activity directed at predicting the direction, magnitude, and impact of human intervention in the biogeochemistry of river basins could provide an important contribution to Earth System Science.

Several activities within individual IGBP Programme Elements support fluvial transport research. However, these have progressed more or less independently and little attention has been focussed on consolidating this facet of the overall IGBP research agenda to minimize any duplication of effort. The principal goal of this Workshop Report is to provide advice to the IGBP on science opportunities in the realm of fluvial transports that could be pursued through an inter-Programme Element collaboration. This Report also presents a series of near-term objectives and outlines a general framework for securing these goals. The contents of this document does not represent the formal IGBP-approved science agenda. However, it is our hope that it will serve as a first step in subsequent inter-Programme Element activities to more completely formulate a joint research initiative within the IGBP.

The key scientific issues were cast as a set of questions of direct relevance to Earth System Science and to our understanding of how changes in fluvial systems ultimately affect human society. These questions were addressed by three Working Groups:

- What are the quantities and chemical attributes of riverborne fluxes to the ocean of water, sediment, carbon, nitrogen, phosphorus, silicon, and micronutrients?
- What are the physical, chemical, and biological controls, including natural and anthropogenic, on the fluxes of water, sediment, carbon, nitrogen, phosphorus, silicon, and micronutrients in the catchment cascade?
- What are the feedbacks of changes in drainage basins on human society and on biogeochemical cycles?

Within the context of these issues, this Report offers a strategy for constructing drainage basin simulations within the 3-5 year time frame. A two-tiered approach is prescribed, developing first data-rich inventories of riverine flux and drainage basin status, and next, a more process-level understanding that would be used to construct models of key controlling factors and feedbacks. Recognizing that material transport in fluvial systems is seldom if ever in steady state, the Working Groups recommended an analysis of several relevant time scales: 18kg before present to the end of the pre-industrial era, the recent historical past from circa 1700 AD, the contemporary setting, and 100 years into the future.

The current generation of estimates on the fluxes of water and waterborne materials from the continental land mass are subject to large uncertainties, hindering progress toward construction of large-scale river process simulations. Short-term progress could be made by developing relatively simple flux inventories. This requires the application of several alternative modelling approaches, a large and growing number of spatially-explicit biophysical data sets, and improvements to the current global network of river monitoring stations. Continental to global scale inventories could be attempted given our current level of understanding and data resources. A key element of the approach requires development of a suitable classification system and "typology" of river systems to permit extrapolation from well-monitored rivers to larger domains.

A critical gap in our knowledge of fluvial systems concerns the internal dynamics of drainage basins and their response to anthropogenic change. An IGBP modelling effort emphasizing process-level understanding could make a significant scientific contribution and provide the mechanism by which river basin simulations could be coupled to Earth System Models. This work would rely heavily on Case Studies cast at the regional scale ( $10^4$  to  $10^5$  km<sup>2</sup>). Several specific models are proposed from relatively simple static material balance models to more complete biogeochemical process simulations. A long-term goal is to model material transformations along the entire continuum of fluvial systems from terrestrial mobilization, through river corridor transport and transformation, with ultimate delivery to the coastal zone. Results from these studies would ultimately be placed into the global context and could be checked against results obtained from the flux inventories.

The Working Groups also considered issues relating to feedbacks from changes in drainage basins on both human society and on biogeochemical cycling. It was recognized that the possible range of feedbacks is large, encompassing changes in climatic forcing, water quality and quantity, flow regime due to water engineering, species shifts, changes in sediment load, and the aesthetic and recreational aspects of rivers. Using the issue of changes to fisheries, the Working Groups discussed an general approach for addressing feedbacks on society, targeting potential models, methods, data sets, and classification schemes. It was recognized that a generic model for global application is probably not now feasible and would require additional study. Emphasis should be placed on more regional Case Studies. For biogeochemistry, it once again was noted that the potential feedbacks are numerous and complex. The Working Groups highlighted, as an example of the much broader set of IGBP-relevant issues, that of linkages between fluvial processes and trace gas emissions. A specific emphasis was placed on the fluxes of nitrous oxide and methane, owing to their well-established dependence on water status, carbon, and nitrogen availability in upland, wetland, and aquatic ecosystems.

This Report offers a summary of current IGBP activities and identifies several which could potentially benefit from an inter-Programme Element collaboration. Biospheric Aspects of the Hydrological Cycle (BAHC), Past Global Changes (PAGES), and Land-Ocean Interactions in the Coastal Zone (LOICZ) have the most clearly articulated research agendas on fluvial transports. Because of the interdisciplinary nature of the subject, it is desirable that other IGBP Programme Elements participate in any future dialogue on this initiative, notably Land-Use/Cover Change (LUCC), Global Analysis, Interpretation, and Modelling (GAIM), and Global Change and Terrestrial Ecosystems (GCTE). The scientific activities envisioned in this Report are data-intensive; additional support and interaction with Data and Information Systems (IGBP-DIS) will therefore be critical. Collaboration is also advised with outside organizations such as the International Human Dimensions Programme on Global Environmental Change (IHDP), World Climate Research Programme (WCRP), United Nations Educational, Scientific and Cultural Organization (UNESCO)/International Hydrological Programme (IHP), World Meteorological Organization (WMO), United Nations Environmental Programme (UNEP), World Health Organization (WHO), and relevant commissions of the International Association of Hydrological Sciences (IAHS).

## Preface

The Report that follows is the product of a three-day workshop entitled "Modelling the Delivery of Terrestrial Materials to Freshwater and Coastal Ecosystems", held in Durham, New Hampshire, USA, from 5-7 December 1994. The Report reflects the contributions of nearly thirty scientists from the disciplines of hydrology, sedimentology, geomorphology, aquatic ecology, nutrient biogeochemistry, terrestrial and aquatic ecosystem modelling, Geographic Information Systems (GIS), and remote sensing technology. Local, regional, continental, and global perspectives on the overall subject of the Workshop were introduced. We served as co-conveners for the meeting and editors of this Report. The Workshop was convened and led by BAHC and PAGES.

There are several activities within individual IGBP Programme Elements that support fluvial transport research. This research has progressed more or less independently and little attention has been focussed on consolidating the work to minimize duplication of effort. This Workshop Report articulates key scientific issues that could be addressed within an overall IGBP context, presents a set of near-term objectives, and outlines a framework for securing these goals. The contents of this Report does not represent the formal IGBP-approved science agenda. However, it is our hope that it will serve as a first step in the formation of subsequent inter-Programme Element activities to more completely formulate a joint research initiative within the IGBP. Although we focus on issues of direct relevance to IGBP, collaboration is advised with outside organizations such as IHDP, WCRP, UNESCO, WMO, UNEP, WHO, and IAHS for modelling the linkages among terrestrial ecosystems, river systems, and the coastal environment.

The Workshop was organized around a set of keynote presentations, brief research "bites", plenary discussion, and break-out writing sessions. Keynote speakers each presented a synthesis on critical issues relating to the topic of constituent transport. Other participants offered brief summaries of their own research and how that work could be used to develop a continental to global-scale perspective. Written summaries of the presentations were collected and organized as a set of preliminary proceedings totalling nearly 200 pages. Interested parties should contact the co-conveners to obtain copies of this document.

Three scientific questions were agreed-upon as focal points for the ensuing dialogue, and break-out groups (Appendix I) were assembled to discuss each. This Report presents a summary of these subgroup discussions (see Organizing Questions), as well as several recommendations for future IGBP inter-Programme Element collaboration. This document will be distributed to the IGBP at large and to organizations such as the World Climate Research Program's Global Energy and Water Cycle Experiment (WCRP/GEWEX), International Hydrological Programme (IHP), and relevant IAHS Commissions. We welcome additional comments on both the scientific and institutional aspects of the Report.

The co-conveners wish to acknowledge the contributions of numerous individuals and sponsors who helped make this Workshop possible. First, we are grateful to Thomas Rosswall (Past Executive Director, IGBP), Chris Rapley (Present Executive Director, IGBP), and Risa Rosenberg (Programme Officer, IGBP) and to Michael Bonell of the IHP in Paris for their encouragement and financial support. BAHC and PAGES contributed travel support for individuals from their respective Programme Elements. We also thank the Chairs and Scientific Steering Committee members from BAHC, PAGES, and LOICZ who provided constructive guidance in the content and execution of the Workshop. We also acknowledge the written reviews provided by the Workshop participants, IGBP scientists, and Programme Officers. Finally, we wish to thank Clara Kustra, Annette Schloss, Faith Sheridan, and Karen Bushold for substantial logistical support before, during, and after the Workshop. They provided us with a smoothly-run meeting that helped make it an enjoyable and ultimately productive endeavour.

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Co-conveners:

C. J. Vörösmarty (BAHC), University of New Hampshire (USA)  
R. Wasson (PAGES), Australian National University (Australia)  
J. Richey (LOICZ), University of Washington (USA)

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## Introduction

Human disturbance of the water cycle is a global phenomenon affecting both water fluxes and the transport and processing of sediments, carbon, and nutrients in aquatic ecosystems. This has led to significant changes in the transport of constituents from terrestrial biomes to the oceans with poorly known impacts on global biogeochemistry. Despite its enormous importance to human society, an arguably neglected element of the global change question surrounds the linkages between the continental land mass, river systems, and the coastal/nearshore environment.

The specific manner in which humans have modified these linkages requires further study. To address the full dimension of anthropogenic change as it relates to water, we will need to consider greenhouse-induced climate change, expanding management and conversion of landscapes, and an ubiquitous alteration of the water cycle for activities such as irrigation, flood control, hydroelectric production, industrial withdrawal, and waste processing.

Numerous studies of coastal systems (*e.g.*, Gulf of Mexico, Baltic Sea, Rhine River) have shown that changes in land use, population growth, and industrialization within contributing upland drainage basins are tied directly to coastal eutrophication and that such changes are important at regional and larger scales. A diminishing fraction of the world's drainage basins can be considered to be in a "natural" state. For example, nitrate-N concentrations in a sample of rivers draining 55 M km<sup>2</sup> of the continental land mass show that less than 80% are pristine and that one-half of the remainder is heavily polluted (Meybeck and Ragu 1995). Multiple-fold increases in constituent loadings have been documented at regional, continental, and even global scales since the start of the Industrial Revolution (*e.g.*, Nixon 1995, Meybeck and Helmer 1989, Wollast 1983, Vörösmarty *et al.* 1986). Further, tests using a coastal ocean biogeochemistry model (Mackenzie *et al.* 1993) have shown that coastal ocean responses to such loadings are likely to occur within the 100-year time frame.

The issue of riverine transports is therefore of direct relevance to the broader question of contemporary global change, with obvious policy implications. Anthropogenic effects such as impending climate change, stream regulation, eutrophication, and increased erosion will collectively influence the long-term functionality of inland and coastal ecosystems to supply drinking water, support fisheries, regulate floods, and transport and process wastes. The reality that approximately 60% of the world's population resides in the coastal zone (IGBP-LOICZ 1995) makes the issue of land-river-coastal zone linkages timely and relevant to global habitability. An IGBP model-

ling activity directed at predicting the direction, magnitude, and impact of human intervention in the biogeochemistry of these linkages could provide an important contribution to Earth System Science.

## Goals and Objectives

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The principal goal of this Report is to provide advice to the IGBP on science opportunities in the realm of fluvial transports that could be pursued through an inter-Programme Element collaboration. It also highlights possible cooperation with outside organizations such as IHDP, WCRP, WHO, UNEP, UNESCO, WMO, and IAHS. This Report is a direct outgrowth of and complement to PAGES Workshop Report, Series 94 entitled *Land Use and Climate Impacts on Fluvial Systems during the Period of Agriculture*, a document that supports PAGES' Focus III activities and helps to elucidate the historical role of humans on the delivery of sediment through drainage systems. The current Report extends the analysis to treat terrestrially-derived materials more generally, and to begin developing a strategy for constructing drainage basin components within emerging Earth System Models. There are several supporting objectives:

- (a) *Establish key scientific issues and opportunities.* Our current understanding of the processes and changes due to humans is derived essentially from Case Studies on individual river systems. Continental and global inventories of material fluxes to date have been based on literature surveys using this information. Techniques need to be developed to extend our understanding to regional and global scales using state-of-the-art tools for monitoring and modelling these changes. The first step in this process is identification of a set of key, answerable scientific questions that can be addressed within an IGBP context and in a 3-5 year time frame. Three questions were presented and discussed in detail:
  - What are the quantities and chemical attributes of riverborne fluxes to the ocean of water, sediment, carbon, nitrogen, phosphorus, silicon, and micronutrients?
  - What are the physical, chemical, and biological controls, including natural and anthropogenic, on the fluxes of water, sediment, carbon, nitrogen, phosphorus, silicon, and micronutrients in the catchment cascade?
  - What are the feedbacks of changes in drainage basins on human society and on biogeochemical cycles?
- (b) *Develop a strategy for constructing drainage basin simulations.* This document offers specific classes of models depicting drainage basin dynamics within the context of coupled Earth System simulations. These component drainage basin models are cast to predict the transport and processing of waterborne materials from the land mass to the coastal zone at regional, continental, and global scales. A time frame focusing on the beginning of the Industrial Age, contemporary conditions, and future 100 years, is envisioned, although the pre-industrial period to 18 K before present is also considered.

- (c) *Establish the data requirements to support model calibration, testing, and validation.* Once a set of target models has been identified the Report goes on to recommend specific data sets for the successful implementation of the proposed models. These data sets will be acquired through integrated regional studies and global assessments as outlined in (d).
- (d) *Promote integrated regional to global assessments.* A goal of this contribution is to initiate an appropriate set of regional and larger scale assessments of the role of drainage basins in the Earth System and in global change. The promotion of such studies will involve both the coordination of existing IGBP Programme Element activities and well as collaboration with other international organizations. Such activities will involve field experiments, monitoring, and modelling.

The products of this research will yield many potential benefits, from the more academic (estimating terrestrial nutrient fertilization on the ocean's carbon cycle; investigating the role of river flow on methane flux; developing a mechanism to interact with ocean modellers) to the applied (assessing broad-scale features of water pollution and drinking water supplies; predicting associated changes in fisheries; estimating changes in hydroelectric potential as a consequence of global change). An enhanced modelling and monitoring capability becomes increasingly important as rapid increases in human population, urbanization, land cover change, and pollution loading, all critical threats to the sustainability of freshwater and coastal zone systems, are likely to continue well into the next century.

## Methodology

The subject matter treated in this document spans a science that is broad, interdisciplinary, and complex. Interconnections exist among the more traditional realms of terrestrial ecosystem analysis, nutrient biogeochemistry, hydrology, climatology and palaeoclimatology, geomorphology, land management, and sedimentology. Additionally, due consideration must be given to a wide spectrum of anthropogenic effects including those associated with land use and land cover change, management of natural resources, and the still poorly quantified effects of greenhouse warming. The scope of relevant activities and definitions of terms are summarized in Figure 1 and described below.

### Specific Constituents

Primary emphasis will be on the fluxes and transformations of biotically-important constituents derived from terrestrial ecosystems; namely, carbon, nitrogen, phosphorus, and silicon. A consideration of both dissolved and particulate fractions will be necessary and attention must be paid to the physical transport of sediments. Since these materials are transported through groundwater, rivers, lakes and wetlands, an analysis of water balances and water fluxes will be essential. Micronutrients, major cations and anions (*e.g.*,  $\text{SO}_4$ , Cl, Ca, Mg, K, Na) and weathering products such as carbonate are important in establishing overall material balances and will provide an additional, although subsidiary, focus.

### System Boundaries

The drainage basin serves as a key organizing principle in this discussion. The overarching goal is to understand how specific terrestrially-derived materials are mobilized, delivered to, and transformed along the full cascade of landscape/fluvial systems. Adequate consideration must be given to terrestrial ecosystem dynamics, the role of wetlands, and interactions within the river-riparian complex. The downstream boundary is restricted to the landward margin of the coastal zone (*i.e.*, river mouths, estuaries, deltas) where LOICZ-specific activities are currently underway. Consideration in this Report of coastal environments will, however, be used whenever necessary to lend support to the overall objectives. Interconnections with atmospheric boundary forcings (predominantly through climatic variables),

atmospheric deposition, and CO<sub>2</sub> enrichment are also relevant, as are feedbacks to the atmosphere through CO<sub>2</sub> and trace gas emissions from aquatic and wetland ecosystems. Addressing such linkages is necessary to define the integration of drainage basin dynamics into a larger Earth Systems context.

## Spatial Domains

A broad spectrum of fluvial systems needs to be considered. The broadest spatial domain (> 10<sup>7</sup> km<sup>2</sup>) is that of the global land mass, using models with either no geographic-specificity (e.g., Mackenzie *et al.* 1994) or coarse-scale algorithms capable of predicting inputs to at least the level of individual ocean basins (e.g., Milliman and Syvitski 1992). Continental-scale models (e.g., Vörösmarty *et al.* 1989, Richey *et al.* 1989) span approximately 10<sup>5</sup> to 10<sup>7</sup> km<sup>2</sup> and consider individual drainage basins or major tributaries contained therein. The smallest domain we focus on is the regional scale, defined from 10<sup>4</sup> to 10<sup>5</sup> km<sup>2</sup>. Although the focus is decidedly on the region and larger domains, the legacy of research findings obtained at smaller scales cannot be ignored and will be incorporated into the analysis as required.

## Time Frames

A critical characteristic of fluvial systems is that their rates of material transport are seldom if ever in steady state (Wasson 1996, Wasson 1994, Meade and Trimble 1974). Such a condition arises due to natural variations in climate, to anthropogenic pressures that vary over time, and to the distribution of response times that the land-river continuum exhibits when disturbed. A contemporary picture is important in establishing benchmarks by which to measure future changes. But fluxes in the present must be interpreted with utmost care since they are in part an expression of the past behaviour of the drainage system and of earlier periods of anthropogenic disturbance. The Working Groups recommended a multi-phased approach, employing studies of past, present, and possible future conditions.

### Palaeo-Perspectives (18,000 Year BP to the End of the Pre-Industrial Era)

The Working Groups suggested detailed studies be carried out on four past climatic regimes:

- 18,000 BP (Last Glacial Maximum)
- 14,000 to 10,000 BP (Deglaciation)
- 6000 BP (Holocene Maximum)
- 1500 AD ("Little Ice Age")

Considering these climates will contrast relatively warm *vs* cold conditions, periods of modest *vs* extreme runoff (and hence material transport), and long *vs* short-term transient events. In addition a palaeo/historical focus on the entire period of sedentary agriculture, emphasized as an activity of the PAGES Fluvial Systems Working Group, is also necessary to provide a context for assessing the longer-term role of humans as active agents of global change.

### Historical Perspectives (From the Pre-Industrial Era)

Global carbon modellers have long recognized that large differences exist in atmospheric CO<sub>2</sub> concentrations between contemporary and pre-Industrial conditions, leading to detailed inventories of the time-varying contributions from disturbed biota and industrial sources (e.g., Keeling and Whorf 1994, Houghton *et al.* 1983). A similar analysis should be undertaken for river fluxes, reconstructing anthropogenic loadings from the pre-Industrial era (from ca. 1700 AD) to the present. Such information should be used to both quantify the long-term influence of humans on biogeochemical fluxes and to clarify the importance of non-steady state conditions on observed contemporary fluvial transports. Such an analysis would also foster integration of riverine fluxes into comprehensive Earth System Models.

### Contemporary Setting (1980 - Present)

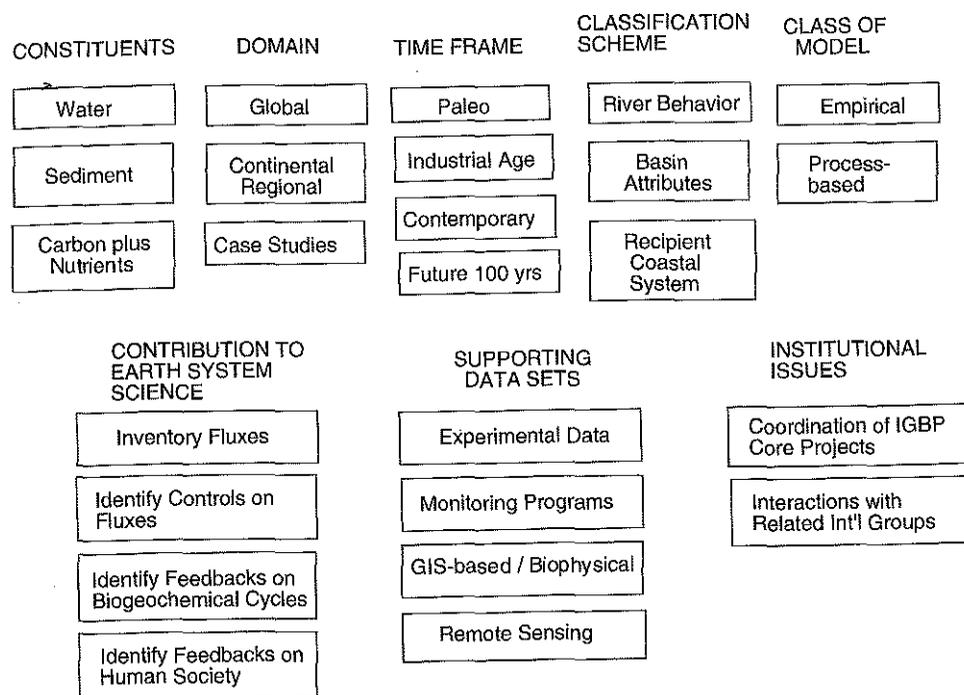
Our understanding of the present-day linkages between the continental land mass and the coastal oceans is incomplete. A pressing need is to provide a synthesis of contemporary material loadings from the terrestrial biosphere, transport by river systems, and concomitant impacts on freshwater and coastal ecosystems. Indeed, success toward this goal will be an important step forward and the bulk of the text is devoted to describing models and data sets to analyse this time frame. Validated contemporary models establish an important baseline to which both past and future drainage basin fluxes can be compared.

### Future 100-Years

Human population growth, industrialization, land conversion in upstream watersheds, intensified use of water resources, the creation of mega-cities, and climatic change will all continue to be important elements of anthropogenic change well into the next century. Since many of these are directly linked to a deterioration in water quality, their cumulative effects on global freshwater and coastal resources are likely to assume an increasing level of urgency in the future. Knowledge gained from both the retrospective and contemporary drainage basin studies will be essential. Thus, the flux inventories, the process-based approach to analyse controls, and feedback studies will contribute to an improved understanding of the connection between anthropogenic change and resulting drainage basin response. This in turn provides the foundation upon which to explore a suite of future policy-relevant questions, such as: Which areas of the globe will be most vulnerable to eutrophication caused by agricultural runoff? What is the aggregate impact of increased erosion on the useful life of impoundments? How will continued urbanization in developing countries accelerate point source loadings and hence affect fisheries production?

**Figure 1**

Conceptual framework for workshop discussions.



## Organizing Questions

### Question 1: What are the Quantities and Chemical Attributes of Riverborne Fluxes to the Ocean of Water, Sediment, Carbon, Nitrogen, Phosphorus, Silicon, and Micronutrients?

This question focuses on defining the magnitude, nature, and timing of boundary fluxes from the continental land mass to the world's coastal zones. These fluxes and their characteristic chemical signatures are the result of complex patterns of mobilization from the land, subsequent processing and transport within and through wetlands, riparian zones, lakes, and river courses. Particulate and chemical delivery at the endpoints of drainage systems provide a convenient integration of numerous processes operating within those systems. Thus, although this question does not serve to elucidate biotic, chemical or physical controls *per se* (as does Question 2), it will provide a continental to global-scale perspective upon which to calibrate and later validate fluvial transport models. In an Earth Systems modelling perspective, the associated fluxes couple freshwater drainage systems to their coastal counterparts — the fluxes simultaneously act as the bottom boundary condition in drainage basin models and as one of potentially numerous lateral boundaries in models of the coastal zone. Flux inventories for biotically-active constituents serve as the basis for assessments of both feedbacks to the biogeochemistry of the coastal zone/oceans as well as to human society dependent on increasingly scarce water, habitat, and food provided by these systems.

### Overall Strategy for Developing Flux Inventories

Several literature-based surveys and syntheses have provided a first-order quantification of the fluxes of terrestrially-derived materials including sediments, carbon, nutrient, and metals (e.g., Degens 1982 to 1990, RIOS 1981, Meybeck 1994a). AI-

though such studies provide important benchmarks in our understanding of these fluxes, they lack a dynamic perspective. Models that embody spatial and temporal variability are the next logical step in the application of this approach. Such a capability is increasingly important as humans modify the land surface of the Earth, manipulate hydrological pools and fluxes, and change the character of the climate system.

WG-1 advocated a two-phased approach for developing improved inventories of fluxes over both space and time. The first phase should be devoted to database development which will provide the necessary raw material for creating drainage basin flux models. Assembling, assessing, and helping to improve the current generation of water survey data sets is nonetheless valuable in its own right, as it will contribute to a better quantification of fluxes from a purely empirical standpoint. The second phase should involve constructing, calibrating, and validating scale-appropriate models that can be applied with geographic-specificity and used to predict past, contemporary, and future fluxes.

After reviewing the current state-of-the-art in data and modelling capabilities at the large scale, WG-1 concluded that a global quantification could be attempted. Estimates emerging from this broad-scale perspective, however, must be made in conjunction with data-rich continental and regional-scale Case Studies that provide necessary cross-validation. Question 2 activities are relevant within this context.

## Data Availability and Assessment

Estimates of riverine fluxes and chemical signatures depend on existing data resources distributed across the globe. It is therefore necessary to inventory, document, and make available such data sets, to identify gaps in our knowledge, and, where necessary, to collect additional data. A partial inventory of riverborne constituent data together with an assessment of the current state-of-the-art with respect to data quality is given in Tables I and II. A more complete discussion is offered in Appendix II.

Some general findings emerge from this initial assessment. In terms of the spatial coverage, frequency, and duration of monitoring, it is easily seen that data currently available at the global scale is patchy at best, and generally associated with the level of economic development. The most abundant data resources are thus available for highly-developed countries. Rapidly-developing regions show an intermediate level of data availability, while less-developed countries are most poorly monitored. Even in the best-represented regions of the globe, a coherent time series is available for only the last 30 years or less, constraining our ability to construct and test riverine flux models. Data quality is yet another issue limiting the usability of water quality data. Standardized protocols, both in terms of sampling frequency, spatial distribution of sampling networks, and chemical analyses are still needed to ensure the production of comparable data sets collected in disparate parts of the globe.

There are, then, several necessary upgrades required of the basic monitoring system for discharge and riverborne constituents at the large scale. IGBP can provide assistance to existing monitoring programmes through the further inventory of discharge and chemical constituents. In this context, a map of existing data sets, their associated drainage basin attributes, periods of record, and rates of population and indus-

trial growth would provide valuable baseline data upon which to make informed proposals for the upgrading of global monitoring networks. As part of such assistance, this inter-Programme Element collaboration should clearly articulate the specific calibration and validation data sets necessary to construct and test biogeochemical models. It should also assist the monitoring programmes in the design of sampling programmes that can provide these data.

## Specific Data Sets

Despite the numerous challenges to our monitoring capabilities there are substantial resources upon which to base the proposed constituent flux inventory. In addition, there is a large and growing series of biophysical data sets that can be enlisted to support large-scale riverine flux studies. This Report reviews the current generation of such data holdings and later gives specific recommendations for improving the reliability of this information base.

### LOICZ and GEMS-GLORI Data Sets

A coherent strategy for assembling and disseminating data on river water chemistry is currently underway through two collaborative efforts. The first is a LOICZ initiative to develop a Global Register of River Inputs (LOICZ-GLORI). The second is the Global Environmental Monitoring System Water Project (GEMS-Water) supported by UNEP/WHO/WMO/UNEP, combining literature-based information with data available through the Collaborating Centre for Freshwater Monitoring and Assessment (Canada Centre for Inland Waters [CCIW], Burlington, ONT).

The first phase of LOICZ-GLORI is complete and contains information on approximately 1000 river mouths giving discharge, area, elevation, TSS, TDS, and DIC. The source of this information is from individuals (e.g. J. Milliman, Virginia Inst. of Marine Studies; M. Meybeck, Univ. of Paris), GEMS-Water, literature reviews, and country-level reports. LOICZ-GLORI includes entries on several hundred catchments below  $10^4$  km<sup>2</sup>, which are extremely important for sediment discharge into regional coastal zones, such as those associated with the major western Pacific islands. Also noteworthy is specification in LOICZ-GLORI of conditions prior to as well as after the construction of major engineering works like dams. A first version of the database, highlighting TSS and TDS data, was released at the LOICZ Manila meetings in April of 1995 (Milliman et al. 1995) and is currently being checked for accuracy by scientists and contributing agency representatives before general release.

The GEMS-GLORI register (Meybeck and Ragu 1995) was formulated as a second database treating river-to-ocean inputs but with an expanded thematic scope. GEMS-GLORI emphasizes nutrients, carbon species, and major ions, in both dissolved and particulate forms. Of the more than 550 reporting stations with similar general information as in LOICZ-GLORI, about 250 are described in terms of the most commonly analyzed nutrients (nitrate, phosphate, dissolved inorganic carbon) while fewer than 80 show data for the less commonly monitored species (organic N, particulate organic C, etc.). Each average concentration value is accompanied by an observation period and an original reference. The coverage of GEMS-GLORI for both sampled contributing area and discharge ranges from about 45 to 70% for individual continents. As in LOICZ-GLORI, the database indicates, wherever possible, both pre- and post-anthropogenic effects on river flow and chemistry. After its presentation at the

GEMS-Water Expert Meeting on Land-based Forms of Pollution (Koblenz, Germany in June 1995) a draft version of the register was circulated widely to the water sciences community for validation. GEMS-GLORI can be used to support regional-scale studies, such as work now being completed on the smallest rivers of the Mediterranean basin and for micropollutants at the request of UNEP.

The GEMS-Water Program serves as a key source of river chemistry data that could be used to enhance the existing GLORI synthesis efforts both now and in the future. Currently, GEMS-Water data cover several hundred river stations worldwide in more than 50 countries including those in the developed (e.g. US, western Europe), underdeveloped (e.g. Nigeria, Vietnam), and rapidly developing (e.g. Brazil, China) regions of the globe. A wide spectrum of rivers is represented, down to 10,000 km<sup>2</sup>, and these represent both the mouths of rivers as well as upstream tributaries. Major ions, nutrients, and trace metals on individual samples are available with a sampling frequency of typically 6-24 per year. Some information is available on micropollutants at 10-20% of the sites. Most of the stations represent contributing upland basins influenced by human activities, and, since GEMS-Water entries have been routinely collected since 1978, they permit an assessment of water quality trends to be made. Retrospective studies of periodic and event-based (e.g. flooding) variability for individual basins, as well as cross-site comparisons, are also made possible through the availability of this archived data.

#### **Additional Biophysical Data**

Table III shows a listing of additional data sets that are currently available for use in constructing a global flux inventory. Although these data sets are more or less freely available, coordination is required to collect and standardize their contents so that they are useful for calculating riverine fluxes. In addition, effort should be directed toward the identification and digitalization of additional data sets. For example, the *Soviet Geographic Atlas of 1964* contains numerous thematic maps (mainly 1:15 M), but these will require significant interpretation and digitization before they can be used in the proposed modelling activities. WG-1 suggested a collaborative effort with IGBP-DIS for locating, preparing, archiving, and disseminating final data sets to the research community at large.

### **Recommendations for Improved Database Development**

The foregoing discussion amply demonstrates the need for a systematic collection and interpretation of data sets relevant to quantifying water and material flux from the world's drainage systems. The GEMS-Water and GLORI initiatives are absolutely critical for quantifying riverine fluxes. Nonetheless, ample opportunity exists for upgrading these and other data sets for their use in modelling applications. WG-1 recommended that the following specific activities to be carried-out within an IGBP framework to help achieve this objective.

#### **Develop an Integrated IGBP Database**

A standardized, geographically-referenced database and supporting software tools should be developed and made available to the research community. The database should maintain a global coverage at relatively coarse spatial resolution (0.5 degree) but simultaneously accommodate more highly resolved regional and Case Study

data sets. The first version of this database should include all data sets listed in Tables III and IV. An appropriately-designed GIS system permitting easy online acquisition and manipulation of data sets should be constructed. Once this data system is available, efforts should be directed toward the checking of existing data sets for consistency and accuracy.

Incorporation of new data sets would be a natural outgrowth of this activity. Archiving of the data sets and software system should be coordinated with IGBP-DIS and relevant ICSU Data Centers.

#### **Promote Continuation of GEMS-Water and GLORI Database Efforts**

Since relatively few coherent data sets are available for global water quality, WG-1 strongly recommended a continuation, and where feasible, an enhancement to the current GEMS-Water and GLORI database efforts. IGBP scientists could contribute to quality assurance and data checking. To ensure that the emerging data sets are of relevance to this inter-Programme Element activity, WG-1 suggested establishing a close collaboration with GEMS-Water.

This inter-Programme Element initiative should also take a pro-active role in promoting the collection of key future data sets. Although the GEMS/GLORI data set includes more than 10<sup>4</sup> pieces of information on the contemporary status of the world's rivers, global coverage is highly irregular (see also Table I). Monitoring of areas undergoing rapid development will be particularly important over the coming decades.

Extension of these data sets to major upstream tributaries will also benefit model development, especially in drainage basins that are highly variable in terms of climate, lithology, or sediment transport capacity. Introducing data on homogenous sub-basins should substantially improve the reliability of existing algorithms.

#### **Support Gauging and Water Quality Surveys that are in Jeopardy**

The recent demise of existing discharge and water quality monitoring networks will confound efforts to model transport rates, not only for global assessments but for regional studies as well. The loss of numerous Russian and African monitoring stations, for example, is particularly acute and substantial capacity rebuilding will be required.

WG-1 supported efforts to sustain existing networks and enhance them accordingly. To this end, agreements should be facilitated by international organizations such as the WMO, the Global Climate/Terrestrial Observational System (GCOS/GTOS), and the UNESCO-IHP. Country and regional-level accords should be implemented and funding support provided by international lending institutions. A vested interest by organizations such as the World Bank could be realized by articulating the connection between well-functioning monitoring programmes and the sound planning of development projects. Well-designed sediment surveys, for example, prevent the misplacement of costly impoundment projects jeopardized by land degradation upstream, and provide an impetus for improving land management practices in the surrounding drainage basin. An effort to quantify the scientific costs incurred by such losses could be made by this IGBP activity, for example, documenting the impact that the loss of hydro-meteorological station data has on quantifying regional inputs to coastal seas.

### Develop Additional Databases

Although there are several existing data-related activities that should be supported under this inter-Programme Element activity, additional data development initiatives are advised.

#### *Time Series Data for a Period Exceeding 30 Years*

Despite its importance in assessing trends in global water quality, the GEMS-Water database provides information routinely from only 1978. In addition, initial GLORI entries provide annual mean values only, so that information on inter and intra-annual variability is not yet readily available. Longer-period time series data are required to document seasonal variability, develop concentration/runoff relations, and create flux-duration curves. These are important for extrapolating to data-poor regions, for designing efficient monitoring programmes, and for interpreting controls on riverine fluxes.

WG-1 suggested therefore that there be an IGBP effort to assemble, archive, and standardize all data sets currently available for a period of time in excess of 25-30 years. WG-1 also suggested that a detailed time series analysis be performed on these data sets to document trends and to identify interactions among measured variables. This activity should be pursued in collaboration with the GEMS-Water Programme. The preparation of such a data set will be important for model calibration and validation, as well as for interpretation of the causes and consequences of anthropogenic change.

#### *Regional-Scale Databases*

The global flux inventory and modelling studies will of necessity be relatively coarse-scale and summarize a series of broad connections between driving variables and attendant fluxes of water and materials. Case Studies in watersheds of 10,000 - 100,000 km<sup>2</sup> will serve to enhance this broad-scale approach and to quantify connections between aquatic chemistry and socioeconomic indicators. Some candidate study sites, for which there is ongoing work and relevant databases, include portions of the Murray-Darling basin in Australia, the Willamette River in the State of Oregon, the entire State of New Jersey, Flathead Lake and River in the State of Montana, tributaries of the Amazon, and the Seine River in France. Maps for topography, vegetation, soils, and climatic drivers are available at relatively high resolution for many parts of the globe. Intercomparison experiments of model results generated by global and higher resolution data sets in selected locations will provide insight into the efficacy of the broader-scale models. A focus on data-rich areas is indispensable for uncovering controls and feedbacks (Questions 2 and 3). Local-scale watersheds of a few km<sup>2</sup> in extent cannot be ignored since these very often are sites for which detailed field studies and comprehensive data sets are available. They are also useful for developing regression-based models or serving as Case Studies for the mobilization of constituents from specific landscapes.

WG-1 suggested an archiving of a computerized database of information derived from such studies, maintained at a central repository and made available to the research community. Coordination should be made with the regional-scale Case Studies of riverine delivery through LOICZ as well as those outlined in the PAGES Fluvial Transport (Bern Workshop) Report. Data sets assembled before and during the Large-scale Biosphere-Atmosphere experiment in Amazonia could also be valuable in this context.

## Table I

Data inventory for existing monitoring programs across the globe. The entries relate to the quantity of available data, indicated by the number of "+" symbols. For the purposes of this assessment data quantity is an aggregate measure of station network density, spatial coverage, frequency of data collection and duration of monitoring programmes. (HDC=highly-developed country; RDC=rapidly-developing country; LDC=less-developed country).

Constituent	HDCs	RDCs	LDCs
Bedload	(+) 0	0	0
TSS	+++	++	+
DIC	+++	++	+
DOC	++	+	0
POC	+	0	0
NH <sub>4</sub>	+++	++	+
NO <sub>3</sub>	+++	++	+
DON	+	0	0
PON	0	0	0
PO <sub>4</sub>	+++	++	+
DOP	0	0	0
TP	++	+	0
Total Metals	+	0	0
Particulate metals	+	0	0
Major dissolved constituents <sup>1</sup>	+++	++	+
Discharge	+++	++	+

<sup>1</sup> SO<sub>4</sub>, Cl, Ca, Mg, K, Na, SiO<sub>4</sub>, CO<sub>3</sub>

**Table II**

Data quality problems and issues in routine monitoring programs for constituents listed in Table I.

Constituent	Relevant Monitoring Issue
Bedload	Very difficult field measurement; no regular survey; must infer from models based on selected Case Studies
TSS	Frequency inadequate; sensitive to existing variety of sampling methods and design
DIC	Appropriate field methods available; tandem pH measurements for pCO <sub>2</sub> calculation
DOC	Older methods still in use; division of measured DOC into labile/refractory pools unknown; fraction of DOC ( <i>i.e.</i> filtered total C) as colloidal-C indeterminate
POC	Labile/refractory fractions normally unknown; size fraction unknown
NH <sub>4</sub>	Differences in sample preservation affect resulting measurements
NO <sub>3</sub>	Generally good
DON	Should be measured more often; report information on labile/refractory pools; still indirectly measured through Kjeldahl-N
PN & PP	Should be measured more often; need information on labile/refractory pools
PO <sub>4</sub>	Sample preservation important; must be filtered on site
DOP	Not routinely measured; virtually unknown
TP	Must be filtered; TP sampling often ill-matched to hydrograph; establish fractionation between particulate P and filtered DOP
Dissolved M+	Essentially useless; high level of sample contamination
Total M+	Fractionation of mobile/non-mobile components currently difficult to achieve in operational monitoring programs; concentration linked to TSS
Trace metals	Free trace metals difficult to determine; current methods contaminate water 10-100x over "true" values and new technology needed; recommendation is to focus on particulates and sediments and use models to predict available concentrations
Major dissolved constituents <sup>1</sup>	Routine monitoring relatively reliable and straightforward
Discharge	Must be measured at each sampling time/station; problems assessing flow in ungauged basins; may require water transport modelling

<sup>1</sup> SO<sub>4</sub>, Cl, Ca, Mg, K, Na, SiO<sub>4</sub>, CO<sub>3</sub>

**Table III**

Some key databases currently available for use in riverine flux inventories.

Attribute	Scale	Source/Archive
• Watershed Boundaries and River Networks	0.5 degree	Vörösmarty <i>et al.</i> (1997)
• Digital Topography	5-10 minute 1 km	Edwards (1989) EROS Data Center (GLOBE Project; in conjunction with IGBP-DIS)
• Surface Attributes		
Potential vegetation	0.5 degree	Melillo <i>et al.</i> (1993); IGBP-DIS/GAIM, Rasool and Moore (1995)
Land cover	1 degree	Matthews (1983), Mylne and Henderson-Sellers (1985)
	2-deg. to 2-min 10-30 min 1 km	NGDC (1995) Olson (1989-91) IGBP-DIS/NASA AVHRR Pathfinder (IGBP-GAIM/DIS 1994)
Soils	2 minute	UNEP/GRID (1992)
• Geology/Lithology/Age	1:25 M maps 1 degree Grid	CCGM/UNESCO (1990) Suchet and Probst (1995) Bluth and Kump (1994)
(regolith)	1:10-1:30 M maps	Derry <i>et al.</i> (1980)
• Fertilizer Inputs	1 degree	Matthews (1994)
• NO <sub>y</sub> Deposition	Grid	Galloway <i>et al.</i> (1994)
• Population		
Human	5 minute 1:86 M maps	Tobler <i>et al.</i> (1995) US Bureau of the Census, (1975, 1980)
Livestock	1 degree	Lerner <i>et al.</i> (1989)
• Climate		
Temperature	Variable grid 0.5 degree	Cramer and Leemans (1994) Legates and Willmott (1988)
Precipitation	Variable grid 0.5 degree Grid	Cramer and Leemans (1994) Legates and Willmott (1988) Global Precipitation Climatology Center (Offenbach, Germany)
Radiation	0.5 degree	University of New Hampshire (computed from Hahn <i>et al.</i> 1988, cloud data)
	2.5 degree	ISCCP (1995)
	Individual sites	Ohmura and Gilgen (1991)
Winds, vapour pressure	Individual sites	NCDC (1993)
• Runoff	0.5 degree Grid Station data	University of New Hampshire Global Runoff Data Center, Koblenz Global Runoff Data Center, Koblenz; GEMS/GLORI; Vörösmarty <i>et al.</i> (1996)
• Large Reservoirs	Individual sites	ICOLD (1984,88); Vörösmarty <i>et al.</i> (1997)

### Remote Sensing Support

Remote sensing is an important tool as we attempt to generalize to the globe results obtained from site-specific studies and river inventories. Such a capability exists both for inland and coastal waters, so in principle, it may be possible to monitor key variables over both space and time. A wide variety of sensor systems, in particular those that are satellite-borne, has provided information on numerous aspects of the hydrological cycle including estimates of precipitation, inferred evapotranspiration, soil wetness, and suspended sediment transport (e.g., Barrett *et al.* 1990). The inundation of wetlands and floodplains flanking large river systems has been monitored using both active and passive microwaves (Sippel *et al.* 1994, Imhoff *et al.* 1987). Emerging high quality land cover data sets (e.g., IGBP-DIS/NASA 1-km Advanced Very High Resolution Radiometer (AVHRR) Land Cover; NASA 30-m TM Pathfinder) will provide a quantitative picture of landscape utilization by humans. When co-registered to additional GIS data sets, these will serve as an important component of spatially-explicit drainage basin models that quantify the impact of anthropogenic activities.

The monitoring of coastal water masses and river plumes using, for instance, retrospective Coastal Zone Color Scanner data and forthcoming SeaWiFS technology offers the opportunity to quantify the effect of river fluxes on coastal ecosystems. Analysis of spectral signatures requires significant additional research, however, such as how to separate pigment from suspended solids and coloured dissolved organic material signals (see Jupp *et al.* 1994). In addition, the monitoring of concentrations does not necessarily yield flux estimates. Hydrodynamic transport, sediment flux, and biotic processing models of the coastal zone must therefore be linked to the image processing analysis.

Remote sensing has its limitations in the context of estimating fluvial transports. However, the promise of such sensor systems, in particular, their potential to detect change at the global scale and to help characterize the drainage basin landscape, merits further attention. It should be more carefully addressed in future research activities under this inter-Programme Element initiative.

### Modelling Activities

The overarching goal of modelling activities under Question 1 is to achieve an understanding of the rates, timing, and controls on riverine transport of C, N, P, Si, sediment, and other key constituents over space and time. Fluxes should initially be predicted using relatively straightforward empirical relationships employing one or more of the models discussed below. Despite their apparent simplicity, such empirical relationships have been used widely and successfully in lake eutrophication studies to predict nutrient loads from observable drainage basin characteristics (e.g., Dillon and Kirchner 1975, Vollenweider 1968). Such a capability is a prerequisite for assessing changes in the dynamic properties of river systems in the context of global change as discussed under Question 2. Modelling exercises also seek to achieve an eventual integration of drainage basin models within larger interactive Earth System Models such as those currently under development through GAIM.

The flux inventory models proposed in this Report are data-rich and based on observational data sets provided by water monitoring programmes. Three classes of models are proposed in this context: (a) multiple regression, (b) concentration *vs* runoff (C

*vs* Q) models, and (c) delivery ratio. These models will be used to quantify fluxes and should not be considered as final endpoints. An additional class of more mechanistic models is discussed under Questions 2 and 3, in association with Case Studies and the issue of feedbacks.

Before these flux inventory models are discussed, a strategy for developing a drainage basin/river system classification is offered.

### Drainage Basin Classification

Our monitoring of river systems is far from complete. Thus, special attention must be devoted towards determining how best to exploit the currently available data sets and sensibly extrapolating observed patterns to unmonitored portions of the globe. River systems vary greatly, both inherently under natural conditions as well as in their response to anthropogenic disturbance. Assigning flux estimates for contrasting states of disturbance in different parts of the globe has proven difficult. It will therefore be necessary to first integrate the current body of knowledge in data-rich areas with the aim of developing models that can be spatially extrapolated to data-poor regions.

It is unlikely that a single set of models or relationships will suffice. Thus, due to differences in biophysical attributes such as topography, vegetation, climate, etc., tundra streams, incised rivers in the semi-arid zone, tropical floodplain rivers, and highly-managed rivers in industrialized areas behave distinctly. Further, the interactions of rivers with their coastal zones are dependent on factors such as the presence or absence of deltas, estuaries, a nearshore shelf system, proximity to oceanic trenches, tidal regime, flushing times, and current structure. Although the specifics are beyond the scope of the current Report, WG-1 strongly advocated an effort to identify a usable drainage basin classification scheme and "typology" derived from statistical analysis of baseline empirical data. This could be achieved through a subsequent, focussed IGBP workshop dealing with this issue. Efforts should be made to harmonize the riverine typology with the coastal zone typology currently being developed by LOICZ.

Several candidate typologies are available. One approach is to use tectonic settings with overlays for climate and runoff (Mackenzie *et al.* 1991). Milliman and Syvitski (1992) used a simple typology based on maximum drainage basin elevation and geographic location for making suspended sediment flux estimates. Another approach is based on either biological or geomorphological indices as reviewed by Gurnell *et al.* (1994). The typology can also be based on intra-annual flow regime (Meybeck 1993).

Within any usable typology, flux data from rivers are used to construct a series of class-specific statistical models. The river/coastal zones of the world are then classified and mapped according to the typology and thereby linked to the appropriate statistical relationships. These models and their associated parameters are then applied to data-poor areas where region-specific, spatially-variable forcing functions distribute predicted fluxes across the land mass. Three specific modelling approaches that would use this overall strategy are outlined below.

**Table IV**

Maps and data sets requiring digitization for use in riverine flux inventories.

Attribute	Scale	Source/Archive
• Runoff	1:10 - 1:30 M maps 1:10 - 1:50 M maps Individual sites	Baumgartner and Reichel (1975) Korzoun <i>et al.</i> (1977) UNESCO (various years)
• Industrial / Demographic Index	Regional-level	UN (1995); World Bank (1995, 1994); (conjunction of basin-specific energy use and population)
• Sewage Collection Rate and Treatment	Regional-level	World Health Organization
• Water Engineering Works Major diversions, dams, etc. Water diversions ( <i>e.g.</i> , irrigation)	Individual sites Point data	IWPDCA (1992); ICOLD (1984,88); Tilsley (1983) International Commission on Irrigation and Drainage
• Hydrogeographic Attributes Groundwater Resources River density	Regional-level 1:1,000,000	UNESCO; Erdelyi and Galfi 1988) Corrections to Digital Chart of the World, ESRI (1993)
Lake density and attributes	1:1,000,000	Corrections to Digital Chart of the World and ARC/WORLD (ESRI 1993)
Wetland density and connectivity	Typology Archive 1 degree To be determined	Meybeck (1994b, 1995) Herdendorf (1984); ILEC (1988-1993); Luther and Rzoska (1971) Matthews and Fung (1987); IGBP-DIS/GAIM Wetland Database

**Table V**

Examples of the statistical approach used in estimating watershed constituent transport.

Constituent	Statistical Approach
<b>TSS</b>	Mozzherin (1992) (Runoff, area, relief, soils) Jansen and Painter (1974) (Climate, relief, land cover, lithology) Milliman and Syvitski (1992) (Area, runoff, location) Meybeck (1993) (Runoff/Temp. typology)
<b>NO<sub>3</sub><sup>-</sup></b>	Cole <i>et al.</i> (1993); Jordan and Weller (1995) (Land use, fertilizer, point sources, and/or deposition) Meybeck (1982) (Demographic index)
<b>TSS / TDS</b>	Meybeck (1976) (Runoff/River size)
<b>PO<sub>4</sub><sup>-3</sup></b>	Caraco (1994) Dillon and Kirchner (1975) (Geology and land use) Meybeck (1982) (Demographic index)
<b>POC / DOC</b>	Meybeck (1993) (Runoff/Temp. typology)
<b>SiO<sub>2</sub></b>	Bluth and Kump (1994) (Runoff/Lithology)

### Multiple Regression Models

Single or multi-factor statistical relationships represent a straightforward means of predicting constituent fluxes. Such relationships have been developed for river nutrient fluxes across a wide variety of scales, from small watersheds, regions, and continents (Jordan *et al.* 1986, Smith *et al.* 1993, Frink 1991, Rekolainen 1990, Neill 1989, Probst 1992, Jordan and Weller 1996) to the domain of the entire globe (*e.g.*, Meybeck 1982, Cole *et al.* 1993). The approach has been used as well to predict changes in nutrient : nutrient ratios (Caraco 1994). Multiple regressions also have been employed in sediment transport studies (Ludwig *et al.* 1996, Pinet and Souriau 1988, Mozzherin 1992, Sidorchuk 1991, 1994, Jansen and Painter 1974), where total suspended solids flux is expressed as a function of numerous variables including discharge, climate, relief, lithology, land use/cover, area, and the presence of lakes & impoundments. Table V gives examples of this approach for dissolved and particulate constituents across a spectrum of spatial scales.

Empirical relationships, up to the global scale, can be developed from existing stream gauge information, topographical maps, digital elevation models, geological maps, remote sensing of land use, and inventories of dams and other water engineering works. These relationships would then be distributed spatially using the drainage basin typology discussed above. This could be achieved by first developing class-specific statistical functions; next, categorizing the river systems of the globe according to the typology; mapping the biophysical drivers necessary to implement the functions spatially; and, finally, applying the statistical functions onto a set of base maps depicting individual drainage basins of the world (Figure 2).

The exercise will yield region-to-region differences in terrestrial constituent loadings, which in turn permits geographically-specific estimates of inputs to regional coastal zones and ocean basins. The regression-based approach for data-poor regions, in conjunction with actual data on major rivers, permits global budgets to be constructed for the contemporary setting, and when suitable forcings are applied, fluxes for past and future conditions. It would be valuable to explore in this context the issue of time lags between changing drainage basin attributes and riverine flux.

### Concentration vs Runoff (C vs Q) Models

Another modelling approach categorizes rivers according to whether their constituent concentrations increase, decrease, or remain constant in relation to variations in discharge (Figure 3). Such responses are constituent-specific. They also are functions of discharge regime, geology, the predominance of lakes and wetlands, and hydraulic engineering works within particular rivers. Well-monitored rivers can thus be classified according to their C vs Q responses. The C vs Q approach is particularly useful for filling-in missing data for single rivers and for designing field sampling strategies. Detailed analysis of well-monitored, representative basins also serves to determine the origin of particular C vs Q responses and thereby to permit a *priori* assignment of the appropriate C vs Q typology to unmonitored settings.

Extrapolation to an unmonitored river requires mapping of the drainage basin onto this appropriate C vs Q regime, specifying point and non-point loads from independent data sets, assigning the position of major engineering works within the river network, determining time-varying discharge from either station data or water transport models, and applying relevant flux relationships.

Well-related yield (tons/km<sup>2</sup>-yr) vs area-specific discharge (litre/sec-km<sup>2</sup>) relationships exist for numerous constituents for different parts of the globe under predominantly natural settings. Deviations from trends could thereby serve as an indicator of the presence of anthropogenic influences and their changes over time.

### Delivery Ratio Approach for Sediments

Sediment delivery concepts have been used successfully to track the mobilization of suspended sediments from local scales with subsequent transport through sequentially larger drainage areas (Sidorchuk 1991, Hadley *et al.* 1985, USDA/ARS 1975). The sediment delivery ratio represents that fraction of total erosion estimated at the local scale that is actually transported across a basin with attendant net losses within depositional zones. It is thus a measure of the catchment yield relative to total mobilization. In many settings, drainage basins demonstrate a high capacity for such trapping and the proportion of material exiting a basin is but a small fraction of that originally mobilized.

The delivery ratio approach for sediments also requires a classification system and "typology" based on biophysical attributes such as climate and geomorphology that affect retention capacities of drainage basins. Such relations should be used to predict fluxes vs area for different types of watersheds with differing levels of human disturbance (Figure 4). Flux at the local scale would be generated from application of the Universal Soil Loss Equation (USLE) or its variants in tandem with estimates of gully and channel erosion in small watersheds. USLE parameters are available for the United States, Europe, Russia, southern Africa, and Australia. WG-1 recommended that an effort be made to develop a global coverage, taking full advantage of existing IGBP activities. For example, required information on rainfall kinetic energy could be supplied from IGBP Weather Generator activities; soil erosion potential from the IGBP-DIS soil pedon initiative; and land cover from the IGBP-DIS 1-km AVHRR product. Higher resolution data would need to be assembled in representative fluvial systems to relate site-specific dynamics to the coarser-scale global analysis.

Material retention within drainage basins is also linked strongly to the occurrence of natural lakes, wetlands, and, of more recent origin, impoundments associated with dam construction. The impact of reservoirs can be enormous with large impoundments capable of storing virtually all incident sediment flux (*e.g.* Lake Nasser on the Nile). Figure 4(b) shows the idealized impact of a single large dam on the sediment transport of a drainage basin with elevated loads due to erosion. Note the attendant decrease in sediment flux through the impoundment itself, followed by an increase due to clear water erosion in the channel below the reservoir outlet, and net deposition farther downstream. Diversion for irrigation may also markedly influence water and material fluxes. In extreme cases, such as the Colorado and Amu Darya Rivers, natural fluxes have been reduced to essentially zero.

### Composite Models

A hybrid model consisting of regressions, C vs Q typology, and delivery ratios is also likely to play a role in improving our ability to estimate fluvial fluxes. Work currently underway at the United States Geological Survey (Smith 1994) represents such a model. The model employs C vs Q relationships to interpolate between measured fluxes, regression analysis to relate fluxes to a variety of independent variables, and exponential decay functions to model losses of materials along river reaches. The

model requires spatially-explicit data on landscape features, loadings, and stream channels. It will soon be complete for the conterminous USA and could be applied to other temperate regions in which the requisite data sets are available.

### Case Studies

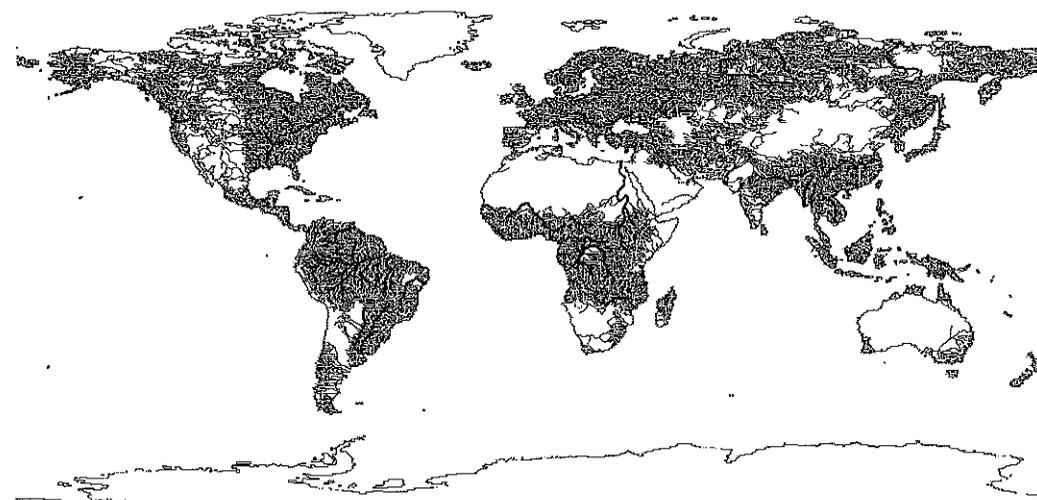
Case Studies on rivers spanning regional to continental scales (*i.e.*,  $10^4$  up to  $10^6$ - $10^7$  km<sup>2</sup>) will form the basis for developing flux models using the approaches described above. Case Studies are also important in the context of quantifying internal drainage basin controls (Question 2) and feedbacks (Question 3).

For the purposes of developing global flux models, WG-1 recommended use of retrospective data sets collected in well-monitored rivers covering at least the last 20-30 years. Within a particular river system, a portion of each time series should be retained for calibration with the remainder used for validation. Further validation over both space and time can be achieved by comparing different rivers of the same type or comparing time series of past fluxes with present fluxes of the same river. Validated models for different river classes could then be applied across the continents and global land mass. In addition, these models form the foundation for extrapolations into the future.

Case Studies in the context of the flux inventory are also an appropriate vehicle for addressing potentially important yet unresolved scientific issues. For example, we can use Case Studies to document the impact of changing landscape features within drainage basins to better predict emergent fluxes. Studies in Scandinavia (Kortelainen and Mannio 1988) have shown that as the proportion of landscape composed of lakes increases, TOC flux decreases, while increases in peatlands show the opposite effect. The degree to which we can utilize simple inventories of the area of wetlands and lakes versus a detailed mapping of the spatial structure and distribution of such landscape features is currently unknown and requires further study. Case Studies can also help to disentangle the effects of an increase in nutrient loading and the simultaneous destruction of riparian zones during the period of industrialization.

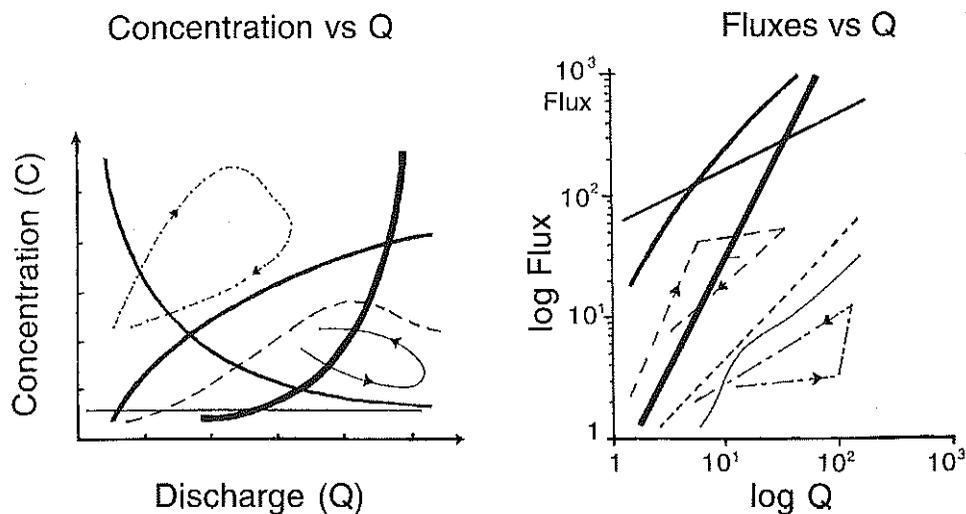
## Figure 2

A simulated river network topology for the globe at 30-minute spatial resolution. At this scale, more than 5000 individual river systems are depicted. Approximately 4000 basins actively discharge water under contemporary climate. Finer resolution networks will be required for the suggested Case Studies. (From University of New Hampshire/Global Hydrological Archive and Analysis System (GHAAS)/ C. Vörösmarty and B. Fekete).



**Figure 3**

A C vs Q typology for river chemistry (Meybeck *et al.* 1992, Meybeck 1993) is a conceptual model that can be used in conjunction with simulated or observed discharges to predict time-varying constituent fluxes. River systems can be classified according to observed relationships linking concentration/flux and runoff/discharge which are known to vary in a predictable fashion for many rivers and particular constituents (several examples are shown below). Calibration/validation is afforded through selected Case Studies and water chemistry databases such as GEMS/GLORI. Flows computed from hydrological models, simulated river networks, and geographically-distributed loadings are necessary for spatial extrapolation.



## Establishing Flux Inventories over Additional Time Frames

In keeping with the multi-temporal strategy discussed earlier, WG-1 considered four broad time domains for the flux inventory: the pre-Industrial period from the beginning of the last glacial maximum (including the period of sedentary agriculture), recent history from 1700 AD, contemporary conditions, and the next 100 years. Characterizing contemporary (1980 - present) fluxes was detailed in the bulk of the preceding text. Additional discussion is given below for considering past and future conditions.

### Palaeo-Perspectives (18,000 Year Before Present to the End of the Pre-Industrial Era)

The regression-based approach can be applied using an appropriate series of paleo-data sets. It has already been attempted for C flux at 18,000 BP (Gibbs and Kump 1994), combining information on glacier-free land mass, increased exposure of the continental shelf due to lowered sea level, and lithology. Additional data will be required to pursue analysis of other constituents as envisioned in this Report. Several key, geographically-referenced data sets, like those used for characterizing the contemporary setting (Tables III and IV), are already available. Others will require assembly, quality control, and testing in this context. For example, digitized maps of the past distributions of climate and vegetation from the COHMAP climate modeling experiments are available at 3,000-year intervals back to 18K BP (available through WDC-A for Paleoclimatology [PAGES data coordination center]; Boulder, Colorado USA). Distributions of glacial extent/retreat and exposure of the continental shelf are given as map products that will require digitization. Precipitation, temperature, and runoff fields can be reconstructed from pollen analysis (PAGES activities, Northern Hemisphere Atlases from Russia [Frenzel *et al.* 1992, Gerasimov and Velichko 1982]).

Validation data are available through analysis of deltaic sediments, and examination of sediment cores for pollen and microfossils. Seismic analysis is also possible in lake systems. Sediments deposited in large lakes, and in lakes with large contributing watersheds have been under-utilized in reconstructing past landscape dynamics and material transport. Yet, there are numerous examples of lake studies that have provided valuable insight into the delivery process. For example, the Great Slave Lake is an 8,000 year-old body of water that acts as an excellent indicator of trends since glaciation. Lake Baikal and the Aral Sea are old lakes and provide a long history of climatic variability and anthropogenic change. Coordination of analyses associated with the PAGES Bern Workshop (Wasson 1996), considering fluvial transport during the last 2,000 years, is recommended.

### Historical Perspectives (From the Pre-Industrial Era)

Data sets for this reconstruction include geographically-distributed estimates of population and population growth; vegetation and climate-induced changes (*e.g.*, SALT Project to map savannah/forest interface using  $^{13}\text{C}$ ); land use (country-level statistics); and, level of industrialization/energy use to construct demographic indices (*i.e.*, population, development intensity) (Marland *et al.* 1994, Vallyntyne 1978). Application of the flux regressions will require reconstruction of the state of the world's drainage basins through time as a function of varying distributions of the key, spa-

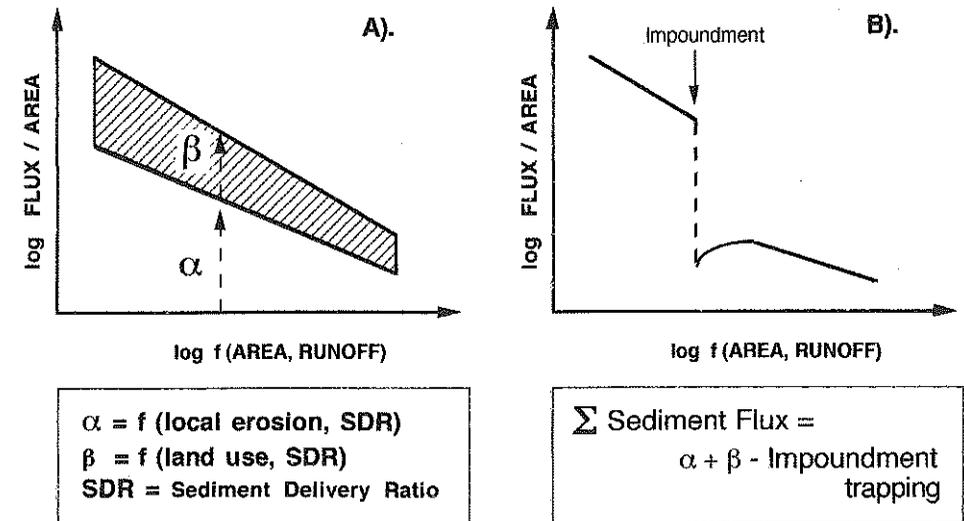
tially-distributed forcings listed above. Validation would be through deltaic and lake cores. Analysis should initially be restricted to those constituents for which strong anthropogenic signals are evident and for which the reliability of chemical analyses have remained relatively stable, namely, POC, PP, sediments, and metals such as cadmium.

#### Future 100-Years

Consideration of potential future conditions places the issue of material transport through river systems into the larger context of global change. The analysis of contemporary, historical, and palaeo conditions will set the stage for such work. The statistical approach will be applied to a set of predicted future distributions of key driving variables. Necessary data sets include projected population and urbanization (e.g., from the UN Population Programme); associated generation, collection, and treatment of sewage; scenarios of fertilizer use; NO<sub>x</sub> deposition; the production of P-based detergents; industrialization; changes in temperature, precipitation (from GCM outputs); vegetation/land use and atmospheric CO<sub>2</sub> change (from emerging coupled Earth System Models); construction of water engineering works and irrigation; and, extrapolations of wetland destruction in various parts of the globe. An examination of future trends in TSS, N, P, Si, Si:N:P, DOC, and POC is possible employing this strategy on a decade-by-decade basis. In this context, the inter-Programme Element effort could rely on an extensive biophysical and climatic driver database archived as part of GAIM intercomparison studies.

### Figure 4

Sediment delivery concepts can be used to quantify, on a drainage basin scale, the differential effects of processes that accelerate and those that restrict fluvial sediment flux. Two examples are shown: (a) elevated erosion associated with poor land use practices and (b) reduced transport from sediment trapping within reservoirs. The  $\alpha$  line represents a natural setting in which the influence of humans is minimal. The  $\beta$  curve shows the influence of land degradation and disturbance of natural vegetative land cover.



## Question 2:

# What are the Physical, Chemical, and Biological Controls, Including Natural and Anthropogenic, on the Fluxes of Water, Sediment, Carbon, Nitrogen, Phosphorus, Silicon, and Micronutrients in the Catchment Cascade?

## The Nature of Human Impacts and Drainage Basin Response

Human use of land and freshwater resources has substantially increased the flux of sediments, nutrients, and metals both within drainage basins and to the oceans, especially during the period of intensive agriculture. Net fluxes of inorganic N and P to the ocean are likely to have been increased by a factor of about two (Meybeck 1982). Although riverine fluxes of TOC, sediments, and dissolved silica are known to be heavily affected by human activities at the regional scale, their changes at the global scale remain to be documented. The flux of metals has generally increased, but by an amount that varies substantially among species (*e.g.*, GESAMP 1987, Martin and Windom 1991). These average increases in fluxes are substantial, representing a major impact on the Earth System, expressed as eutrophication, anoxia, degraded ecosystems, loss of water resources, and accelerated sedimentation.

Some of these increases are concentrated geographically, producing profound regional effects with, ultimately, global ramifications. For example, high mountains that are tectonically active yield most sediment (Milliman and Syvitski 1992, Pinet and Souriau 1988, Ludwig *et al.* 1996), and about 70% of the global flux is produced in southern Asia and large Pacific Islands, an area dominated by mountainous source areas, rapidly increasing population, and land cover change (Milliman and Meade 1983). Excessive fertilization in industrialized western Europe has increased regional inorganic N loads in rivers by a factor of ten to perhaps twenty times ambient (Meybeck and Helmer 1989).

Local effects can be even more dramatic, as for example in small headwater areas, where this increase can be 100-fold. Hundredfold increases are to be expected in even intermediate-sized basins (*i.e.*, order 3 to 6). The magnitude of these increases has also changed through time. Immediately after initial disturbance by clearing, fluxes of materials increase rapidly, often reaching a new quasi-equilibrium after some decades. This quasi-equilibrium can be altered, in turn, by new land use practices, by autocatalytic changes within drainage networks, and by climatic changes. Examples of such dynamic fluvial systems are provided by Sidorchuk (1996), and Berglund (1991). The historical record provides an account of the interactions between fluxes and controlling variables that are, for the present day, expressed spatially.

The primary controls on the fluxes of riverine constituents around the world are qualitatively known. Broadly, these controls on both particulate and dissolved material fluxes are climatic (via runoff and temperature), tectonic (via lithology, relief, and

altitude), biotic (via terrestrial biogeochemistry), and human (via rural land use, mining, industrialization, and urbanization). These primary controls have been or are currently being mapped globally, thereby providing (a) a means of visualizing the spatial distribution of controls, (b) at least a qualitative explanation of fluxes, and (c) a semi-quantitative means of extrapolation to regions where fluxes have not been measured. There is no doubt, however, that improvement can be made in the spatial representation of these controls, and their associated fluxes. As described under Question 1, several existing or newly emerging global databases (Tables III and IV) are appropriate to the task of evaluating both natural and human-induced fluxes.

The critical gap in our knowledge, however, concerns the internal dynamics of drainage basins and nearshore environments. With few exceptions (*e.g.*, Billen *et al.* 1994, Richey *et al.* 1980), there is little understanding of the rates and means of redistribution of constituents resident within both drainage basins and in the nearshore environment. Without this knowledge, it is extremely difficult to identify and/or quantify the secondary controls on the redistribution and fluxes of constituents within fluvial systems. It is the uncertainty regarding these secondary controls (such as the detailed pattern and history of land use and climate in particular catchments; topography; intensity of tectonic activity; nearshore circulation patterns) that is of direct significance to society and its decision-makers. A major new research initiative therefore will be required to yield not only scientific insight but also guidance in resource management since some of these secondary controls can, in fact, be manipulated to change constituent fluxes and concentrations, for the betterment of the environment and of human society.

## Overall Research Strategy for Process Studies

Owing to the complexity of processes occurring within drainage basins and their associated coastal zones, a two-tiered approach is prescribed. By monitoring and then appropriately modelling representative, well-studied sites a sufficient process-level knowledge can be gained. This knowledge, in turn, will form the basis for constructing drainage basin sub-components in emerging Earth System Models.

### Case Studies

The construction of models, and the collection of supporting data, are most effectively carried-out by using a spatially explicit framework in which sources, zones of transport and transformation, and sinks are identified. This framework is independent of spatial scale because it can be defined for areas of any size. At the largest scale, an entire drainage basin can be subdivided into these three components. In the case of the Amazon basin, for instance, the Andes could be defined as the principle source zone of particulate material; the downstream drainage network as the zone of transport, transformation and intermediate storage; and, the ocean as the final sink. In the same drainage basin, the same three units can be recognized for a small headwater catchment. Equally, in the coastal zone, rivers are sources, transport occurs in the littoral zone and in offshore plumes, and sinks occur on the shelf, slope, and in the open ocean.

## Global

There is also a need to classify drainage basins and nearshore zones globally for the construction and application of process-based models. Existing process theories are not adequate for predicting fluxes across all river types. Thus, model calibration on relatively few well-monitored sites must necessarily be used to represent broad geographic domains. Empirical observations therefore should be collected at locations representative of larger areas. An example of this strategy is provided by Mackenzie, *et al.* (1991, 1993), who proposed a regionalization of the globe for the planning and implementation of nearshore transport studies. A coastal zone typology is also being developed under LOICZ Framework Activity 2, using in part GLORI data.

Controls on fluxes as well as model parameters differ geographically. It is important to recognize this in establishing or augmenting any monitoring programme that will help serve the needs of the global modelling community. As discussed earlier, the IGBP modelling community needs to become pro-active in alerting those responsible for water monitoring programmes to the data requirements of the emerging simulations. The present inter-Programme Element activity could provide an important service to the Earth Systems modelling community in this regard.

Equally as important, the results of such research will affect decision-making at regional to local scales and be directly related to classes of existing, specific river systems. A classification of basin types, and of source and transport zones, therefore provides a way of determining where observations should be taken, and those areas to which results can be extrapolated for both scientific and management purposes.

## Modelling Activities

To identify the set of key fluvial controls, the most fruitful approach will depend heavily on modeling that ultimately can be used to formulate a set of general rules by which fluvial systems function. These, necessarily, must be developed from a set of sparse measurements. While qualitative assessments are also essential, researchers must aim to produce quantitative statements whenever possible. Such a quantification is important for several reasons: (a) drainage basins and the nearshore coastal zone are complex, thereby limiting the utility of qualitative assessments, (b) there is a need to generalise from data-rich regions and continents to data-poor areas, (c) within a relatively short period of time, regional results can be generalized to the globe, and (d) critical data requirements are most readily identified during the rigorous analysis required of model construction.

As for the flux inventory described under Question 1, it is not anticipated that a single, generic process model can be constructed and applied to all of the world's catchments. Different types of models will be required to elucidate controls for different areas and for addressing different problems. The types of models that are likely to be most useful are:

- Static material balance models (*e.g.*, box models that use average fluxes between storages, and/or average transitional probabilities, either measured or estimated by models of system components)

- Dynamic material balance models (*e.g.*, box models that depict fluxes as probability distributions or rate constants, growth models of budget components such as gullies, or 3-dimensional hydrodynamic models)
- Sub-catchment loading models (*e.g.*, statistical relationships between catchment characteristics and fluxes of constituents to estimate loadings on water bodies)
- Biogeochemical process models (*e.g.*, models that include processes of transformation of constituents within water bodies and between vegetation and other key components of the Earth System).

In an approximate way, the models listed above are given in order of increasing elaboration and disaggregation of processes. In the same order, they also contain an increasing number of free parameters that need to be estimated. That is, the representation of processes becomes more realistic down the list, but the danger of over-parameterization increases thereby limiting the predictive capability of the highly-elaborated models. Nonetheless, it is recognized that each of the levels of complexity can be useful in supporting the process-level modelling.

A long-term goal is to model a series of material transformations along the entire continuum of fluvial systems from the points of terrestrial mobilization to delivery and processing in the coastal zone. The fluxes of constituents in all states would be included in such models, paying particular attention to processes such as flocculation, settling, gaseous losses (such as denitrification), phosphate sorption and desorption, silicon uptake and release from siliceous organisms, degassing of water bodies, etc. The extent to which each biogeochemical process is specifically modelled depends on understanding, data, and the purpose for which the model was constructed. Multiple component models would be required representing terrestrial ecosystem processes (*e.g.*, Rasool and Moore 1995), river continuum concepts (Vannote *et al.* 1980, Sedell *et al.* 1989), nutrient cycling (Billen *et al.* 1994) and spiralling (Elwood *et al.* 1983, Newbold 1992).

Coupling of models between drainage basins and the nearshore will also be necessary to provide a complete analysis of the interactions between terrestrial and coastal zone ecosystems. Such coupling may require coastal physical oceanographic models linked to biogeochemical process simulations of regional land-coastal margin ecosystems (*e.g.*, Hofmann 1991, Ver *et al.* 1994). Harmonization with ongoing LOICZ modelling efforts (*e.g.*, Gordon *et al.* 1996) is advised.

## Support for Modelling

An exhaustive list of the research methods and techniques that will be required to build, test, and validate the models outlined above is beyond the scope of this Report. However, two broad categories of supporting methods and techniques are of particular relevance to the topic of this Workshop. These are offered below:

### Empirical Budgeting

This technique relies on the estimation of fluxes from several sources. The most prominent of these include the compilation of fluxes estimated from hydrometric networks; the application of component models (*e.g.*, hillslope erosion models for

sediment and particulate P fluxes); tracer studies (e.g.,  $^{137}\text{Cs}$  and  $^{210}\text{Pb}$  for soils and sediment,  $\delta^{18}\text{O}$  for the  $\text{PO}_4$  ion) to estimate dominant source types and contributing areas; and, analysis of sediments (dated through laminae and tracers such as  $^{210}\text{Pb}$ ,  $^{14}\text{C}$ ,  $^{137}\text{Cs}$ ) to estimate yields and storage rates through time. These methods can be used to estimate either static or dynamic material balances, although the trends in most basins and coastal zones can only be estimated from sedimentary evidence because monitoring archives are usually  $\leq 30$  years in length while records for some micropollutants (e.g., PCBs) are totally missing. This approach has been applied to time periods of  $< 10^3$  years. Further detail on some of these methods is provided in Wasson (1996).

### Statistical Relationships to Produce Loading Estimates

To describe the water quality of contributing areas within large drainages, generalization from measurements of point and diffuse source loadings is required. Multiple regression models incorporate assumed controlling variables, like land use, population density, and catchment area (see Question 1). The inclusion of such models in Decision Support Systems can increase their ease of use, especially if the computer system includes feedback on the accuracy and precision estimates of fluxes in unmonitored watersheds. In this approach, estimated fluxes are assumed to subsume transformations of materials, or transformations are parameterized by using first-order spatial decay terms that remove material from transport (e.g., Smith *et al.* 1993).

## Specific Recommendations for Research

### Case Studies

It is important to recognize the projects already in existence that can potentially contribute to some of the IGBP objectives identified in this Report. Several such projects already exist or are being planned: in the Baltic, Mississippi (GEWEX-GCIP), BAHC - Amazon Large-Scale Biosphere-Atmosphere Experiment (LBA), Atlantic drainages (ORSTOM), the Danube, and at U.S. LMER (Land Margin Ecosystem Research) and Long Term Ecological Research (LTER) sites. WG-2 recommend findings from this Workshop be called to the attention of this community of researchers. WG-2 also recommend that research groups that are in a position to meet the objectives of this Report be invited to participate in this IGBP activity. Groups potentially in this position in the near term include, for example, researchers in the Murray-Darling, Niger, and Mediterranean drainage basins.

In addition, WG-2 strongly recommend that a much greater effort be expended to answer the key scientific questions in this Report for South, Southeast, and East Asia. This was suggested because the prospects for rapid change of both human controls and material fluxes are greatest in this region, the impacts on people of the material fluxes is very large and will increase, and the impacts of humans in this region on the global system are substantial (Galloway and Melillo 1997). The SARCS/IGBP/IHDP/WCRP Integrated Southeast Asian Land-Use Change Study (in preparation) may provide a useful framework for pursuing fluvial research in this area.

It is recommended that a project should be carried out in this region, containing at least the following elements:

- Classification of the catchments of the region using the elements identified above
- Assembly and synthesis of flux data for catchments chosen according to both availability and a workable classification scheme (emphasizing sediment, C, N, P, Si)
- Generalization of the fluxes to catchments for which measurements are not available, using statistical techniques
- Construction of a simple static budget for areas where data exist, and, if possible, a dynamic budget model for various time periods since the beginning of agriculture
- Assessment of the principal flux controls within the framework of both the first-order classification and constituent budgets.

It is recognized that there are parallel activities relating to the coastal zone within LOICZ, and that coordination with these efforts is desirable.

### Global Application

Several global models of modern constituent fluxes already exist, (e.g., Wollast *et al.* 1993, Mackenzie *et al.* 1993). Understanding secured through the Case Study work should be carried forward to the global scale and used to enrich this ongoing research. WG-1 supported such an activity and recommended the following as important contributions by an IGBP fluvial research effort:

- The development of a disaggregated land component within existing global transport models, using at least the primary controls on fluxes identified earlier
- Identification of primary flux controls by sensitivity analyses on these models.

Improved global models should be developed in tandem with the flux inventories characterizing the contemporary setting (Question 1) and compared for consistency. Validated global models developed under Question 2 can then more justifiably be applied to both retrospective and future time series analysis. These activities can also be used as the quantitative basis for assessing the issue of feedbacks discussed under Question 3 which follows.

### Question 3:

## What are the Feedbacks of Changes in Drainage Basins on Human Society and on Biogeochemical Cycles?

Human-induced changes in river systems have consequences for not only biogeochemical cycles but human society itself. In recognition of the multitude of feedbacks possible, WG-3 examined this issue by summarizing a small set of specific problems. The problems discussed should not be considered exhaustive, but merely representative of a much broader set of themes that an IGBP research agenda could address. This agenda could build directly on the information and techniques developed under both Questions 1 and 2.

### Direct Feedback on Human Society

#### Boundaries of the Problem

Direct feedback onto the human sector is essentially one of economic forcing, whereby changes in a drainage basin would exact a particular economic cost and impact on material well-being. The nature of this disturbance could be determined (*i.e.*, modelled) if the dynamics of the changes themselves could be understood. It was further understood that a critical issue was the time scale of both the perturbation itself, and of the system response to that perturbation. For example, an engineering structure that would be hastily installed could have an impact lasting decades to several centuries. This response time plus long-term economic costs strongly influence possible reversal or mitigation strategies (*e.g.*, removal of dams).

#### Examples of Feedbacks Affecting Humans Directly

The range of possible feedbacks is large. WG-3 chose to identify several examples, not only because they are important, but to illustrate the breadth of research (and mitigation or response) strategies that would have to be developed. These included:

- Changes in climatic forcing. Although human activities in drainage basins may not have a strong influence on climate variability, the impacts of climate change on drainage basins may be exacerbated due to rapid population growth and land use change (*e.g.*, increased monsoon frequency leading to severe floods in sensitive areas of South Asia)
- Changes in water availability (quality and quantity) and distribution. This is a critical feedback issue. Agents of such change include large-scale water projects (dams, diversions), irrigation, domestic and industrial consumption, and transmission of disease vectors
- River alteration and control, necessitated by the use of fluvial systems to transport people and commercial goods

- Alteration of aesthetic and recreational values of fluvial systems and their associated coastal zones
- Ecological perturbations via species shifts (*e.g.*, exotics, loss of endemics)
- Changes in river fisheries via altered thermal conditions, water quality or hydrological regimes, as well as fishing pressure, and corresponding impacts on commercially-important and subsistence fisheries species, including those on floodplain rivers.

### Towards a Model Structure for Analysing Direct Feedbacks: An Example Using Fisheries

Given the wide range of feedback problems, WG-3 recognized that an efficient strategy would be to consider a "minimum common denominator" approach to targeting models, methods, data sets, and classification schemes. Such a scheme might ultimately have applicability to a broader range of problems.

The scheme might start by considering the necessary hydrological phenomenon, then adding the issue of sediment flux (which depends on water, but not chemistry), and then chemistry (which depends on water and sediments). The nesting of spatial scales and the hierarchical structure at which the model might operate must be considered. The structure outlined under Question 2 combining (a) Case Studies with global application and (b) process-level modelling could be applied in this context.

As a test case, WG-3 chose to examine how the problem might be approached for riverine fisheries. This problem was selected because it incorporates several elements that are common to all problems (*e.g.*, water routing), and also because it raises issues that may not be immediately obvious:

- Fisheries are typically concentrated on one or a few species in a particular basin, so impacts must be evaluated in the context of the ecology of particular species
- Coldwater fisheries and tropical floodplain river fisheries embody very different considerations
- To evaluate fisheries impacts, a hydrological model of sufficient detail is needed that can forecast discharge dynamics as a function of precipitation inputs to a basin. Realistic flow routing is critical, to transport water between "nodes" and to predict floodplain inundation
- Temperature is important, at least for coldwater fisheries. A model is needed which predicts the time evolution of water temperature along the downstream reaches of the river system. A moderately sophisticated, physically-based model of water temperature for headwater streams is also needed
- Spawning of some river fisheries is heavily reduced by excessive sedimentation. Hence, a relatively fine scale model of sediment transport may be required. It would have to be sophisticated enough to estimate sediment delivery through the fluvial network as well as the hydraulics of particular reaches to estimate erosion and subsequent deposition

- Large floodplain rivers present an additional problem. Maintenance of floodplain integrity (vegetation, inundation regime) are critical for certain fisheries. Hence, models addressing alteration of the exchanges of water and sediment between mainstream rivers and their floodplains are required
- Changes in riverine chemistry affect fish species to varying degrees. Increasing nutrients may benefit/degrade fisheries depending on whether modest increases in primary production result or if over-production and eutrophication occur. Trace contaminants present the potential to degrade fisheries by making fish unfit for human consumption, even though they may have no acute effects on fish populations/production.

To what extent are the above examples relevant to or manageable within global-scale Earth System Models? With this compilation of example feedbacks, WG-3 considered the diversity and scale of the respective problems. It was recognized that, while these problems may be important to human society, they may occur at a space resolution which may sometimes be too fine or a time scale that may be too long (or too short) to be addressed by river basin models which are subsets of Earth Systems Models to be developed over the 3-5 year time scale. A generic model for global application is probably not feasible in the case of fisheries, so regional studies will need to be emphasized.

The conclusion of the entire Workshop, however, is that the issues are sufficiently important to society to merit further development of a strategy to address them in an IGBP framework. The issue should be revisited in further inter-Programme Element discussions. The importance of linking physically/biologically/chemically-based models to a human-decision framework, as in developing "integrated assessment" modelling efforts, was also recognized.

## Feedbacks on Biogeochemical Systems

### Boundaries of the Problem

Feedbacks on riverine biogeochemistry involve several highly dynamic and complex processes that will provide a challenge to understand. As explained earlier under Question 2, we still lack an adequate quantitative picture of how natural river systems function. Adding the dimension of human change increases the complexity still further. Nonetheless, these are the very processes and changes that will serve as linkages to several elements of the Earth System, actively being studied as part of the larger IGBP research agenda. Below WG-3 highlights some key linkages of river biogeochemistry and changes in river biochemistry, in relation to other Earth System processes. Again, an exhaustive listing was beyond the scope of the Workshop, and the list should be viewed as representative. This portion of the WG-3 Report ends by considering in more detail the issue of trace gas fluxes derived from river systems.

### Examples of Feedbacks Arising from Changes in Riverine Biogeochemistry

In a manner analogous to the approach for the human dimensions response, WG-3 noted the complexity of the issue and identified example feedbacks between changes in drainage basins and biogeochemical processes. Processes both internal as well as external to fluvial systems themselves were considered:

- Changes in riverine sediment loads, via impoundment or increased erosion. In the case of impoundment this leads to decreased sedimentation rates in coastal areas and, in turn, net subsidence of coastal marshes/riverine deltas
- Impoundments and the increased year-round water use that results alter the hydrologic cycle by enhancing evaporative losses at the cost of runoff. Salinization of runoff from soils irrigated by water drawn from reservoirs is also common, especially in arid and semi-arid regions
- Large-scale hydrologic alterations of fluvial systems may desiccate natural wetlands or permanently inundate land that was formerly dry or inundated only seasonally. This can alter carbon cycling and CO<sub>2</sub> fluxes from these land surfaces, by, for example, enhanced oxidation of soil organic matter in drained wetlands or the enhanced accumulation of organic matter in newly created aquatic systems
- River pollution with nutrients and altered sediment loads can affect the primary productivity of coastal marine ecosystems. Altered coastal-zone productivity may significantly affect carbon processing and storage, nutrient delivery to support "new" production in the oceans, and perhaps dimethyl sulfide (DMS) emission that originates from phytoplankton. Qualitative changes in riverborne sediments may affect the bioavailability of nutrients in the coastal zone.

### Trace Gas Emissions as a Further Example of Feedbacks Arising from Changes in Riverine Biogeochemistry

Through IGAC (IGBP-IGAC 1994) the IGBP is already actively involved in research on trace gases, and future river system studies in IGBP would need a close coordination with these ongoing efforts. WG-3 identified two trace gas species whose analysis could be enhanced by explicit consideration of fluvial transport processes:

- Nitrous oxide (N<sub>2</sub>O) emission is considered most important in lower order streams, where riparian zones intercept groundwater inputs to streams, and denitrification and other N transformations can occur at very high rates. This phenomenon has been studied mainly in agricultural areas in which groundwaters are highly NO<sub>3</sub>-enriched. Its importance involves N<sub>2</sub>O emission to the atmosphere as well as reduced NO<sub>3</sub> transport into the fluvial system. Estuaries and floodplains can also be important sites for transformation of N compounds, particularly in N-enriched river systems. To model the N fluxes in the riparian zone, it may be sufficient to study representative headwater streams, then extrapolate to the entire basin using information on fluvial geomorphology such as drainage density and channel/floodplain geometry
- Methane (CH<sub>4</sub>) emission occurs throughout the fluvial system wherever anoxic conditions develop. Emission of CH<sub>4</sub> is likely to occur from headwater riparian zones to the hyporheic zone to floodplains along larger rivers. River regulation may result in net loss of floodplain area, but increases in reservoir area. The net effect on CH<sub>4</sub> emission from the overall system may be positive or negative. Dissolved CH<sub>4</sub> can be surprisingly high in rivers without obvious sources, suggesting that groundwater inputs may be significant sources of CH<sub>4</sub> that may eventually reach the atmosphere. Source areas may include ephemerally or perma-

nently water-saturated soils that may not be directly connected to fluvial systems (e.g., ponds, bog, or lakes). In the tropics, conversion of natural wetlands and previously dry land to rice cultivation results in large net increases in CH<sub>4</sub> emission. Sources associated with rice cultivation may be as important as natural wetlands. These areas are often adjacent to rivers, or dependent on water from rivers. To evaluate the net effect of river alteration on CH<sub>4</sub> emission, a landscape perspective is necessary. A model would have to account for the spatial distribution of source areas (both natural and anthropogenic) as well as their differential rates of emission.

An IGBP-GAIM/DIS/IGAC/BAHC/LUCC Workshop held in early 1996 in Santa Barbara, California, USA, initiated an effort to secure a detailed mapping of global wetlands for use in trace gas studies. WG-3 recommend an ongoing interaction between that effort and the IGBP river modelling community.

## Opportunities for Coordination of Fluvial Transport Research Within the IGBP

An important aspect of the overall IGBP initiative is coordination of individual Programme Element efforts to maximize the use of resources for carrying-out field and modelling studies (e.g., IGBP-BAHC/IGAC/GCTE coordinated field studies; GAIM/IGBP-DIS/GCTE terrestrial ecosystem model intercomparison studies). The scientific issues articulated in this Report provide an organizing framework for executing regional and ultimately global assessments of the role that drainage basins play in the Earth System and in global change. Recommendations for specific scientific issues that could be pursued collaboratively within an IGBP framework are summarized in Table VI. This listing is based on the findings of this Workshop as well as recognition of existing activities within the IGBP and outside organizations. These ongoing efforts are summarized below, followed by a list of programmatic recommendations for improving their coordination across the IGBP.

### Ongoing IGBP Programme Element Activities

Three IGBP Programme Elements have interests directly related to the issue of riverine transports — BAHC, PAGES, and LOICZ. There are several overlapping and complementary activities within each of these projects that potentially could benefit by a closer coordination of effort.

BAHC emerged from a realization that complex interactions exist between the land surface biota and the hydrosphere. These interactions not only constitute those associated with vertical fluxes but with horizontal components as well. By vertical fluxes we refer to a wide spectrum of processes including precipitation, soil recharge, and evapotranspiration. Horizontal fluxes include the generation of stormflow, baseflow, and the routing of runoff through river networks organized at the drainage basin level.

These spatial concepts are not only applicable to water cycling but also to the exchanges of inert and biotically-active constituents. Carbon dioxide and trace gas flux in the vertical domain have therefore been addressed as key components in the BAHC Operational Plan (IGBP-BAHC 1993). Under Focus 3 ("Diversity of Biosphere-

Hydrosphere Interactions"), Task 3.1.3 of Activity 3.1 as well as Activity 3.2 are of most relevance to the subject of this Workshop. These consider the mobilization of water, soil, nutrients, and carbon and their transport through drainage systems. These activities seek to trace the transport of materials from overland and subsurface source areas to riparian zones, to small streams, and to sequentially larger main-stream rivers. The key organizing concept is the drainage basin. Horizontal mobilization, delivery, and transport of carbon and nutrients in both dissolved and particulate fractions were also recognized as important to both donor upland systems and recipient aquatic ecosystems. A Typology of Global River Systems (TYGRIS-BAHC) was proposed and adopted at the 1996 Scientific Steering Committee meeting (IGBP-BAHC 1996). This effort will facilitate integration of BAHC modelling efforts by linking data sets and models for use in water, energy, and constituent flux models, both within BAHC and through collaboration with outside organizations.

Additional BAHC Focus 3 activities consider the issue of human disturbance. Well-documented changes in water and constituent balances are associated with land use and land cover change and human-induced impacts are felt at local, regional, and even continental scales. It also can be demonstrated that the history of disturbance is of considerable importance to water and constituent fluxes as ecosystems restructure themselves, often to new dynamic steady states.

The PAGES Fluvial Systems project, under Focus 3, Activity 3.1: "Human Impacts on Past Environments", also encompasses several specific activities highlighted in this Report. For example, a catchment classification system is being developed, and the resulting typology will be used to identify specific sites for Case Studies. This project is also attempting to provide guidelines for synthesis of Case Study results incorporating fluvial modelling studies over a broad spectrum of time, both past and future. PAGES activities will contribute to the definition of temporal trends in land form change and fluvial fluxes, controls, and feedback. Special attention is being devoted to the interactions between climate and land use during the period of agriculture. A key contribution is identification of thresholds and response times of fluvial systems to disturbance.

An important element of the overall mission of LOICZ is to understand the impacts on the coastal zone associated with changes in both riverine inputs and oceanic fluxes. This work constitutes Focus 1, "The Effects of Changes in External Forcing or Boundary Conditions on Coastal Fluxes." Within Focus 1, Activity 1.1 addresses "Catchment Basin Dynamics and Delivery."

The overall objectives for Activity 1.1 are to determine at regional and global scales:

- The quantities and temporal variations of river water and its chemical attributes (bulk sediments, and particulate and dissolved chemical species C, N and P) delivered to the ocean
- The physical and chemical controls operating at continental-scales on these fluxes
- The relationship between these fluxes and changes in the upstream environment

- The marine fate of the riverborne materials, given the characteristic properties that survive the journey from land to the coastal zone (a cross-cutting issue with Focus 3).

These objectives are to be met through a series of specific tasks including: "Development of a Theory and Practice of Regional Scale River Delivery Models" (Task 1.1.1); "Time Series Definition of Selected and Representative Rivers" (Task 1.1.2); and, "Chemical Composition: Gradients from Terrestrial Sources to Marine Burial" (Task 1.1.3). These tasks reflect several themes also stressed in the present Workshop, for example, the identification of river typologies, the assembly of electronic global data bases of drainage basin and water quality characteristics, application of models for flux inventories to the coastal zone, the fostering of river monitoring programs, and the formulation of scenarios depicting future anthropogenic change.

Owing to the interdisciplinary nature of the subject, it desirable that other IGBP Programme Elements participate in any future dialogue on this initiative, notably LUCC, GAIM, and GCTE. The scientific activities envisioned in this Report are data-intensive; additional support and interaction with IGBP-DIS will therefore be critical.

## Specific Recommendations

We recommend liaison activities among IGBP Programme Elements in areas of mutual interest and benefit. For example, the series of LOICZ representative river basin studies could be augmented through PAGES and BAHC regional-scale research to maximize the efficiency of data collection and facilitate an IGBP global-scale synthesis of fluvial transport. Another excellent opportunity for collaboration is in the upcoming large-scale field experiment in Amazonia (Becker and Dunne 1997, Sellers *et al.* 1992) where an explicit drainage basin framework has been adopted for studying both water and riverborne constituent fluxes.

In the context of these complementary activities, we suggest that several steps be undertaken to catalyse the interaction among IGBP Programme Elements and other international scientific bodies in the context of riverborne delivery of constituents from the land mass to the ocean:

- Assemble representatives from each of the IGBP Programme Elements and IGBP Secretariat's office to carry out the set of near-term objectives
- Disseminate the results of this Workshop to the global change research community at large
- Enlist participation of other IGBP Programme Elements having a natural thematic connection to the concepts articulated in this Report. These include GAIM and LUCC. In addition, official representation should be sought from IHDP (beyond LUCC), WMO, UNESCO, and WHO GEMS-Water, etc.
- Within one-year of publication of this document, convene another Workshop to: (a) further identify and consolidate allied activities within IGBP and other international organizations; (b) develop a detailed time table for implementing the specific activities and tasks of this inter-Programme Element activity; (c) schedule a series of small, focussed Workshops to complete the specific tasks, and (d) produce a Science Plan

- Develop protocols for data archiving and exchange among participating organizations
- Create a common IGBP database for the numerous thematic, hydrological, and biogeochemical data sets identified as necessary to carry-out this research. Enlist the assistance of IGBP-DIS
- Support the ongoing PAGES Fluvial Working Group activities emphasizing human impacts during the period of sedentary agriculture
- Coordinate efforts with the PAGES Fluvial Working Group to: (i) identify suitable drainage basin typologies, select candidate Case Study sites, and develop sediment transport models; and ii) assess changes to river basin boundaries over the last 18,000 years due to sea level change, climate, and glaciation
- Convene a well-focussed workshop to coordinate development of a drainage basin/coastal zone typology across individual IGBP Programme Elements
- Convene a BAHC-led Workshop on the issue of runoff generation and horizontal water transport schemes for use in the models proposed here (with WMO-Global Runoff Data Center /UNESCO-International Hydrological Programme)
- Participate in the planning, execution, and follow-up activities of the IGBP-GAIM/DIS/IGAC/BAHC/LUCC Wetlands Workshop
- Interact with international river monitoring programs (e.g., GEMS-Water and WMO's Global Runoff Data Center) to articulate the needs of the riverine biogeochemical modelling community
- Coordinate with GAIM the inclusion of a drainage basin component in ongoing terrestrial modelling inter-comparison studies, treating past, present, and future time frames
- Foster the inclusion of horizontal water and constituent transport into the planning of field campaigns such as the Amazon Large-scale Biosphere-Atmosphere (LBA) experiment
- Focus a set of initial modelling exercises on South, Southeast, and East Asia (coordinate with the SARCS/IGBP/IHDP/WCRP Integrated Southeast Asian Land-Use Change Study which is under preparation)
- Interact with GCTE researchers to derive terrestrial loading terms
- Collaborate with IGAC to quantify linkages between hydrological transports and trace gas fluxes in aquatic and wetland ecosystems
- Organize follow-up workshops to better articulate the issue of feedbacks on human society brought about by changes in fluvial systems.

## Table VI

Review of recommended scientific issues amenable to IGBP Inter-Programme-Element collaboration.

### General Recommendations:

- Seek a more complete understanding of the multi-temporal aspects of drainage basin response. Focus on: 18,000 BP to the end of the pre-Industrial era/Industrial period/Contemporary (1980-present)/Future 100 years
- Quantify the changing fluxes of riverine carbon, sediments, and key nutrients from regional to continental and global scales over the four proposed time frames
- Encourage the development of suitable models for gaining a process-level understanding of the controls on these fluxes and feedbacks to the Earth System as well as to human society.

### Flux Inventory and Assessment of Drainage Basin Status:

- Identify usable drainage basin classification system and "typology" derived from empirical data, for extending site-specific knowledge to unmonitored catchments
- To achieve near-term progress, employ this typology in conjunction with simple statistical models to estimate riverine fluxes of carbon, sediments, and nutrients, performing analysis on selected Case Studies ( $10^4$  to  $10^5$  km<sup>2</sup>) up to the global scale ( $10^6$  to  $10^7$  km<sup>2</sup>)
- Further inventory, map, and assess the available hydrometeorological and water quality monitoring data sets that can directly support drainage basin model development and testing
- Perform trend analysis in water quantity and quality for at least the period of the last 30 years to quantify the changing character of human activities in drainage basins and their impacts
- Assess the current efficacy of runoff generation and horizontal transport models for discharge.

### Controls and Feedbacks:

- Through selected Case Studies in basins (from  $10^4$  to  $10^5$  km<sup>2</sup>) identify key controls on water, sediment, and biogeochemical fluxes
- Proposed focus on feedbacks to the Earth System: CH<sub>4</sub>/river/wetland interactions
- Proposed focus on feedbacks to human society: Fisheries

Cont...

Cont...

- Further assess the opportunities for using remote sensing in the context of monitoring drainage basin behaviour
- Owing to its importance as an area of rapid population growth and economic development, focus initial modelling efforts on South, Southeast, and East Asia
- Disaggregate land surface and river components in existing Earth System Models
- Pursue a global river and lake water temperature analysis.

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## Acronyms and Abbreviations

ARS	Agricultural Research Service (USDA)
AVHRR	Advanced Very High Resolution Radiometer
BAHC	Biospheric Aspects of the Hydrological Cycle (IGBP)
BATERISTA	Biosphere-Atmosphere Transfers and Ecological Research <i>in situ</i> Studies in Amazonia
CCIW	Canada Centre for Inland Waters
COHMAP	Cooperative Holocene Mapping Project
DIC	Dissolved inorganic carbon
DIS	Data and Information System (IGBP)
DMS	Di-methyl sulfide
DOC	Dissolved organic carbon
ESRI	Environmental Systems Research Institute
GAIM	Global Analysis, Interpretation, and Modelling (IGBP)
GCIP	GEWEX Continental Integration Project (WCRP)
GCM	Global Circulation Model
GCOS	Global Climate Observing System
GCTE	Global Change and Terrestrial Ecosystems (IGBP)
GEBA	Global Energy Balance Archive
GEMS	Global Environmental Monitoring System
GESAMP	Group of Experts on Scientific Aspects of Marine Pollution
GEWEX	Global Energy and Water Cycle Experiment (WCRP)
GIS	Geographic Information System
GLORI	Global Register of River Inputs (LOICZ)
GRID	Global Resource Information Database

GTOS	Global Terrestrial Observing System
HDC	Highly Developed Country
IAHS	International Association of Hydrological Sciences
ICOLD	International Commission on Large Dams
ICSU	International Council of Scientific Unions
IGAC	International Global Atmospheric Chemistry Project (ICAGP/IGBP)
IGBP	International Geosphere-Biosphere Programme
IHP	International Hydrological Programme (UNESCO)
IHDP	International Human Dimensions Programme on Global Environmental Change
ILEC	International Lake Environment Committee
ISCCP	International Satellite Cloud Climatology Project (NASA)
IWPDCA	International Water Power and Dam Construction Association
LAMBADA	Large-scale Atmospheric Moisture Balance of Amazonia using Data Assimilation
LBA	Large-scale Biosphere/ Atmosphere Experiment for Amazonia
LDC	Less Developed Country
LMER	Land Margin Ecosystem Research (US National Science Foundation)
LOICZ	Land-Ocean Interactions in the Coastal Zone (IGBP)
LTER	Long Term Ecological Research (Site) (US National Science Foundation)
LUCC	Land-Use/Cover Change (IGBP/IHDP)
NASA	National Aeronautics and Space Administration (USA)
NCDC	National Climate Data Center (USA)
NGDC	National Geophysical Data Center (USA)
NOAA	National Oceanic and Atmospheric Administration (USA)
NSF	National Science Foundation (USA)
PAGES	Past Global Changes (IGBP)
POC	Particulate organic carbon
PP	Particulate phosphorus
RDC	Rapidly Developing Country
RIOS	River Inputs to Ocean Systems
SALT	Savannes à Long Terme
SARCS	South east Asia Regional Committee for START

SeaWiFS	Sea Wide Field Sensor
SSC	Scientific Steering Committee
START	Global Change System for Analysis, Research and Training (IGBP)
TDS	Total dissolved solids
TOC	Total organic carbon
TSS	Total suspended solids
TYGRIS	Typology of Global River Systems (BAHC)
UN	United Nations
UNEP	United Nations Environmental Programme
UNESCO	United Nations Educational, Scientific and Cultural Organisation
USDA	United States Department of Agriculture
USLE	Universal Soil Loss Equation
WCRP	World Climate Research Programme
WDC-A	World Data Center - A (ICSU)
WHO	World Health Organisation
WMO	World Meteorological Organisation

# Appendix I

## Working Group Membership

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The scientific questions addressed during the Workshop fell broadly into two categories. The first was devoted to a quantification of water and material fluxes in tandem with a broad-scale characterization of drainage basins. The second involved more process-oriented research to uncover controls on fluvial transports and potential feedbacks from changes in drainage basins and their associated river systems. The membership of each group that considered these themes was as follows:

### Flux Inventory and Assessment of Drainage Basin Status

#### WG-1

What are the quantities and chemical attributes of riverborne fluxes to the ocean of water, sediment, carbon, nitrogen, phosphorus, silicon, and micronutrients?  
M. Meybeck (Chair), W.B. Bowden (Rapporteur), C. Barnes, N. Caraco, T. Jordan, G. Poole, A. Sidorchuk, R. Victoria, and C. Vörösmarty

### Controls and Feedbacks

#### WG-2

What are the physical, chemical, and biological controls, including natural and anthropogenic, on the fluxes of water, sediment, carbon, nitrogen, phosphorus, silicon, and micronutrients in the catchment cascade?  
R. Wasson (Chair), R. Smith (Rapporteur), A. Becker, M. Bonell, J. Campbell, J. Hobbie, F. Mackenzie, and T. Dunne

#### WG-3

What are the feedbacks of changes in drainage basins on human society and on biogeochemical cycles?  
J. Richey (Chair), A. Gurnell (Rapporteur), S. Hamilton, D. Kicklighter, J. McDonnell, B.J. Peterson, A. Schloss, B.L.K. Somayajulu, and A. Townsend

## Appendix II

### Assessment of Currently Available Monitoring Data

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This Appendix supplements the summary discussion on Data Availability and Assessment given earlier in the body of the text under Question 1. Table I on data quantity and Table II on data quality also appear in the text and are focal points in this discussion.

For the purposes of this assessment, data quantity represents the spatial coverage, frequency, and duration of monitoring. Table I is organized by three levels of economic development. Two endpoints are identified, namely, rivers in less-developed countries (LDC's) and, at the opposite extreme, those located in highly-developed and industrialized countries. The latter is exemplified by regions such as Western Europe, North America, parts of Australia and countries like Japan; the former, by various African and Southeast Asian countries. Between these two relatively static extremes lie drainage basins within rapidly-developing regions such as Central America, Brazil, India, China, and Indonesia. This division offers guidance in the design of future sampling strategies, especially in rapidly-changing areas of the globe. In this context, a map of existing data sets, their associated drainage basin coverage, periods of record and rates of population and industrial growth would provide valuable baseline data upon which to make informed proposals for the upgrading of global monitoring networks. Such a map does not currently exist.

Even in the developed parts of the globe, a coherent time series of water quality data is generally available for only the last 30 years. This presents an important challenge for both calibration and validation of transient riverine flux models, since retrospective analysis can cover only the relatively recent past. The body of the text under Question 1 details an effort to extend the available record and make it available to the fluvial modelling community.

Total suspended solids (TSS) are generally much better monitored relative to bedload, and the quantity of TSS data is linked closely to a country's development status. Dissolved inorganic carbon and nitrogen are much better monitored than

their dissolved organic counterparts; monitoring of their particulate fractions is often non-existent. Phosphate is generally better monitored than total phosphorus, but no attempts are made to routinely collect information on dissolved organic phosphorus. Dissolved and particulate metal content data are generally not available, with the relatively best data sets in the highly developed countries. Major anions and cations are measured, with best representation in highly-developed and rapidly-developing countries. Silica is fairly well monitored in the developed world, with somewhat less reliable coverage elsewhere. Finally, discharge measurements are among the better represented attributes of river systems, despite the loss of monitoring stations in LDC's, most notably in Africa (Rodda *et al.* 1993, WMO/UNESCO 1991). Again, the number of data sets is closely linked to development status. Necessary upgrades of monitoring networks will be required to complete basin-wide inventories of carbon, nitrogen, phosphorus, and silicon.

Data quantity is but one measure by which the reliability of the global water quality monitoring networks can be assessed. Data quality is also of obvious importance. Table II lists some of the limitations for specific constituents and issues concerning both the chemical/physical determinations as well as the associated field programs. Adequate laboratory analyses are currently available for many of the constituents listed in the table, but more careful and standardized procedures must be implemented in operational monitoring programs. Ammonium ion ( $\text{NH}_4^+$ ) is a good example for which chemical determination is relatively simple, yet differences in sample preservation techniques make intercomparisons of results from different parts of the world difficult. General expansion of monitoring for particulate and dissolved organic forms of carbon, nitrogen, and phosphorus should be accompanied by additional processing of samples to quantify labile and refractory components. In the case of free trace metals, new analytical techniques will be required.

Data collection protocols also determine the ultimate usability of water quality data. One critical consideration is the frequency at which samples are collected. Sampling programs should therefore be designed to accommodate differences in flow regime and the flow duration characteristics of rivers. Thus, sampling should be stratified (*i.e.*, volume-weighted) to maximize the sampling of constituents during times of high flow. High ratios of peak flow to minimum flow indicate the need to intensify sampling at those times of highest flows, often only a small proportion of the year. Information must therefore be collected and analyzed on concentration-discharge relationships (Figure 3). Data on the frequency and intensity of extreme events should be collected wherever possible, and is critically important in drier parts of the world.

A further consideration involves the spatial distribution of sampling locations. To monitor the mobilization of constituents from landscapes, care must be given to sample properly those locations that are important sources within the drainage basin. Dominant source areas can be identified by their geographical association with, for example, high elevation mountains, high runoff-producing areas, rapidly increasing population densities and/or active land use. Whenever possible, the identification of subregions with high mobilization potential for waterborne constituents should be checked through the use of tracers such as chemical (including isotopic) and mineralogical indicators, because identification of sources, without these additional constraints, can be easily mistaken.

## Appendix III

### Workshop Participants

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Dr. Chris Barnes  
Division of Water Resources  
CSIRO  
GPO Box 1666  
Canberra ACT 2601  
Australia  
Tel: (61-6) 246 5808  
Fax: (61-6) 246 5800  
E-mail: cjb@cbr.dwr.csiro.au

Dr. Alfred Becker  
Potsdam-Institute for Climate Impact  
Research  
Postfach 601203  
D-14412 Potsdam  
Germany  
Tel: (49-331) 288 2541 or 2525  
Fax: (49-331) 288 2600  
E-mail: alfred.becker@pik-potsdam.de

Dr. Mike Bonell  
Division of Water Sciences  
International Hydrological Programme  
UNESCO  
1, rue Miollis  
F-75732 Paris, Cedex 15  
France  
Tel: (33-1) 45 68 40 05, 45 68 39 96  
Fax: (33-1) 45 67 58 69  
E-mail: m.bonell@unesco.org

Dr. William B. Bowden  
Department of Natural Resources  
James Hall  
University of New Hampshire  
Durham, NH 03824  
USA  
Tel: (1-603) 862-1020  
Fax: (1-603) 862-4976  
E-mail: wbowden@christa.unh.edu

Dr. Janet Campbell  
Ocean Process Analysis Laboratory  
Institute for the Study of Earth,  
Oceans, and Space  
University of New Hampshire, Morse Hall  
39 College Road, Durham, NH 03824-3525  
USA  
Tel: (1-603) 862 1070  
Fax: (1-603) 862 0243  
E-mail: campbell@kelvin.unh.edu

Dr. Nina Caraco  
Institute of Ecosystems Studies  
The New York Botanical Garden  
Mary Flagler Cary Arboretum  
Box AB  
Millbrook, NY 12545  
USA  
Tel: (1-914) 677 5343  
Fax: (1-914) 677 5976

Dr. Thomas Dunne  
Department of Geological Sciences  
University of Washington  
Seattle, WA 98915  
USA  
Tel: (1-206) 543 7195  
Fax: (1-206) 543 3836  
E-mail: dunne@geology.washington.edu

Dr. Angela Gurnell  
School of Geography  
The University of Birmingham  
Edgbaston  
Birmingham B15 2TT  
UK  
Tel: (44-21) 414 5526 or 5518  
Fax: (44-21) 414 5528

Stephen K. Hamilton  
Department of Biological Sciences  
University of California  
Santa Barbara, CA 93106  
USA  
Tel: (1-805) 681 0382  
Fax: (1-805) 893 4724  
E-mail: shamilto@lifesci.lscf.ucsb.edu

Dr. John Hobbie  
Ecosystems Center  
Marine Biological Laboratory  
Water Street, Lilly Bldg.  
Woods Hole, MA 02543  
USA  
Tel: (1-508) 548 3705 ext 470  
Fax: (1-508) 457 1548  
E-mail: jhobbie@lupine.mbl.edu

Dr. Thomas E. Jordan  
Smithsonian Environmental  
Research Center  
PO Box 28  
Edgewater, MD 21037  
USA  
Tel: (1-410) 798 4424  
Fax: (1-301) 261 7954  
E-mail: jordan@serc.si.edu

David Kicklighter  
The Ecosystems Center  
Marine Biological Laboratory  
Woods Hole, MA 02543  
USA  
Tel: (1-508) 548 3705  
Fax: (1-508) 457 1548  
E-mail: dkick@lupine.mbl.edu

Dr. Fred Mackenzie  
Department of Oceanography  
SOEST, University of Hawaii at Manoa  
1000 Pope Road, MSB 502B  
Honolulu, HI 96822  
USA  
Tel: (1-808) 956 6344  
Fax: (1-808) 956 7112  
E-mail: fredm@soest.hawaii.edu

Dr. Jeffrey J. McDonnell  
College of Environmental Science and  
Forestry, State University of New York  
One Forestry Drive  
Syracuse, NY 13210-2778  
USA  
Tel: (1-315) 470 6565  
Fax: (1-315) 470 6956  
E-mail: jemcdonn@mailbox.syr.edu

Dr. Michel Meybeck  
Laboratoire de Géologie Appliquée  
University of Paris  
Place Jussieu  
F-75005 Paris, France  
Tel: (33-1) 44 27 51 48  
Fax: (33-1) 44 27 51 25

Dr. Berrien Moore III  
Institute for the Study of Earth,  
Oceans and Space  
University of New Hampshire, Morse Hall  
Durham, NH 03824-3525  
USA  
Tel: (1-603) 862 1766  
Fax: (1-603) 862 1915  
E-mail: b.moore@unh.edu

Dr. Scott Nixon  
Department of Oceanography  
University of Rhode Island  
Kingston, RI 02881  
USA  
Tel: (1-401) 792 6800  
Fax: (1-401) 789 8340

Dr. Bruce Peterson  
Ecosystems Center  
Marine Biological Laboratory  
Water Street, Lilly Building  
Woods Hole, MA 02543  
USA  
Tel: (1-508) 548 3705 ext 484  
Fax: (1-508) 457 1548  
E-mail: peterson@lupine.mbl.edu

Dr. Geoffrey Poole  
Flathead Lake Biological Station  
The University of Montana  
311 Biostation Lane  
Polson, MT 59860  
USA  
Tel: (1-406) 982-3301  
Fax: (1-406) 982 3201  
E-mail: goff@selway.umt.edu

Dr. Jeff Richey  
School of Oceanography  
University of Washington  
Box 35 79 40, Seattle, WA 98195  
USA  
Tel: (1-206) 543-7334  
Fax: (1-206) 685-3351  
E-mail: jrichey@u.washington.edu

Ms. Annette Schloss  
Complex Systems Research Center  
Institute for the Study of Earth,  
Oceans and Space,  
University of New Hampshire  
Durham, NH 03824  
USA  
Tel: (1-603) 862 1792  
Fax: (1-603) 862 0188  
E-mail: ag@imago.unh.edu

Dr. Aleksey Sidorchuk  
Laboratory of Soil Erosion and Fluvial  
Processes, Geographical Faculty  
Moscow State University, Moscow, 119899  
Russia  
Tel: (7-095) 426 3725  
Fax: (7-095) 932 8836  
E-mail: sidor@global.geogr.msu.su

Dr. David Skole  
Institute for the Study of Earth,  
Oceans, and Space  
University of New Hampshire, Morse Hall  
Durham, NH 03824  
USA  
Tel: (1-603) 862-1792  
Fax: (1-603) 862-0188  
E-mail: dave@igapo.unh.edu

Dr. Richard Smith  
U.S. Geological Survey  
410 National Center  
Reston, VA 22092  
USA  
Tel: (1-703) 648-6870  
Fax: (1-703) 648-5295

Dr. B. L. K. Somayajulu  
Physical Research Laboratory  
Navrangpura, Ahmedabad-380009  
India  
Tel: (91-272) 462 129  
Fax: (91- 79) 460 502

Dr. Alan Townsend  
Center for the Environment  
Cornell University  
200 Rice Hall  
Ithaca, NY 14850  
USA  
Tel: (1-607) 255 1216  
Fax: (1-607) 255 0238  
E-mail: art4@cornell.edu

Dr. Reynaldo Victoria  
Centro de Energia Nuclear na Agricultura  
University of São Paulo, Piracicaba  
Avenida Centenario 303, Caixa Postal 96  
13400 Piracicaba, SP  
Brazil  
Tel: (55-194) 335 122  
Fax: (55- 194) 228 339  
E-mail: reyna@ciagri.usp.br

Dr. Charles Vörösmarty  
Complex Systems Research Center  
Institute for the Study of Earth,  
Oceans and Space, University of New Hampshire  
Morse Hall, 39 College Road  
Durham, NH 03824  
USA  
Tel: (1-603) 862 1792  
Fax: (1-603) 862 0188  
E-mail: charles.vorosmarty@unh.edu

Dr. Robert Wasson  
Department of Geography  
School of Research and Environment Management  
Australian National University  
Geography Building, Linneaus Way  
Canberra, ACT 0200  
Australia  
Tel: (61-6) 249 2745  
Fax: (61-6) 249 3770  
E-mail: robert.wasson@anu.edu.au

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#### **No. 12**

*The International Geosphere-Biosphere Programme: A Study of Global Change (IGBP).  
The Initial Core Projects (1990). IGBP Secretariat, Stockholm, 330 pp.*

The IGBP science plan is composed of research projects aimed at answering a number of key questions related to global change, through the establishment of Core Projects on the distinct sub-components of the Earth system, and related activities on data systems and research centres. An implementation strategy provides for its fulfilment.

#### **No. 13**

*Terrestrial Biosphere Exchange with Global Atmospheric Chemistry. Terrestrial Biosphere Perspective of the IGAC Project: Companion to the Dookie Report. Report on the Recommendations from the SCOPE/IGBP Workshop on Trace-Gas Exchange in a Global Perspective. Sigtuna, Sweden, 19-23 February, 1990. Edited by P. A. Matson and D. S. Ojima (1990). IGBP Secretariat, Stockholm, 103 pp.*

The Sigtuna workshop contributed to the development of a scientific action plan on terrestrial ecosystem gas exchange, complementing the International Global Atmospheric Chemistry Project (an IGBP Core Project) in areas of natural variability, boreal regions, global integration and modelling of fluxes, and trace gas fluxes in mid-latitude ecosystems.

**No. 14**

*Coastal Ocean Fluxes and Resources*. Report of a CP2 Ad Hoc Workshop, Tokyo, Japan, 19-22 September 1989. Edited by P. Holligan (1990). IGBP Secretariat, Stockholm, 53 pp.

The focus of IGBP Coordinating Panel 2 on Marine Biosphere-Atmosphere Interactions is the elucidation and prediction of the feedback loops between climate and ocean biogeochemistry under conditions of significant anthropogenic changes to the trace gas composition of the atmosphere. The workshop concentrated on global change and the coastal oceans.

**No. 15**

*Global Change System for Analysis, Research and Training (START)*. Report of a Meeting at Bellagio, December 3-7, 1990. Edited by J. A. Eddy, T. F. Malone, J. J. McCarthy and T. Rosswall (1991). IGBP Secretariat, Stockholm, 40 pp. Also available in Spanish and French.

START is a plan for the development of an international network of regional research centres and sites to gather data and study global change problems in their regional contexts. These regions are identified. Issues to be addressed are: How changes in land use and industrial practices alter the water cycles, atmospheric chemistry and ecosystems dynamics; how regional changes affect global biogeochemical cycles and climate; and how global change leads to further regional change in the biospheric life support system.

**No. 16**

*Report from the IGBP Regional Meeting for South America*. São José dos Campos, SP, Brazil, 5-9 March 1990 (1991). IGBP Secretariat, Stockholm, 58 pp.

The workshop discussed, in a South American context, past global changes, the effects of climate change on terrestrial ecosystems, the role of ocean processes in global change, land transformation and global change processes, the importance of the Andes for general circulation models, and regional research centres. Recommendations promote the role of South American science in global change research.

**No. 17**

*Plant-Water Interactions in Large-Scale Hydrological Modelling*. Report of a Workshop, Vadstena, Sweden, 5-8 June 1990 (1991). IGBP Secretariat, Stockholm, 44 pp.

The workshop addressed plant-water interrelationships at landscape to continental scales: the spatial pattern at landscape level of the dynamics of water flows and waterborne fluxes of dissolved and suspended matter; plant/vegetation characteristics and properties affecting return flow to the atmosphere; methodological issues of large-scale modelling; research in humid tropical, semi-arid and temperate zones.

**No. 18:1**

*The Recommendations of the Asian Workshop, New Delhi, India, February 11-15, 1991*.

Edited by R. R. Daniel (1991). IGBP Secretariat, Stockholm, 36 pp.

Recommendations of the Workshop address issues of prime concern to Asian countries, with reports and recommendations from Working Groups on IGBP Core Projects and key activities.

**No. 18:2**

*Proceedings of the Asian Workshop, New Delhi, India, 11-15 February 1991*. Edited by R. R. Daniel and B. Babuji. Madras, Committee on Science and Technology in Developing Countries (COSTED) and the Indian National Committee for the IGBP (1992). Madras, COSTED, Asia Regional Office, 152 pp.

The Proceedings include 19 papers on Earth system research and global environmental change in Asia, and national reports on global change programmes.

**No. 19\***

*PAGES Past Global Changes Project: Proposed Implementation Plans for Research Activities*. Edited by John A. Eddy (1992). IGBP Secretariat, Stockholm, 112 pp.

The Past Global Changes (PAGES) project will secure better understanding of the natural and human-induced variations of the Earth system in the past, through studies of both natural and written records. Focus is on changes within two temporal streams: global changes for the period 2000 BP, and changes through a full glacial cycle. Implementation plans address: solar and orbital forcing and response, Earth system processes, rapid and abrupt global changes, multi-proxy mapping, palaeoclimatic and palaeoenvironmental modelling, advances in technology, management of palaeodata, and improved chronologies for palaeoenvironmental research.

**No. 20\***

*Improved Global Data for Land Applications: A Proposal for a New High Resolution Data Set*, Report of the Land Cover Working Group of IGBP-DIS. Edited by John R. Townshend (1992). IGBP Secretariat, Stockholm, 75 pp.

This report outlines a proposal to produce a global data set at a spatial resolution of 1 km derived from the Advanced Very High Resolution Radiometer primarily for land applications. It defines the characteristics of the data set to meet a number of requirements of IGBP's science plan and outlines how it could be created. It presents the scientific requirements for a 1 km data set, the types and uses of AVHRR data, characteristics of a global 1 km data set, procedures, availability of current AVHRR 1 km data, and the management needs.

**No. 21\***

*Global Change and Terrestrial Ecosystems: The Operational Plan*. Edited by W. L. Steffen, B. H. Walker, J. I. Ingram and G. W. Koch (1992). IGBP Secretariat, Stockholm, 97 pp.

The objectives of GCTE are: to predict the effects of changes in climate, atmospheric composition, and land use on terrestrial ecosystems, including agricultural and production forest systems, and to determine how these effects lead to feedbacks to the atmosphere and the physical climate system. The research plan is divided into four foci: ecosystem physiology, change in ecosystem structure, global change impact on agriculture and forestry, and global change and ecological complexity. Research strategies are presented.

**No. 22**

*Report from the START Regional Meeting for Southeast Asia.* Arranged by the International Geosphere-Biosphere Programme: A Study of Global Change (IGBP), in collaboration with Human Dimensions of Global Environmental Change (HDGEC) Programme (1992). IGBP Secretariat, Stockholm, 114 pp.

The report presents general recommendations on global change research in the region, thematic studies relating to IGBP Core Project science programmes, global change research in studies of eight countries in the area, and conclusions from working groups on the participation of the region in research under the five established IGBP Core Projects and the related HDGEC programme.

**No. 23**

*Joint Global Ocean Flux Study: Implementation Plan.* Jointly published with the Scientific Committee on Oceanic Research (SCOR) (1992). IGBP Secretariat, Stockholm, 78 pp. (JGOFS Report No. 9)

The Report describes how the aims of JGOFS are being, and will be, achieved through global synthesis, large scale surveys, process studies, time series studies, investigations of the sedimentary record and continental margin boundary fluxes, and the JGOFS data management system.

**No. 24**

*Relating Land use and Global Land-Cover Change: A Proposal for an IGBP-HDP Core Project.* A report from the IGBP/HDP Working Group on Land-Use/Land-Cover Change. Edited by B. L. Turner, R. H. Moss, and D. L. Skole (1993). IGBP Secretariat, Stockholm, 65 pp. (Human Dimensions of Global Environmental Change Programme, HDP Report No. 5)

The report presents the main findings of the joint Working Group of the IGBP and the International Social Science Council on Land-Use/Land-Cover Change; it describes the research questions defined by the group and identifies the next steps needed to address the human causes of global land-cover change and to understand its overall importance. It calls for the development of a system to classify land-cover changes according to the socioeconomic driving forces. The knowledge gained will be used to develop a global land-use and land-cover change model that can be linked to other global environmental models.

**No. 25**

*Land-Ocean Interactions in the Coastal Zone (LOICZ) Science Plan.* Edited by P.M. Holligan and H. de Boois, with the assistance of members of the LOICZ Core Project Planning Committee (1993). IGBP Secretariat, Stockholm, 50 pp.

The report describes the new IGBP Core Project, giving the scientific background and objectives, and the four research foci. These are: the effects of global change (land and freshwater use, climate) on fluxes of materials in the coastal zone; coastal biogeomorphology and sea-level rise; carbon fluxes and trace gas emissions on the coastal zone; economic and social impacts of global change on coastal systems. The LOICZ project framework includes data synthesis and modelling, and implementation plans cover research priorities and the establishment of a Core Project office in the Netherlands.

**No. 26**

*Towards a Global Terrestrial Observing System (GTOS): Detecting and Monitoring Change in Terrestrial Ecosystems.* Report of the Fontainebleau Workshop. Edited by O. W. Heal, J.-C. Menaut and W. L. Steffen (1993). Paris: MAB, 71 pp. (UNESCO Man and the Biosphere Digest 14)

The Fontainebleau Workshop, July 1992, defined a strategy to initiate a global terrestrial monitoring system for the IGBP project on Global Change and Terrestrial Ecosystems, the French Observatory for the Sahara and the Sahel, and the UNESCO Man and the Biosphere programme, in combination with other existing and planned monitoring programmes. The report reviews existing organisations and networks, and drafts an operational plan.

**No. 27\***

*Biospheric Aspects of the Hydrological Cycle. The Operational Plan.* 1993. Edited by BAHC Core Project Office, Berlin (1993). IGBP Secretariat, Stockholm, 103 pp.

A presentation of the mandate, scope, principal subjects and structure of the BAHC research plan is followed by a full description of the four BAHC Foci: 1) Development, testing and validation of 1-dimensional soil-vegetation-atmosphere transfer (SVAT) models; 2) Regional-scale studies of land-surface properties and fluxes; 3) Diversity of biosphere-hydrosphere interactions; 4) The Weather Generator Project.

**No. 28**

*The IGBP in Action: The Work Plan 1994-1998.* 1994. IGBP Secretariat, Stockholm, 151 pp.

This Report provides an overview of the global change research to be carried out under the aegis of the International Geosphere-Biosphere Programme over the next five years. It represents a follow-up to IGBP Report No. 12 (1990) that described the basic structure of the global change research programme, the scientific rationale for its component Core Projects and proposals for their development. The IGBP Core Projects and Framework Activities present their aims and work programme in an up-to-date synthesis of their science, operational and implementation plans.

**No. 29**

*Africa and Global Change.* A Report from a Meeting at Niamey, Niger, 23-27 November, 1992. (1994). IGBP Secretariat, Stockholm. (English and French under the same cover) 55 pp.

A summary is given of the conference arranged by the Global Change System for Analysis, Research and Training (START) on behalf of the IGBP, the Human Dimensions of Global Environmental Change Programme (HDP), and the Joint Research Centre of the Commission of the European Communities (CEC) that describe the global change scientific research situation in Africa today.

**No. 30**

*IGBP Global Modelling and Data Activities, 1994-1998.* 1994. Strategy and Implementation Plans for Global Analysis, Interpretation and Modelling (GAIM) and the IGBP Data and Information System (IGBP-DIS). IGBP Secretariat, Stockholm, 86 pp. This report sets out the goals and directions for GAIM and IGBP-DIS over the next five years, expanding on the recent overview of their activities within IGBP Report 28 (1994). It describes the work within IGBP-DIS directed at the assembly of global databases of land surface characteristics, and within GAIM, directed at modelling the global carbon cycle and climate-vegetation interaction.

**No. 31**

*African Savannas and the Global Atmosphere. Research Agenda.* 1994. Report of a joint IGBP/START/IGAC/GCTE/GAIM/DIS Workshop on African Savannas, Land Use and Global Change: Interactions of Climate, Productivity and Emissions, 1-5 June 1993, Victoria Falls, Zimbabwe. Edited by C. Justice, B. Scholes and P. Frost. IGBP Secretariat, Stockholm, 53 pp. The workshop focused on interactions between African savannas and the global atmosphere, specifically addressing land-atmosphere interactions, with emphasis on sources and sinks of trace gases and aerosol particles. The report discusses the ecology of African savannas, the research issues related to carbon sequestration, ongoing and proposed activities, and gives a research agenda.

**No. 32**

*International Global Atmospheric Chemistry (IGAC) Project. The Operational Plan.* 1994. IGBP Secretariat, Stockholm, 134 pp. The goals of IGAC are to: develop a fundamental understanding of the processes that determine atmospheric composition; understand the interactions between atmospheric chemical composition and biospheric and climatic processes, and predict the impact of natural and anthropogenic forcings on the chemical composition of the atmosphere. The Operational Plan outlines the organisation of the project. The plan describes the seven Foci, their related Activities and Tasks, including for each the scientific rationale, the goals, strategies.

**No. 33**

*Land-Ocean Interactions in the Coastal Zone. Implementation Plan.* 1995. Edited by J.C. Pernetta and J.D. Milliman. IGBP Secretariat, Stockholm, 215 pp. LOICZ is that component of the IGBP which focuses on the area of the Earth's surface where land, ocean and atmosphere meet and interact. The implementation plan describes the research, its activities and tasks, and the management and implementation requirements to achieve LOICZ's science goals. These are, to determine at regional and global scales: the nature of these dynamic interactions, how changes in various compartments of the Earth system are affecting coastal zones and altering their role in global cycles, to assess how future changes in these areas will affect their use by people, and to provide a sound scientific basis for future integrated management of coastal areas on a sustainable basis.

**No. 34**

*BAHC-IGAC-GCTE Science Task Team. Report of First Meeting. Massachusetts Institute of Technology, Cambridge, Massachusetts, USA, 10-12 January, 1994.* 1995. IGBP Secretariat, Stockholm, 45 pp. The Science Task Team discussed and developed recommendations for multi-Core Project collaboration within the IGBP under three headings: process studies in terrestrial environments, integrated modelling efforts, and partnership with developing country scientists. Three interrelated themes considered under process studies are: transects and large-scale land surface experiments, fire, and wetlands. Methods for implementation and projects are identified.

**No. 35**

*Land-Use and Land-Cover Change. Science/Research Plan.* 1995. Edited by B. L. Turner II, D. Skole, S. Sanderson, G. Fischer, L. Fresco and R. Leemans. IGBP Secretariat, Stockholm, HDP Secretariat, Geneva, (IGBP Report 35/HDP Report 7) 132 pp. The Science/Research Plan presents land-use and land-cover change and ties it to the overarching themes of global change. It briefly outlines what is currently known and what knowledge will be necessary to address the problem in the context of the broad agendas of IGBP and HDP. The three foci addressed by the plan are: (i) land-use dynamics, land-cover dynamics - comparative case study analysis, (ii) land-cover dynamics - direct observation and diagnostic models, and (iii) regional and global models - framework for integrative assessments.

**No. 36**

*The IGBP Terrestrial Transects: Science Plan.* 1995. Edited by G. W. Koch, R. J. Scholes, W. L. Steffen, P. M. Vitousek and B. H. Walker. IGBP Secretariat, Stockholm, 53 pp. Also available in Chinese. The IGBP Terrestrial Transects are a set of integrated global change studies consisting of distributed observational studies and manipulative experiments coupled with modelling and synthesis activities. The transects are organised geographically, along existing gradients of underlying global change parameters, such as temperature, precipitation, and land use. The initial transects are located in four key regions, where the proposed transects contribute to the global change studies planned in each region.

**No. 37**

*IGBP Northern Eurasia Study: Prospectus for an Integrated Global Change Research Project.* 1996. Edited by W.L. Steffen and A.Z. Shvidenko. IGBP Secretariat, Stockholm, 95 pp. Also available in Russian. This report was prepared by scientists representing BAHC, IGAC, and GCTE. It is a prospectus for an integrated hydrological, atmospheric chemical, biogeochemical and ecological global change study in the tundra/boreal region of Northern Eurasia. The unifying theme of the IGBP Northern Eurasia Study is the terrestrial carbon cycle and its controlling factors. Its most important overall objective is to determine how these will be altered under rapidly changing environmental conditions.

**No. 38**

*Natural Disturbances and Human Land Use in Dynamic Global Vegetation Models. A report of a workshop co-convened by the GAIM, GCTE, LUCC, and IGBP-DIS Programme Elements of the IGBP.* 1997. Edited by F.I. Woodward and W.L. Steffen. IGBP Secretariat, Stockholm, 49 pp.

This report summarises the findings and recommendations of an International Geosphere-Biosphere Programme (IGBP) Workshop which aimed to develop an approach to modelling landscape-scale disturbances in the context of global vegetation change.

**No. 39**

*Modelling the Transport and Transformation of Terrestrial Materials to Freshwater and Coastal Ecosystems, Workshop Report. Recommendations for IGBP Inter-Programme Element Collaboration.* 1997. Edited by C.J. Vörösmarty, R. Wasson and J. Richey. IGBP Secretariat, Stockholm, 84 pp.

This report is the major product of a three-day workshop entitled: "Modelling the Delivery of Terrestrial Materials to Freshwater and Coastal Ecosystems" held in Durham, NH, USA from 5-7 December 1994.

**Book of Abstracts**

*Book of Abstracts. Natural and Anthropogenic Changes: Impacts on Global Biogeochemical Cycles. Asian Change in the Context of Global Change.* Beijing, 23-25 October, 1995. IGBP Secretariat, Stockholm, 107 pp.

This book of abstracts is a result of materials presented at the scientific symposium held in conjunction with the Fourth Scientific Advisory Council for the IGBP (SAC) held in Beijing, 23-25 October, 1995.

**IGBP Booklet\***

*A Study of Global Change.* 1989. Edited by IGBP Secretariat, Stockholm, 9pp.

**Global Change: Reducing Uncertainties**

Prepared by P. Williamson, with editorial assistance from the Scientific Committee for the IGBP (June, 1992; reprint August 1993), IGBP Secretariat, Stockholm, 40 pp.

**IGBP Directory**

IGBP Directory. No. 1, February 1994

IGBP Directory. No. 2, October 1995

IGBP Directory Update: 1996, April 1996

IGBP Directory 1997, February 1997

**IGBP NewsLetter**

Global Change NewsLetter. Quarterly, No. 1, 1989 (latest issue No. 29, March 1997)