IGBP Water-Sediment Workshop Summary Report
Boulder, Colorado
Sept. 25-27, 2000

James Syvitski: organizer/host
Institute of Arctic and Alpine Research, University of Colorado, P.O. Box 450,
Boulder CO, 80309-0450

Attendees: Nelly Bobrovitskaya, Bob Buddemeier, John Dearing, Katie Farnsworth, Björn Kjerfve, Michel Meybeck, John Milliman, Scott Peckham, Gerardo Perillo, Yoshi Saito, Alexsiey Sidorchuck, Bob Stallard, Charlie Vorosmarty, Des Walling, Bob Wasson

The IGBP Water Group held its first meeting in Stockholm (Feb 7-9, 2000), to discuss our knowledge of continental aquatic systems, and how they have been impacted by climate or humans across the last 50 years, and how they may change across the next 50 years. Participants came from the IGBP core project scientific steering committees: GCTE, LUCC, GAIM, PAGES, LOICZ, and BAHC. On September 25-27, 2000, a subset of this group (see appendix 1) met at the Institute of Arctic and Alpine Research, University of Colorado, Boulder. The workshop participants discussed anthropogenic influences at the global scale, on the supply and flux of sediment along hydrological pathways (see appendix 2). Representative experts came from three IGBP core projects (BAHC, LOICZ, and PAGES), augmented by selected invitees. This report provides a brief synopsis of the findings. A full report will be published as a special issue of Global and Planetary Change (see appendix 3).

1.0 Sediment flux to the coast, presently, in the past, and under pristine conditions.

River systems evolve through time, and as such the modern river systems are strongly influenced by past conditions within the watershed as well as modern conditions. Understanding the discharge of sediment across a broad time-scale will allow us to make better predictions for the future. The trapping efficiency of terrestrial reservoirs, both man-made and natural, is important to understanding the future discharge of sediment to the coastal oceans.

1.1 Present Flux to Coast

Current estimates put the annual sediment flux to the global ocean between 18×10^9 to 24×10^9 metric tons (Milliman and Syvitski, 1992, Syvitski, Vorosmarty and Morehead, in prep.). These estimates are based on sediment gauging records of varying time-scales and quality. The variance in these estimates is due to a variety of methods used to extrapolate data to understudied regions. Important considerations:

- Data are based solely on suspended sediment load, bedload was not considered. For many rivers this will not be an issue, but for some regions (Siberian Arctic) bedload may represent a significant proportion of the annual sediment flux.

- Relative to their number, very few small rivers have been monitored throughout the world. The large number of small rivers in many regions leads to a severe lack of data in some areas. It is difficult (perhaps impossible) to extrapolate data from large rivers to the smaller rivers — akin to a comparison of apples and oranges. The importance of events (landslides, floods, etc.) from small rivers has also been severely neglected.

- Actual global estimate is not of sediment flux to the coastal ocean, but sediment flux to the last gauging station on the rivers. These locations may be well inland, and many factors (such as estuarine trapping) could influence the fate of the sediment after the gauging station and before the coastal ocean.

- Most data (water discharge and/or sediment concentration) are collected only for a short duration (a few years). This leads to the question of the usefulness of mean numbers for sediment and water discharge. Both inter- and intra-annual variations within river basins need to be considered.

- Rivers are not monitored during the same time period, ranging for periods over the last hundred years. Much of the data are from the 1960's and 1970's. Therefore, sediment flux estimates for the present day are actually a few decades old. The construction of dams and other engineering within watersheds may have affected this number significantly. Vorosmarty et al. (1997) estimates that approximately 30% of the sediment is trapped behind the large reservoirs of the world.

1.2 Paleo Flux and Pristine Conditions

It is important to gain an understanding on the fluvial systems of the past, as they are the keys to the geomorphic character of rivers today. Fluvial systems evolve along with the landscape, and much of the sediment yield we see today is influenced by the paleo-systems. Much of the groups' discussion centered on the determination of what a "pristine" river would be. Due to natural variability within the systems, this is hard to pin down. Currently there is no accepted value for the paleo flux of sediment to the coastal oceans. Important things to note:

- In any one region, pristine conditions may have existed long after the intense development by humans in other regions. Therefore, what time period should we be trying to calculate the paleo flux? Do we try to obtain estimates when all rivers were pristine? When exactly was that? Some studies have been determining the times of maximum sedimentation rates on the continental shelves. Should this time period be used for the paleo estimation?

- Some have used a substitution of space for time. This allows using data from modern pristine rivers to estimate the sediment flux from rivers that are no longer pristine. Many issues arise when using this method; but the group did not discuss them in detail.

- Most studies have been small regional studies, and are not easily extrapolated to calculate a global estimate.

- Changes due to man and/or climate affect small river basins more dramatically than larger river basins. This modulation by larger rivers, coupled with a predominance of studies in larger basins may provide a skewed view on paleo-flux estimates.

- We do not fully understand the affect of man and climate change on the planet. Determining the balance between increasing sediment loads (land use, engineering, climate change, climate variability, etc.) and decreasing sediment loads (reservoirs, engineering, climate change and climate variability, etc.) due to the these effects is of utmost importance.

1.3 Future Sediment Flux

The future flux of sediment to the coastal oceans is important to consider. The main understanding needed to carry out that task is the balance of increased sediment versus decreased sediment due to the influence of man and/or climate change. Important things to note:

- It is thought that the future load of rivers will be less than the current estimates provided above, mostly because of the construction of large dams on rivers. This may not be correct, as we do not fully comprehend the balance between sediment retention schemes and soil erosion perturbations.

- We need time-series data to determine trends, with a focus on the last 20 years. These data are lacking and new methods need to be developed (or old ones reassessed) to utilize available data for water discharge.

- When modeling the possible future sediment flux, economics needs to be considered. The affect of development and land use is vital in understanding the global sediment flux.

- The total volume of sediment entering the coastal zone may not be the important variable to calculate. The change in the sediment yield on a region may be of much more importance than a global number. For example, sediment-starved regions may undergo erosion, while sediment-inundated regions may experience biological consequences such as burial of benthic biota. The total mass also says nothing about sediment composition (texture, quality).

1.4 Sediments in River Basins

It is understood that the erosion of bedrock by rivers takes place almost entirely in the headwaters of the catchment. This newly eroded sediment must then be transported to the coastal zone. How long it takes for this transport and how sediment makes the journey are the two important questions. Sediment budgets are the best method to increase understanding in these systems. Questions to ponder when creating budgets:

- What is the source type of the eroded sediment? Did it come from slopes, gullies, landslides, etc.?

- What is the river size and therefore the natural storage capacity for water and sediment?

- What is the sediment-transit times for different segments of the river?

- What roles do biogeochemical processes play in the system?

- What is the affect of man on the system? Are there reservoirs, levees, and other engineering projects? Is sediment permanently removed from the system or transferred to another basin (sand mining, dredging)?

- What is the delivery ratio of eroded sediment in a catchment, region, globally? Some have estimated that globally it may be ~4%.

- On a global basis, how long until we fill the terrestrial sediment sinks (natural and man made)? What affect will this have on the coastal zone and the global sediment flux?

- What is the sensitivity to erosion on a global scale? Can we create some index related to this that may inform us of the relative erosion change in regions due to disturbance (man or climate)?

1.5 Recommendations

- Global mapping of sediment sources and/or sensitivity to disturbance. This would allow for a better understanding of the affect of change on the system.

- Creation of an index to understand sediment transit times within basins. This is complete only with the inclusion of smaller river basins, as transit times are expected to be much shorter than that for the larger rivers. This infers that changes occur much more rapidly in smaller basins than larger ones.

- Determination of how long before river loads fill up the terrestrial sediment traps, and what the subsequent impacts will be downstream (e.g. the coastal zone). The effort needs to establish the linkages between land and ocean.

- Research the balance between increasing and decreasing sediment loads due to man and/or climate change.

- Coastal sediment budgets need to be linked to terrestrial sediment budgets. This would allow a bridge between the data from upstream gauging station and the coastal ocean, taking into account the interaction within estuaries.

2.0 Global Change & Sensitive Areas

2.1 Sensitivity

Several perspectives can be taken as to what constitutes a sensitive region or process, in light of global change and sediment transport. These may be geographic regions, curvilinear features such as river channels or coastlines, biological communities that may be especially vulnerable to either warming, changes in quantity or style of runoff, or changes in erosional processes. One might also include regions or situations that rapidly demonstrate the effects of global change to policy makers. Sensitive areas may also be regions where the interactions between growing populations and their associated infrastructure greatly alters the erosion and sediment transport processes such that people are placed at risk.

2.2 Sensitivity as a Research Issue

Our environment is not in a steady state; everything is transitory: regional populations and economies, reservoir storage, soil inventories, vegetation cover, etc. Moreover, we are not necessarily dealing with linear (cause and effect) systems. Our understanding of forcing and responses remains inadequate. An analysis of sensitivity should therefore be oriented towards an understanding of the dynamics of landscapes.

A critical issue in an analysis of the effects of global change on sediment fluxes is the role of thresholds, which, when crossed, effect a substantial change in the nature of erosion and sediment transport. What are these thresholds? For a particular scenario, what is the likelihood that a threshold will be crossed? How do we aggregate scales? How long does it take for the effects of local processes to propagate into larger-scale systems (e.g., Gilbert cycles)?

Most rivers are event-driven, with the tendency for the greatest impact to be on smaller and drier river systems. We need to monitor these significant events on a variety of scales to characterize fluxes to oceans and the eventual fate of sediments.

What are the teleconnections, whereby changes in one region substantially modify the state of another, perhaps distant, and region? For example drying and land-use change in Africa, causes substantial dust deposition in the Caribbean.

2.3 Paleo-reconstruction and the Mining of Historic Data

In searching for sensitivities, we need to document the prehistoric impact of changes in climate in the post-glacial world. Geomorphic analysis of landforms and reconstruction of sedimentary histories are clearly important. What are some additional the tools?

In the historic time frame, data related to the effects of land-use change might be buried in government or academic data archives. These archives need to be identified, preserved, cataloged and mined. With regard to predicting global change, extreme years in the historic record may reflect conditions that resemble the world under a changed-climate scenario.

2.4 Arctic

The Arctic may be the only terrestrial region where the effects of climate change may dominate over human effects. Here, we must consider the interaction of glacial and snow-melt-dominated hydrological regimes and sediment transport. Presumably, the changes in erosion and sediment transport will be markedly different in mountainous regions, such as Alaska and the vast flat regions in northern Europe, Siberia, and Canada. Fire, for example, is a major element of the boreal forest. In these regions, much of the landscape is so flat that there is not enough erosivity to form gullies, and the erosional response of deforestation appears minimal and regeneration is rapid. Instead we must consider the effects of an extension of the warm season and changes in precipitation. For example, in Amur River, a one-degree warming would cause an eleven-day increase the warm period per year; precipitation would increase 38 mm per year (600-mm/yr normal). In mountainous areas with glaciers, we might witness big spikes in the sediment load, followed by a decrease in load with soil formation and reforestation. Would this decrease drop erosion to rates that were less than a time when glaciers were the dominating force?

In the Arctic, we must also consider the role of mining and oil exploration on sediment transport down river to ocean, including consideration of economic activity/inactivity cycles.

2.5 Low-Runoff Areas

The superposition of climate (drying) and human water utilization drive many hydrological and erosional systems. Two issues might be considered: (1) areas that become moister and start generating runoff, thereby initiating sediment transport to the ocean, and more probably (2) areas that cease flowing to the ocean because a combination of drying and water utilization by growing populations. Important regions include the Mediterranean basin, Sub-Saharan Africa, southwestern North American and Central Asia. Research must identify the population thresholds and behaviors that have strong hydrologic and erosional effects. Some coastal issues include the erosion or subsidence of sediment-starved deltas and delayed responses. The coupling of increased nutrient inputs and decreased sediment loads may promote coastal-zone eutrophication (dominated by cyanobacteria) and hypoxia.

Does air-borne sediment transport out of these regions exceed fluvial transport? If so, by how much?

2.6 Wet Mountainous Areas

In many regions, landslides dominate the hillslope erosional regime. Triggering events, such as threshold-crossing rainfall or earthquakes are often required for natural landslide erosion. Climate shifts might increase the number of landslide-producing rainstorms. Simultaneously, many human activities, notably intensive agriculture, construction, and road building, promote landslides by undercutting hillslopes or by altering hillslope hydrology. Where lands have been deforested, rates of slide-related erosion are many-fold greater. We know that in tropical mountains, without supply-limited substrates, rates of physical erosion increase steeply at runoffs greater than 800 mm/yr. We also know enough to be able to construct landslide-hazard maps in any region given a sufficiently high-resolution DEM, geology, and rainfall distribution. In this context, prognostications about both the roles of growing populations and shifting rainfall regimes should be possible. Deforestation also reduces ET and induces spikier runoff in deforested mountainous regions.

2.7 Other General Issues

- How does land-use change affect erosion? What is the role of road building and mechanized agriculture / sylviculture? What about tillage styles? How important is mining in steep versus mountainous landscapes?

- Reservoir construction: Reservoirs clearly trap sediment and modulate flows. Additionally, what is the role of modulated flow down-river from a reservoir? Does this promote additional trapping of sediment contributed from downstream tributaries? Reservoirs present a transitory trapping process. What happens for the future as reservoirs fill?

- Hydrologic engineering - levees, dams, etc.: What are their effects?

- Stream Order: What is the role of stream order in a sensitivity analysis? Presumably there is a strong relation to stream order. Those low-order rivers that deliver to the ocean have major impact. Increase in sediment: yield from deforestation and changes in storminess.

- Tropical Estuaries (e.g. Bahia Blanca): Turbidity has a major impact on biological structure.

2.8 Gaps

- There is a need to assemble existing maps and databases for the coastal zone morphology and sediment situations at the global scale. The observations made from this activity could be linked to upriver processes.

- There is a need to compile information about rates of change of documented human impact. Vignettes should be compiled for each critical region, globally. Clearly documented examples provide a way to construction a typology guided by the use of typical scenarios for these representative regions. Politicians and policy makers think in vignettes.

- How do we incorporate this into a GIS and an ensemble of process models?

- Understanding of long-term dynamics remains lacking. Long-term data need to be assembled into formats that are easily accessible and useful to the community as a whole.

- We need to assemble information about the range of natural variability. This needs to be documented in general, globally.

2. 9 Opportunities

- Examine the linkages to the risk community such as the insurance industry and public policy groups. Connections need to be made with the agricultural community.

- Can we plug sedimentary work into big (IGBP) hydrological studies?

- Examine the use of remote sensing. Microwave could be used for salinity and coastal plume studies (also SeaWiFs). TRMM - Tropical Rainfall Monitoring Mission could be used for rainfall intensity and landslide work. We need to figure out ways to scale fine-grained information in the SLAR topographic map of the earth, to practical scales for other types of data.

- Improve use of correlations and hydrological descriptions to fill in data gaps. To recover data in Russia, data are aggregated to a monthly basis and sediment and water discharges are transferred into monthly time series.

3.0 Data - Typology (upscaling, downscaling)

3.1 Data

1. Discharge and sediment loads are available for about 600 to 700 of the largest rivers; these drain about 80% of total landmass.

2. The number of small rivers draining to the ocean (including very small ones) is very large (thousands), but their total contribution (in terms of discharge and sediment load) is small compared to the big rivers.

3. Quality of discharge and sediment load data is not the same for all rivers.

4. Based on total length of coastline, global data is sparse. Based on total discharge and sediment load budgets, global data is better.

5. Cores and other proxy stratigraphic data are the "tape recorders" of earth history. These include lake cores, delta cores, mangroves, and bore holes.

6. Satellite imagery is not yet compiled and used to back calculate the sediment flux to the ocean.

3. 2 Access to Data

1. Available (with some governments)
2. Unavailable (with other governments, or data held by industry as proprietary)
3. Individual databases
4. Collections i.e.:
   - Enhanced Milliman & Syvitski data set
   - GLORI database
   - Government (nonshared) data sets

- USGS SSC database
- Water Survey of Canada SSC database

3. 3 Data Issues

- Compatibility of data sets from different sources (e.g. countries)
- Different methodologies. Different periods of observation (years spanned), different temporal resolution.
- Pristine basins as benchmark to measure change.
- Pristine basins may tend to be more headward; further from coasts. Most of population of earth is concentrated in coastal zone.

3.4 Typology

Typology is essentially a spatial-statistical similarity analysis. An example from the analysis of deltas is the classical fluvial- vs. tidal- vs. wave-dominated delta descriptors. Milliman and Syvitski (1992) approach is a "crude" typology as is the Syvitski and Morehead (1999) approach. Jansen and Painter (1974) provide a more "classic" typological approach. Other examples are the similarity/scaling of river plumes using dimensionless numbers (Skene et al., 1998), or the Master Environmental Library that describes the climatology in the coastal ocean (http://mel.dmso.mil).

3.5 New Opportunities

Synthesis is now imminent based on collection of data, collection of tools. The conjunction of several data sets allows value-added products through typology. Products include:

1. A global, consistent data set for fluxes of sediment to the coastal zone,
2. Development of global inventories,
3. Development of process-level understanding of dimensionless numbers for upscaling, downscaling algorithms,
4. GIS layers of global data with ability to engage in sub-grid-scale parameterization,
5. Innovative use of remote sensing data.

3.6 Action Items

IGBP should foster or catalyze this linkage through an integrated set of activities to:

(a) Develop globally integrated databases and budget (error checking, harmonization, verification, and temporal compatibility),
(b) Community-wide model building (numerical, conceptual, and other models) and analysis,
(c) Understand the geographical differences (regional analysis, high vs. low, humid vs. arid, tropical vs. temperate, temperature effects)
(d) Impact to broader earth and human system.
(e) Major typology workshop in Hawaii (October or November 2001) to blend TIGRIS and LOICZ typologies, link land to coastal zone.

4.0 References

Milliman, J. D. and Syvitski, J. P. M. 1992. Geomorphic/tectonic control of sediment discharge to the ocean: The importance of small mountainous rivers. Journal of

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Syvitski, J.P. and Morehead, M.D., 1999. Estimating river-sediment discharge to the ocean: application to the Eel Margin, northern California. Marine Geology, 154, 13-28.

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APPENDIX 1

IGBP WATER/SEDIMENTS WORKSHOP
BOULDER, COLORADO
SEPTEMBER 25-27, 2000

PARTICIPANT ADDRESS LIST

Nelly N. Bobrovitskaya
State Hydrological Institute
23 Second Line
St. Petersburg, 199053, RUSSIA
E-mail: LVCH@NB1411.SPB.EDU
Fax: 812-323-1028
Phone: 812-323-1249

Robert W. Buddemeier
Kansas Geological Survey
1930 Constant Avenue
University of Kansas
Lawrence, KS 66047-3726
E-mail: buddrw@kgs.ukans.edu
Fax: 785-864-5317
Phone: 785-864-3965

John Dearing
Department of Geography
University of Liverpool
Liverpool L69 7ZT, UK
E-mail: j.dearing@liv.ac.uk
Fax: 44 (0) 151 794 2866
Phone: 44 (0) 151 794 2873

Katie Farnsworth
Virginia Institute of Marine Science
PO Box 1346
Gloucester Point, VA 23062
E-mail: farnswor@vims.edu
Phone: 804-684-7267

Michel Meybeck
UMR Sisyphe
University of Paris 6 Place Jussieu
75253 Paris CEDEX 05, FRANCE
E-mail: meybeck@biogeodis.jussieu.fr
Fax: (33) 1 4427 5125
Phone: (33) 1 4427 5148 or 5149

John Milliman
School of Marine Science
College of William and Mary
Gloucester Point, VA 23062
E-mail: milliman@vims.edu
Fax: 804-684-7250
Phone: 804-684-7112

Scott Peckham
INSTAAR, University of Colorado
1560 30th Street
Boulder, CO 80309-0450
E-mail: Scott.Peckham@Colorado.EDU
Fax: 303-492-6388
Phone: 303-492-6752

Gerardo M. E. Perillo
Instituto Argentino De Oceanografia
CC 107 - 8000 Bahia Blanca, ARGENTINA
E-mail: perillo@criba.edu.ar
Fax: (54-291) 861527
Phone: (54-291) 861519

Yoshiki Saito
Marine Geology Department
Geological Survey of Japan
Higashi 1-1-3, Tsukuba
305-8567 JAPAN
e-mail: yoshi@gsj.go.jp

Aleksey Sidorchuk
Geographical Faculty
Moscow State University
Moscow 119899, RUSSIA
E-mail: sidor@yas.geogr.msu.su

Charles Vorosmarty
Water Systems Analysis Group
Morse Hall
University of New Hampshire
Durham, NH 03824
E-mail: charles.vorosmarty@unh.edu

Des Walling
Depart of Geography
University of Exeter
Amory Building, Rennes Drive
Exeter, EX4 4RJ, UK
E-mail: d.e.walling@exeter.ac.uk

Bob Wasson
Centre for Resources and Environmental Studies
Australian National University
ACT 0200, AUSTRALIA
E-mail: Director.CRES@anu.edu.au

APPENDIX 2.

IGBP Water/Sediments Workshop
Boulder, Colorado
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Sunday, September 24
17:00 - 19:00: Icebreaker: INSTAAR conference room, RL1 Rm. 269.

Monday, September 25
09:00: **Introductions, agenda, logistics**: James Syvitski

Sessions: each session has two coordinators, charged with keeping presenters on topic and on time, for coordinating discussion, and for recording key points. Sessions may include breakout groups where needed. Coordinators to present findings on last day, to the group.

09:10: **Meeting Charge, Products**: James Syvitski

Charge: Determine what we know (i.e. state-of-the-art) and what we don't know (i.e. future research plans) on the flux of sediment across continents and to the coastal zone: before human perturbation, under anthropogenic influences and given future global change scenarios. Where are the sensitive areas? Can we map the historical variability and man's impact, by data? By typology?

Products: Workshop Report: to BAHC, PAGES, LOICZ, and IGBP IPOs.
Version of Workshop Report to EOS or Science or Nature
Special Issue of Global and Planetary Change

09:30-15:30 **Session 1: Data Issues** Coordinators: Björn Kjerfve & John Milliman
-Regional and world data sets on long term averages, inter-annual and intra-annual variability,
-Pristine condition data, paleo data sets
-Typology
-Data quality issues: precision and accuracy
-Data poor regions, data rich regions, scaling

15:45-18:00 **Session 2. New Methods** Coordinators: Charlie Vorosmarty & Nelly Bobrovitskaya

-Reservoir sedimentation
-Imagery, GIS
-Typology
-Climate-hydro modeling
-PAGES; LUCIFS
-SCOR working group
-Trend analysis
-Pristine data analysis

Tuesday, September 26
09:00-12:00: **Session 2 continues**; presentation of session summary
12:00-13:30: lunch, **mini-INSTAAR tour, computer demonstration**
13:30 -18:00 **Session 3. Science Issues** Coordinators: Des Walling and Yoshi Saito

1. What is the present flux of sediment to the coast, and paleo flux under pristine conditions?
2. What is the trapping efficiency of reservoirs, flood plains, and coastal plains?
3. What is the impact of global warming on these estimates?
4. Where are the sensitive areas?
5. What are the gaps in our knowledge (i.e. upscaling threats to the continental and coastal aquatic system)?
6. Can we map the historical variability and man's impact by data? By typology?

Wednesday, September 27
09:00-13:30: Session 3 continues and presentation of breakout group reports
13:30-16:00 **Session 4. IGBP water program and plans for the future** Coordinators: Bob Wasson and Michel Meybeck
16:00Wrap up James Syvitski: homework assignments.

APPENDIX 3

The supply and flux of sediment along hydrological pathways: Anthropogenic influences at the global scale

Editors: James P.M. Syvitski (IGBP-LOICZ), Michel Meybeck (IGBP-BAHC), and
Robert Wasson (IGBP-PAGES)
Sponsor: IGBP IPO and their Water Group

1. Introduction

J.P.M. Syvitski, M. Meybeck, R. Wasson, and G. Perillo: IGBP and their international programs on sediment fluxes in a changing world. Paper to deal with the science plans (vision, objectives, and goals) of the IGBP Water Group and the Water-Sediment Sub-Group, PAGES-LUCIFS, SCOR/LOICZ Sediment Budget in Estuaries.

2. Soil Erosion, Sediment Deposition and River Function

Bob Wasson: Bridging the gap between soil erosion and sediment fluxes observed in rivers.
Bob Stallard, Deborah Martin, J. Matheson and Mathew C. Larson: Modeling the role of landslides on the sediment load of small tropical rivers.
Alexsiey Sidorchuck: Natural impoundment of sediment on flood plains: lessons from the past.
Scott Peckham: The typology of landscapes: spatial resolution versus function.

3. Sediment Load of Rivers

Katie Farnsworth and John Milliman: The long-term sediment load and yields of rivers.
Nelly Bobrovitskaya: Regional typology of Eurasian and Siberian sediment yields: trends in change
Michel Meybeck, James Syvitski, Bob Stallard (co-author order?): Scaling the natural variability of the sediment load of rivers.
Mark Morehead and James Syvitski: Modeling the inter-annual and intra-annual variability in the flux of sediment in ungauged river basins.

4. Changes in the Sediment Load of Rivers

Des Walling and Don Fang: Global trends in the suspended sediment loads of large rivers.
Bob Meade and Nelly Bobrovitskaya: Reservoir impacts on the flux of sediment on large rivers: Mississippi, Yenesiy, and Ob
Charlie Vorosmarty, Michel Meybeck, and Bob Stallard (author order?): Global patterns in the growth of reservoirs, impoundment of sediment and the impact on downstream sediment variability.
John Dearing: Human impacted changes on soil erosion as captured by lake records.

5. Sediment Delivery to the Coastal Zone

Yoshi Saito: Changes in the sediment loads carried by large Asian rivers.
Charlie Vorosmarty and James Syvitski: Modeling the flux of sediment to the coast using a global typology approach
Bob Buddemeier: Assessment of thresholds in sediment fluxes to the coastal zone: coral functions, seagrass productivity
Gerardo Perillo, Eric Wollanski, and Bjorn Kjerfve (author order?): Sediment retention in estuaries as influenced by upstream changes in river hydrology.