Land Use and Climate Impacts on Fluvial Systems during the Period of Agriculture

Recommendations for a Research Project and its Implementation

edited by
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TABLE OF CONTENTS

1. PREFACE 4

2. INTRODUCTION 5

3. THE PLANNING MEETING 8

4. SUMMARY OF THE KEY IDEAS PRESENTED AT THE WORKSHOP 10

4.1 Benefits of a Long Term Perspective 10
4.2 Fluvial System Response to Land Use Change 11
4.3 Fluvial System Response to Climate Change 13
4.4 Interaction of Land Use Change and Climatic Change / Variability 17
4.5 The Significance of the Direction and Timing of Climatic Change 20

5. SUMMARY OF THE WORKING GROUPS' DISCUSSIONS 22

6. THE PROJECT STRATEGY 26

6.1 Global Regionalisation 26
6.2 Selection of Case Study Catchments 29
6.3 Case Studies 29
6.3.1 The Uses of Lakes and Reservoirs 31
6.3.2 Constructing Fluvial Sediment Budgets 32
6.3.3 Analysis of Case Study Time Series 35
6.3.4 A Modelling Framework 36

7. COMPLEMENTARY ACTIVITIES 38

7.1 LOICZ and PAGES 38
7.2 BAHC and PAGES 40
7.3 IAEA and PAGES 42
7.4 IHDP / IGBP - LUCC and PAGES 43

8. IMPLEMENTATION PLAN 44

8.1 Outputs 46
8.2 Project Management 46

9. ACKNOWLEDGEMENTS 47

10. REFERENCES 48

1. PREFACE

The PAGES (Post Global Changes) Core Project of the IGBP published its Research Plan in 1992, emphasising the following key aims: to distinguish between natural variability and human impact in global changes currently underway; to identify forcing factors and climate sensitivity; to reconstruct greenhouse gas concentrations and biologic feedbacks; and to determine the response of ecosystems to climate change and abrupt events (Eddy, 1992).

The 5-year Plan of PAGES gives greatest emphasis to climate change. This is an appropriate emphasis because climate change represents a significant challenge to humankind's adaptive abilities, but also because the majority of scientists allied to the perspectives of PAGES can make their major contribution to our understanding of climate change and its impact on ecosystems. Focus III of the 5-year Plan, however, emphasises human impacts on the Earth System, both on the atmosphere and on the biosphere.

Along with other core projects of the IGBP, PAGES is now contributing to a wider range of components of the Earth System. This report is one such contribution, in this case to one of the key components of the Earth's biogeochemistry. The history of interaction between climate and land use is recorded in lake and river sediments, and the unravelling of these records is a key task for PAGES. Without such records, advice to governments and decision makers will be less complete and so less useful. The past is in many cases the key to both the present and the future.

Ray Bradley
Chairman,
PAGES Scientific
Steering Committee

2. INTRODUCTION

Global Change research recognises the major interactions between the Earth's physical, biogeochemical, and human societal systems (*Figure 1*). Global Change is both systemic (involving changes to whole-Earth systems such as the atmosphere and oceans) and cumulative (involving many local and/or regional changes that in aggregate have a global effect). The IGBP Core Projects have designed research to examine the major global interactions (see *Figure 1*), and a system-wide approach is being adopted by GAIM.

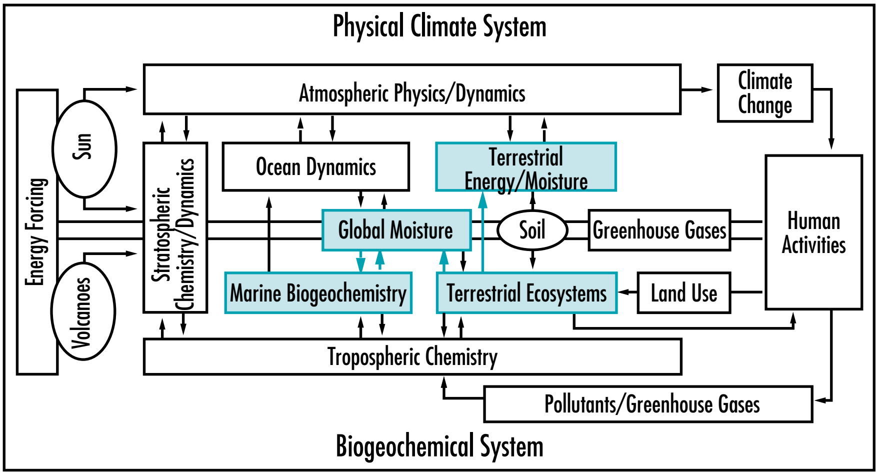

Figure 1.
A conceptual diagram of the Earth system showing aspects of the interaction between the biogeochemical subsystem and the physical-climate subsystem. Interactions where fluvial systems are of key importance are coloured. (After Moore and Braswell, 1994).

Not well represented in the current plans of the IGBP core Projects is an examination of the horizontal transport of water and biogeochemically important materials in fluvial systems, that is, in both rivers and their catchments. The interactions in the global system where fluvial systems are of key importance are depicted on *Figure 1*. These interactions occur between terrestrial ecosystems, the hydrologic cycle (global moisture), and marine biogeochemistry.

As depicted in *Figure 1*, fluvial systems play a systemic role in the global system, where riverborne fluxes of C, N and P fertilise the oceans with consequent feedbacks to the atmosphere via the carbon cycle. A more important and cumulative effect, however, is on the life-support systems of nearshore ecosystems where C, N, P and sediment can be either beneficial or detrimental. Increased fluxes of these materials are observed almost everywhere catchments have been converted from natural vegetation to agricultural land uses. The consequent effect on the nearshore is to foul the marine ecosystem with sediment, and fertilise the waters to the point where eutrophication can be a serious threat to human well-being. Similar effects are seen within the catchments, with eutrophication and sedimentation of rivers, reservoirs and lakes, and sediment fouling of freshwater ecosystems. Where reservoirs have been constructed, fluxes to the oceans have been reduced, in some cases to less than pristine quantities.

Fluvial systems therefore play a key role in both systemic and cumulative human impacts on the global system. Rivers are the primary agents of horizontal transport of biogeochemically important materials from the land to coasts. Within the context of the IGBP, it is important to know the magnitude of these transport rates, the mechanisms that control them, and how land use and climate change affect them. While it is useful to build a global inventory of modern riverine fluxes, it is much more difficult to investigate the sensitivity of fluvial systems to climate change and land use change using only modern data. For this investigation, and to build models of predictive value, the palaeo-record is essential.

The key role of the fluvial system in the horizontal transport of water, sediment, P, N and C has been recognised by BAHC, LOICZ and PAGES. The current report is the result of the PAGES meeting, while the BAHC, LOICZ and PAGES meeting produced a report entitled 'Modelling the Transport and Transformation of Terrestrial Materials to Freshwater and Coastal Ecosystems'.

Both planning meetings formulated key scientific objectives within a broad framework:

- quantification of land form change and river-borne fluxes of water, sediment, C, N, P (and micronutrients where relevant), both today and in the past;
- identification of the controls on these fluxes in the catchment cascade, both today and in the past;
- identification of the feedback on both human society and biogeochemical cycles of changes in the fluxes of these materials.

The time of greatest human impact on the Earth is the period of agriculture. This period is the focus of this project.

3. The Planning Meeting

Within the context of IGBP's objectives, an emphasis on the agricultural period, and PAGES objectives (Eddy, 1992), a planning meeting was held in Bern, Switzerland, in February 1994. This report sets out the key research recommendations of the meeting. It also includes a strategy and implementation plan. Much of the discussion in this report centres on sediment, but the scientific questions and research techniques apply equally to other materials that are preserved in palaeo-records (eg P and C). It is noteworthy, however, that there are few studies of the behaviour of C or P in fluvial systems during the agricultural period. While the palaeo-record contains information of unique importance (see Section 4.1), it is also restricted in some ways. For example, there is no known unambiguous palaeorecord of dissolved chemical species, and alteration of C and migration of P in sedimentary records can complicate the interpretation of fluxes through time. Emphasis in this report is therefore on those materials for which a plausible interpretation can be obtained by analysis of palaeo-records.

On the first day of the meeting, the objectives of the meeting were set out, the complementary role of IGBP core projects identified, along with a possible role for the International Atomic Energy Agency. Presentations of key ideas and results were made by the participants (Section 4, below), and then methods for investigation and a project strategy were considered (Section 6, below).

On the second day, the group split into two working groups to consider:

- The response of fluvial systems to land use change;
- The role of climate change in fluvial systems response

Each working group was asked to use the following questions to stimulate discussion:

1) What are the major scientific questions in this field?

2) What are the major natural resource management questions that should be answered?

3) What are the practical and scientific benefits of a temporal perspective longer than the instrumental record on fluvial system change?

4) What is the appropriate period of time for investigation and with what temporal resolution?

5) Is there a particular spatial scale that should be emphasised?

6) What regions of the world should be given emphasis?

7) What should be the products of this research?

4. Summary of the Key Ideas Presented at the Workshop

4.1 Benefits of a Long Term Perspective

Within the three broad categories given in the Introduction, there are several important ways in which a long term perspective on the dynamics of sediment, C and P in fluvial systems can enhance understanding of contemporary problems and our appraisal of the future implications of global change:

- Instrumental records can be extended by means of well calibrated proxy indicators to derive longer time series with which to investigate the interacting impacts of land use change and climatic variability
- A more realistic understanding of cumulative effects can be attainedon timescales longer than the period of direct monitoring, of longer term leads and lags within complex fluvial systems, and of delayed downstream responses to major events or changes
- Long term trends upon which short term fluctuations and responses are superimposed can only be detected and quantified within a historical framework
- Documentation and evaluation of extreme events becomes possible beyond the reach of the instrumental record and outside the range of variation represented by processes observable at the present day. Examples of such events (e.g. Bork, 1989) have important implications for future human responses to environmental change
- Careful documentation of antecedent conditions responsible for the context within which recent and contemporary processes operate, is essential before any realistic attempt is made to develop dynamic models of fluvial system responses to future change
- A longer time perspective provides a credible basis from which to launch educational programs, inform policy and public opinion, and evaluate the potential scope and limitations of purely technical responses to changes and variations in fluvial systems.

4.2 Fluvial Response to Land Use

The most profound effect of land use on catchments and rivers results from clearing and/or grazing of natural vegetation, cultivation, and urbanisation. Bare or partially vegetated and compacted soils shed water at a much higher rate than vegetated and uncompacted soils. Under most natural conditions, soil is conserved, and nutrients such as N and P are moved in a tight cycle between soil, vegetation and atmosphere. Little is lost to surface runoff or to groundwater. Under natural conditions, this tight cycle is broken by fire and flood, or by major environmental changes such as glaciation and vegetation shifts. Once cleared, grazed and cultivated, however, sediments, nutrients and carbon move laterally in runoff into streams and then to the oceans. Urbanisation also increases the flux of nutrients to rivers, and, during development phases particularly, can also increase sediment yields. For soluble reactive phosphorus (SRP) and dissolved N (mostly NO_3), Caraco (1995) showed that the flux of these nutrients in rivers increases with population density and the proportion of a catchment that is urbanised. Population density and energy consumption were previously found to be useful simple descriptors of nutrient fluxes (Meybeck, 1982). While the mechanisms at work are not clear, it is plain from these results that the presence of increasing numbers of people in a catchment, particularly in urban centres, increases nutrient fluxes.

Human land use has therefore fundamentally changed the Earth's biogeochemistry, and this is predicted to change again as a result of an enhanced Greenhouse Climate. However, it would be wrong to conclude that only land use and climate control the flux of materials in fluvial systems. Land use is probably the dominant control on particulate fluxes in areas of low relief and large-scale urbanisation, but in mountainous catchments that are still tectonically active, it is likely that land use plays a role subsidiary to that of mass movement and stream incision. In mountains that are no longer tectonically active, it is likely that land use is once again significant as a control on fluxes of materials. These ideas are speculative but consistent with conclusions reached by Pinet and Souriau (1988), McLennan (1993), and Milliman and Syvitski (1992). They also imply that climate is a second-order control on material flux, a conclusion consistent with the inability of researchers to find a clear global relationship between sediment yield and climate. This conclusion must also apply to particulate P, given that its flux is highly correlated with that of suspended sediment. Comparisons of pristine and developed rivers have provided estimates of the rate of P transport to the oceans both before and during the period of agriculture (Tiessen, 1995). There are no regional or global estimates based on sedimentary records, and there are few long time series of transport and/or deposition rates to examine the role of climate change in the flux of P.

Land clearing in low relief areas increases suspended sediment and phosphorus yields from small catchments (< 10 km^2) by up to 1000X, but more usually ~10X (Dedkov and Mozzherin, 1982; Douglas, 1993). The effects further downstream, expressed as P and sediment yields from catchments >1000 km^2, are smaller, with suspended sediment yields increased typically by 3-4X (Dedkov and Mozzherin, 1984). But these estimates both of yield and change are uncertain, because of the wide variety of sampling and analytical methods used by different researchers. Global compilations of sediment yields include many unknowable errors, and so it is only first-order relationships that are visible from analysis of these data.

The effects of land management, as distinct from land use, are not detectable in these global data sets. When data are carefully collected from small catchments where land management changes occur, it is sometimes possible to detect the effects of land management. But, in the main, it is land use that stands out. Some unexpected relationships have been exposed in these studies: the same yields can occur from catchments of identical size despite different land uses, implying that catchment morphology is the dominant control on yield; there are two extreme system types in areas of low relief, one where sheet and rill erosion dominate sediment fluxes, and the other where channel erosion dominates; instream sediment and P stores can be mobilised because sediment supplies from hillslopes are cut off by soil conservation. These and other results suggest that causal relationships between land use, climate, and material fluxes are compounded by other factors that we must attempt to understand.

Responses to land use type and change are scale dependent. That is, increases of sediment and P yield are greatest in small catchments, but they are also most variable between catchments at small scale. Response times are also scale dependent. For example, changes of channel dimensions resulting from increased runoff from cleared areas can take decades to centuries to equilibrate in large catchments. Of course, all these changes are driven by individual events, the frequency-magnitude spectrum of which varies in different parts of the Earth and also changes with land cover and climate change. Despite these complexities, it should be possible to define catchment response types at different spatial scales given various combinations of controlling factors.

4.3 Fluvial System Response to Climate Change

The context

The response to land use change of fluvial systems will frequently interact with, and be modulated by, the effects of climatic change and climatic variability. Thus in some situations the impact of land use change may only become fully apparent when the system responds to extreme events or climatic discontinuities, while in other cases it may be difficult to disaggregate the effects of land use change from those of climatic variability. It is therefore important to consider the complex interaction of both sets of potential forcing factors when reconstructing longer-term changes in the response of fluvial systems. If, however, an attempt is made to isolate the potential impact of climatic variability and change, a wide range of possible effects can be identified. Changes in the overall water balance and in moisture availability could, for example, influence both the magnitude and the seasonal variation of land cover density and therefore result in changes in erosion rates. Shifts in the magnitude and frequency, seasonality, and inter-arrival times of extreme precipitation and runoff events may also result in significant changes in both erosion and delivery to streams of sediment, P and C. Several examples of changes in the key hydrological factors which drive the fluvial system, caused by climatic change and climatic variability, may be usefully introduced.

The impact of climatic change on catchment hydrology

A valuable example of the impact of climatic variability on flood magnitude and frequency is provided by the work of Knox (1984, 1993), who demonstrated substantial temporal variations in the flood behaviour of the tributaries of the Upper Mississippi in south-western Wisconsin, USA, over both long (10^3 years) and short (10^1 years) time scales (*Figure 2*). Such variations in flood response clearly have important implications for sediment transport. Knox emphasises that these changes in flood behaviour were associated with relatively modest shifts in average conditions. These involved changes in mean annual temperature of only ca. 1-2°C and changes in mean annual precipitation of <10-20%. It is important to recognise that small changes in average conditions could be associated with substantial changes in the magnitude and frequency of extreme events.

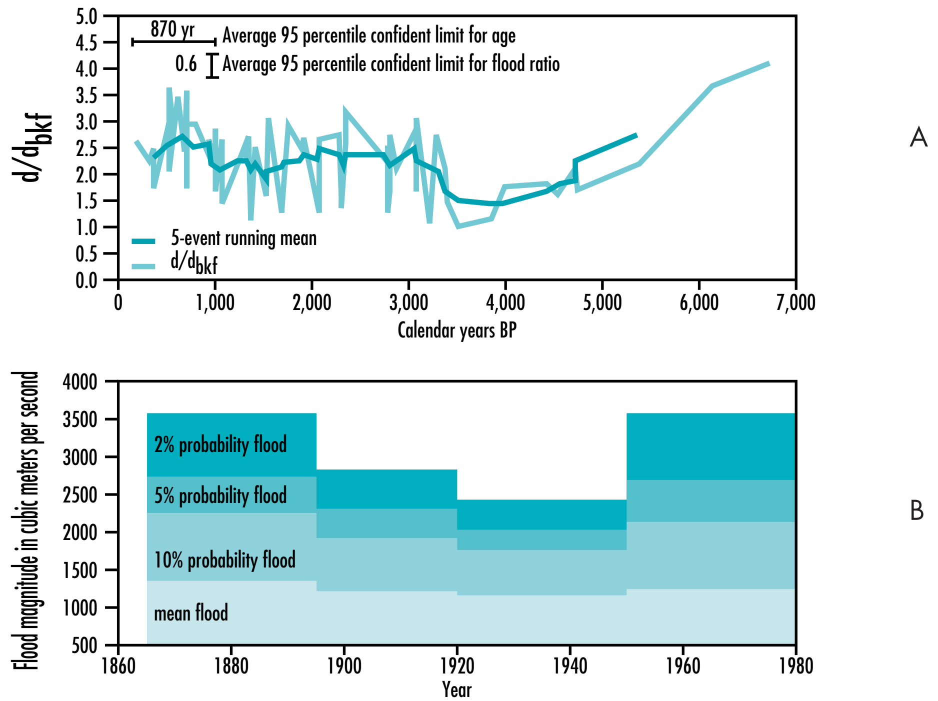

Figure 2.
Temporal variability of flood magnitude and frequency in southwestern Wisconsin. A [based on Knox (1993)] shows the reconstructed record of long-term variations in later Holocene flood magnitudes, as represented by relict floodwater depths (d), expressed as a ratio to the corresponding bankfull stage water depth dbkf at the same site. B [based on Knox (1984)] plots recent changes in the magnitude of floods of a given recurrence interval.

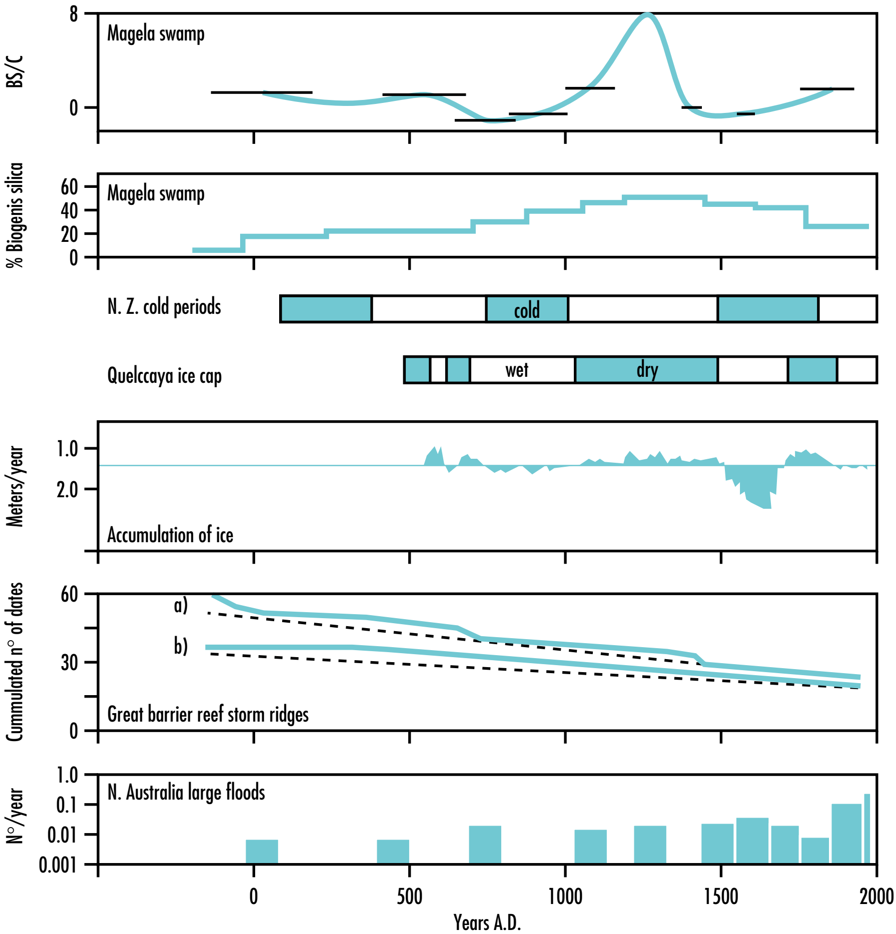

Figure 3.
Southern Hemisphere climatic variability, as expressed by biogenic silica accumulation in Magela swamp, N. Australia, New Zealand cold periods and the activity of the Quelccaya Ice Cap, and its relation to variations in geomorphic activity in Australia as expressed by the frequency of coastal storms and of large floods in N. Australia. Based on Wasson (1992).

The impact of shifts in global atmospheric circulation on river flood behaviour will, however, vary in different parts of the globe. The inter-arrival times of extreme events and the associated grouping of such events have been shown to exert an important influence on the behaviour of some geomorphic systems. A contrast is provided by a comparison of the frequency of extreme floods in Northern Australia and the incidence of high magnitude coastal storms on the Great Barrier Reef over the past 2000 years (*Figure 3*). In both cases there is little evidence of changes in event frequency during this period, despite the clear evidence of climatic shifts provided by the record of Southern Hemisphere ice accumulation and of biogenic silica accumulation in the Magela Swamp in northern Australia. In this environment, the frequency of extreme events would appear to have been relatively stable over the past 2000 years and therefore essentially independent of shifts in the average climate.

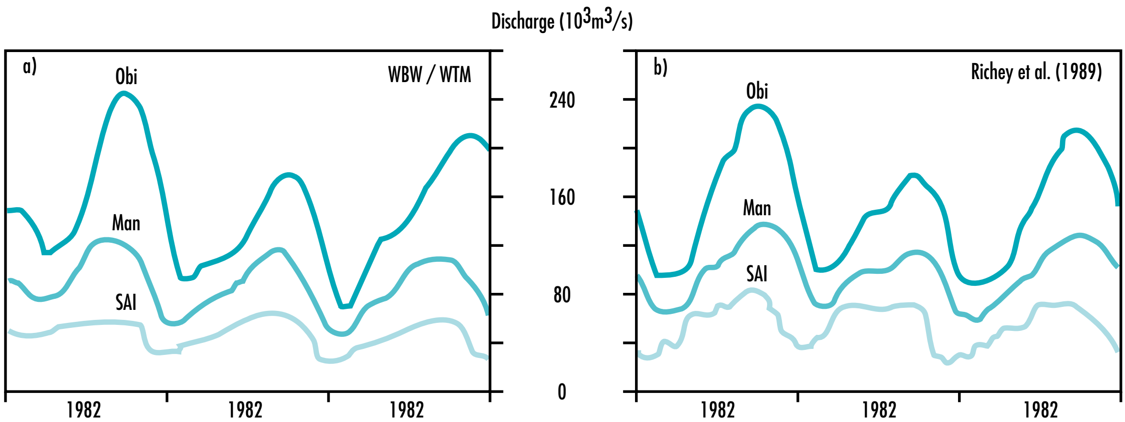

Figure 4.
River discharge at three locations along the mainstem Amazon: a) simulated by Vörösmarty et al., 1996; and b) observed records from Richey et al., 1989. The 1982-83 ENSO event is evident in both time series as a significant decrease in discharge. Years given refer to water years starting in September:
Obi = Obidos, 56.0°W/2.0°S;
Man= Manacapuru, 61.0°W/3.5°S;
SAI = Antonio do Ica, 67.5°W/3.0°S.

Although changes in the magnitude and frequency of extreme events are commonly of greatest significance in terms of the impact of climate change on sediment and P (and probably N and C) transport in fluvial systems, other changes may also be significant. In large tropical rivers such as the Amazon, the seasonal flood which occurs each year dominates the pattern of material transport. Shifts in the global atmospheric circulation which cause shifts in regional rainfall patterns may have significant effects on the magnitude and timing of the seasonal flood, which will in turn result in changes in sediment response. Vörösmarty et al. (1996) have, for example, demonstrated how the El Niño event of 1983 was reflected in a substantially reduced flood peak on the lower Amazon (*Figure 4*). In contrast, records from the Paraná river for the same period indicate that on that river the same El Niño event was reflected by substantially increased flows.

In rivers where glacier wasting and snow melt represent an important component of the flow, changes in rates of melting may also have an important influence on the flow regime and the relative contribution of runoff from different sources. Both could influence the response of the river. Schotterer et al. (1993), for example, have employed measurements of the oxygen-18 content of water from the Rhine and Rhone rivers to demonstrate that significant changes in the relative importance of different runoff sources have occurred in both rivers over the past decade (*Figure 5*).

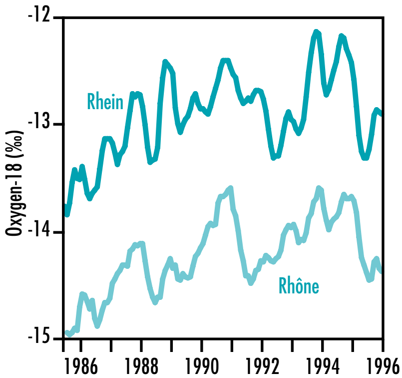

Figure 5.
Recent changes in the oxygen-18 content of the Rhine and Rhône rivers (Schotterer et al., 1993, updated by Schotterer 1996).

4.4 Interaction of Land Use Change and Climatic Change/Variability

Existing evidence suggests that the interactions of land use and climatic change may involve considerable complexity in terms of their combined impact on the response of fluvial systems. In some cases the two appear to operate essentially independently, whereas in others they are closely linked and the impact of land use change may only be fully apparent when coupled with climate. Zangger (1992) and van Andel et al. (1990), for example, have reviewed the chronology of Holocene alluviation events in Greece and the Aegean (*Figure 6*) and found little or no synchroneity between events in different parts of the area. This led him to suggest that alluviation was controlled primarily by the

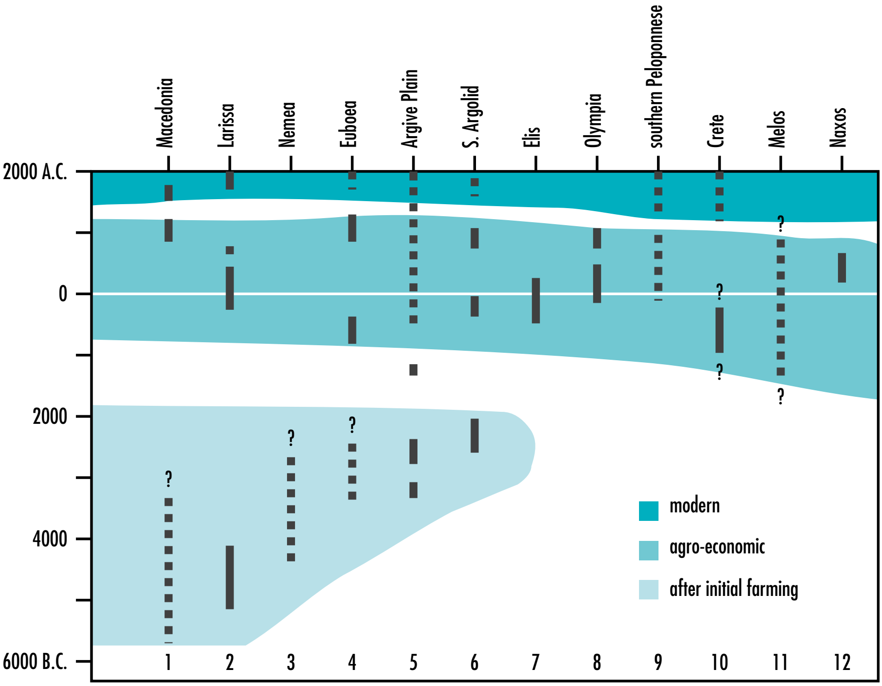

Figure 6.
Chronology of Holocene alluviation events in Greece and the Aegean.
Broken bars are dated uncertainly or represent intermittent deposition.
The numbers 1 to 12 refer to the source references listed in van Andel et al. (1990), Figure 10, p. 389.

timing of agro-economic activities in different areas. An investigation of the erosional impact of more recent changes in land use on the Russian Plain reported by Sidorchuk et al. (1996) has similarly failed to identify any significant correspondence between the timing of periods with high rates of gully erosion and the pattern of climatic variability as documented by the incidence of periods of anomalously large spring floods and wet summers reconstructed by Borisenkov et al. (1988) (*Figure 7*). Again, the timing of land clearance and land use activities in the area appears to exert the dominant control, and the main peaks in erosional activity occurring after 1600 AD can be linked to the major phases of agricultural expansion in the region.

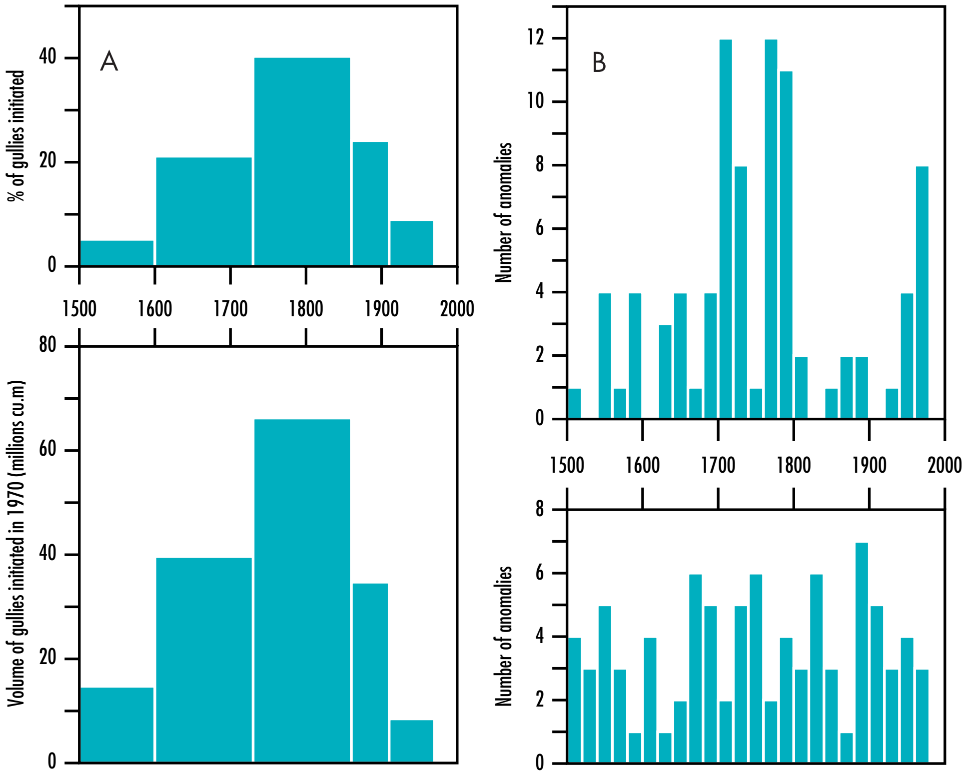

Figure 7.
Temporal changes in gully erosion rates on the Russian Plain during the past 500 years reconstructed by Sidorchuk et al. (1996) (A), and the pattern of climatic variability for the same area documented by Borisenkov et al. (1988) (B).

In contrast, a countrywide investigation of the chronology of episodes of Holocene alluviation in British river basins reported by Macklin and Lewin (1993) places considerable emphasis on the synchroneity of these episodes across large areas of both uplands and lowlands, and the key role played by relatively short periods of abrupt climatic change characterised by major changes in flood magnitude and frequency. Macklin and Lewin argue that although prehistoric and historic forest clearance and agriculture were important for initiating soil erosion, significant redistribution of eroded sediment may have occurred only during periods of climatic change. They therefore suggest that the Holocene fluvial record in the UK is primarily climatically driven, although culturally blurred. Significant time lags are implied by this explanation, with pulses of sediment delivery to streams a long time after they were first created by upland erosion. These mechanisms must also apply to particulate P.

Any attempt to reconcile the apparent discrepancies between the conclusions reached by the studies outlined above must, however, recognise that the precise response of a catchment and river to land use and climate change will depend upon its physiographic and hydrological characteristics and the history of land use change. Scale is once again likely to be important, since whereas upstream gully activity, as investigated by Sidorchuk and his co-workers in the Russian Plain, might be expected to reflect closely the pattern of land use change, downstream alluviation is more likely to reflect the influence of changes in flood magnitude and frequency conditioned by climatic shifts.

The interaction of land use change and climatic change has a further dimension. Climate change may induce land use change, by making agriculture either possible or impossible. If people change land uses approximately in phase with climatic changes, then the fluvial response will be a result of both. But if people make decisions that either see them starve to death (e.g. the Norse in Greenland in the sixteenth century, McGovern, 1994) or thrive by making no change to their land uses, then the fluvial response will be to the climatic change only. It seems likely, therefore, that climatic changes acting on societies that are economically marginal for environmental reasons will be reflected in land use changes only if decisions are taken that lead to the survival of such societies. Fluvial responses may be dominated by the climatic shift in such circumstances.

In some cases, therefore, the impacts of climatic shifts and land use change will be closely intertwined and thus difficult to disentangle. Such a situation appears to exist in the Middle Yellow River basin in China where attempts to assess the beneficial effects of soil conservation works in reducing sediment yields have found it necessary to distinguish the reduction in sediment load associated with conservation works from that associated with an essentially synchronous shift towards reduced annual precipitation and runoff. Zhao et al. (1992) report the results of a detailed analysis of flow and sediment transport records from the 4161 km^2 Sanchuanhe basin which indicate that the mean annual sediment yield in this basin decreased from 36.8 x 10^6 t, during the period 1957-1969, to 9.6 x 10^6 t in the 1980s, a reduction of 74%. Approximately 50% of this reduction was ascribed to the reduced precipitation and 50% to the soil conservation measures introduced in the catchment, of which check dams had proved the most effective.

4.5 The Significance of the Direction and Timing of Climatic Change

Because of the close interdependence between climate, land use, vegetation cover density and erosion rates, the direction and timing of climatic shifts will frequently exert an important influence upon the nature of the resultant sediment response. Where a climatic shift occurs gradually, vegetation cover and land use may adjust to the changing moisture regime, and changes in response may be limited. Where the discontinuity is abrupt, however, lack of time for adjustment may result in marked changes in erosion and material transport. For example, marked increases in erosion and material transport could be expected to occur within a semi-arid area if a rapid shift to wetter conditions occurred. Under semi-arid conditions vegetation cover may be limited and a rapid increase in rainfall amount or erosivity without a compensating increase in vegetation protection would result in an initial increase in erosion. As the vegetation cover density subsequently increased in response to the increased moisture availability, erosion rates would decline towards a new baseline, which may be lower than that associated with the preceding drier conditions. Where the shift is in the opposite direction, that is from wet to drier conditions, an abrupt discontinuity could result in only a limited impact on erosion rates in the initial period before the land cover adjusted to the drier conditions.

Roberts and Barker (1993) have reported an example from East Africa which usefully illustrates the above interrelationships. In this region a significant and abrupt meteorological shift occurred during the early 1960s (Lamb, 1966), with a sharp rise in precipitation between 1959 and 1961 following a decade of rela-

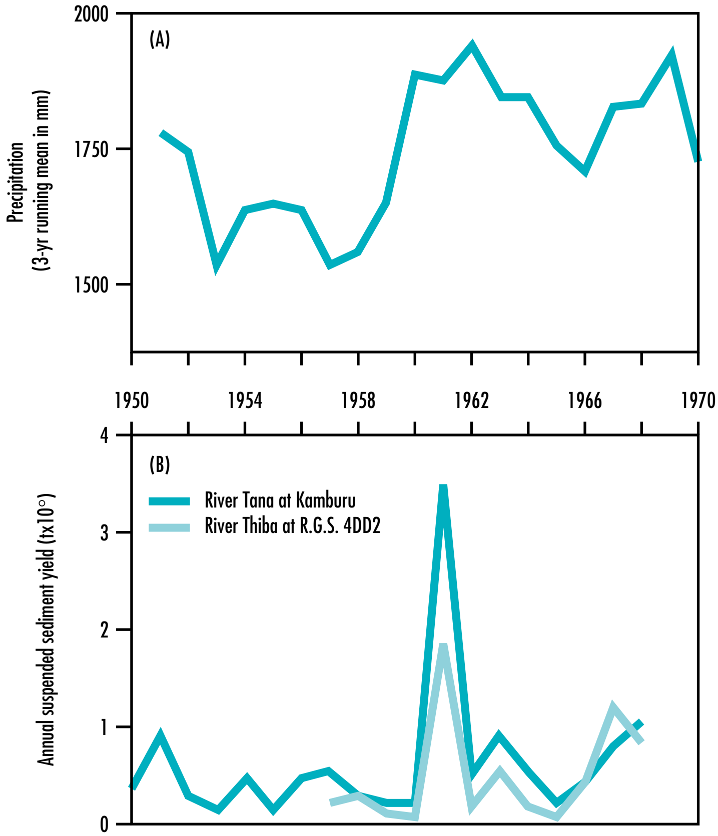

Figure 8.
Changes in precipitation over Lake Victoria (A) during the period 1950 -1970 and the variability of sediment transport by two Kenyan rivers (B) during the same period. Based on Roberts and Barker (1993).

tively low rainfall (*Figure 8a*). This period of rapid change in precipitation receipt was associated with a short period of markedly increased sediment loads in two Kenyan rivers (*Figure 8b*) for which sediment yield data are available (cf. Walling, 1984). To reconstruct such patterns over long periods, and in areas where instrumental records are lacking, will require at least annual resolution in proxy records such as sediments and tree rings.

5. SUMMARY OF THE WORKING GROUPS' DISCUSSIONS

Five key scientific questions were identified at the planning meeting, each relating to fluvial system responses to climate and land use change. The immediate spatial context for these questions is the catchment, which contains all of the elements of the fluvial system. The larger spatial context depends on a regionalisation of the Earth, a topic to be returned to below. The temporal context of these questions is the agricultural period, identified not to exclude other land uses but rather to concentrate on the time when human impacts on the Earth have been greatest. In more detail, the temporal context contains trajectories of societal change that drive land use changes. These trajectories also have a spatial expression that can be combined with the regionalisation to be discussed later.

The scientific questions can be answered using a variety of techniques and sources of data. These include instrumental records (that in most countries are only a few decades long), documentary records, and stratigraphic sequences. That most of the questions cannot be answered using instrumental and documentary records alone should be obvious, recalling the discussion in section 4.1 on the benefits of a long term perspective. Not only is it impossible to answer these questions without long highly resolved stratigraphic records, but these questions are posed in a way that exploits the availability of such records.

The stratigraphic record of fluvial deposits provides an important archive of information that can provide insights into the linkages, pathways and time scales that characterise the movement and storage of sediment P, and C through the drainage hierarchy in response to past environmental changes involving various adjustments in land cover.

Beyond the general principal that land use normally enhances the sensitivity of fluvial responses to climatic events, a number of major process response issues are poorly understood at the present time. The fluvial sediment archive is a potential source of information that can be used to help identify key environmental factors, thresholds, and temporal and spatial variations of sensitivities of material fluxes to environmental change. The key scientific questions follow:

1) What is the sensitivity to climatic change of the spatial distribution of sediment, P and C fluxes in different climate/vegetation regions?

The various climate/vegetation zones of the earth's surface are associated with seasonally or annually dominant air masses, and large scale atmospheric circulation regimes that together influence the types as well as magnitudes and recurrence frequencies of runoff-producing hydrologic events. The type of land cover, whether-natural or human-controlled, is an important filter that affects the range of runoff and sediment, P, and C responses that occur with any given runoff producing climatic event. The long-term stratigraphic record of fluvial sediments provides a basis for documenting the sensitivity of fluvial sediment, P, and C to global scale climate changes as they influenced various natural regions operating under differing types of agriculture and land disturbance (e.g. catchments of comparable scales, and relief, should be compared for fluvial sediment, P, and C sensitivity).

2) How do sediment, P, and C flux sensitivities to land use under climatic shifts reflect stages of land use history?

Here it is recognised that the relative sensitivity of sediment, P, and C responses must necessarily integrate preceding environmental conditions, as those conditions determine the availability of sediment, P, and C to be eroded. For example, sediment, P and C responses to initial land clearance or urbanisation will normally differ from responses that might occur after subsequent episodes of land use change and successions. Magnitudes of deposition documented for climatic events or climatic episodes provides a basis for quantifying flux sensitivity under various stages and episodes of land use history.

3) How are fluvial system response sensitivities under various land uses influenced by the direction of climatic change?

The ability of a given climatic change to influence material fluxes in the fluvial system also is influenced by the sum of environmental conditions prior to the shift toward, or to, a new climatic regime. For example, if a landscape has been under the dominance of a relatively dry climate episode, which may have stressed the protective land cover, then a relatively sudden shift to wetter climatic conditions is likely to yield much greater impacts on the fluvial system than if the climatic shift were in the opposite direction. Integration of the palaeoclimatic record with land use and fluvial stratigraphic records can provide a reference base to estimate the relative sensitivities of the fluvial material budget to different directional changes in climate under various types of land cover.

4) What are the thresholds and response and recovery of fluvial systems for different combinations of land use and climatic change?

The coupling of palaeoclimatic and historical land use data within the framework of detailed analyses of fluvial strata can provide crucial information useful for identifying threshold limits of climate stress for a given land use/environment involving fluvial system destabilisation and massive material fluxes out of the system. Careful dating by archaeological, geochemical, radiometric, dendrochronological and other techniques at locations in the drainage hierarchy can be especially instructive about the spatial differences of initial response in the drainage system as well as the place to place differences in the length of time necessary to recover the fluvial system to a new quasi-equilibrium state. We presently know little about how response and recovery times vary within drainage systems under particular types of climate changes.

5) How do engineering and other human-related modifications, including dams and reservoirs, levees, channel morphology alteration, and wetland drainage enhance or suppress climatic impacts on sediment, P, and C fluxes in various climate/vegetation regions?

Dams and reservoirs are (temporary) material sinks, interrupting the downstream transport of sediment and related nutrient loads. Dams and reservoirs tend to greatly reduce the magnitude of flood peak discharges downstream of their location. Channel erosion is common downstream of dams where relatively sediment free water is introduced into the channel reach, whereas much further downstream, flood plain systems may tend to store material on channel margins as erosive high stage flows are eliminated or become relatively infrequent. Changes in the morphology of the channel cross section geometry and expansion of the drainage network through, for example, wetland drainage tends to increase the magnitude and recurrence frequencies of high stage flows as well as the capacity of the channel to transport water, sediment, P and C. Changes in carrying capacity increase the ability of fluvial systems to transport material downstream. Channelisation and wetland drainage have been shown also to be associated with massive channel bed incision and gully development in some environments where sediments are easily eroded.

Coupling of detailed stratigraphic analyses of the fluvial stratigraphic record for the period since the beginning of agriculture within various climate change/land use settings provide a framework to isolate key environmental factors that are especially likely to destabilise fluvial systems and cause massive adjustments in the flux of fluvial sediments, P and C. These key factors can also be useful for identification of stability thresholds involving the effects of climate change/land use interactions that determine both the locations of fluvial responses and the time necessary for the fluvial system to recover a new quasi-equilibrium state.

6. THE PROJECT STRATEGY

The strategy for the project consists of four components:

1) A global regionalisation that takes account of the major control and state variables relevant to the flux of sediment, P and C both within catchments and to the oceans.

2) Selection of case study catchments using the global regionalisation, taking account of the locations of appropriate research groups, and the likely availability of palaeo-records, land use histories, and climatic reconstructions.

3) Execution of the case studies using an agreed protocol. The framework for these studies is a material budget. For at least the major components of the budget (e.g. hillslopes; catchment outlets represented by deltas and/or lakes; floodplains) determine the history of material accumulation and/or loss, along with land use and climatic history.

4) A modelling framework to allow 'what if' questions to be answered about the future. The purpose of this project is to understand how fluvial systems might respond to future changes of climate and land use by using the archive of past responses. While valuable analogue information will be available for foresighting by documenting past responses, models that generalise these responses will be necessary to provide decision makers with a view of future changes.

Each of these components is discussed below.

6.1 Global Regionalisation

The project depends on a global regionalisation from which case study catchments will be chosen. By this means local and regional processes and impacts will not be lost in global generalisations but such generalisations will be possible as the sum of the case studies. Both the systemic and cumulative themes of Global Change science will be thereby served.

The flux of water, sediment, P and C in pristine fluvial systems is controlled by relief, climate and lithology (Meybeck, 1994). In disturbed systems, land use must be considered. There are therefore four primary control variables and four state variables, making a regionalisation that takes explicit account of each variable impractical. A global regionalisation has therefore been adopted that relies on two axes each of which encapsulates other variables (*Figure 9*).

Kates et al. (1993) listed seven modes of regional environmental transformation (Table 1), seeing in each a trajectory over the last 300 years. Some modern modes occurred at earlier times on the trajectories of other modes, so to some extent the spatial array of the modes can be ordered in a temporal sequence. This is only partially the case, however, because there is no prior example of the scale of Pioneer settlement (7) or of the intensity of Rapid industrialisation (5).

Figure 9.
A global regionalisation based upon catchment Modes of Environmental Transformation (see Table 1) and catchment relief classes (see Table 2).

	Mode of Environmental Transformation							
		1	2	3	4	5	6	7
Relief Classes	1	Switzerland	NZ Alps	Caucasia			Himalayas	
	2		Murray-Darling		Java			Andes
	3		Great Plains (USA)	Stavrapol Highland	Indo-Gangetic Plain	Mexican Basin	N. Thailand	Kalimantan
	4	Sweden	Australian Wheat Belt	Russian Plain	N.E. China	W. Java	Nigeria	Amazonia
	5	N.E. USA	S.E. Canada	Baltic States	E. coast of South Africa	S. Thailand	Bangladesh	Sumatra

The modes in Table 1 are used as one of the axes of our global regionalisation (*Figure 9*). Because the modes include agrarian, industrial, and urban land uses, they are likely to be correlated with fluxes of sediment, C and P.

The second axis (*Figure 9*) for our global regionalisation is the classification of catchment relief used by Milliman and Syvitski (1992), namely maximum altitude above sea level (Table 2). This variable has been shown to correlate with mean annual fluxes of sediment across five orders of magnitude of catchment area. Although not demonstrated, it is also likely to correlate with fluxes of P (? And C) (see Meybeck, 1994) if adjusted for population density and perhaps fertiliser application (Caraco, 1995) and catchment vegetation (Kempe, 198-). For sediment, the correlation between flux and relief is much stronger than between climatic variables and flux. But climate is nonetheless important as it impinges on land use and modes of environmental transformation. Therefore, in using *Figure 9* as a basis for choosing case

Table 1: Modes, Characteristics and Trajectories of Regional Environmental Transformation. After Kates et al. (1993)

Modes	Characteristics and Trajectories	Examples
1. Advanced industrial	relatively high population density; move to service economy; near-zero population growth; rural areas reverting to forest; reduced pollution emissions	Sweden, Switzerland, NE USA
2. Industrial agricultural	relatively low population densities sustained by industrial agriculture; set in an advanced industrial economy; major repair of environment underway	American Great Plains, Australian Wheat Belt
3. Developing industrial (a)	late to enter an industrial phase; continuing population growth from low densities; growing commercial agriculture	Russian Plain, Caucasia
4. Developing industrial (b)	high rural population density for a long time; developing industry, often in urban areas; degradation of rural lands as a result of high population	Huang-Huai-Hai Plains, Indo-Gangetic Plain, Java
5. Rapid industrialisation	exceptionally high concentrations of population; concentration of industrial activity; major pollution problems	Basin of Mexico, Jakarta area
6. Agrarian	population and economy primarily agrarian; population growth very high; some industry; conversion of marginal lands for agriculture	Nigeria, E. African Highlands
7. Pioneer settlement	until recently, sparse populations in only slightly disturbed landscapes; dramatic recent deforestation for lumber and agriculture	Malaya-Borneo, Amazonia

study catchments, a sufficient range of examples must be identified to include the major climatic regions of the Earth. The version in Table 2 of the classification employed by Milliman and Syvitski is modified using the results of Pinet and Souriau (1988). These authors showed that, for mountains on young orogens the denudation rate is much higher than for mountains on old orogens. This difference is believed to relate to differences of slope gradients and earthquake activity. Although

Table 2: Relief Categories of Catchments, largely reflecting tectonic history.

Category	Maximum Altitudes	Secondary Factors	Examples
High Mountains	> 3000 m		Himalayas
Mountains	1000-3000 m	orogeny > 250 Ma, orogeny < 250 Ma	Murray-Darling, NZ Alps
Uplands	500-1000 m		Volga
Lowlands	100-500 m		St Lawrence
Coastal Plains	< 100 m		E Sumatra

not yet demonstrated, it is likely that the flux of particulate P is similarly influenced by the tectonic environment; and C flux may also be correlated with these variables through the Earth's biogeography.

6.2 Selection of Case Study Catchments

The global regionalisation will be used to select case study catchments. Examples of regions of the world that fall into the regionalisation are given on *Figure 9*. The organisers of the project will select a group of about 10 case study catchments, taking account of the locations of appropriate research groups, and the potential for (or availability of) palaeorecords, land use histories, and climatic reconstructions.

6.3 Case Studies

Each case study will be carried out within the framework of an agreed protocol. The emphasis of the proposed research is on catchment-based studies that produce detailed time series of erosion and deposition of sediment, P and C, ideally for a significant part of the agricultural period, and certainly for a significantly longer period than the instrumental record. The organising framework for such time series is a catchment-wide material budget for which the individual components are readily identifiable sources (e.g. hillslopes), stores (e.g. floodplains) and sinks (e.g. lakes, reservoirs, deltas). In conjunction with time series of sediment fluxes, it will be necessary to reconstruct land use/land cover and climate in the same catchments for which material budgets are constructed. These series will then be analysed for their covariance, using understanding and models of linkages between land use change and human responses to environmental changes, and between climate and hydrologic change.

Reference works are available for those not familiar with the reconstruction of climate from proxy evidence (e.g. Berglund, 1986; Bradley, 1985), and will not be described further here. The techniques available for reconstructions of past land use and land cover are more dispersed in the literature. They rely on: pollen and macro-fossil analysis from lakes, reservoirs and bogs; the use of relict cultural landscapes as analogues for previously more widespread landscapes; archaeological evidence of agricultural methods and societies, including palaeobotanical evidence; documentary evidence of past landscapes recorded in maps, census results, diaries, old aerial photographs, almanacs etc.; soil types and their truncation to reflect both the natural vegetation and agricultural impacts. The listed techniques will not be applicable in all parts of the Earth, but sufficient materials should be available except in the harshest environments. Two recent publications provide guidance (Berglund, 1991; Chambers, 1993), mostly from the northern temperate areas of western Europe and north America.

To achieve most of the aims set out in this report, chronometry is essential. This is not the place for a detailed exposition on chronometric methods, but key references are as follows: ^{14}C, Gupta and Polach (1985); Thermoluminescence and Optically Stimulated Luminescence, Aitken (1994); U series dating, Ivanovich and Harmon (1992).

In the following sections, a more detailed account will be given of the use of lakes and of sediment budgeting.

6.3.1 The Uses of Lakes and Reservoirs

Where small lake catchments lack long-term sediment stores, lakes can often serve as a record of the output from the slope system under changing conditions of land use and climate (Dearing, 1991). They can therefore provide a long-term record of changing input to those fluvial systems responding to the same sequence of climatic and anthropogenic changes. The lake sediment record will often provide good evidence for the nature of land use and land cover changes in the catchment - through it's changing pollen content and other related sedimentary records (charcoal, macrofossils, aquatic organisms and sediment chemistry). In extreme cases, the sedimentary record can be resolved on an even-by-event basis (e.g. Burrinjuck Reservoir in Australia; Wasson et al., 1987) or, in less strongly variable and event-driven regimes, on a seasonal basis where varves are present. Such records clearly hold out the promise of reconstructing historical time series with very fine temporal resolution. Multiple coring and core correlation techniques can also allow this type of record to be expressed in terms of sediment yield from the whole catchment. Even where lake sedimentation can be less directly linked to the fluvial sediment systems, the sediments can, in some cases, yield evidence for both land use and climate change as well as an improved chronological framework.

Where lakes and reservoirs have been formed within more complex valley systems, they can provide long term records of sediment delivery from these systems. Most successful studies of this kind have used reservoirs, so their time frame has been limited to the most recent past. There is scope to explore natural lake sediment records especially where they offer the possibility of reconstructing with fine temporal resolution, records of climate change, sediment delivery and land use change to which analyses of upstream fluvial sediment fluxes and budgets can be linked.

A major challenge for contributors to this research will be to identify lake/reservoir sediment sequences where:

- Chronologies can be based on the recognition of seasonality.
- The allochthonous components of the sediment record can be used to characterise and quantify sediment delivery from the catchment.
- The pollen and associated evidence can be used (alongside documentary and archaeological records) to reconstruct the pattern and sequence of land cover and land use change.
- The sediment-based reconstructions can be related in detail to the independently reconstructed record of climatic change and variability assembled from the full range of evidence available for the region. This may include instrumental, documentary, tree ring or sedimentary records

6.3.2 Constructing Fluvial Sediment Budgets

As already argued, the organising framework for documenting the history of fluvial systems should be the material budget, set out in the following equation:

$$T=SLe - SLs + Re + Ge - Gs + Ce - Cs + RIVe - RVIs$$

where T is sediment, P or C yield, and the other terms are defined below. Note that the techniques suggested are indicative, and allow estimates to be made of fluxes both at the present and in the past. The discussion applies directly to sediment and particulate P, and may apply to particulate C. There are too few studies of the erosion, transport, storage, and re-erosion of particulate C in catchments to know if this approach is appropriate.

Erosion estimation

SLe - Sheet erosion of slopes

- In many parts of the world, soil horizonation is well understood, and estimates of soil and particulate P loss can be based on profile truncation, and P fractionation between particle sizes in soils, by comparing eroded sites with non-eroded or weakly eroded sites. This method works best on gentle slopes where soil morphology is not a function of either slope or aspect. It provides an estimate of total soil loss over the period of agriculture (e.g. Larionov et al., 1973).
- This method can be combined with the fallout radionuclides ^{137}Cs and ^{210}Pb to estimate loss (or gain) of soil over periods up to 100 years in the case of ^{210}Pb, and over the last 35 or so years using ^{137}Cs.
- Where slopes are connected directly to dams or ponds, the mass of sediment trapped in the waterbody provides an estimate of the loss of soil from the slope; if corrected for the trap efficiency of the waterbody (Dearing, 1991).
- On forested slopes, soil loss can be estimated from tree age and root exposure.
- Surface elevation changes on slopes can also be estimated by using erosion pins and/or repeated levelling.
- Sheet (and rill) erosion can be estimated using the Universal Soil Loss Equation (USLE), or equivalents.

Re - Rill erosion of slopes

- This can be estimated using an erosion equation (like the USLE).
- It is also estimated by direct measurement of rill volumes in the field, or by photogrammetry.

Ge - Gully erosion

- The volume of gullies in a large area is estimated by measurement of key gullies of different dimensions and inclination. Correlations are then developed with features of the landscape that can be measured from topographic maps

and/or aerial photos so that a regional estimate of gully volumes can be made.
- The age of gullies and their volume can be estimated by dating the fans at their mouths, or from aerial photographs, old maps, diaries, etc. Dendrochronology or radiometric dating of trees growing in gullies can also provide minimum estimates of gully age. Dating of inset terraces within gullies provides part of the history of development.
- Modelling of gully evolution is becoming possible to provide an estimate of the time sequence of sediment yields from such sources.

Ce and RIVe - Creek and river erosion, respectively.

Bank erosion rate and volume can be estimated by:
- Repeated measurements of cross-sections.
- Comparisons of maps, aerial and ground photographs, satellite images, and pins.
- Dating of floodplain sediments and the positions of old channels.

Bed erosion rate and volume can be estimated by:
- The methods given above.
- Dating of terrace or floodplain steps when channel incision is evident.

Deposition estimates

SLs - Deposition on slopes
- Where soil horizonation is well understood, deposition can be identified and the mean rate since the beginning of disturbance can be estimated.
- Ideally, chronometry should be used to estimate the age of sediment accumulation.
- Repeated measurements of pins can provide modern rates.

Gs, Cs, RIVs - Deposition in gullies and balkas (partially infilled gullies), creeks, and rivers, respectively.
- Many of the methods for estimating erosion can be applied to estimate deposition (e.g. comparison of pins, cross-sections, maps, tree root burial).

- Dating of deposits is however essential to provide a longer history. The techniques rely upon ^{14}C, TL, OSL, ^{210}Pb, ^{137}Cs and possibly, ^{32}Si.
- Chronologic markers, such as artefacts, pollen, macrofossils, pollutant layers like Pb, and volcanic ashes are all valuable.
- In rare circumstances, annual laminations can be counted.
- It is important to measure deposition at a variety of places along a river, because sediment and particulate P tends to move as a wave through a catchment. This also provides an estimate of travel times of sediment.
- All of these deposition sites that are useful for the construction of material budgets, also potentially hold evidence of land use (e.g. pollen, macrofossils, artefacts), and climate, and so are complementary to data derived from lakes and reservoirs.

6.3.3 Analysis of Case Study Time Series

As noted previously, the identification of causal linkages between climate change, land use change, and fluvial responses is not necessarily straightforward. It is not sufficient, for example, to analyse the statistical co-variance of say a record of land use, climate, and sedimentation in a lake, to identify causality.

In a natural (i.e. undisturbed) catchment that is tectonically stable, climate change and autocatalytic factors within the fluvial system (e.g. gradient) will produce a fluvial response (e.g. sediment or particulate P yield changes). The superimposition onto the natural system of land use (clearing, grazing, cultivation, urbanisation) adds a new control on fluvial responses. Once land use has been superimposed, further climate changes will lead to further land use changes, but via the decision making processes of people. So the new land use change may or may not reflect the new climate.

These interactions are different at different spatial scales, so that land use effects are often dominant at small scale (i.e. in small headwater catchments) but become less important than climate-driven hydrologic changes as catchment area increases. But land use change in a small upland catchment may in turn reflect climate if farmers' decisions were a response to climate change.

Further downstream, a river can produce changes that are the result of coupled transport systems upstream, for example, hillslopes coupled to rivers (Humphrey and Heller, 1995). Linked erosional, transport, and depositional systems include feedbacks that result in internally governed oscillations. These oscillations may be reflected as, for example, quasi-periodic deposition and erosion on a floodplain, unrelated to external causes (the complex responses of Schumm, 1977). An external perturbation to such a coupled system, from climate or land use change, can produce complex responses that again cannot be readily related to a specific cause.

Despite these difficulties, careful selection of sites where the number of external changes is minimised, along with analysis that is based on as much understanding as possible rather than 'black box' correlations, will produce useful results (e.g. Berglund, 1991).

6.3.4 Modelling

Two types of models are envisaged:

- Empirical material budget models constructed as static descriptions at various times through the period of agriculture, and/or including simulations of the temporal responses of important budget components related to external driving forces.
- Semi-mechanistic routing models that simulate the movement of sediment, P and C through catchments following perturbations.

If the historical record of perturbations, and combinations of perturbations, and consequent responses, is long and complete, then empirical models are likely to provide a workable basis for evaluating future changes. However, if future perturbations are likely to lie outside the historical experience, then more mechanistic models will be essential.

Simulation of response (Trudgill, 1977) is likely to be attempted first, depending on the kind of fluvial responses that emerge from the case studies. Budget models combined with empirical response curves can be combined to produce empirical dynamic simulation models.

More mechanistic models, applied at the catchment scale, are not yet available (Nicholas et al, 1995) and are unlikely to be fully developed during the life of this project. It is possible that the data produced by this project will provide stimulus for construction and testing of such models.

7. Complementary Activities

A few key linkages to other activities are highlighted here. This is not an exhaustive account of complementary activities, and each research group that adopts this research plan is encouraged to form their own networks of complementary activities.

7.1 LOICZ (Land-Ocean Interactions in the Coastal Zones - IGBP) and PAGES

The coastal zone is an extremely varied environment threading around the continental margins for about l million kilometres and passing through all climatic zones. Coastal systems respond both to short-term and local, as well as long-term and global, changes. Freshwater, sediment, nutrient and organic inputs are among the most important land-derived forcing functions that affect coastal stability, inshore current patterns, ecological succession and community structure, and the biogeomorphology of the coastal zone. Natural and anthropogenic changes in these inputs can cause major changes in the coastal zone. LOICZ has, therefore, a strong interest in river basin research.

The four LOICZ research foci are:

1) The effects of changes in external forcing or boundary conditions on coastal fluxes.

2) Coastal biogeomorphology and sea level rise.

3) Carbon fluxes and trace gas emissions.

4) Economic and social impacts of global change in coastal systems.

In all four foci river inputs and characteristics play a prominent role, particularly in Focus 1, activity 1.1 'Catchment basin dynamics and delivery', and activity 1.5 'Reconstruction of past changes in the coastal zone'. However it should also be noted that the carbon input from rivers is an important parameter in constructing the carbon budgets of coastal seas. LOICZ has established a working group to address this issue.

It is important to note however, that raw transport data provide no indication of possible temporal trends nor do they provide information on the response of river transport to climatic changes, natural events (ENSO events, volcanic eruptions, regional droughts, fires and floods for example) and anthropogenic influences. In order to develop predictive capability concerning coastal response to such forcing functions, possible future changes in river catchments and their inputs must be determined. The sediment discharge of a river in the coastal ocean may be enhanced, for example, by clearance of a catchment or completely interrupted by dam construction. As a consequence of dam construction, deltas may be starved of sediment and erosion of previously accreting coasts downcurrent may occur. Even small dams may alter the nutrient budget of rivers. While losses of nitrogen and phosphorus from river water may occur through the settling of phytoplankton blooms in reservoirs, these are often balanced by continuous anthropogenic inputs from sewage, industrial and agricultural wastes along the river course. In contrast, silica the most important nutrient for diatom blooms, is not replaced downstream, resulting in an overall global decrease in silica inputs to coastal waters. This decline in silica inputs has already had observable effects in terms of the structure of food webs in inshore waters (Kempe 1984).

Such recent anthropogenic changes in river catchments have important consequences for coastal systems. To place such changes in a wider temporal context it is necessary to reconstruct changes which have occurred over the last few millennia, and historic records are insufficient for this purpose. Proxy data derived from sediment records, coral growth rings, tree rings and other time dependent phenomena need to be studied in order to provide this wider temporal context. Since the history of the world's coastline is determined by riverine sediment input, sea level and climatic changes, an understanding of the impacts of such forcing functions is vital to developing a modelling and predictive capability. Close co-operation between LOICZ and PAGES is therefore extremely important if LOICZ is to achieve its long-term goals.

7.2 BAHC (Biospheric Aspects of the Hydrological Cycle - IGBP) and PAGES

The IGBP-BAHC Core Project emerged from a realisation that there exist complex interactions between the land surface biota and the hydrosphere. These interactions include both vertical and horizontal interactions. By vertical components we refer to a wide spectrum of processes including, among many others, precipitation, soil recharge, and evapotranspiration. Horizontal fluxes include the generation of stormflow, baseflow, and the routing of runoff through river networks. Thus, the products of essentially distributed point processes are concentrated in discharge, and the integrating effects of the drainage basin can be exploited in any broad-scale integration of such processes.

These spatial concepts are not only applicable to water cycling but as well to the exchanges in inert and biotically-active constituents. $C0_2$ and trace gas flux in the vertical domain have therefore been addressed as key components in the BAHC Science and Operational Plans. The horizontal mobilisation, delivery, and transport of carbon and nutrients, in both dissolved and particulate fractions, was also recognised as important to both donor upland systems and recipient aquatic ecosystems, and must be considered to secure a quantitative picture of land-river interactions.

To promote this perspective in coupled Earth System studies, BAHC and PAGES co-sponsored (with assistance from LOICZ) a Workshop in Durham, New Hampshire (USA) entitled 'Modelling the Delivery of Terrestrial Materials to Freshwater and Coastal Ecosystems'. This workshop brought together top scientists in the field of landscape/fluvial system coupling to produce a science plan on the mobilisation, transport and processing of constituents through the aquatic domain to (a) identify our capacity to provide a benchmark of contemporary conditions against which future global change can be assessed; (b) assess the role of land use, of climate change and variability, and of water engineering works; and (c) develop a strategy for coupling terrestrial ecosystem and drainage basin transport models. The PAGES Fluvial Working group participated by leading relevant sessions on sediment yield and transport. A portion of the workshop will be dedicated to the identification of models and key data sets for fluvial sedimentary transport studies from local to continental scales.

Also central to a variety of BAHC themes is the notion of formally developing tools to study the disturbance of water and biogeochemical cycling across broad geographic domains. Well-documented changes in water and constituent balances are associated with land use and land cover change, and the human-induced impacts are felt at local, regional and even continental scales. In addition, it can be demonstrated that the time course and history of disturbance are of considerable importance to water and constituent fluxes, as ecosystems restructure themselves to a new dynamic equilibrium. Such disturbances are explicitly stated in a series of BAHC planning documents. A linkage to the PAGES initiative thus clearly presents itself.

A consideration of climatic variability is also a prerequisite to understanding the behaviour of landscape systems under past, current and future eras. The BAHC Focus 4: The Weather Generator Project is analysing point, radar, and remotely sensed data streams to determine the spatial and temporal statistical characteristics of weather that can later be used in the analysis of ecosystem and water cycle dynamics. The project is currently determining the data needs of the hydrological and ecological communities. We recommend that PAGES assign a liaison who can provide information on the key data requirements of the Fluvial Systems group.

BAHC Core Project activities are also directed toward furthering our understanding of how terrestrial ecosystems and river systems interact. Indeed, Activity 3.2 of the Focus 3 operational program explores issues relating to the 'Waterborne Transport of Soil, Nutrients, and Carbon'.

This activity seeks to trace the transport of materials from overland and subsurface source areas to riparian areas, to small streams and sequentially larger mainstream rivers. The key organising concept is the drainage basin and BAHC will provide inputs to proposed LOICZ activities in the coastal zone. The PAGES Fluvial Systems project will therefore benefit from a linked terrestrial/fluvial transport perspective afforded through ongoing BAHC and LOICZ activities along the full spectrum of river systems draining to the sea.

7.3 IAEA (International Atomic Energy Agency) and PAGES

The key opportunity for collaboration is in the development and use of isotopic techniques to investigate fluvial systems. The opportunities fall into the following categories:

- Further development of tracers of soil loss, currently depending on ^{137}Cs, ^{210}Pb and ^{7}Be. There is a prospect that ^{32}Si can be used in this way, and lobe also has potential.
- Use of both stable and unstable isotopes to estimate major components of the water balance that are otherwise difficult to quantify accurately, including the use of artificial tracers.
- Further development and application of radioisotopic chronometers, and the development of ^{32}Si as a reliable chronometer.
- Further development of sediment source tracers, and of phosphate tracers via oxygen isotopes.
- Development of radioisotopic methods for calculating sediment travel times.

7.4 International Human Dimensions Program (IHDP), Land-Use/Cover Change (LUCC) and PAGES

IHDP (Relating Land Use and Global Land-Cover Change, IHDP Report 5) has proposed a project structure based on the idea that Human Driving Forces lead to Environmental Impacts that in turn contribute cumulatively to Global Environmental Change, and are in turn affected by such Global Change. These Global Environmental Changes engender a Human Response that modifies the Human Driving Forces. This model is essentially the same as the Pressure-State-Response model used by the OECD for State of the Environment Reporting. LUCC is using the IHDP model, placing particular emphasis on identifying the Driving Forces and Change Types.

The Human Driving Forces fall into six categories: population, level of affluence, technology, political economy, political structure, attitudes, and values. These Forces produce Common Situations of Change (e.g. rapid growth in population and international commodity demand in frontier forest areas). These linkages are not, however, well enough understood either locally or globally, and there is not yet a globally accepted land use classification. So the models that will be used to project the patterns and dynamics of land use/cover change from driving force are not in existence. But they represent one of the major research goals of IHDP/LUCC.

Wherever possible, the PAGES project will identify from the historical and/or archaeological record analogues of the IHDP Human Driving Forces and Common Situations of Change, recognising that this will not be easy. However the Modes of Environmental Transformation (*Figure 9*) in the PAGES global regionalisation (see Section 6.1) correlate with the Common Situations of Change and, in some circumstances, the Human Driving Forces can be interpreted in the historical and/or archaeological record.

8. Implementation Plan

The key role of the fluvial system in the horizontal transport of water and biogeochemically important materials in the Earth System has been recognised by PAGES, BAHC, LOICZ and GCTE. This recognition is reflected in planning meetings held in 1994 for PAGES and 1995 for BAHC, LOICZ and PAGES. Two science plans have been produced from these meetings: P1 'Land Use and Climate Impacts on Fluvial Systems During the Period of Agriculture' (PAGES), and P2 'Modelling the Transport and Transformation of Terrestrial Materials to Freshwater and Coastal Ecosystems' (BAHC, PAGES, LOICZ).

For both planning meetings, the key scientific objectives were formulated within the following general framework:

- quantification of land form change and river-borne fluxes of water, sediment, micronutrients, C, N and P, both today and in the past;
- identification of the controls on the fluxes of these materials in the catchment cascade, both today and in the past;
- identification of the feedback on human society and biogeochemical cycles of changes in the fluxes of these materials.

The PAGES activities will contribute to defining the temporal trends of landform change and fluvial fluxes, controls, and feedback, paying particular attention to the interaction of climate change and land use change during the period of greatest human impact on the planet - the agricultural period. P1 is concerned with sediment and those biogeochemically important materials that leave a palaeo record, namely P and C.

The planning meetings of PAGES, BAHC and LOICZ have identified key scientific questions and some of the strategies and methods for answering these questions. The two projects (P1 and P2) will be managed concurrently, while maintaining the distinct character of each project.

The operating plan has the following components:

1) A global classification of fluvial catchments based on relief and stage of regional environmental transformation has been constructed. This classification will be used to both organise existing data relevant to the project and to choose representative catchments for case studies.

2) The leaders of existing relevant research groups will be invited to participate in the project. The currently targeted areas for case studies are: India, China, Russia, USA, Switzerland, Sweden, Australia, S Africa, W Africa, New Zealand, UK and or Italy. Others will be added to this list if appropriate.

3) In late 1996, a workshop is planned at which the leaders of the case studies will be asked to agree on (at least) the following matters:

- a protocol of studies so that case studies can be compared;
- additional case studies;
- a reporting method and schedule for work;
- a strategy for synthesis of the case studies;
- a modeling strategy to both generalise the results and provide a catalogue of fluvial systems responses to future land use and climate that can be used to estimate future responses.

4) A symposium will be held three years after the project starts, at which results are presented. A monograph will be produced from this symposium, along with a plain language version suitable for policy makers.

5) Each research group will be responsible for its own management and funding, but assistance may be provided by the convenors to stimulate fund raising. A newsletter will be provided every six months to keep project members in touch.

8.1 Outputs

Already completed studies from various parts of the world have demonstrated that it is feasible to carry out the individual case studies required by this project. The major new output of this project will be a globally coherent set of responses to land use and climate change that, by analogy at least, will provide a means of anticipating (if not predicting) future global changes to fluvial systems.

In addition, truly global models of the major biogeochemical cycles will be tested and their terrestrial component will be enhanced by being provided with greater temporal depth and resolution. Global biogeochemical databases will also be enhanced. A new global model based on landscape sensitivity will also be developed.

The strategy of building a global picture from regional case studies allows capacity building in various parts of the world while not losing the global perspective. It also allows what might be otherwise parochial case studies to take on a global significance. This is akin to the philosophy adopted in PANASH (PAGES 1995).

8.2 Project Management

The convenors of the PAGES planning meetings (R. Wasson, D.E. Walling, A.Yu. Sidorchuk) have agreed to act as the managers and steering committee for the project. The leaders of P2, C. Vörösmarty and J. Richey, are liaising with Wasson to ensure concurrent development of the two projects. Funds are currently being sought for a final planning workshop in late 1996, and for providing the linkage between case study groups. It is possible that a small secretariat may be established at the University of New Hampshire in conjunction with the office of the GAIM core project to manage P1 and P2. Resources for each of the case studies will be sought nationally.

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10.

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