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Riverine transport and its alternation by human activities

by C. Vörösmarty and M. Meybeck

Water quality is critical to the sustainability of aquatic habitats, food webs, and commercial fisheries that serve as a major protein source for humans. It is also of enormous importance to the availability of freshwater resources serving a large and rapidly industrializing global population. We believe that the changing nature of inland water chemistry is important within a larger Earth Systems context. The transport of biotically active materials (nutrients and toxic substances) to the coastal zone through long-distance river transport ultimately links the continental land mass to the oceans. And, since it is believed that more than 90 percent of the world's fisheries catch depends in some way on the estuarine / coastal ocean and more than 50% of the human population resides within the coastal zones of the world, riverine transport and its alteration by humans constitutes a relevant global change and habitability issue.

Within this context, water engineering works — impoundment, withdrawal, interbasin transfers, and net water consumption — have significantly fragmented river corridors and their connections with the ocean. This produces a severe distortion of natural hydrographs leading to the potential loss of critical habitat, biodiversity, and altered material transport. Further, river loadings of biotically-active elements, metals, and pesticides are known to have increased several-fold since the beginning of the Industrial Era. From numerous individual river basin and coastal zone studies (e.g. the Baltic region; Mississippi River / Gulf of Mexico; North Sea; Northern Adriatic; the Black Sea) we know that elevated levels of waterborne nutrients, shifts in nutrient limitation, coastal eutrophication, toxic phytoplankton blooms, and bottom-water hypoxia are a consequence of human settlement and industrialization. Such site-specific changes in the delivery of land-based constituents collectively impart a biogeochemical signal of continental and global dimension. It has been estimated that riverine transports of inorganic N and P to the world oceans have increased several-fold over the last 150 to 200 years and it has been difficult to identify the population of truly pristine rivers. In certain regions, as in Western Europe, this increase is commonly 10 to 20 fold.

Drainage basins are a convenient organizing unit for large-scale hydrological and nutrient flux studies. Through river networks, spatially-distributed runoff and mobilized materials are collected and focused through river corridors which link disparate landscapes, for example high mountain source areas to coastal plains. River networks perform a natural integration of these processes and provide, through judicious sampling of water and constituent fluxes at discrete monitoring stations, a low-error estimate of otherwise difficult to quantify, spatially-distributed biogeochemical fluxes. In our contemporary world, river basins comprise a complex amalgam of natural landscapes, human-dominated landscapes, natural and controlled river channels. Since riverine fluxes are sensitive indicators of global change either related to climate change or to direct human impacts on continental aquatic systems, a comprehensive analysis of river basin behavior appears warranted from a larger global change perspective.

History of BAHC Research in River System Transport

A critical attribute of the terrestrial water cycle is its capacity to exchange both matter and energy, and a primary focus of early BAHC activities was the interaction between the land surface and atmosphere. By 1993, however, the BAHC Operational Plan (IGBP Report No. 27) presented several drainage basin-related concepts that were formally adopted during its execution phase. Among several others, a specific task directed at studies of the mobilization and fate of water and constituents through river basins set the stage for our current riverine transport work.

At the same time that BAHC began pursuing its initial work on drainage basins, there emerged an awareness of the relevancy of the changing nature of river systems as a legitimate component of the global change issue. This awareness took the form of several international workshops and symposia, newly-established research programs, and key papers in the peer-reviewed literature. In December of 1994, with the aid of PAGES and LOICZ, BAHC convened a three-day scientific workshop in Durham, New Hampshire, entitled "Modeling the Delivery of Terrestrial Materials to Freshwater and Coastal Ecosystems". The approximately 30 workshop participants were drawn from several Project Elements of the IGBP including BAHC, PAGES, LUCC, GAIM, and LOICZ. Representatives also attended from UNESCO, IAHS, and GEMS-Water (Global Environmental Monitoring System) as well as from the general scientific community active in the area of drainage basin and riverine transport analysis.

The Durham Workshop report (IGBP Report No. 39) provided a community consensus on important issues regarding fluvial transport through which the IGBP can take a leadership role. It was recognized that IGBP could make a significant contribution by providing (a) flux inventories for water and biogeochemical constituents, (b) an identification of the controls on terrestrial mobilization and aquatic transport of materials to the world's coastal zones, (c) an analysis of critical feedbacks due to human activities on biogeochemical systems, and (d) an identification of feedbacks due to drainage basin alteration on human society.

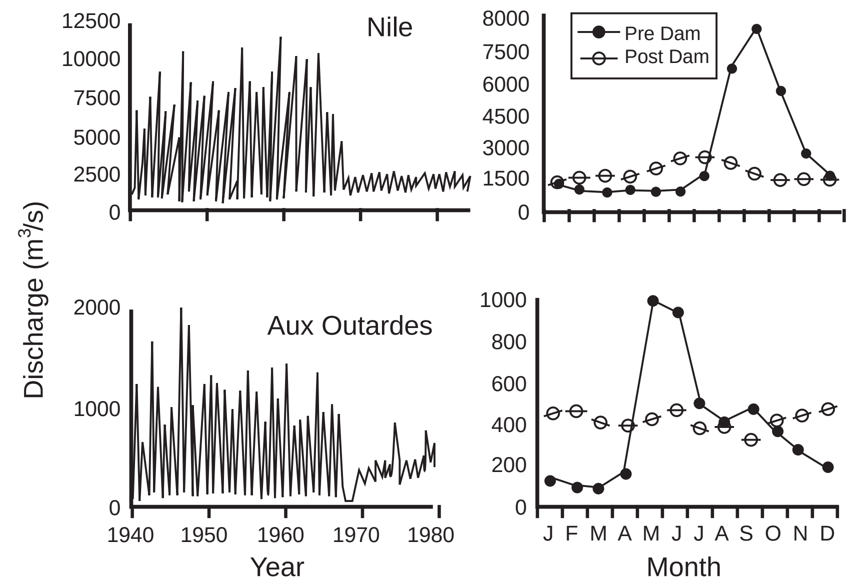

Figure 1. History of flow distortion by impoundments in two heavily-regulated rivers. Nile discharge is recorded just below the Aswan High Dam; the Aux Outardes site is near the river mouth. It is not difficult to identify in each case the time at which a dam was constructed and reservoir filled with significant changes to discharge regime before and after impoundment. Note reduced flows for the Nile due to lake evaporation and water use for irrigation. Note also the shift in the timing of the hydrograph in both cases, resulting in a major distortion of runoff. Such environmental changes are virtually instantaneous changes and a fundamental component of contemporary river systems, and hold important consequences for global sediment and nutrient transport, aquatic habitat and biodiversity, and waste processing. (Data from http://www.csrc.sr.unh.edu/hydro/welcome.html).

In addition, understanding the eminent role that mountains play as primary source areas of water and constituent fluxes through riverine systems and thus in the global water and biogeochemical cycles, another workshop was organised in Kathmandu, Nepal (March/April 1996) which resulted in the IGBP Report No. 43 "Predicting Global Change Impacts on Mountain Hydrology and Ecology". It was organized by the IGBP Core Projects BAHC and GCTE with support from START and attended also by representatives of LUCC. It finally led to the creation of an "Initiative for Collaborative Research" on "Global Change and Mountain Regions" (Becker and Bugmann, 1999) where BAHC, GCTE, LUCC and PAGES participate as primary partners. (A brief summary of this initiative is given in a separate box in this newsletter.)

Current BAHC Project Research

The recent reorganization of BAHC led to the creation of BAHC Key Theme 6, which provides the framework for quantifying and assessing the impacts of global change on river basins. The Key Theme's specific aim is to improve our understanding of the relative and distinctive contributions of climate change and anthropogenic activities on observed riverine fluxes. A central scientific question surrounds this work:

What are the key controlling factors that define the transport of water, particulate material, C, N, P, and Si through river systems and how have changes in these factors altered the linkages between the continental land mass and the world's oceans in the past, under contemporary conditions and into the future?

It is explicitly recognized that terrestrial water and material transport are linked, highly dynamic over both space and time, and reflect a complex interplay among climatic forcings, topography, land cover and vegetation. Through Key Theme 6 we recognize that humans have had an important hand in defining the nature of riverine fluxes due to land-cover and land-use change, population growth, industrialization, urbanization, and possibly greenhouse warming. Direct modifications of continental aquatic systems as river damming, water diversion, irrigation, wetland filling are definitively changing the water balance and the river material fluxes from the local to global scales.

However, fluvial systems have also changed substantially over a geological time frame, well before any significant, direct impacts from human society. Identifying the nature of these forcings is a major theme articulated by the IGBP more generally and we see an important opportunity for BAHC to collaborate with other Programme Elements.

We have organized our research around several suporting questions which collectively seek to formulate an overall research agenda on fluvial transport within BAHC. The research associated with these questions has a two-fold objective. The first seeks to achieve a better quantification of river basin fluxes over several time frames. The second objective is to explore the primary controlling factors that lead to observed patterns of riverine water and material flux. Our initial focus is on contemporary and past conditions as preparation for the analysis of future conditions. The combined inventory / process-level approach using multiple time frames provides a benchmark against which future system states can be measured. Three hypotheses have been formulated to organize our work:

HYPOTHESIS 1

The natural rates of water and material transport across drainage basins and within river systems of the world have varied significantly over the last 18 000 years. Prior to the growing influence of humans, the predominant controls have been derived from climate variability.

Over the last 18,000 years the architecture of river systems and rates of fluvial water and material transport have changed dramatically due to several natural forcings: (1) climate change affecting runoff; (2) variable sea level; (3) variations in the distribution and storage of water in ice caps; and, (4) occurrence of giant lake systems (>100,000 km^2) at the boundaries of ice caps and in endorheic (internal) basins. This is a critical global change question since all of these factors have themselves varied dramatically over both space and time. Understanding past changes and the response of river systems to these natural variations will be a key to understanding the future state of global river systems. A comparative analysis is required to test this hypothesis, contrasting contemporary, historical, and paleo-time frames. The mapping and characterization of present-day river basins without significant human influence is a convenient starting point.

HYPOTHESIS 2

Human activities from the beginning of the period of sedentary agriculture to the Industrial Era have significantly altered the rates of water and material transport across drainage basins and river systems of the world. These activities have been the major force shaping the character of contemporary fluvial transport.

Beginning about 6 000 years ago with the advent of sedentary agriculture, humans have progressively altered the mobilization and transport of constituents from the land mass. Today global river fluxes of water and riverborne material likely have been much more dramatically affected by human activities than by recent climate change, particularly over the last 100 years.

Owing to these several factors, this particular question needs to be addressed through a set of parallel efforts focusing on the global reduction of river-water discharge to oceans and internal basins, the simultaneous global increase in land erosion counter-balanced by a marked reduction of sediment transport due to reservoir siltation, and global changes in aquatic nutrient chemistry and carbon transport.

These changes involve direct alteration of both the fluxes of water per se and of particulate and dissolved materials. Water transport is already significantly affected in regions like the Gulf of California, Mediterranean Sea, Arabian Sea, Aral Sea where river inputs have been lowered from 25% to 100% due to reservoir building, massive irrigation, water transfer. Dramatic and virtually instantaneous changes are recorded in water fluxes measured at river discharge monitoring stations before and after impoundment, as shown in Figure 1.

Global sediment flux has been greatly increased through erosion on human-managed lands but simultaneously reduced through reservoir siltation. The global reduction in sediment transport due to trapping in reservoirs can be estimated conservatively at 20-30% of the present-day aggregate transport. Some biogeochemical fluxes, for example for N and P, have been already multiplied by a factor two to three on a global scale and up to 20 on a regional scale like to the North Sea. These changes represent a collective alteration of natural fluxes due to point-source pollution and non-point runoff, such as from industrial agriculture. There is also mounting evidence that the stoichiometric changes (nutrient:nutrient ratios for nitrogen, phosphorus and silica) in riverborne nutrient concentrations are adversely influencing coastal zone productivity, brought about by increased pollution from the landscape and trapping of materials within impoundments.

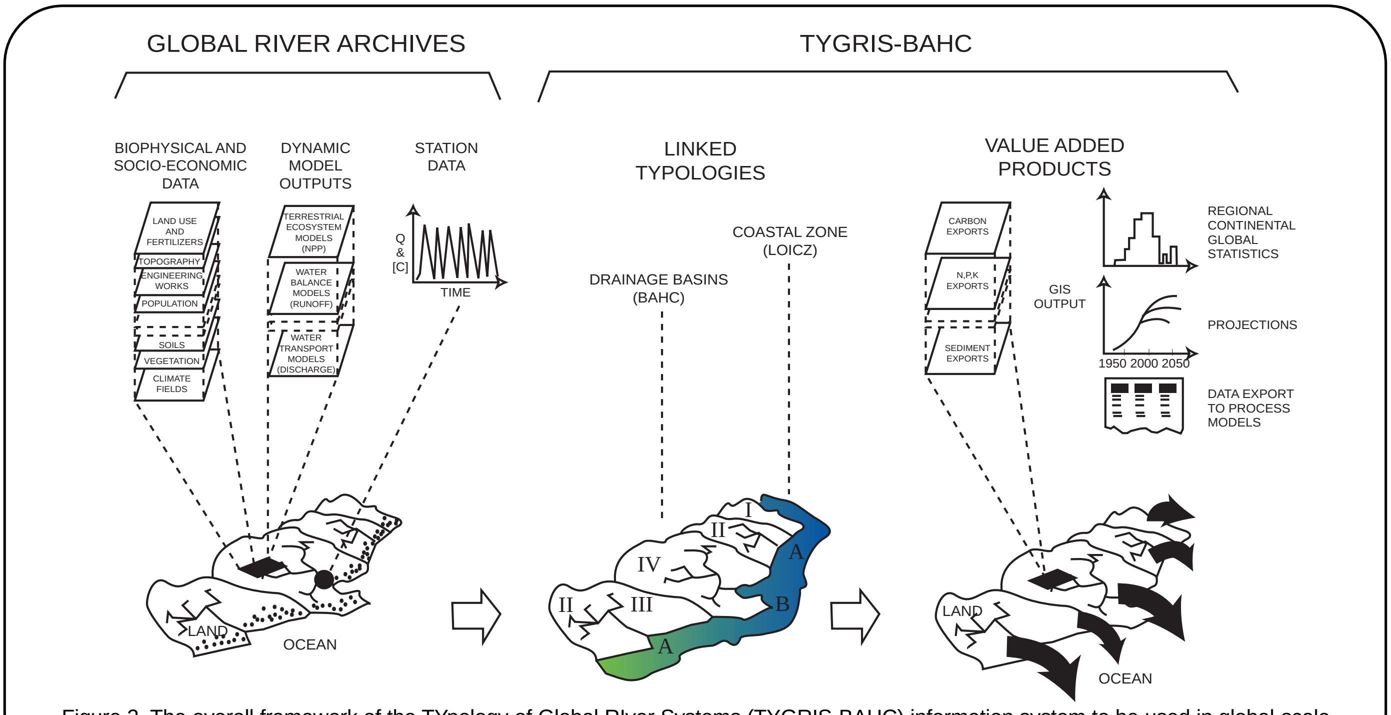

Figure 2. The overall framework of the TYpology of Global RIver Systems (TYGRIS-BAHC) information system to be used in global-scale analysis of inland water transports to the coastal zone.

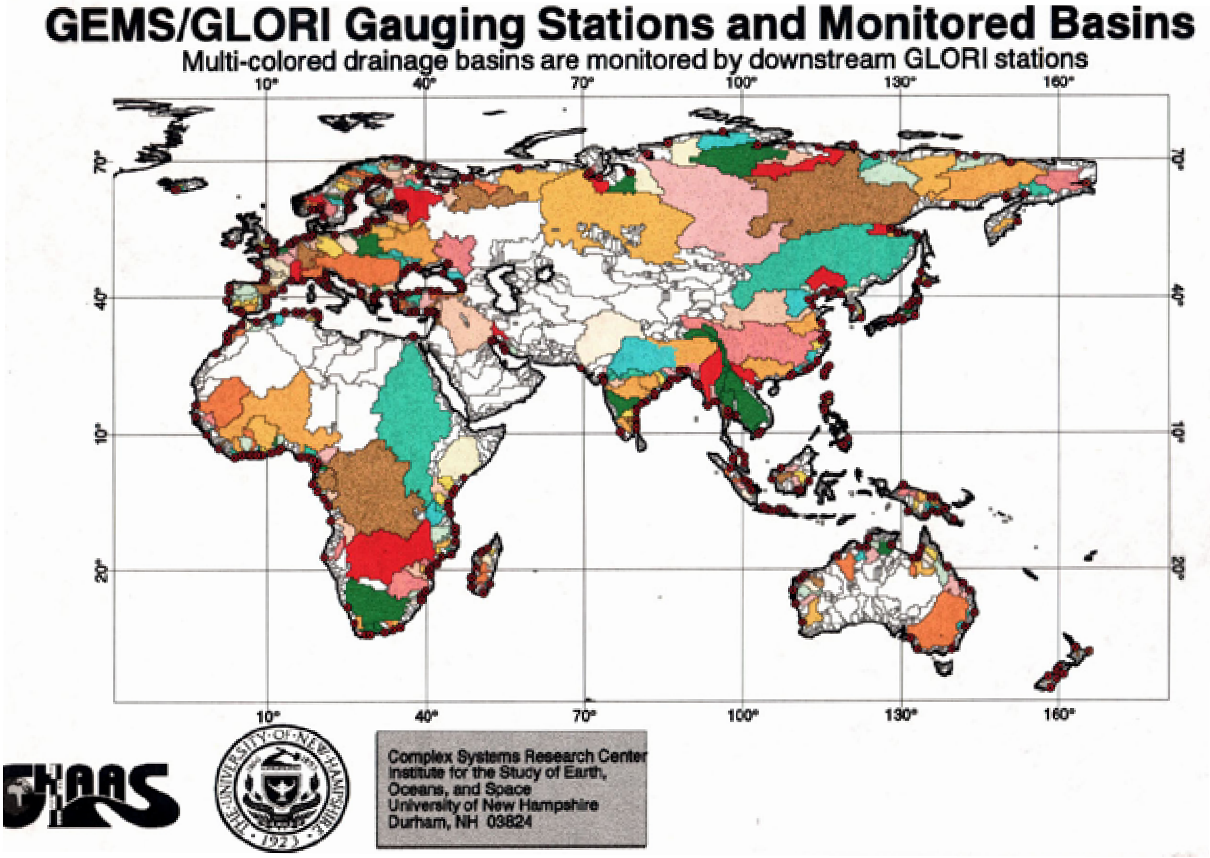

Figure 3. The geographic co-registration of the GEMS-GLORI (Global River Inputs to the Ocean) river chemistry data base to TYGRIS-BAHC provides important calibration and validation data sets for models of riverine transport.

HYPOTHESIS 3

Potential climate change and direct anthropogenic activities will produce unprecedented changes in water and material transport across populated drainage basins and river systems of the world over the next 100 years.

The mean residence time for water transported by rivers within the hydrological cycle — from its source in the atmosphere, through soils, and fluvial networks — is on the order of only a few months. For rivers themselves, this turnover time is on the order of about two weeks, except for few river systems influenced by large lakes, suggesting that these systems are and will continue to be sensitive indicators of global anthropogenic change. Indeed, river transport is one of the fastest changing global fluxes through the myriad of processes that both accelerate water and material flux (e.g. deforestation, rapid urbanization) and decelerate these transports (e.g. reservoir construction that traps sediment and enhances evaporation). This question is therefore highly linked to (1) global climate change, (2) population growth, (3) projected rates and levels of economic development particularly of irrigated agriculture, and (4) the evolution and enforcement of environmental regulations.

To develop a prognostic capability, we will focus on river system response in the face of several agents of ongoing global change, namely, climate variability, greenhouse warming, accelerated erosion due to land conversion and poor land management, water engineering, elevated nutrient flux from point and non-point source pollution. An additional and important element to consider is the purposeful regulation, through environmental protection laws, of emissions that discharge directly into water bodies and those associated with atmospheric deposition. For some classes of riverine material a major reduction of anthropogenic river fluxes has already been achieved through environmental control measures, for example for metals and phosphorus in North America and in some Western European rivers such as the Rhine.

TYGRIS-BAHC

A computer-based analysis tool is currently under construction to help pursue our research agenda. It is a characterization scheme, or TYpology of Global RIver Systems (TYGRIS-BAHC), using geographically-referenced attributes organized within a topological hierarchy of flow pathways through drainage basins. Once developed, TYGRIS-BAHC would be used in conjunction with models and multi-regression techniques to identify key controlling factors on drainage basin flux.

The need for such a system is clear. At present we can develop, at best, but a highly fragmented picture of the state of world rivers based on the observational record alone. This is certainly true for discharge (currently data for only about 55% of the land mass is routinely monitored and released) and the situation is even worse for constituents. For example, no more than approximately 25% of the globe's discharge is monitored for inorganic N. These models will be calibrated and validated using river discharge and water quality data sets from existing monitoring programs such as those developed at WMO for river discharge and at UNEP/WHO for water quality (GEMS-Water). Parallel efforts will then be directed toward characterizing river basins at selected, well-documented periods within the period of intensive agriculture and the last 18,000 years.

The overall organization of TYGRIS-BAHC is shown in Figure 2. Five components constitute the system:

- A data bank of geographically referenced information characterizing the world's drainage systems. The global TYGRIS-BAHC is initially organized at 30-minute spatial resolution, incorporating several data sets already available over the global domain (Table 1), many developed through ongoing IGBP initiatives. Over 6000 drainage basins can be delineated at 30′ spatial resolution. Enhancements to this resolution can be easily made as emerging needs dictate, for example made possible by the emergence of IGBP 1-km land cover and topography data sets. At any scale, these GIS-based data sets will serve as the raw material by which the world's drainage networks can be characterized.

- Data from water monitoring programs representing both water quantity and quality. These are available both from global archives (e.g. GEMS-Water, WMO-Global Runoff Data Center) and regional-to-continental scale holdings (e.g. Arctic Mapping and Assessment Programme). A specific Durham Workshop recommendation was the development of a 30-year time series of information by which to characterize the contemporary state of rivers, documenting their "mean" condition as well as their inter and intra-annual variability. An active and ongoing collaboration between BAHC and the existing monitoring programs will be essential. A linkage of the GEMS-GLORI (Global River Inputs to the Ocean) data base to TYGRIS-BAHC has recently been completed (Figure 3).
- A framework to derive a global river basin classification system that can be used in a set of first principle models of drainage basin water and material fluxes. This basin classification system will use information from the TYGRIS-BAHC biophysical data sets in conjunction with the river monitoring data to develop a set of rules by which information from well-monitored watersheds can be extrapolated to unmonitored basins. This typology will be applied to various classes of models to derive time and space-varying fluxes. A close collaboration with GEMS-Water, IGBP PAGES and LOICZ, and relevant commissions of the International Association of Hydrological Sciences (IAHS) is envisioned.
- A product generation component that can be used to produce maps and summary statistics. TYGRIS-BAHC will facilitate scientific visualization of the spatial patterns of drainage basin response. This will be called upon as well to produce regional, continental, ocean basin, and global-scale summaries of riverine fluxes.
- Integration of geographically-referenced process models within the overall GIS framework. These will include prototype horizontal transport models predicting time-varying discharge. Support could also be given toward, for example, the development of IGBP suspended sediment transport models in collaboration with the PAGES Fluvial Transport Group. Eventual linkage to Earth System Models currently under development through GAIM can also be envisioned.

Support for IGBP and Other Water-related Initiatives

The development of TYGRIS-BAHC is intended to catalyze drainage basin research both within IGBP and with other affiliated organizations and programs such as IAHS, WMO, UNESCO, WHO/GEMS-Water, SCOPE (Scientific Committee on Problems of the Environment). TYGRIS-BAHC figures prominently in SCOPE-N

TABLE 1. Proposed initial contents of the GIS data bank of TYGRIS-BAHC version 1.0. These data sets are at a variety of resolutions, from 1 km to 0.5 degree (lat. x long) for gridded data and from 1:1M to 1:80M for maps. There are also local site-specific data. Several data sets are already available in computerized format. A full listing including detailed citations are given in the Durham Workshop Report (IGBP Report No. 39).

- **Watershed Boundaries and River Networks**
- **Digital Topography**
- **Surface Attributes**
  - Potential vegetation
  - Land cover
  - Soils
- **Geology /Lithology / Age**
- **NO_y Deposition**
- **Population**
  - Human
  - Livestock
- **Climate**
  - Temperature
  - Precipitation
  - Radiation
  - Winds,vapor pressure
- **Industrial / Demophoric Indices**
- **Sewage Collection Rate and Treatment**
- **Water Balance Elements**
  - RO, ET, Δ storage
- **Water Engineering Works**
  - Major diversions, dams, etc.
- **Hydrogeographic Attributes**
  - Groundwater resources
  - River density
  - Lake density and attributes
  - Wetland density and connectivity
- **Fertilizer Inputs**

activities in attempting to globally map anthropogenic loadings of N from the land mass to the coastal zones of the world. These estimates will be made on the more than 6000 individual drainage basins simulated within TYGRIS, which in turn will be loaded as boundary conditions to the LOICZ coastal zone typology system for nutrients.

These activities will also support the newly-formed IGBP Water Group (now headed by M. Meybeck) which forms the IGBP-wide context for drainage basin research. The charge of this group is to integrate the several individual elements of the IGBP Programme Elements dealing with the inland waters issue and to coordinate these efforts both within the IGBP and with other international organizations such as the World Meteorological Organization (WCRP, GEWEX, ISLSCP), Global Climate / Terrestrial Observational Systems (GCOS/GTOS), UNESCO's International Hydrological Programme, UNEP/WHO-GEMS-Water, IHDP (International Human Dimensions Programme on Global Environmental Change), and ICSU (International Council for Science) Data Centers.

A Major Challenge: Deterioration of Monitoring Network Data Holdings

The scientific basis for developing this knowledge will ultimately depend on an appropriate data base management system as well as modelling tools. We recently convened a Workshop on Global Hydrological Data Sets at the IAHS IUGG Congress in Birmingham, bringing together experts from both the water sciences, water policy, and state-of-the-art digital data management fields. It was recognized that no matter how sophisticated our computing and hydrological software systems become, they will simply remain inadequate without basic information on water quantity and quality data, and information that is of high quality and relevance to the study of freshwaters at the global scale. As the water sciences community struggles to cope with the disastrous loss of monitoring stations in regions such as Africa and the former Soviet Union, it becomes increasingly important to inventory, collect, and in some cases "rescue" precious data sources. Even in relatively well-monitored parts of the globe, there has been a sustained decrease in monitoring capacity. For example, the US Geological Survey has recently been abandoning about 80 gauging stations per year.

Arming the community with such data sets will be an increasingly critical challenge into the 21st century. With this goal in mind, we propose the development of a Global River and Drainage Basin Archive Series that can supply the water sciences and management communities with a coherent suite of information resources upon which to monitor the status of freshwaters, analyze the role of drainage basins in the global change question, and promote the wise use of increasingly scarce water resources. We envision the Archive Series as a multi-year effort involving several international organizations and scientific contributors.

The Global River and Drainage Basin Archive Series will serve as a repository for basic information on river discharge, river and lake chemistry, and the biophysical attributes of drainage basins. Each volume in the Archive Series would be developed by community consensus, geographically co-registered to detailed maps, provided with a common naming convention, systematically checked for errors, tabulated in a standardized format, and distributed widely in digital form. A meta-data base listing hydrological data sets described at the IUGG Global Data Sets Workshop is currently being constructed (see: http://www.csrc.sr.unh.edu/hydro/welcome.html) in the hopes of creating an initial focal point for such data resources.

The archives could be built around several topical areas and foster IGBP interactions with other agencies dedicated to the water sciences. For example, one topical area could be contemporary river discharges bringing together information from prior UNESCO river archives, data from the WMO-Global Runoff Data Center, and individual researchers. A CD-ROM is currently being pressed which combines WMO station hydrological archives and 30-minute spatial resolution river networks which will be available freely and without restriction. Data from the GEMS-Global River Inputs to the Ocean project (GEMS-GLORI) (Figure 3) will also soon be available on CD-ROM and together with the runoff data base can be considered as the first release of the Archive Series. Additional subjects could be water use for irrigation, flow regime alteration by impoundments, nutrient chemistry changes in developing region drainage basins, changes in suspended sediment flux, and the changing status of water chemistry in inland lakes and reservoirs. A specific global data base on pristine river chemistry is also in progress.

Given the importance and tremendous scope of this effort, the Global River and Drainage Basin Archives Series will need to be supported by a broad spectrum of international agencies, including IGBP, GEMS-Water / UNEP / WHO, UNESCO, and IAHS. Scientific sponsorship would be from IGBP and several of its individual Programme Elements (i.e. BAHC, PAGES, LOICZ), UNESCO-IHP technical groups, GEMS-Water / UNEP / WHO, WMO's Global Runoff Data Center, and the International Lake Environment Committee (ILEC). The scientific networking capabilities of UNESCO, WMO, and IAHS should facilitate the assembly of interested participants, and when each volume is complete, dissemination to a wide audience of scientists and environmental managers. Funding for the initiative could be from UNEP/GEMS/GEF and individual national agencies. We strongly recommend the IGBP take the lead in facilitating workshops and expert working group activities to help stem the tide on this significant loss of scientific information.

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