Chapter D.8

Conclusions: Scaling Relative Responses of Terrestrial Aquatic Systems to Global Changes

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D.8.1 Terrestrial Aquatic Systems and Earth System under Pressure

From an even cursory reading of the material presented in this chapter, it should be quite apparent that terrestrial aquatic systems encompass a broad set of biogeophysical landscape features and complex processes. Terrestrial aquatic systems include water, waterborne material, sediment and biota in vegetation, the soil unsaturated zone, groundwaters, wetlands, rivers, lakes and artificial water bodies such as reservoirs, canals. The fundamental drivers of water circulation and related material fluxes (for nutrients, carbon, particulate matter, pollutants) are multiple and combine physical, chemical and biological processes including open water evaporation, precipitation, infiltration, water runoff generation, water routing, erosion, leaching, weathering, silting, evapotranspiration, biological uptake and bacterial degradation. Together with their associated coastal zones, terrestrial aquatic systems constitute what we define as continental aquatic systems (CAS) (Fig. D.94).

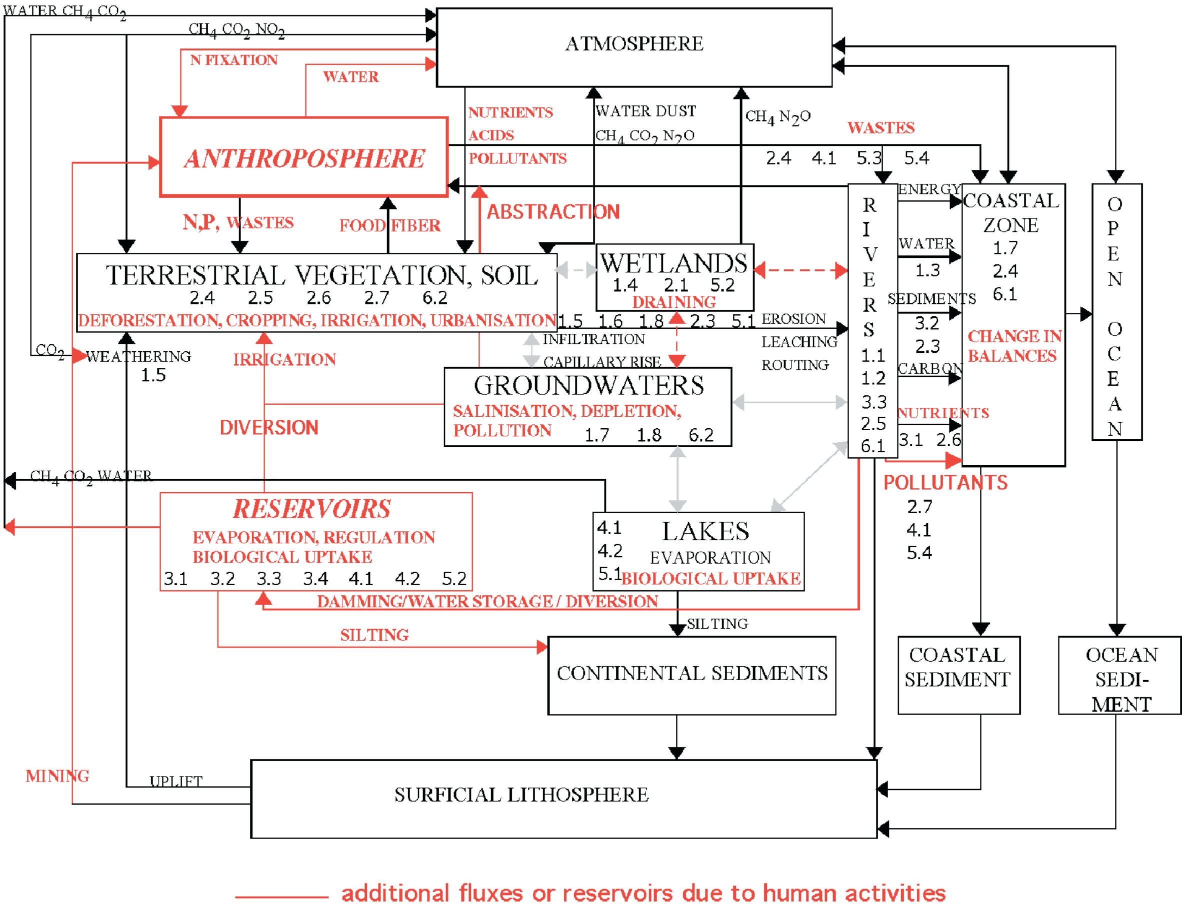


Fig. D.94. Continental aquatic systems (CAS) in the present-day Earth system (in *red*: major impacts of human activities; *grey*: water flux; *numbers* refer to Table D.30; Meybeck 2003)

Some CAS fluxes have very short cycles of only days to weeks, such as those associated with major atmospheric cycles, while others have very long cycling times that span geological time scales. The time domain of water transferred from headwaters to the receiving bodies ranges from a few days when routed through river channels (Vörösmarty et al. 2000b), to years and even a century if large lakes and/or groundwater pools are pres-ent. At the global scale, river waters continuously carry enormous fluxes of material to the oceans (40 000 $km^3\,yr^{-1}$ of water with 20×10^{15} g of suspended matter, 4×10^{15} g of dissolved salt as Ca^{2+}, SO_4^{2-}, dissolved inorganic carbon and 0.4×10^{15} g of organic carbon). They also provide the coastal zone with essential nutrients as nitrogen, phosphorus and silica as well as with $25 \pm 10 \times 10^{15}$ g of particulates that regulate coastal morphology.

Human activities have greatly modified the Earth system through climate change, land-cover and land-use changes, water engineering, and the release of wastes to aquatic systems. In the past 50 years, this anthropogenic influence has exceeded natural forcings in many parts of the world, or for some issues such as the nitrogen and phosphorus inputs to ocean, helping to define a new era, the *Anthropocene* (Crutzen and Stoermer

Table D.30. Major global pressures on Continental Aquatic Systems and the mapping of local-to-regional scale impacts to the global scale (also reported in Earth system dynamics, Fig. D.94, adapted from Meybeck 1998). *A*: human health, *B*: hydrological cycle balance, *C*: water quality, *D*: global carbon balance, *E*: fluvial morphology, *F*: aquatic biodiversity, *G*: coastal zone impacts. Only the major links between issues and impacts are listed here (POPs = Persistent Organic Pollutants)

Pressures	Local to regional changes of environmental states	Global impacts						
		A	B	C	D	E	F	G
1 Climate variability and climate change	1.1 Development of non-perennial rivers		•	•	•	•	•	•
	1.2 Segmentation of river networks					•	•	
	1.3 Changes in flow regimes		1		1	✒	✒	1
	1.3 Development of extreme flow events		•			•	•	•
	1.4 Changes in wetland distribution	•	•	•	•		•	•
	1.5 Changes in chemical weathering				•			•
	1.6 Changes in soil erosion				•	•		•
	1.7 Salt water intrusion in coastal groundwaters		•					
	1.8 Salinisation through evaporation		•	•			•	
2 Land use change	2.1 Wetland filling or draining			•	•		•	
	2.2 Changes in water passways		1	1				
	2.3 Change in sediment transport				•	•		•
	2.4 Urbanisation	•	•					•
	2.5 Alteration of first order streams					•	•	
	2.6 Nitrate and phosphate increase	•		•	•			•
	2.7 Pesticide increase	•		•				•
3 River damming and channelisation	3.1 Nutrient and carbon retention				•			•
	3.2 Retention of particulates				•	•		•
	3.3 Loss of longitudinal and lateral connectivity						•	
	3.4 Creation of new wetlands	•		•	•		•	
4 Industrialisation and mining	4.1 Increases in heavy metals and POPs	•		•				
	4.2 Acidification of surface waters			•			•	
	4.3 Salinisation	•		•			•	
	4.4 Sediment sources					•		•
5 Urban wastes	5.1 Nitrate and phosphate increase	•		•	•		•	•
	5.2 Enhancement of water-borne diseases	•						
	5.3 Organic pollution	•		•			•	
	5.4 Heavy metals and POPs increase	•		•				•
6 Irrigation/water transfer	6.1 Partial to complete decrease of river fluxes					•	•	•
	6.2 Salinisation (evaporation and percolation)		•	•				

A: Human health, *B:* hydrological cycle balance, *C:* water quality, *D:* global carbon balance, *E:* fluvial morphology, *F:* aquatic biodiversity, *G:* coastal zone impacts. Only the major links between issues and impacts are listed here (*POPs* = Persistent Organic Pollutants).

2000). Few of these contemporary material fluxes are completely new. They represent major modification of existing transfers of water and constituents. For example, mining can be considered to enhance the natural processes of erosion and weathering. Similarly, in the case of N_2 fixation from the atmosphere for nitrogen chemistry, the fixation by artificial fertiliser usage now exceeds the natural fixation. Most natural elemental cycles are accelerated, i.e. fluxes between Earth system reservoirs are increasing. Xenobiotic organic compounds (CFCs, PCBs, solvents or pesticides) that do not occur in nature are produced in increasing quantities and their fate in the environment represents a unique anthropogenic signature on the chemistry of the planet.

The Anthroposphere (Fig. D.94) is a new component of the Earth System, here defined by the land-use acceleration by humans in agriculture, urbanisation and industries by technical means, with their related energy and material transfers within and between these systems and releases of material to the environment. Many of the environmental impacts associated with the Anthroposphere can be regarded as permanent or irreversible even on human time scales of a few generations. Examples abound, including dam/reservoir construction, river diversion, storage of pollutants in major continental aquatic system subcomponents, and inland and coastal water eutrophication. Many of the changes in water and dissolved matter fluxes may affect inland aquatic systems virtually immediately, with consequent impacts on the coastal zone delayed to varying degrees, up to several years for large basins. In contrast, coastal zone changes with respect to riverborne particulate fluxes can take decades or more, due to the much slower transfer of sediments through continental aquatic systems. The human impact on linkages between the continental land mass and the world's coastals zones thus depend on the specific elemental flux we are interested in, the degree of human disturbance, level of socio-economic development and environmental governance, and the geophysical time constants involved (von Bodungen and Turner 2001).

The changes we note yield other important consequences, affecting also water availability and quality, fluvial morphology, aquatic biodiversity and human health (Table D.30). We acknowledge that these are of great importance to society, but have not been covered in this synthesis (see for example, Revenga et al. 2000; Vörösmarty and Sahagian 2000; Rotmans and deVries 1997; Vellinga 1996).

D.8.2 Spatial Organisation of Terrestrial Aquatic Systems and Their Responses to Anthropogenic Change

The spatial heterogeneity of terrestrial aquatic systems is always high, and any aquatic system can be regarded as "complex and very heterogeneous". Of course, the perceived degree of heterogeneity will depend on the scale of interest (Fig. D.95). Thus, what a small catchment process hydrologist might consider to be an overly simplistic representation of processes in a land surface hydrology model embedded within a global circulation model, could be entirely appropriate for the task at hand.

At the plot scale (10^1–10^4 m), the distribution of root systems and soil water show a marked vertical heterogeneity (see Chapt. D.2). At such a scale, the lateral transfers of water and constituents are difficult to study except by using lysimeters or erosion plots. Here, human perturbation can arise from several sources such as direct land cover change or diffuse atmospheric pollution (Fig. D.95) or the response of vegetation to atmospheric CO_2 increase.

At the small catchment scale (10^{-1} to 10^3 km^2) vertical heterogeneities still exist, in particular associated with groundwater (A) (Fig. D.95), but important lateral transfers of water, particulate and dissolved materal are also observed, both episodically or on a permanent basis. Vertical heterogeneities continue to be associated with the complex mosaic of land cover and its sensitivity to climate and CO_2 change (B), land use and management (C), use of agrochemicals (D), fine topography (E) and its related microclimate. Upstream-downstream flow structure is organised through a "waterscape" (F) that includes rills, gullies, brooks, small streams, and local wetlands, as well as artificial waterbodies, drainage works, ditches, rice paddies, ponds or farm reservoirs. Biogeochemical recycling of nutrients in wetlands (G) or within the riparian corridor (H) mow must be considered for understanding water and constituent fluxes at this scale.

At the larger river basin scale (10^2 to 10^5 km^2) heterogeneities arise both laterally and longitudinally. A first set of natural heterogeneities is apparent when comparing different subbasins in terms of river flow regimes, sediment supply and transfer, water chemistry linked to climate, relief, lithology and others (I, J, K). A second set of natural variations includes the longitudinal, downstream increase in stream order, decrease in water velocities, and of the increased deposition of sedimentary materials. A final set of heterogeneities concerns the position and dynamics of the individual elements that constitute the natural and anthropogenic waterscape. These specifically include the floodplain (L), regional aquifers, swamps, individual lakes or lake provinces (M), reservoirs (N), surface and groundwater water use by humans (R), levees, navigation and irrigation canals (O), urbanisation, leaching of agricultural soils (P), point sources of pollution (Q), (R), damming and barrage operation (S). In the greatest basins shared by many countries the water policy and the economic development stage may add yet another type of heterogeneity. When rivers fi-

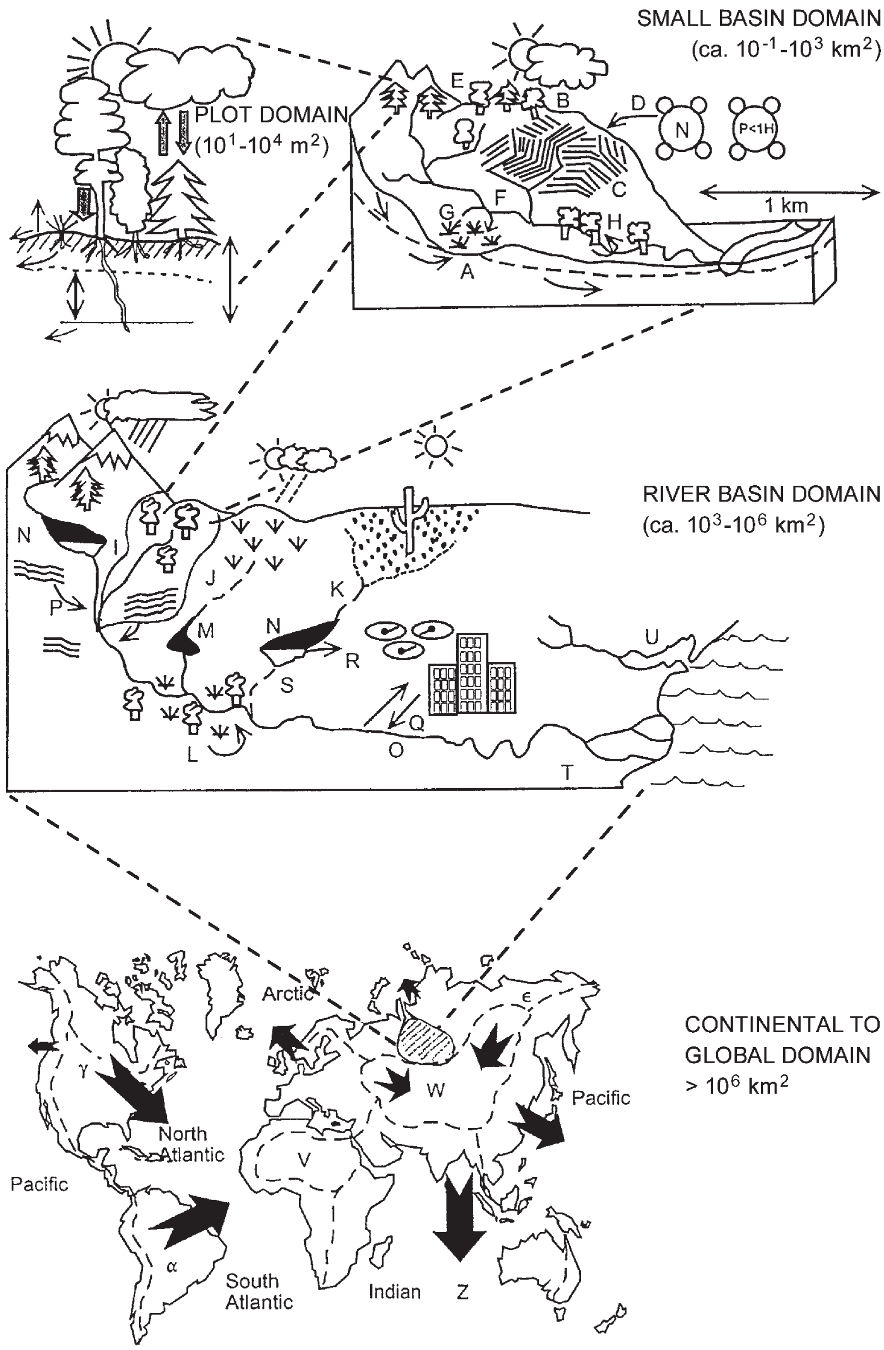


Fig. D.95.
Spatial organisation of terrestrial aquatic systems and key processes (see text for definitions of *individual letters*)

nally discharge water and materials to the ocean, their influence on the recipient coastal zone will depend on the geological, morphological, tidal, and hydrodynamical conditions at the local land/ocean interface (e.g. estuaries, deltas, lagoons) which may completely modify and/or weaken the river signal (T, U).

At the global scale (Fig. D.95) the overall heterogeneity of flux in terms of water, sediment, carbon, nutrients, pollutants can be assessed from direct field measurements. If the first 250 world exhoreic rivers were monitored they would correspond to about half of world basins area discharging to oceans (Meybeck and Ragu 1997). These measurements can be used to set up the causal factors contributing to the global pattern of water and material fluxes, such as climate, lithology, relief, land use, population density, and socio-economic activities. These relationships permit us to then extrapolate riverine fluxes from better-known to nondocumented areas of the Earth. Global maps have now been established at various resolutions from 2' to 30' (latitude × longitude). From such

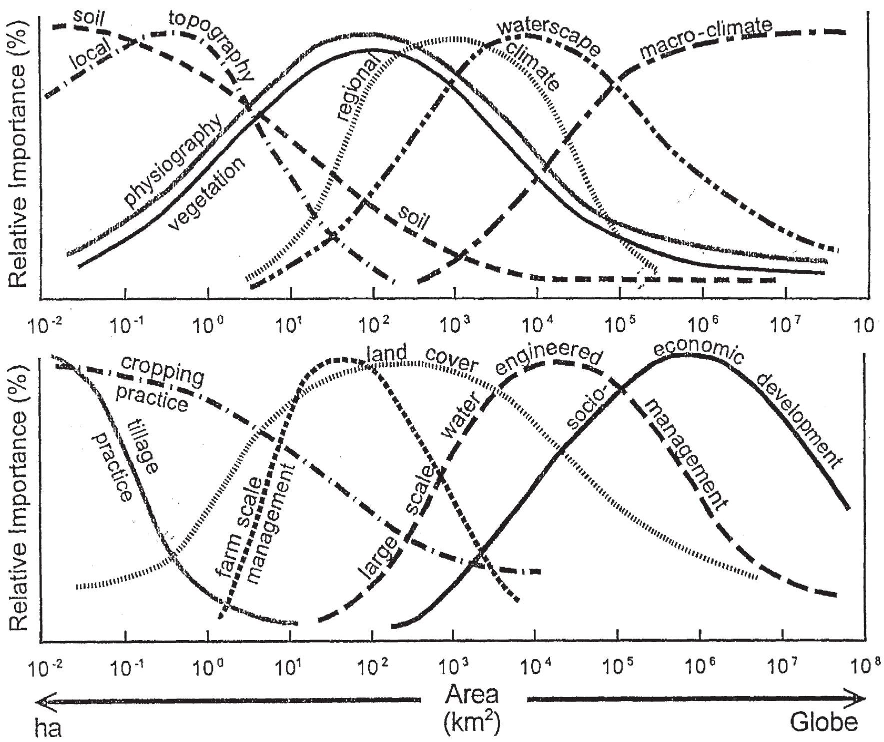


Fig. D.96.
Natural drivers (*top*) and anthropogenic pressures (*bottom*) occur across a range of spatial scales, but dominate hydrological responses over a narrower spectrum

analysis (see Chapt. D.4) it is noted that the land mass is, again, highly variable, with specific riverine fluxes (per unit land area) commonly ranging over two to three orders of magnitude for the land area bearing permanent and occasional runoff (> 3 mm yr^{-1}). Moreover, these emerging models allow us to separate and map three types of land-ocean connections (Fig. D.95):

- arheism (V), which corresponds to the absence of surface runoff and riverine fluxes to receiving waters as over the Sahara;
- internal river drainage or endorheism as the Volga basin and in Central Asia (W); and,
- external river drainage to oceans or exorheism as in South East Asia (Z).

These models can also identify and apportion the sources of material originating from different areas within river basins as for the Amazon (α) and the sinks of land-derived material, such as for carbon species in major lakes, floodplains, and reservoirs as in the Saint Lawrence basin (γ). Oceans and regional seas freshwater and material budgets can also be facilitated once their drainage boundaries have been carefully setup. Past river connectivity to oceans due to climate change, as for the Kerulen/Amur system (ε) or new endorheism due to water use on basins (e.g. Colorado, Nile) illustrate the rapidly progressing nature of changes in river systems and their coupling to the coastal zone at the global scale.

D.8.3 Spatial Scale of Drivers Operating on Terrestrial Aquatic Systems

Spatial scales in hydrology (e.g. plot, field, small catchment, river basin or continental scales) are not fixed in their areal definitions, but rather merge into one another and therefore overlap. From the plot and field scales to the domain of whole large river basins, numerous types of dominant drivers can be identified that are both natural and anthropogenic (Fig. D.96).

D.8.3.1 Natural Drivers

At the plot scale (*c.* 10^{-5} to 10^{-2} km^2) natural drivers are related to soil (texture, structure, chemistry) and vegetation (biomass, leaf area index, root depth). At the crop field level (*c.* 10^{-2} km^2) and at the hillslope and/or elementary catchment level (*c.* 10^{-2} to 10 km^2) topography, microclimate, landslide occurrence, water routing within the soil toposequence figure prominently. For small to medium basins (*c.* 10^1 to 10^4 km^2) meso-scale landscape physiography (relief patterns, altitudinal gradients, wetland and small lake occurrence) as well as lithology must be considered. In large basins (*c.* 10^5 to 10^7 km^2) differences in regional climatic patterns (precipitation, temperature, evaporation) and fluvial system characteristics (channel types, floodplain extent, connections with major aquifers, estuarine types) are es-

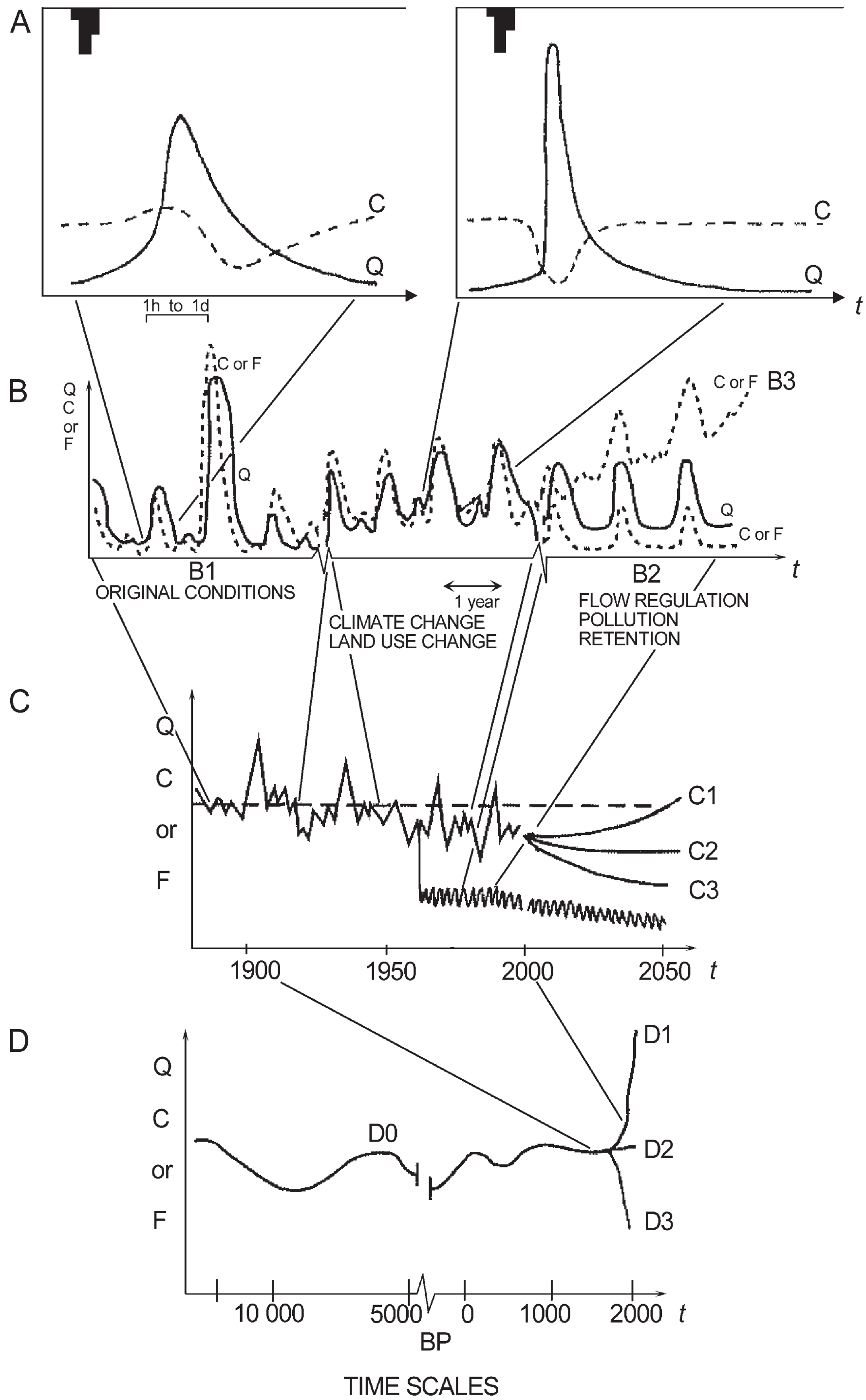


Fig. D.97.
Nested and contrasting time scales in the responses of aquatic systems to natural and anthropogenic change from the individual hydrological response of representative basins (*A*) to the long-term Holocene evolution of catchments (*D*). Future evolution corresponds to different scenarios *B1* to *B3*, *C1* to *C4*, *D1* to *D3* (*C*: water quality; *Q*: river discharge; *F*: flux)

sential determinants of river flux regime and of net inputs to the coastal zone. At the global scale, the dominant features defining the overall pattern of runoff and material fluxes are macroclimatic attributes as latitude, prevailing weather systems, continentality, endorheism, present-day tectonics, and past geological and climatic history.

D.8.3.2 Anthropogenic Drivers

Anthropogenic pressures can also be classified with respect to pertinent spatial scales. Over cultivated fields, water and material transfers are dependent on tillage and soil conservation (terracing, contouring), at the farm level on crop choice, planting dates, rotation patterns, plant densities, and fertiliser use. The presence of small dams and ponds, local irrigation, borehole abstraction, also should be taken into account. For whole basins (10^3 to 10^6 km^2), water management plays a major role on water and material fluxes through the operation of medium and large dams (storage from 10^8 to 10^9 m^3), large irrigation schemes (> 10 000 ha), overpumping of large aquifers, levees and lock operations, water diversions, urbanisation, industrialisation, and mining. Land cover change resulting from deforestation, afforestation, plantation cropping, transition from pasture to cultivation also markedly affect water and its related fluxes at local to regional scales. Its accumulated effects on land-surface hydrology through feedbacks with the climate system, as discussed earlier in this volume, may also make such changes important to the water cycle at the global scale.

D.8.3.3 Integrated Water Management and Governance

Differences in demographics and stage of economic development, as well as the history of environmental protection, water policy and governance, add another dimension of complexity to identifying key drivers. These transcend the realm of the natural system and are organised as a set of human dimension issues, particularly relevant at the country level up to the global scale. It must be noted that most such anthropogenic factors are spatially distributed according to administrative and political bound-aries, or sometimes to cultural and religious boundaries, which rarely correspond to those of the natural drivers. This discrepancy is one of the many difficulties we find at any scale for effectively applying integrated water management. In a limited number of international river basins some regional water management treaties have been set up (e.g. Colorado, Nile, Danube, Rhine, Baltic Sea basin). However, apart from drinking water standards set up by the World Health Organization, there is still no evidence for the international governance of the multiple water-related issues which have been identified here at the global scale. A harmonisation of conceptual and geographical boundaries to adequately manage both natural and human drivers are clearly needed.

D.8.4 Time Scales of Responses of Continental Aquatic Systems (CAS) to Imposed Changes

The time scales of continental aquatic systems (CAS, i.e. all terrestrial aquatic systems plus the land-ocean interface) responses to changes is tentatively illustrated on Fig. D.97. The shortest time scale considered here is associated with stream and river hydrographs, which range from a few hours for the response of a small catchment to a single rainfall event, to a few weeks or months for seasonal high-water periods in the largest river basins. Two types of changes can be identified. In the first, the hydrograph response to a unit rainfall can be modified rapidly by a land cover/land use change or by a change in the regime of rainfall intensity, or duration may change the regime due to climate variability. In both cases, the pattern of water quality variation (C) with river discharge (Q) may also be quantitatively and qualitatively changed (Fig. D.97 A).

Over longer time horizons (for example, from 50 to 150 years), when long riverine records are available, we see that the year to year variability of hydrological fluxes can sometimes be modified by climate or land-cover changes, producing the more "spiky" hydrographs as in Fig. D.97 (B1). However, the most striking changes at this time scale are those observed on regulated rivers (Fig. D.97, B2) or polluted rivers (Fig. D.97, B3). When the hydrological and constituent fluxes are modelled and validated over the period of documentary records, they can be used to explore the future evolution of aquatic systems (Fig. D.97, C, C1 to C3), provided that reliable scenarios are available for both climate change and/or socio-economic pressures and water uses.

Other models, generally based on environmental archives, can be used to reconstruct the evolution of aquatic systems during the Holocene due to climate and land use change, then extrapolated to future conditions according to given socio-economic scenarios (Fig. D.97, D, D1 to D3). For some hydrological fluxes, such as for suspended matter, the human impact from the first wave of deforestation (Fig. D.97, D1) can largely exceed the variability induced by climate change only (Fig. D.97, D0). Such events are particularly well recorded in lake sediments and will be collected at the global scale within LUCIFS programme of IGBP-PAGES (LUCIFS 2000). Recent evolution of aquatic systems shows various patterns including rapidly increasing fluxes (D1) such as for nitrates and some metals, decreasing fluxes to oceans (D3) in highly regulated river basins, or slight changes (D2) which are still difficult to differentiate from natural variability (D0). Table D.31 provides a summary of the various state changes of continental aquatic systems to natural drivers and human pressures with their related time scales.

D.8.5 Continental Aquatic Systems and Emergence of the Anthropocene

Major human pressures on continental aquatic systems have existed since the start of agriculture some 7 000 to 5 000 years ago. During this early period, impacts were

Table D.31. Major changes occurring on continental aquatic systems over different time scales (adapted from Acreman 2000 and Schulze 2001)

Time scale (years)	Drivers and pressures[a]	Changes of state of aquatic systems
10^6	Tectonic uplift	Stream incision Increased soil erosion River channel change
10^5	Glacial and inter-glacial periods (CV)	Changes in land/ocean connection
10^4	Changes in vegetation and partitioning of rainfall	Gradual evolution of river regime
		Changes in soil formation and erosion
10^3	Agricultural development (LU)	Transpiration, partitioning of water
	Urbanisation (LU)	Increased peak discharges
10^2	Industrialisation (DI)	Surface and groundwater contamination
10^1	Groundwater abstraction (DI)	Declining water table
	Fertiliser/pesticide applications (DI)	Surface and groundwater pollution
	Industrial decline, waste treatment (DI)	Cleaner rivers
	Land use/management change (LU)	Streamflow generation mechanisms Stormflows and baseflows changes
10^0	Interannual variability climate (CV, CC) (e.g. ENSO)	Droughts; flood; sincreased evaporation
	Change in crop types (LU)	Flow regime modification
	Large dam operation (DI)	Stormflow and baseflow regulation
10^{-1}	Seasonal climate variability (CV, CC)	Evapotranspiration Partitioning of water
	Tillage practices (LU)	Soil loss/sediment yield
10^{-2}	Extreme flood event (LU, CC)	Flood damage
	Small dam operation (DI)	Fewer spates; steadier flow
	Chemical spill and accident (DI)	Fish kills and damage to biota

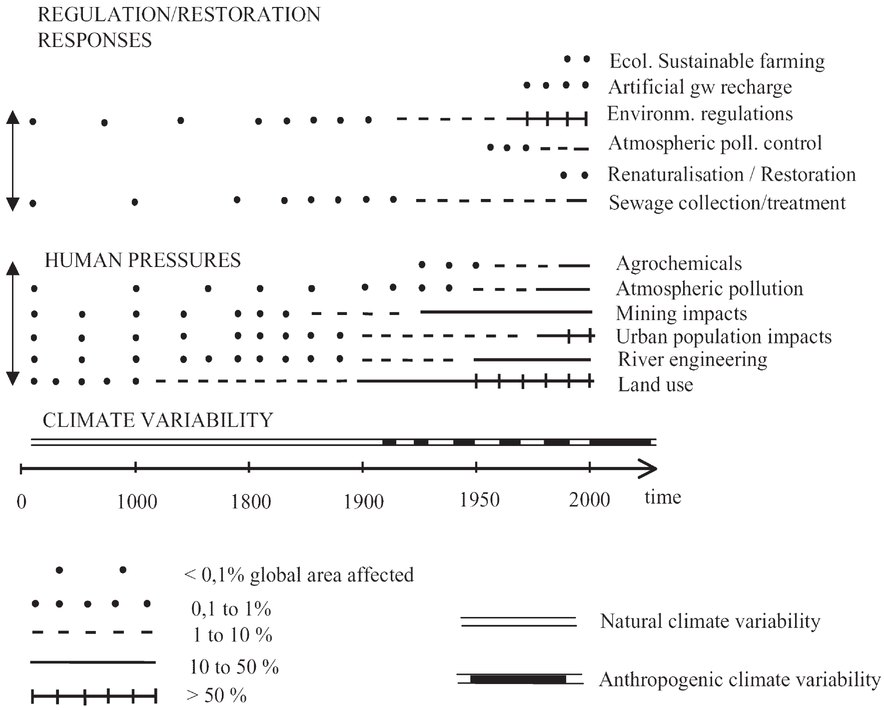
[a] *CV:* Climate variability; *CC:* climate change; *DI:* direct human impacts (water use, waste releases); *LU:* land use change.

fairly localised as land use was effectively operating on much less than 1‰ of the Earth's surface. The development of major, centralised civilisations in Egypt, Mesopotamia, Indus Valley and China, some 3 000 years ago has often been accompanied by important land and water management and river engineering schemes. Notable examples exist in the Nile, Shaft El Arab, Indus and Chiang Jiang basins, then over the whole Mediterranean basin following expansion of the Roman Empire. Evidence of several mining impacts (e.g. Rio Tinto in Spain, Leblanc et al. 2000) and of general atmospheric pollution in the mid-northern latitudes around 2 500 BP in the ancient world has also been found in coastal marshes (Alfonso et al. 2001) and in peat bogs (Shotyk et al. 1998).

The development of such mining activities first in Eurasia, then in South America and the rest of the world, has resulted in a dotted distribution of hot spots of metal contamination sites. These sites now gradually leak contaminants to the downstream catchments. Careful studies of sedimentary archives of lakes, river deltas, estuaries (Valette-Silver 1992) and flood plains allow for the detailed reconstruction of these impacts which can last for a hundred years and more (Middelkoop 2002; Grosbois et al. 2001; Macklin et al. 1997; Hudson-Edwards 1999) and constitute a major threat for the future.

The progressive development in time and space of human pressures leading to the Anthropocene is presented in Fig. D.98 as a working hypothesis to be tested through future analysis. We limited ourselves to gross categories of human pressure and postulated how an increasing fraction of the Earth's surface has been exposed to these. The progression to a global-scale impact can take two pathways. With the first, impacts are displayed locally, but due to the pandemic distribution of a particular class of change, the consequences are global in domain. A good example is the widespread conversion of land to agriculture and forestry. Global-scale impacts also arise from teleconnections operating over the planetary domain. For example, increased climate variability, hypothesised to be linked to greenhouse warming, has the potential to influence the entire planetary surface. Another example is the long-range atmospheric transport of pollutants as NO_x and SO_2, responsible for the acidification of surface waters, sometimes hundreds of kilometres away from emission sources. These statements should not imply that all impacts are now globally significant. In fact, most well-documented impacts on aquatic systems are essentially localised. And even for truly global phenomena, like greenhouse-induced climate change, some regional responses may be

Fig. D.98.
Working hypotheses on the occurrence of some major pressures on continental aquatic systems at the global scale and related environmental remediation responses (note the time acceleration; adapted from Meybeck 2003)



far more important than the overall mean change across the entire planet.

Since the majority of human-induced sources of pressure on continental aquatic systems – such as population density, deforestation, urbanisation, use of agrochemicals, dam construction – have had an exponential rate of increase over the last two hundred years, the spatial distribution of these combined forces has now moved to the planetary scale. The continuing, fast rate of change thus necessitates an appropriate time scale adjustment on Fig. D.98. Only few indicators of pressures have been stabilised in recent decades (e.g. global mine production) but in most cases their impacts (e.g. of mines tailing) are still developing. Such delayed responses, termed environmental or ecological "time bombs", are still not addressed at the global scale.

Knowledge of the exact timing and extent of continental aquatic systems' pressures now requires in-depth analysis of human development at the global scale, including demographics and level of industrial development, over a long time horizon. Here, case studies can provide an important and practical mechanism for validating these hypotheses. For example, we have implicitly postulated that the impacts of mines on the aquatic environment or on human health, at the global scale, may have preceded those associated with urbanisation. Only through carefully assembled documentary evidence can a sufficiently detailed environmental history can be developed. A multidisciplinary approach is critical. For instance, the use of medical records to assess the history of lead poisoning versus cholera will yield important insights into the pressures at work in particular basins.

D.8.6 Continental Aquatic Systems Shared by Social Systems and the Biogeophysical Earth System: An Extension of the DPSIR Approach

The Driver-Pressure-State-Impact-Response or DPSIR concept (Sect. D.3.1) originally developed by OECD is now used in environmental resource studies linking the natural and social sciences (Turner et al. 1997; Salomons et al. 1999; von Bodungen and Turner 2001). While there are easily identified biogeophysical attributes of CAS (e.g. surface and groundwater reservoirs, sediment retention, nutrient cycling) these also can be viewed from a human perspective as a set of resources to provide drinking water, water for food and fibre, fish and game habitat, flood control, transportation, and instream processing of wastes. From this perspective CAS provide a set of free goods and services of great value to society.

The provision of CAS resources and services, their use and abuse leads to a complex interplay between physical and socio-economic phenomena as presented on Fig. D.94. The use of CAS for human benefit is driven by a broad array of socioeconomic drivers, including demographic evolution, economic development, security needs, education level, conflict, social and economic crises. These operate in tandem with pressures on inland water resources such as damming, waste release, water diversion, abstraction and regulation, agrochemicals use. These pressures collectively modify CAS state – a process generally regarded as environmental impact within the Earth sciences community. As described throughout this section, the resulting changes invoke a multitude of biogeo-

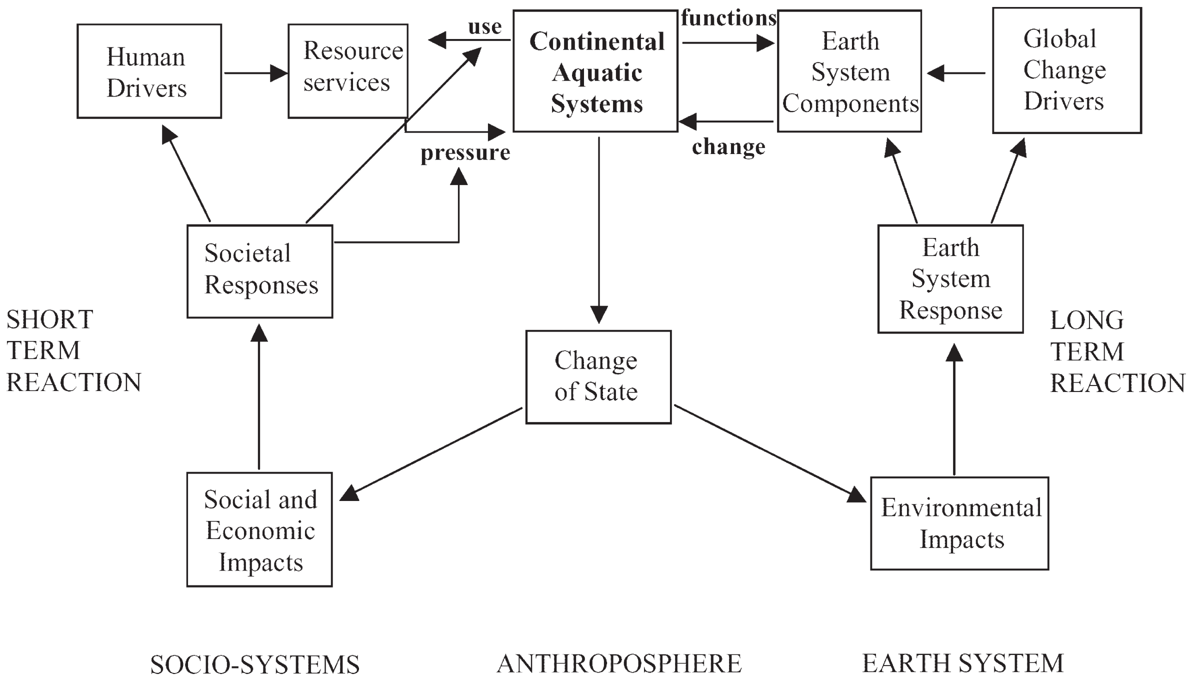


Fig. D.99. Continental aquatic systems shared by socio-economic and biogeophysical Earth systems during the Anthropocene (Meybeck 2003)

physical impacts. However, there are social and economic impacts as well, manifested as famine, insecurity, poverty, morbidity. These have been termed societal passive responses which, in most cases, lead to still further active responses aimed at decreasing these impacts through mitigation, rehabilitation, change of behaviour, conflict resolution, integrated management and resources sharing (Falkenmark 1997). When social and economic impacts are left unresolved or mismanaged, societal response to aquatic systems degradation often include migration, nomadism and conflict (Fig. D.99). The socio-economic dimension of these issues extend to the historical, political, cultural and even religious realm.

We believe it is fair to state that contemporary anthropogenic impacts on continental aquatic systems have now reached a state at which regional and even global environmental systems are or will soon be modified in a quantitatively meaningful way. In Part D, we have documented this for water storage, sediment budgets, nutrient and other fluxes. These changes are just beginning to be taken into account in global Earth System analysis and models where they interact with other drivers such as climate change, land use/cover change. We are now at the point, both conceptually and technically, to simulate key interactions between aquatic systems and socio-economic systems (Vellinga 1996; Rotmans and de Vries 1997; Ehlers and Krafft 2001). These should now be entrained within the next generation of Earth System models (see Fig. D.94). This is an important step to take, as it will aid us in improving global-scale estimates of material budgets as well as in elucidating transboundary interactions within the coupled Earth System, for example, land use/cover change in one basin giving rise to modified rainfall patterns in an adjacent river system. Human pressures on continental aquatic systems therefore yield two types of consequences (Fig. D.99) that must be simulated: (*i*) short-term (10^{-1} to 10 yr) and localised impacts on aquatic resources, and (*ii*) long-term (10 to 10^2 yr) and sometimes broad-scale impacts on Earth system components with corresponding Earth system response and changes.

A critical gap in our knowledge of fluvial systems concerns the internal dynamics of drainage basins and their response to anthropogenic change. A modelling effort emphasising process-level understanding could make a significant scientific contribution and provide the formal mechanism by which river basin simulations could be coupled to Earth System Models. This work would rely heavily on case studies cast at the regional scale (*c.* 10^4 to 10^5 km^2). Several specific models can be envisioned, from relatively simple static material balance models to more complete biogeochemical process simulations based on various socio-economic scenarios, such as the change in diet in nitrogen flux simulation for 2050 (Kroeze et al. 2001; Seitzinger et al. 2002). The long-term goal of modelling material transformations along the entire continuum of fluvial systems from terrestrial mobilisation, through river corridor transport and transformation, with ultimate delivery to the coastal zone should now fully integrate the human dimension of Earth systems, characteristic of the new Anthropocene era.