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Global analysis of river systems: from Earth system controls to Anthropocene syndromes

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Continental aquatic systems from rivers to the coastal zone are considered within two perspectives: (i) as a major link between the atmosphere, pedosphere, biosphere and oceans within the Earth system with its Holocene dynamics, and (ii) as water and aquatic biota resources progressively used and transformed by humans. Human pressures have now reached a state where the continental aquatic systems can no longer be considered as being controlled by only Earth system processes, thus defining a new era, the Anthropocene. Riverine changes, now observed at the global scale, are described through a first set of syndromes (flood regulation, fragmentation, sediment imbalance, neo-arheism, salinization, chemical contamination, acidification, eutrophication and microbial contamination) with their related causes and symptoms. These syndromes have direct influences on water uses, either positive or negative. They also modify some Earth system key functions such as sediment, water, nutrient and carbon balances, greenhouse gas emissions and aquatic biodiversity. Evolution of river syndromes over the past 2000 years is complex: it depends upon the stages of regional human development and on natural conditions, as illustrated here for the chemical contamination syndrome. River damming, eutrophication and generalized decrease of river flow due to irrigation are some of the other global features of river changes. Future management of river systems should also consider these long-term impacts on the Earth system.

Keywords: global change syndromes; rivers; water resources; Anthropocene; chemical contamination

1. INTRODUCTION

Since the Dublin Conference on water in 1992 and the development of global change programmes in the 1980s, water-related issues have figured prominently both in international sustainable development agenda and in Earth system science programmes. It is increasingly recognized that the continental aquatic systems that were controlled by Earth system drivers, such as climate, relief, vegetation, and lithology, are now also controlled by social, societal and economic drivers, such as population growth, education, urbanization, industrialization, water engineering, and international environmental regulation (Vitousek *et al.* 1997*a*; Vörösmarty *et al.* 1997*a*; Schellnhuber & Wenzel 1998; Messerli *et al.* 2000; Ehlers & Kraft 2001; Tyson *et al.* 2002; Kabat *et al.* 2003). In many regions of the world the Earth system components are now more controlled by anthropogenic forcing than by natural drivers (Turner *et al.* 1990; Messerli *et al.* 2000), a status that characterizes the Anthropocene era (Crutzen & Stoermer 2000). It was Vernadski (1926) who coined this concept at a time when human pressures were still very limited.

A major breakthrough in our understanding of Earth system–human impact interactions has been made by Turner *et al.* (1990) in the publication '*The Earth as transformed by human action*', which included several chapters on river transfer alteration. Other relevant attempts to bridge the gap between an Earth system analysis of continental aquatic systems and a water resource management analysis have been noted in the recent valuation of environmental services given by wetlands, lakes, rivers, groundwaters (Costanza *et al.* 1997), the combination of ecosphere and anthroposphere components (Vellinga 1996) and the decomposition of human–natural system interactions using the DPSIR analysis, particularly for coastal ecosystems (Salomons *et al.* 1999; Turner *et al.* 2001; Von Bodungen & Turner 2001). Risk and vulnerability analysis is another fast-growing interdisciplinary domain linking Earth system and socio-system analysis. In the synthesis of the GACGC (2000), 16 syndromes of human pressures leading to global change have been described, many of them related to aquatic systems.

In a scenario of global warming and modified climate variability, increased population and economic growth for the next 100 years, water demand and flood control demand will rise (Falkenmark 1997, 1998). Water resources will be exposed to increasing withdrawal, storage, flow regulation and consumptive use by evaporation and transpiration, and to pollution (Falkenmark & Lundqvist 1995; Lundqvist 1998); also, in some regions, the water availability, both on an annual run-off and on a seasonal flow basis, is likely to change markedly because of global climate change (Kabat *et al.* 2003). The security of future water resources is now threatened (Falkenmark & Lundqvist 1998).

This paper is an attempt to analyse and synthesize on the global scale the role and change of continental aquatic systems, particularly the river systems within the Earth

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system in the Anthropocene era. Drivers, pressures, states and impacts of riverine changes will be briefly described in a set of river syndromes occurring on all continents. Working hypotheses on the past evolution and possible future of some syndromes are also proposed.

This paper results from the author's personal experience on global river geochemistry and its alteration (Martin & Meybeck 1979; Meybeck 1979, 1982, 2001*a*,*b*,*c*, 2002; Meybeck & Helmer 1989; Meybeck *et al.* 1989, 1991; Fraser *et al.* 1995; Peters & Meybeck 2000). It also considers other issues, such as river flow regime and sediment transport, which have been addressed by various authors. This analysis has also greatly benefited from the multidisciplinary Piren–Seine programme, which is studying multiple impacts on the Seine basin (Meybeck *et al.* 1998*a*,*b*), and from the International Geosphere Biosphere Programme–BAHC project (Vörösmarty *et al.* 1997*b*,*c*; Vörösmarty & Meybeck 1999; Vörösmarty & Sahagian 2000), which has recently been synthesized (Kabat *et al.* 2003; Meybeck *et al.* 2003*b*; Vörösmarty & Meybeck 2003) and from the EU-funded project on river catchments, EUROCAT.

2. THE POSITION OF RIVER SYSTEMS IN THE EARTH SYSTEM

The continental aquatic systems (rivers, lakes, wetlands, soilwater groundwaters, coastal marshes and estuaries) within an Earth system analysis (Garrels & Mackenzie 1971; Garrels *et al.* 1973; Berner & Berner 1987; Mackenzie & Mackenzie 1995; Kabat *et al.* 2003) are classically regarded in terms of fluxes, reservoirs and cycles of material, such as water, carbon, nutrients, ions, metals, sediments originating from and/or controlled by major processes, such as atmospheric fallout, soil leaching and erosion, chemical weathering, biological uptake, and the food-web cycle (figure 1). These processes are mostly driven by climatic, lithological and tectonic factors. Other natural riverine fluxes, such as heat and mechanical energy, and controls such as hydrothermalism and volcanism, are locally and regionally important. However, they are not considered in this simplified presentation. Riverborne material can reach the coastal zone and oceans, or be stored in continental sinks, as hill slopes, lakes and floodplains, or in endorheic basins that characterize the internal regions, not currently connected to open oceans, of 18.8 million km^2 of the continental area (Vörösmarty & Meybeck 2003).

Before any marked influence of humans on the Earth system, the continental aquatic systems have been highly dynamic over the Quaternary period (Benito *et al.* 1998; Vörösmarty & Meybeck 2003). Since the late glacial maximum (18 000 years BP), the area drained by rivers to oceans (exorheic area) and all related water and waterborne fluxes have dramatically changed (Gibbs & Kump 1994), owing to de-glaciations, sea level rise, and connection/disconnection of rivers or tributaries to exorheic regions. The legacy of past glaciations on continental aquatic system distribution and function is still important today.

During the last de-glaciation/glaciation cycles, river systems have also been exposed to hydrological variability (Gataulin *et al.* 2001), the maximum of which is reached in Central Asia for the Aral–Caspian–Black Sea system; these regional seas have been connected/disconnected several times during the past 18 000 years. Until AD 1500, the Amu–Darya was connected to the Caspian Sea through the Uzboi River, which is now completely dry, i.e. arheic (Létolle & Mainguet 1996).

The transfer of river material at the Earth's surface is a key component of the hydrological balance, the carbon balance at the decadal to centennial scale, the sediment balance, the nutrient balance (P, N, Si) and of the biodiversity of surface waters. It also controls the coastal zone functioning to a great extent (Milliman *et al.* 1987; Martin & Windom 1991; Caddy & Bakkun 1994). These global natural riverine transfers have been established over 40 years (Livingstone 1963; Garrels & Mackenzie 1971; Martin & Meybeck 1979; Meybeck 1979, 1982, 1993*a*,*b*; Milliman & Syvitski 1992; Ludwig *et al.* 1996; Ludwig & Probst 1998).

A pristine picture of river fluxes within the Earth system is now seldom found, except in some parts of Canada and Alaska, Amazonia, Congo Basin and in some Siberian rivers. Less than 17% of the present-day continental surface can be considered without direct human footprint. These regions consist of warm deserts, such as the Sahara, Central Australia desert and the Kalahari, of the boreal regions of Siberia and North America, of the cold deserts of Central Asia, of the Amazonian forest and of part of the Congo Basin forest (Sanderson *et al.* 2002). Except for nutrient budgets, many Earth scientists, particularly geochemists, are still working without the full recognition that river systems are not in a pristine state any more and are modified, used and even controlled by human activities.

3. ANALYSIS OF THE PRESENT SITUATION OF RIVER SYSTEMS

(a) *General pressures on river systems and related symptoms*

The continental aquatic systems, the rivers in particular, can also be analysed in terms of water resources that should be exploited in an optimal way and/or of potential risk that should be controlled, especially for health issues and flooding hazard (Falkenmark & Lundqvist 1997; Lundqvist & Gleick 1997). Within the present-day Anthroposphere, characterized by its main economic activities (mining, smelting and energy production, industries, agriculture and forestry and urbanization), the surface water transfers are modified and/or mastered through various actions, such as land cover change (modification of the soil–water balance, wetland draining, agricultural drains) (Becker *et al.* 2003), construction of artificial aquatic systems (reservoirs, irrigation canals, navigation channels), and development of water storage and flow regulation structures (dams and reservoirs, dykes, water transfers, ground-water pumping) (Schulze 2003; figure 1). In parallel to this general regulation of continental water transfers, a global-scale modification of their chemical and biogeochemical properties is noted (Meybeck & Helmer 1989; Holland & Peterson 1995; Mackenzie & Mackenzie 1995).

The human pressures on continental aquatic systems and the related symptoms of river changes are summarized in table 1 as: (a) land use (agriculture, forestry); (b) mining,

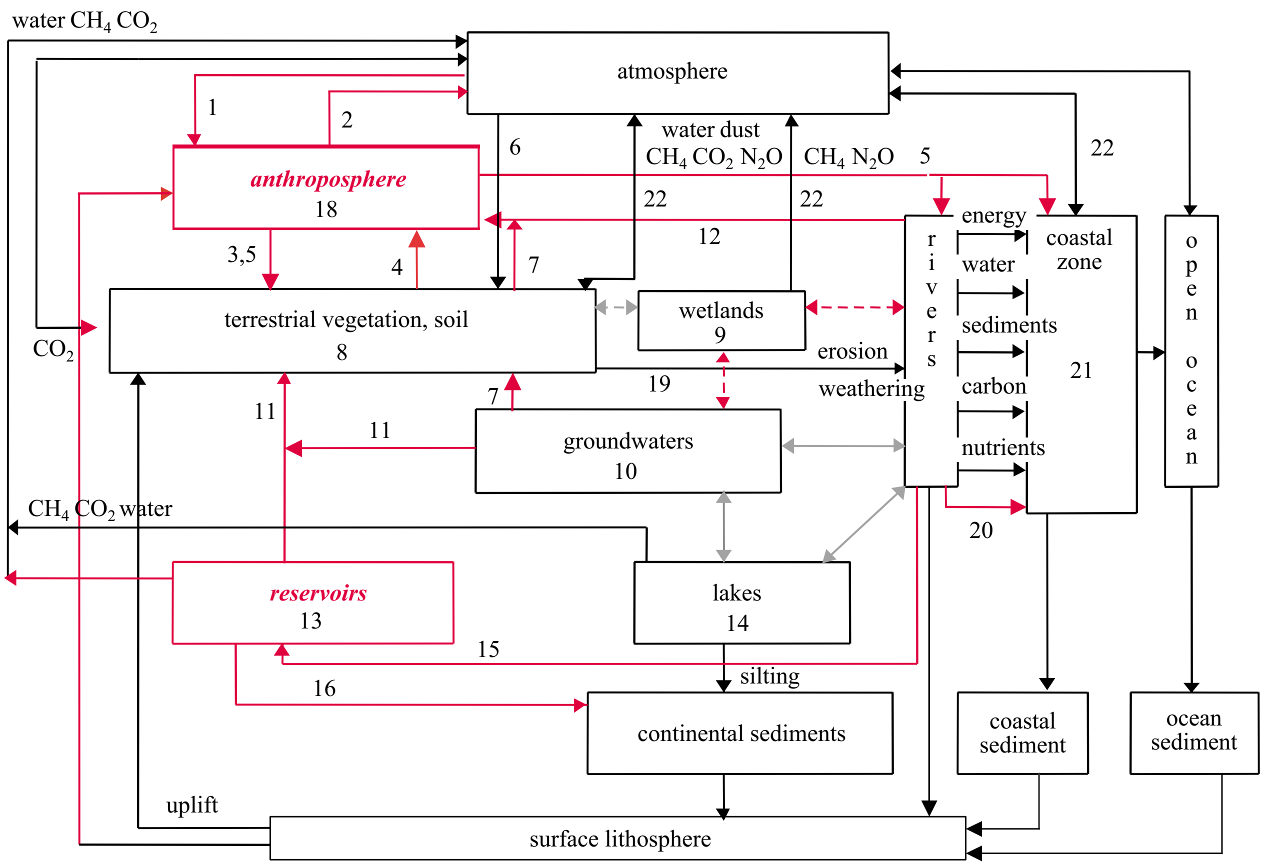

Figure 1. Continental aquatic systems in the present day Earth system. Black, natural fluxes and pathways of material; red, major impacts of human activities: 1, N fixation; 2, water consumption; 3, fertilization; 4, food and fibre consumption; 5, waste release; 6, atmospheric pollutants fallout; 7, water abstraction; 8, land use (deforestation, cropping, urbanization); 9, draining; 10, salinization, contamination, depletion; 11, irrigation; 12, diversion; 13, evaporation, regulation, eutrophication; 14, eutrophication; 15, damming, water storage, diversion; 16, silting; 17, mining; 18, industrial transformation; 19, enhanced soil erosion; 20, xenobiotic fluxes; 21, changes of inputs to coastal zone; 22, changes in greenhouse gas emissions.

smelting and energy production (except for hydropower); (c) industrial transformation; (d) urbanization; (e) construction and operation of reservoirs; (f) irrigation; and (g) other water management types (dredging, channelization, canalization, flood control by levees). Each of these activities can modify the fluxes of natural river material (table 1, fluxes 1–6 and 9) and generate fluxes of xenobiotic substances (no. 8), i.e. non-generated in natural conditions. They also modify the riverine morphology and river-bed characteristics, i.e. the aquatic habitats (no. 11), the river hydrological regime (no. 10, e.g. peak floods, positions of monthly extremes) and considerably lower the average flow of some rivers (no. 9). Water-borne diseases, such as the occurrence and levels of bacteria, parasites and viruses (no. 7)—critical for human and animal welfare—can also be generated or enhanced by human impacts. Other human pressures on aquatic systems, although not addressed here, must be mentioned: introduction or invasion of exotic aquatic species, changes in thermal regime and radionuclide contamination.

Some of these changes are now well documented at local to regional scales. The alteration of water quality is probably one of the best studied. Although complex, other changes such as river artificialization and sediment retention can be illustrated.

(b) *Water quality alterations*

Early warnings on the degradation of riverine water quality resulting from human activities have been given by individual scientists on eutrophication (Beeton 1965), sulphur contamination of rivers (Berner 1971), and general degradation of river quality (Wolman 1971).

There are only a few reviews of water quality issues at the global scale. In 1968, Richard Vollenweider produced a eutrophication assessment, probably the first report on continental aquatic system degradation made at the global scale. The first synthesis on global water quality issues was published by United Nation agencies within the GEMS-Water Programme (Meybeck *et al.* 1989). It pointed out numerous growing issues on eutrophication, salinization, acidification, contamination by metals and POPs. In 1978, the GEMS-Water Programme started to collect water quality data on more than 600 targeted worldwide stations, from major ions to POPs; this constitutes the only global-scale dataset so far (Fraser *et al.* 1995; GEMS-Water 2002; Robarts *et al.* 2002). In parallel, the SCOPE-Carbon Programme, also sponsored by UNEP, collected a wide set of case studies over a decade on some major world rivers, particularly for carbon and nutrients (Degens *et al.* 1991). Regional studies on water quality issues are now available on the Mississippi (Meade 1995), Western

Table 1. Principal symptoms of river system changes in relation to human pressures: 1–8 water quality changes.
(a, land-use change (agriculture, forestry…); b, mining and smelting; c, industrial transformation; d, urbanization; e, reservoir construction and operation; f, irrigation; g, other water management types (flood control and navigation); ×–×××, amplitude of change; +, increase; – decrease (thermal regime alteration and radionuclide pollution are omitted here).)

	water uses/human pressures						
symptoms	a	b	c	d	e	f	g
1. organic matter	++−		+	+++	+−−	−	+
2. salts	+	+++	+	+	+	+++	
3. acids							
3.1. direct inputs		++	+				
3.2. atmospheric changes		+	++	++			
4. metal							
4.1. direct inputs		++	++	+	−−−		
4.2. atmospheric inputs changes		+++	++	+			
4.3. historical		+++	+	+	−−−		
5. TSS	+++	++	+	+	−−−	−	−
6. nutrients	+++		+	++	−−	+	
7. WBD	+−			+++	+	+−	+
8. POPs							
8.1. direct inputs	++		++	++	−−		
8.2. atmospheric inputs	+		+	+			
8.3. historical			+++	++			
9. mean run-off	+−		−	+	−	−−−	
10. flow regime	×			×	×××	×	×
11. aquatic habitat changes	×	××		××	×××	×	×××

Europe (Stanners & Bourdeau 1995), the Amazon (McClain *et al.* 2001), China (Wang *et al.* 2000), USA (USGS 1985) and the former Soviet Union (Kimstach *et al.* 1998). Detailed sources of information on world rivers and average river chemistry can be found in a UNEP report (Meybeck & Ragu 1996, 1997).

Most human activities result in a modification of riverine concentrations or fluxes and many of them can be regarded as intentional in some ways: (i) one of the most common and earliest use of waters is still the dilution and downstream transfer of wastes; (ii) agrochemicals are directly applied on continental aquatic systems; and (iii) in many mining operations, deep saline groundwaters are pumped and connected to surface waters. Although riverine fluxes of nutrients and pollutants are generally increasing, they can also decrease if the anthropogenic retention (e.g. in reservoirs) and the transformation processes exceed the additional sources of material (Meybeck 2002).

Many alterations of water quality have been described, and their main causes and symptoms are summed up in table 1. Most of them have been described at the global scale (Meybeck *et al.* 1989, 1991).

Salinization results from the marked increase of Na^+, Cl^- and SO_4^{2-} due to industrial and mining wastewaters or from poor irrigation practices (Chilton 1989); urban and agricultural wastes can also result in increasing the ionic contents of rivers but they are very limited (Meybeck 1979; Tsirkunov 1998). The Central Asian rivers (irrigation (Fedorov *et al.* 1998)) and the Rhine River (mining (ICPR 2001)) are some spectacular examples of salinization causing major water use limitations.

Acidification of surface waters has been a major issue in the 1970s and 1980s. It is caused by the impact of acid rain on non-carbonated rock types as in northeastern America, Scandinavia, Central Europe (Hultman 1998; Chernogaeva *et al.* 1998), and could gradually develop in other regions downwind of industrial and urban sources (Rodhe *et al.* 1995; UNEP/RIVM *et al.* 1999).

Eutrophication, i.e. the increased primary production of lakes, reservoirs and rivers, results in an increased load of organic matter, very labile, which can modify the oxygen, nutrients and pH balances, and the aquatic food webs in the producing water bodies or in downstream portions of river systems (estuaries, coastal zones). It has developed at the global scale since the 1950s and 1960s because of increased nutrients loads (P and N) to water bodies (Vollenweider 1968; Vollenweider *et al.* 1992; Jorgensen & Richardson 1996) including that from atmospheric NO_x fallout (UNEP/RIVM *et al.* 1999).

The discharge of untreated organic wastes in aquatic systems, also commonly named as 'organic pollution', results in hypoxia and anoxia in receiving water bodies, and increased concentrations of reduced chemical species, such as NH_4^+, Fe^{2+} and Mn^{2+}. It is generally combined with high faecal contamination (Geldreich 1989) and is the most common and earliest form of water quality degradation (Meybeck *et al.* 1989; Kimstach *et al.* 1998).

Metal contamination of rivers is now well assessed, particularly for suspended particulates (Horowitz 1995; Foster & Charlesworth 1996). Pathways of contaminated particles are complex. They combine the natural pathways of soil-derived particles plus wastewater release in rivers, the recycling of treated urban sewage sludges on agricultural fields, the erosion of mine tailings, etc. (Lacerda & Salomon 1997; Hines *et al.* 2001). Atmospheric inputs, generated either on the river basin or outside, have to be considered for some highly volatile metals such as mercury. The anthropogenic impacts on river particulate quality are all the more important when the ratio of pressure/river sediment flux is high. Particulates in the Seine River (median suspended matter *ca.* 20 mg l^{-1}) are greatly impacted by domestic and industrial inputs downstream of Paris, a mega-city (10 million people): their enrichment factors, with regards to prehistoric levels measured in sediment archives, are two to five for organic C and P, and from 10 to 50 for Cd, Cu, Hg, Pb and Zn (Meybeck 1998; Horowitz *et al.* 1998). Similar enrichment factors have been reported in western European rivers such as the Meuse, Rhine (ICPR 2001) and Elbe. At the other end of the dilution scale, in the Huang He, or Yellow River (China), which has one of the highest dilution powers for particulates, with an average suspended matter concentration near 10 000 mg l^{-1}, it is difficult to identify any human impact on the metal content.

The historical contaminations (table 1, nos 4.3 and 8.3) refer to the contamination by metals and other persistant pollutants of soils (Lacerda & Salomon 1997) and industrial sites, mine tailings (Hines *et al.* 2001), abandoned industrial and urban landfills and dumps. They should be set apart for multiple reasons: (i) by definition, the related pressures do not exist any more; in many cases they have not been identified (e.g. non-registered landfills) or the responsibility cannot be identified (the so-called orphan pollutions (e.g. ancient mines)); (ii) the resulting background levels of concentrations in river systems are increased by one order of magnitude, and more, above the pre-anthropogenic values and may be stable over decades to centuries; and (iii) waste regulation and treatment are not applicable and long-term *in situ* restoration measures, when technically applicable, are extremely expensive. Soil 'chemical time bombs' (Stigliani *et al.* 1991) can be ranked in the historical contamination category. They result from the accumulation of contaminants, such as mercury (from atmospheric deposition) or cadmium (from some P-fertilizers), which can eventually be remobilized under changing conditions like soil acidification.

The term 'natural pollution', which is still often used to qualify the natural state of some aquatic systems with extreme pH, redox, organic carbon, dissolved salts (e.g. F^{-}), total suspended solids or metals levels, should be discouraged (Meybeck 1996). Land–ocean boundaries, such as estuaries and coastal lagoons, have never been regarded as naturally polluted by seawater mixing. Extreme aquatic environments, such as acidic crater lakes, brackish and saline lakes, 'black waters' (dilute waters that are very rich in organic matter), evaporated rivers, saline groundwaters and others, although generally unfit for human use, can be rich in endemic aquatic species.

In addition to the alteration of natural products found in the CAS, the Anthroposphere also generates new organic molecules that do not exist in natural conditions, termed xenobiotics, such as PCBs, DDT, solvents and PAHs: the last of these may exist in natural conditions but in trace amounts. Many of these harmful products are not easily degraded in the environment and are termed POPs. Some of these products are volatile and can be transported over long distances to pristine areas where no direct pollutant sources exist (e.g. northern Canada). The true pristine state of the CAS does not exist any more.

(c) *Artificialization of river networks*

Reservoir construction is without any doubt one of the greatest changes that has affected continental aquatic systems in the past 100 years (Dynesius & Nilsson 1994; Petts 1984; Vörösmarty *et al.* 1997*b*; Nilsson & Berggren 2000). The rate of construction of large reservoirs (with a volume of more than 0.1 km^3) in numbers and/or total volume peaked 1961 to 1970, but has now been reduced by more than 50% 1991 to 2000 (Avakyan & Iakovleva 1998). The total volume of large reservoirs is presently *ca.* 6400 km^3 for more than 2800 impoundments (Avakyan & Iakovleva 1998); i.e. the total volume of all reservoirs, including medium and small ones, is of the order of 10 000 km^3. This figure already represents 5.5% of the total volume of the world's freshwater lakes (116 000 km^3, Caspian and Aral Seas excluded) (Meybeck 1994) and the total reservoir area (0.5 Mkm^2) is *ca.* 20% of the total freshwater area. The number of registered dams exceeding 15 m in height is currently *ca.* 40 000 (Avakyan & Iakovleva 1998). Considering the fact that in the USA alone more than 80 000 reservoirs are known (R. Stallard, personal communication), the global number of reservoirs is probably several hundreds of thousands when China, Brazil, India and West Africa are included.

The artificialization of continental aquatic systems is also developing through the channelization of rivers for navigation and/or flood protection, and through the construction of irrigation canals. The total length of river waterways altered for navigation exceeded 500 000 km in 1990; the total canal length was 63 125 km in 1960 (Gleick *et al.* 2001). In most non-desert regions of the world, the density of navigated reaches is of the order of 1 km per 100 km^2. In desert regions, the density of irrigation canals may reach 50 km per 100 km^2, as in the Nile Delta (Nixon 2003).

The storage of water in major reservoirs results in a 'river ageing' that can be up to 1 year and more from some reservoir cascades in Russian and Ukrainian rivers (Dniepr, Dnestr, Don, Volga) or for one single reservoir as in Lake Nasser on the Nile River, whereas the natural water residence in river channels is only a few weeks (Vörösmarty *et al.* 1997*b*). The reservoirs also fragment the river courses, thus modifying the aquatic ecosystem. All migratory species (eel, salmon) are no longer found in such impounded basins. This ecological impact is probably the most adverse effect of river damming, particularly in the Northern Hemisphere where most river courses are now impounded (Dynesius & Nilsson 1994). Reservoir operations also markedly alter the river flow regime. This flow regulation for water storage, flood control or hydropower results in flow regime distortion, generally more regular with multiple cycles (daily, weekly, seasonal) or, on the contrary, with very stabilized flow as for the Moskova River (Kimstach *et al.* 1998). This flow regulation is also widely spread and efficient at the global scale (Vörösmarty *et al.* 1997*b*; Vörösmarty & Sahagian 2000; Vörösmarty & Meybeck 2003).

(d) *Modification and regulation of river particulate matter transfer*

In natural conditions, the riverine transfer of sediments from headwaters to the coastal zone can be described as a succession of erosion, mobilization, transfer, deposition and remobilization processes from the headwaters to the coastal zone at time-scales ranging from days (rainstorm erosion) to millennia (river-bed sediment transfer) (Trimble 1977; Meade 1982, 1988; Meade & Parker 1985; Bravard 2001). Generated sediment fluxes from unit area to the coastal zone are extremely variable in time and space and range from less than 10 t yr^{-1} to 10 000 t yr^{-1} km^{-2} for individual river basins (Milliman & Syvitski 1992; Meybeck *et al.* 2003*a*). These sediment sources, pathways, transfers and sinks are now greatly modified, although in contradictory ways.

Natural soil erosion is greatly accelerated by deforestation and most land-cover change (Walling 1999; Dearing 2000; PAGES-LUCIFS 2000). In small, steep catchments, as in Taiwan, the transfer of the total suspended solids may be accelerated by one order of magnitude as a result of the forest conversion to cropland (Kao & Liu 2002). Mining and extraction of construction material is another potential source of sediment in river basins: Hooke & Le (2000) estimate that the amount of earth intentionally moved through mining, sand extraction, canals, etc. is now averaging 6 t cap^{-1} yr^{-1} (31 t yr^{-1} for a US citizen), corresponding to 35×10^9 tons yr^{-1}, i.e. twice the present river load to oceans (Milliman & Syvitski 1992). Humans should now be considered as the major geomorphic agents. The greatest part of this enormous accumulation of particulate matter is now stored at the Earth's surface in constructions, public works, mine tailings, and another part in river basin sediments. Mine tailings are to be particularly considered when looking at metal fluxes and cycling at global scales (Nriagu & Pacyna 1988). Direct release of solid wastes into river networks, mostly from industrial and urban sources, and in some basins from mining activities, should also be considered in present sediment budgets. In most human-impacted river basins, the sediments are also contaminated (see previously).

Reservoir construction introduces, in impounded basins, an efficient cascade of sediment traps (Meade & Parker 1985), which could currently store more than 30% of river sediments at the global scale (Vörösmarty *et al.* 2003). In many impounded basins (e.g. Colorado, Rio Grande, Nile, Volga), this retention exceeds 90%. Occasional sluicing of reservoirs, as for dam inspection, may re-mobilize ancient contaminated sediments even recovered by recent layers of unpolluted material. Floodplains are also efficient traps for riverine particulates including their pollutants, nutrients and organic carbon (Stallard 1998; Smith *et al.* 2001). These multiple sinks are very efficient. This could explain why, despite enhanced erosion observed at the plot or field scales (Pimentel *et al.* 1995), particularly in mountainous regions, the sediment transport trends in world rivers at their mouths do not present a significant increase (Walling 1999; Walling & Fang 2003).

The long-term evolution of the river-bed depends directly on the river transport of the coarser sediments. These processes are complex and very slow at the human time-scale, from decades to hundreds of years (Meade 1988; Petts *et al.* 1989; Bravard 2001). The Arno river bed, in Florence, has been silted up, then scoured to a depth of several metres (2–9 m) since antiquity owing to land-use change in the catchment, reservoir construction and sand extraction (Billi & Rinaldi 1997). In the Sacramento River (California), the river bed has been elevated by several metres because of the hydraulic gold mining started in the 1850s. After the ban of this process in 1885, it took more than 30 years for this river to recover its original profile (Meade 1982).

In the Huang He basin, sediment control has been the main issue of river management for more than 2000 years. It is related to flood control in the lower basin where the natural shift of this river course extends over hundreds of kilometres. Over the past 1000 years, the sediment flux to the Huang He Delta has increased from 0.1 to more than 1.0 billion tons yr^{-1} because of forest clearing and cultivation of the Loess plateau, particularly over the past 200 years (Cheng & Zong 1998; Saito *et al.* 2001). The sediment load peaked in the 1980s and has now decreased by 20% owing to recent soil conservation measures, reservoir construction, diversion of waters for irrigation and possible climate variations (Hu *et al.* 1998; Wang *et al.* 1998). The enormous sediment load is partly deposited on the river bed in the lower reach at a rate of 1 cm yr^{-1}. As a consequence, the present river course is flowing 5–10 m above its floodplain: any major flood or an intentional dyke outbreak during conflicts may cause dramatic human losses, as happened to up to one million people in the 1930s.

The management of riverine particulate matter is a growing issue that develops in parallel with water management and soil conservation. It involves many economic drivers and their related environmental pressures, such as: (i) mountain tourism, forest management, agriculture and mining for the control of sediment sources; (ii) reservoir construction and operation, river navigation for sediment deposition and transfers; (iii) mining, industrialization, agriculture and urbanization, river transport for sediment contamination; and (iv) irrigation, recreation, fisheries, drinking water supply, coastal aquaculture and shellfish culture, as they may be regulated by sediment quality criteria.

(e) *Water diversion and irrigation losses: vanishing rivers*

In dry and semi-arid regions, river discharges to oceans or internal regions are decreasing markedly owing to the diversion and/or consumption of water, mainly for irrigation. This evolution is now found at the global scale (Vörösmarty & Sahagian 2000). In basins with high original flow, a marked water use may not induce complete river dryness, and a permanent and regulated river flow to the ocean can be kept (e.g. Ebro river). In semi-arid and arid regions, river systems fed by wetter mountainous regions (the so-called water towers of the world), which then flow across vast desert areas (i.e. allogeneous rivers, such as the Indus, Nile, Shatt el Arab, Amu Darya, Syr Darya, Colorado, Rio Grande, Orange, Murray rivers), are more sensitive to water uses. This may result in a seasonal river dryness, as has been observed for the Colorado, the Syr Daria and the Huang He rivers. The ultimate stage of this evolution is a permanent dryness and a cut-off from its natural outlet, as for the Amu Darya River (Fedorov *et al.* 1998). This can be qualified as 'neo-arheism', or new absence of flow, using the terminology of physical geographers.

Most allogeneous rivers will now face this final evolution (Colorado, Rio Grande, Nile, Indus, Shatt El Arab, Murray, Orange Rivers, Pampa Rivers in Argentina) if a minimum regulated flow is not maintained. The Colorado river is a good example: although minimum flow and maximum water salinity are ensured at the USA–Mexico border by a bilateral treaty (Schwartz *et al.* 1990), the remaining flow is nearly used up downstream for irrigation before it reaches the Colorado Delta.

In the endorheic regions, such an evolution results in a shortening of the river course because of the upstream water use for irrigation as for the Draa River (Sahara) and the Tarim River in the Takla–Makan Desert (China). These regions are also particularly sensitive to natural climate variability, and multiple examples of past historical or recent disconnections within river basins can be found (Amu Darya–Uzboi, Okawango–Zambezi, Kerulen–Amur, Turkana–Sobat–Nile, Titicaca–Desaguadero–Uyuni) for which the climate variability and human impacts will have to be disentangled (Vörösmarty & Meybeck 2003). Other expected effects of increased dryness or of excess water use are the cut-off of river courses into two parts at reaches where the annual natural run-off is already low, *ca*. 30 mm yr^{-1}, i.e. the limit of permanent flow in most river systems. Such a minimum run-off occurs in some basins as in the Niger, downstream of the delta central, and the Nile below the Bahr El Gazal swamps. The present cut-off of the Kerulen and Amur in Mongolia, still connected in the nineteenth century, is an example of this process.

4. GLOBAL RIVER SYNDROMES

(a) *Definition of syndromes*

These multiple facets of riverine changes caused by human pressures can be clustered and organized in a set of global river syndromes. The concept of global syndromes has been developed by the German Advisory Council on Global Change (GACGC 2000) and defined as 'typical patterns of problematic people–environment interactions which can be found worldwide and can be identified as regional profiles of damage to human society and ecosystems'. This concept has been extended to rivers, for which eight syndromes are developed here: flow regulation, fragmentation of river course, sediment imbalance, neo-arheism, chemical contamination, acidification, eutrophication and microbial contamination (table 2). Other syndromes, such as thermal regime alteration, radionuclide contamination, microbiological contamination and biological invasion, are likely to occur but are not developed in this paper. Syndromes will be considered in terms of damage to human society, to ecosystems and to the Earth system, i.e. biogeochemical cycles, climate, Earth's surface morphology, etc.

Each syndrome is defined by a set of symptoms and causes (table 2) and can be illustrated from well-studied river basins. The neo-arheism syndrome corresponds to the drastic reduction of river flow due to water diversion and water use, particularly for irrigation. Although strictly speaking neo-arheism means no more flow to the receiving waters, it is understood here as a flow reduction of at least 50% compared with the previous average.

(b) *Impacts of global river syndromes on the Earth system*

The modification of river systems, either natural or anthropogenic, can be analysed from both the Earth system and water resources perspectives. The Earth system responses affect: (i) the sediment balance, which controls fluvial and coastal morphology and generates alluvial aquifers and flood plain habitat; (ii) the hydrological balance, of large continental water bodies and regional seas in particular, which may also influence coastal nutrient dynamics as from upwelling, and the deep ocean water formation (Peterson *et al.* 2002); (iii) the carbon balance (Meybeck & Vörösmarty 1999) such as organic carbon transfer and burial, CO_2 uptake during silicate rock weathering, a major control of atmospheric CO_2 at the geological time-scale (Berner *et al.* 1983), and CO_2 release by wetlands and large rivers (McClain *et al.* 2001); (iv) the nutrient balance of nitrogen, phosphorus (Meybeck 1982; Galloway *et al.* 1995; Vitousek *et al.* 1997*b*; Kroeze & Seitzinger 1998; Caraco & Cole 1999; Seitzinger *et al.* 2002) and silica species, which control the level and type of aquatic primary production (e.g. diatoms versus cyanobacteria) (Rabalais & Turner 2001, 2003); (v) the emission of greenhouse gases (Vörösmarty *et al.* 1997*a*; Seitzinger & Kroeze 1998); and (vi) the aquatic biodiversity and trophic balance of continental and coastal systems. The ecological responses of the continental aquatic systems to these syndromes are not developed here, except for eutrophication, although their extension and importance is now increasingly established (Revenga *et al.* 1998, 2000; WCMC 1998; Rabalais & Turner 2001).

These Earth system responses are analysed in table 3, with a relative magnitude scale and a neutral appreciation. They generally occur at medium (10–50 years) to long-term time-scales (more than 50 years) (compared with human time-scales) after the beginning of riverine change and at local (10^2–10^4 km^2), regional (10^4–10^6 km^2) continental and global (10^6–10^8 km^2) scales. They can develop far away from their primary causes (tele-connections over 1000 km). For instance, the impacts of large dams rapidly and profoundly modify the sediment routing of fine suspended particles and of sand, but the related coastal zone erosion and shoreline regression in response to this 'sediment starving' may be maximized with a 50–100 years time-lag after the reservoir construction and last as long as the reservoir, i.e. tens to hundreds of years, as is observed today in the Nile Delta after the High Asswan Dam completion in the 1960s.

Other major impacts of riverine changes on Earth systems are related to the increase of greenhouse gas fluxes to the atmosphere (CH_4, CO_2, NO_x, water vapour). The dissolved CO_2 emitted and/or transferred by rivers to the coastal zone should be considered, as pointed out by Kempe (1984) and by McClain *et al.* (2001) on the Amazon. Wetlands including rice-paddies are well-known emitters of CH_4, and most of the anthropospheric N_2 fixed by the fertilizer industry is eventually returned to the atmosphere as NO_x through denitrification processes occurring in the continental aquatic systems, particularly in the riparian zone and in wetlands. Kroeze & Seitzinger (1998) estimate that, between 1990 and 2050, estuarine and river emissions of N_2O will increase by a factor of three to four, a figure similar to the current increase of atmospheric N_2O.

The increase of water vapour flux from the continent to the atmosphere caused by consumptive water use, especially in large-scale irrigation in arid and semi-arid

Table 2. Major syndromes of primary riverine changes at the Anthropocene[a] caused by human pressures.

syndrome	river symptoms	pressures[b]	examples
1. flow regulation	water discharge and/or water level control flood-plain area reduction, channelization geo-morphological changes	e_{10}, g_{11}	most European and US rivers, most dammed rivers (Moscova, Nile, Indus, Ebro, Murray Rivers)
2. fragmentation	succession of impoundments biotic changes (loss of migratory species and others) TSS trapping river-bed changes high Fe^{2+} and Mn^{2+} change in thermal regime	e_{11}, g_{11}	Colorado, Rio Grande, Columbia, Missouri, Volga, Dniepr, Murray, Bay James tributaries, Orange, Sao Francisco Rivers
3. sediment imbalance	changed TSS levels accelerated bed erosion/deposition river course shifting in flood plain	a_5, b_5, e_5	Huang He, Kotri (Nepal); Madagascar Rivers; most small tropical island rivers; Queensland rivers; some New Guinea Rivers
4. neo-arheism	shift from permanent flow to seasonal drought, or major reduction of annual flow marked to total reduction of material fluxes at river mouth	f_9	Colorado, Rio Grande, Nile, Indus, Huang He, Amu Darya, Syr Daria, Shattel Arab, Ebro, Orange Rivers
5. salinization	increased salt contents dominance of Na^+, Cl^-, SO_4^{2-}	f_2	Amu Darya, Syr Daria, Colorado, Murray Rivers
	decreased HCO_3^-	b_2	Rhine, Weser rivers, mining districts
6. chemical contamination	6A. asphyxiation high BOD/COD high DOC & POC high NH_4; H_2S traces low dissolved oxygen	a_1, d_1	most W. European rivers in mid-1900s, Piraricaba, India (e.g. Yamuna), populated China
	6B. inorganic contamination increased particulate metals (Cd, Cr, Cu, Hg, Ni Pb, Zn,…) increased As, CN^-	b_4, c_4	most W. European rivers (1950–1980), Kola peninsula rivers, Don River
	6C. xenobiotic occurrence agrochemicals, pesticides, industrial xenobiotics, PAHs, PCBs, solvents	a_8, c_8, d_8	western European rivers, Mississippi River; rivers impacted by mega-cities
	6D. historical pollution high metals high xenobiotics	$b_{4.3}$, $c_{4.3}$, $d_{4.3}$	Idrija R., Rio Odiel, Cœur d'Alene L., Wales, Love Canal, Niagara River
7. acidification	decrease of pH increased Al loss of biotic diversity	b_3, c_3, d_3	Scandinavia, Kola P., E. Ontario, Quebec, Pennsylvania
8. eutrophication[c]	nutrient (P, N) increase silica decrease N : P : Si imbalance high algal biomass changes in algal distribution	a_6, d_6, e_6	western European rivers (Rhine, Seine, Loire), Volga; Mississippi, Danube; North Sea, Brittany coastal zones
9. microbial contamination	high faecal coli and related pathogens	d_1, d_7	global occurrence when the ratio of population to sanitation efficiency is high (e.g. Africa, South America, South Asia, East Asia)

[a] Thermal regime alteration, radionuclide pollution, water-borne diseases such as parasites, and aquatic species introduction are not developed here.
[b] Refers to table 1.
[c] Includes dystrophy as well (green tides, harmful algal blooms).

areas, is estimated globally to be *ca*. 4000 $km^3\ yr^{-1}$ (Gleick *et al.* 2001), i.e. *ca*. 10% of natural river water flux to oceans should be considered in global climate models.

The response of river biocoenoses and of its biodiversity to changes may be rapid (i.e. the effect of damming on migratory species) or slow (e.g. species invasion through

Table 3. Principal Earth system responses and impacts on water resources resulting from riverine syndromes. (Numbers 1–9, see table 2; ×, − and + see table 1.)

	syndromes											
	1	2	3	4	5	6A	6B	6C	6D	7	8	9
impacts	Reg	Frag	Sed	Arh	Sal	Asph	Cont	Xeno	H. pol	Acid	Eutr	Mcb
Earth system responses (rivers to coastal zone) (× to ×××: magnitude of change)												
sediment balance	×	×××	×××	×××								
hydrological balance	××	×		×××								
carbon balance[f]	×	××	×	×××	×	×				×	××	
nutrient balance	×	×		×××		×					×××	
N_2O emission	×	×				××					×	
aquatic biodiversity	−−	−−−	−	−−−[a]		−−−	−−	−−	−?	−−−	×××	
impacts on water resources (– negative impacts, + positive impacts)												
water resource and storage security	+++	+++	−−	−−−[c]								
flood control	+++	++	−−−									
navigability	+++	−+	−−−	−−−[c]							−[e]	
health hazards	−+			−[b]		−−	−−	−−	−−	−−−	−−[d]	−−−
halieutic resources	−+	−+		−−−[c]	−	−−−	−−	−−	−	−−−	−−	−
water treatment	+	−	+−		−−−	−−	−−−	−−−	−−	−	−−	−−

[a] On coast.
[b] Loss of dilution power.
[c] On downstream reaches.
[d] Harmful algal blooms.
[e] Development of water hyacinths.
[f] Including CH_4, CO_2 emissions.

interconnection of basins by navigation canals). The global loss of aquatic biodiversity is certainly a major change in the Earth system, although its long-term impact has not yet been assessed.

The indirect and/or long-term impacts of riverine changes on oceans and climate are seldom taken into account in Earth system analysis, except in some global biogeochemical models considering the gradual increase of river nutrient flux since the 1800s (Ver *et al.* 1999). The inorganic N and P fluxes to oceans have already increased by at least a factor of three at the global scale (Caraco 1995; Kroeze & Seitzinger 1998; Caraco & Cole 1999; Bennett *et al.* 2001), and even more for the North Atlantic Ocean (Howarth *et al.* 1998).

The impact of human activities on nutrient budgets to the coastal zone can be complex owing to: (i) a marked increase of inorganic N and P due to agriculture and urbanization, with variations of the N : P ratio from original values; (ii) a decrease of inorganic N and P and of dissolved silica in low agriculture–low population impounded basins owing to reservoir retention, also with changes in Redfield ratios (Humborg *et al.* 1997, 2000); and (iii) a change in coastal circulation of nutrients. In the Nile Delta coastal zone, the recent anthropogenic N and P inputs to the river from Egyptian agriculture and urbanization now balance the dramatic loss of natural river nutrients by water diversion and irrigation that occurred since the construction of the High Asswan Dam (Nixon 2003). In the East China Sea, river flow reduction will affect the cross-shelf upwelling and/or the upward flow of nutrient-rich subsurface water, a major source of nutrients in some regional seas, as expected in the East China Sea after the reduction of the Yang–Tse–Kiang River flow by the operation of the Three Gorges Dam (Chen 2002). In the Louisiana coastline, the gradual change in the Si : N Redfield ratio is responsible for the severe modification of coastal zone food-webs, including impacts on regional halieutic resources (Rabalais & Turner 2001), an illustration of the unexpected impacts resulting from changes, which are now occurring at the global scale (Turner *et al.* 2003) far upstream.

(c) *Impacts of global river syndromes on water resources and their uses*

River modifications should also be analysed in terms of water and aquatic resources. The principal impacts may affect the quantity of water resources, human security from flooding, the river transportation potential, the water-related health hazards, the halieutic resources and the water quality for given uses. Other resources, such as material extracted from the river flood plain (sand, clay), wood and fibre, are not developped here. These impacts are here analysed (table 3) in terms of gains (+) and losses (−) for human development and security.

The contrast between the positive and negative impacts is striking. So far, the positive impacts essentially concern water quantity: water storage for drought protection, reduction of extreme flows and increased flow regularity have been permanent targets of civil engineers over millennia. Some water-related health hazards have also been reduced by land-use changes such as wetland reclamation and pesticide use against malaria or onchocerciasis (Holland & Peterson 1995).

By contrast, the negative impacts of river syndromes on aquatic resources mostly concern water quality (table 3), as is documented at the global scale (Meybeck *et al.* 1989, 1991) and for the former Soviet Union (Kimstach *et al.* 1998). The most common negative aspect of water quality is certainly related to the microbial contamination and to the development of pathogens in river basins (Geldreich

1989; Gleick 1993). In the least developed countries, where populations are still forced to use untreated waters for their personal use, there is a growing and alarming health issue concerning water quality. Among the many water-related diseases, the diarrhoeal diseases (3 300 000 deaths yr^{-1}), helminth infections (100 000 deaths), and schistosomiasis (20 000 deaths) are strongly related to unsanitary excreta disposal contaminating surface and groundwaters; malaria (1 500 000 deaths), dengue fever (20 000 deaths), filariasis (72 million people infected each year) and onchocerciasis (40 000 deaths) are related to water storage, water-point operation, drainage, and poor water management in large-scale projects (filariasis and onchocerciasis) (Gleick *et al.* 2001).

Cholera expanded worldwide in 1991–1992 from Latin America, which proves that countries are falling behind in providing adequate sanitation, particularly in large urban areas (Gleick *et al.* 2001). In endemic regions for cholera, seasonal and inter-annual variability is strongly dependent on river hydrology, e.g. floodplain inundation in the Amazon basin, and river pH in the Ganges and Brahmaputra basins, El Niño Southern Oscillation events (Pascual *et al.* 2002), suggesting that changes in river flow by regulation and damming, as well as climate change (Colwell 1996), may have an impact on cholera occurrence.

In the most developed countries, where the sanitation level is higher, water quality issues concern more the chemical contamination that limits some water uses or implies increasing water treatment costs (Meybeck *et al.* 1989, 1991).

Harmful algal blooms are dangerous for animal and human drinking water resources due to the release of toxins. Some of these, as *microcystis*, have been recently proved to be fatal for people undergoing haemodialysis (Puoria *et al.* 1998). Such blooms can be enhanced by eutrophication, although the nutrient enrichment effect on harmful algal blooms is species-specific (Anderson *et al.* 2002). Relationships between aquatic ecology and infectious disease are now established (Wilson 2001), opening another perspective on aquatic systems and health.

Commercial and recreational fishing is also generally affected by water quality degradation and aquatic habitat losses, although increased total fish yields may be found in impounded rivers and in eutrophied aquatic systems.

Other important negative impacts on water resources concern the sediment imbalance syndrome and its impacts on flood control or on navigation and, for the coastal zone only, the neo-arheism syndromes. The overall direct losses and gains for humans of hundreds to thousands years of water use and management are therefore very contrasted.

Such gains and losses may be difficult to appreciate, for instance in terms of halieutic resources. Fish biodiversity in the Seine River basin (65 000 km^2) is a good example (Boët *et al.* 1998). The number of indigenous fish species (i.e. pre-Roman period) is relatively moderate ($n = 24$–32), limited by the past peri-glacial history of the basin. The present-day richness is now 50–52 species, which could be considered as an 'improvement'. However, when looking into the detailed history of the fish diversity, this judgement should be balanced: the Seine River has lost six of seven migrating and very valuable species (salmon, sea trout, sturgeon, shad,…) between 1850 and 1920 because of damming and navigation locks, and has gained 19 exotic species: (i) from very early species introductions for fish farming from the Roman times to the Middle Ages (carp, tench, roach, rudd, pike); (ii) from acclimatization of exotic species common throughout the nineteenth century (pumpkinseed, cat fish, rainbow trout); and (iii) from uncontrolled invasion through canals and navigation as early as in the seventeenth century (ruffe, nase, pike, perch). In terms of the Earth system, this introduction of exotic species and the loss of migrating species brings major changes. In terms of halieutic resources, the number of species has increased; however, the mediocre water quality between Paris and the river mouth is still limiting species richness and fish production in this reach, where the less valuable and pollution-tolerant species are now dominating (Boët *et al.* 1998). This example illustrates the difficulty in establishing a reference situation for a 'good ecological state', which should be determined for all European river basins according to the recent European Union Water Framework Directive.

The present global distribution of these river syndromes and a few others will have to be established. They are closely linked to the human–environment interactions, and it is difficult to predict their future evolution without a complete understanding of these interactions as illustrated by the historical evolution of some syndromes.

5. HISTORICAL DEVELOPMENT AND POSSIBLE FUTURE OF RIVER SYNDROMES: THE CHEMICAL CONTAMINATION EXAMPLE

Most of the studies on which the river syndromes are based on were done during the 1970–2000 period. Their historical evolution in connection with human occupation and river basin development has seldom been addressed (Schwartz *et al.* 1990; Messerli *et al.* 2000). A first attempt is made here to reconstruct the evolution of some syndromes at the regional scale, followed by three possible scenarios of river evolution.

(a) *Reconstruction of past riverine evolution*

The human alteration, regulation, fragmentation and contamination of the hydrosphere have been very gradually developed over the past 4000 or 5000 years, since the beginning of agriculture, mining and construction of the first dams, irrigation canals and flood protection levees. These changes occurred mostly on major river courses, such as the Nile, Indus, Tigris/Euphrates, Huang He, where the first hydraulic civilizations were established.

Early riverine changes due to human impacts are likely to have occurred in small- to medium-sized catchments owing to land-use change some 5000 or 6000 years ago, in the Middle East. However, some regions of the world can still be considered to be without human footprint (Sanderson *et al.* 2002), except for atmospheric pollution, now reaching all remote places such as northern Canada (Macdonald 2000). In many parts of the Americas, Africa and Australasia, changes have only occurred in the past 100 years or even recent decades. The riverine changes over the past 6000 years are also due to the climate variability, and it is sometimes difficult, or even impossible, to separate land-use impacts from climate variability effects (PAGES-LUCIFS 2000), especially in some climate-sensitive basins, mostly in semi-arid regions as the Aral Sea basin (Létolle & Mainguet 1996). These past river trends can be reconstructed by a combination of approaches (Messerli *et al.* 2000; PAGES-LUCIFS 2000).

(i) Sedimentary archives (10^2–10^3 years): they can be deciphered to reconstruct the past riverine concentrations and/or fluxes on alluvium, in lakes, deltas and coastal sediments (Valette-Silver 1993; Foster & Charlesworth 1996; PAGES-LUCIFS 2000). More recent archives can be obtained from reservoirs. River-bed sediments are generally not suitable because of lack of continuous deposition.

(ii) Archaeological and historical archives give precious information on river systems and their uses and on societal responses to river basin changes (Guillerme 1983; Schwartz *et al.* 1990; PAGES-LUCIFS 2000). The longest and most promising records of human–river interactions are probably Chinese (Elvin 1993; Elvin & Liu 1998).

(iii) Direct observations: modern river water and sediment analysis dates back to the early 1800s, and the earliest regular river surveys started before 1900s, as for the Thames (Schwartz *et al.* 1990), the Rhine (ICPR 2001) and the Seine rivers (Cun *et al.* 1997). Long-term river surveys (more than 50 years) remain exceptional (Anderson *et al.* 1996) as for the Rhine, Mississippi, Saint Lawrence and many Russian rivers (Kimstach *et al.* 1998). In some basins, historical surveys can still be used to assess the long-term evolution, as those performed before World War I by the US Geological Survey on all the US territories (Clarke 1924). Aquatic biota inventories, particularly for fishes, available in western Europe over centuries, and most probably in China, can also be used to assess river system evolution.

(iv) Back-casting of river basin quality combines present-day validated biogeochemical or ecological models and historical information on human pressures, such as land use and water use. For instance, organic pollution in the late 1800s in Belgium, the nitrogen cycling in medieval rural streams impacted by Cistercian abbeys and the Seine River quality over the past 50 years have thus been reconstructed through models that have been validated for the present-day period (Billen *et al.* 2001).

(b) *Evolution of contamination in western Europe and South America*

The schematic evolution of some river quality indicators related to the chemical contamination syndrome is here proposed for western Europe and for South America (figure 2) as a working hypothesis, using an accelerated time-scale, reflecting the evolution of some human impacts, using table 1 numbering: organic and faecal contamination (nos 1 and 9), nitrate (no. 6), heavy metals (no. 4) and pesticides (no. 8). A simplified issue-severity scale in three steps is used here, where C_N is the natural or pristine concentration (or flux), C_R a first threshold above which environmental impact, or health issue, cultural or economic losses are occurring, and C_L a second threshold above which severe impacts are occurring (Meybeck 2001*b*, 2002).

In western Europe (figure 2*a*), the earliest changes in river chemistry and assumed severe impacts have been recorded for metals in mining districts (no. 4) as early as the Bronze Age (4500 yBP) period as in the Rio Odiel, Spain (Leblanc *et al.* 1999), with maximum levels of Hg, Pb and Zn equivalent to those found currently in some highly contaminated European rivers. Such mining impact is likely to have been very localized: larger basins were probably much less contaminated. Metal contamination from mining has gradually developed since Roman times (Welsh rivers and the Humber catchment, England (Macklin *et al.* 1997)), then during the Middle Ages as in central Germany (Goslar) or, in the 1700s, in Brittany. Contamination peaks have been observed in the nineteenth century as in the Rhine and Meuse flood deposits (Middlekoop 1997). Recent contamination generally peaked in most western European rivers between 1950 and 1980.

Organic and faecal contaminations (no. 1) can be multicyclic, as is well documented for the past 150 years in the lower Thames River (Schwartz *et al.* 1990). It mostly depends on the relative production, collection and treatment of urban wastes, i.e. on the ratio of collected population/sanitation, as is also well documented for the Seine Basin (Barles 2002). In many west European rivers, the maximum contamination was noted in the 1950s and 1960s when the sewage collection rate increased, yet without appropriate wastewater treatment, which was generalized in the 1970s and 1980s. This evolution is well documented through oxygen demand, ammonia and faecal coliforms, which peaked during the 1950–1970 period.

Nitrate contamination has gradually developed since World War II following the general use of fertilizers in agriculture (Cole *et al.* 1993). In western Europe, it is now approaching the severe impact level set by the World Health Organization at which the water should not be used for drinking. But the severe level for coastal phytoplankton development, set at a much lower river concentration, was already reached in the 1960s to 1970s, and excess algal developments have followed in the North Sea and in Brittany. In the Rhine River, nitrates have been slowly decreasing since 1990 (ICPR 2001); in other rivers, they are nearly stabilized (Seine) or still increasing (southern Europe).

Contamination by pesticides (no. 8) has been rapidly growing since the 1970s and, in a medium-sized basin such as the Seine's, over 100 different active molecules can be used (Chevreuil *et al.* 1998). The use of such xenobiotic substances is now more and more regulated in western Europe and North America. However, the societal response to xenobiotic use is slow: it takes about a decade for environmental chemists to analyse routinely and at moderate costs a new product, then another decade to fully assess its environmental distribution and eventual deleterious impact, particularly across the whole trophic food web from primary producers to super-predators. Therefore, bans, when they exist, generally occur two to three decades and more after the first commercial use of these products, as for DDT (banned in the 1970s), for PCBs used in industries (1980s ban) and for atrazine, a common herbicide (2000s ban). The PCB and DDT records in sedimentary archives are different from the

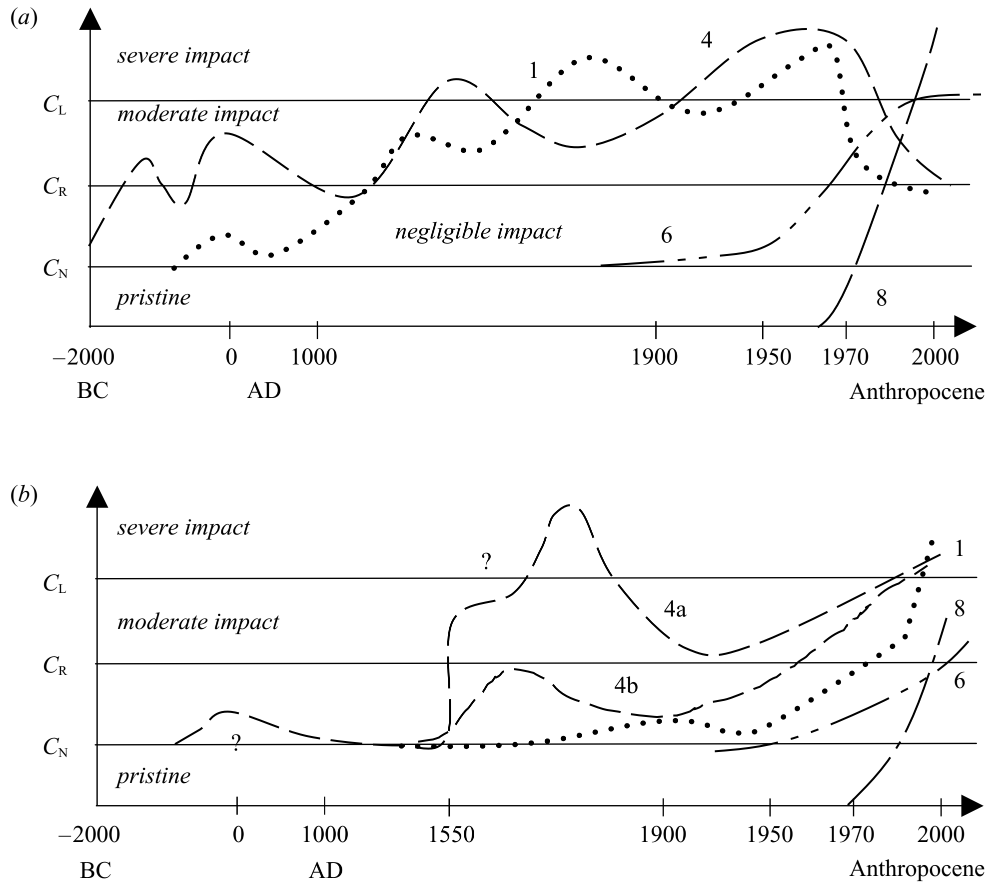

Figure 2. Working hypotheses on the evolution of some symptoms of river system changes (chemical contamination), using the same numbering as in table 1, in medium-sized (*a*) Western Europe and (*b*) South American river basins. In (*a*) 1, organic and faecal contaminations; 4, metal contamination; 6, nitrate contamination; 8, pesticides. Accelerated time-scale. C_N, C_R, C_L, natural, recommended and limit levels for related water uses. In (*b*) 4a, evolution of basins affected by mining in Colonial America; 4b, other South American rivers.

pesticide trend presented here: they peaked in the 1970s and are now markedly decreasing as also recorded in US estuaries (Valette-Silver 1993), but the persistence of POPs in the continental aquatic systems can be high. Also, their degradation products can be more toxic than the parent molecule, as for atrazine. Because of our poor knowledge of their long-term effects, xenobiotics should definitively be regulated on the basis of precaution principle (Gilbertson 2001).

In South America, the evolution of river chemistry is somewhat different (figure 2*b*). Riverine quality is not likely to have changed much before the arrival of European settlers, except for limited agricultural land-use impacts from Pre-Columbian civilizations as on river sediment fluxes. A very slight lead contamination through global atmospheric transfer during the Roman times is theoretically possible because long-range human impact of Pb and Ag mining and smelting has been documented in the Northern Hemisphere (Shotyk *et al.* 1998; Renberg *et al.* 2000). If it were to be confirmed, such a large-scale transfer would mean that true pristine rivers, i.e. without any direct human impact, have not existed on the planet for 2000 years.

The most striking possible feature of human impacts on South American rivers could be found in Peru and Bolivia (no. 4a): the gold and silver mining and the mercury amalgamation performed by the Spanish settlers since the mid-1500s (Brading & Cross 1972) have probably generated an enormous direct and indirect mercury contamination through atmospheric pathways (Lacerda *et al.* 1999).

In other South American regions, riverine evolution is likely to be more rapid than in Europe: in this continent, most pressures have been developed during the second half of the twentieth century, especially through the development of mega-cities. Organic pollution, toxic metals and xenobiotic contamination are probably now reaching their maximum levels, owing to the growing imbalance between pressures and environmental regulation. A typical example is the Piracicaba River in Sao Paulo, which presents severe and growing levels of degradation for many issues (Mariely *et al.* 2002).

These trends are still very hypothetical, and local to regional differences may be found (e.g. trend numbers 4a and 4b; figure 2*b*). Basin size should also be considered in further river basin analyses because, for pollution point sources, the impact severity is very much linked to the dilution capacity, i.e. to basin size as is observed for the Seine River (Meybeck 2002). The historical development of river engineering (dams, channelization, canals, irrigation), of the evolution of aquatic biocenoses (including species introduction, acclimatization, extinction, invasion), of thermal changes, radionuclide contamination and water-borne diseases should also be addressed to complement this river chemistry analysis. This

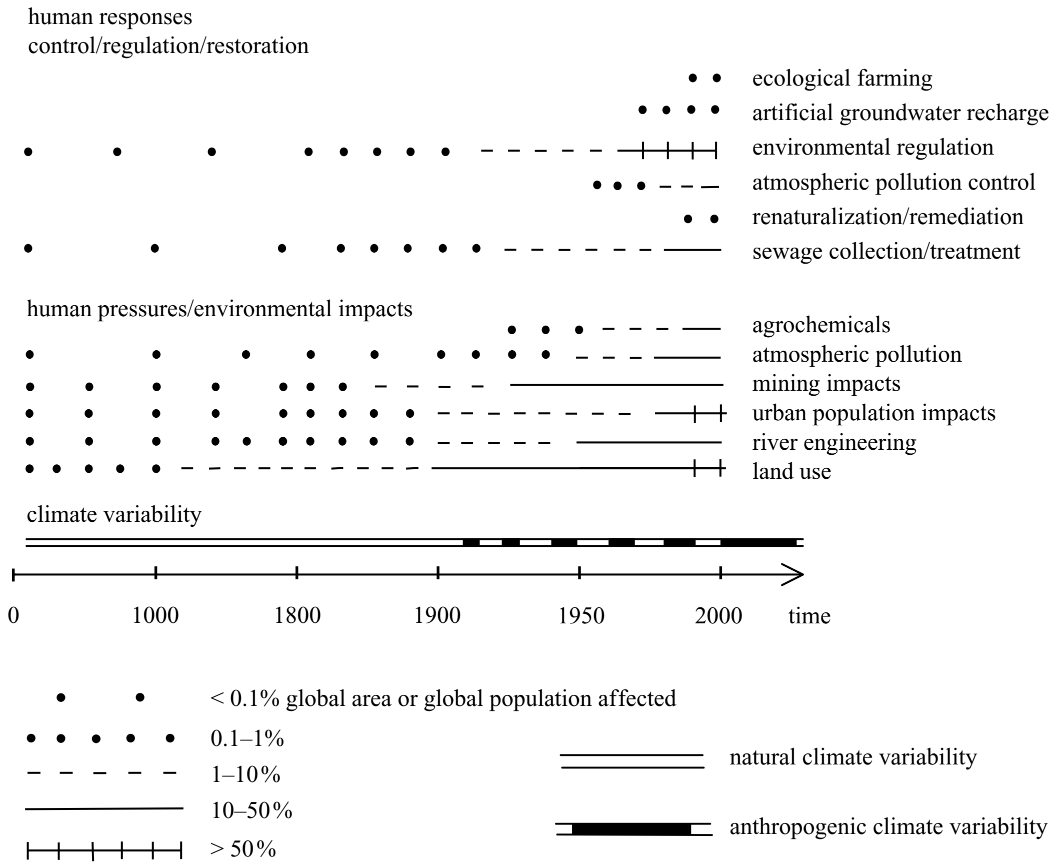

Figure 3. Working hypotheses on the occurrence of some major pressures on continental aquatic systems at the global scale and related environmental remediation responses (accelerated time-scale).

reconstruction of the past evolution of the continental aquatic systems and their interactions with societies is of paramount importance to prevent further deterioration of their situation, as was shown by Harremoës (2001).

(c) *Timing of human pressures and responses*

The global time and space picture of human interactions with riverine systems remains to be drawn and understood in full detail (Meybeck *et al.* 2003*b*). The timing of some human pressures, environmental impacts and societal responses over the past 2000 years is schematically presented in figure 3 at the global scale.

Some of the major human pressures only are considered here, and it is postulated how an increasing fraction of the Earth's surface has been exposed to these. River engineering here includes damming, channelization, diversion and irrigation canals. The evolution of proportions of global area or affected global population is still speculative owing to the lack of databases (e.g. sewage collection, industrial development, past mining register, small dams register), but there are growing efforts in historical reconstruction of land cover (Leemons *et al.* 2000) and population density. The progression towards a global scale impact can take two pathways. With the first, impacts are locally displayed, but because of the pandemic distribution of a particular class of change, the consequences are global. 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, hypothetically linked to greenhouse warming, has the potential to influence the entire planetary surface. Another example is the long-range atmospheric transport of pollutants such as NO_x and SO_2, responsible for the acidification and/or eutrophication of surface waters, sometimes hundreds of kilometres away from emission sources. These statements should not imply that all riverine impacts are now globally significant. In fact, most well-documented impacts on aquatic systems are local to regional. Because most human-induced sources of pressure on the continental aquatic systems have had an exponential rate of increase over the past 200 years, the spatial distribution of these combined forces has now moved on to the planetary scale. The continuing and fast rate of change thus necessitates the accelerated time-scale adjustment on figure 3 as for figure 2.

The key control of river syndrome development is the relative timing of human pressures and societal responses, such as regulation, emission control and restoration, as is developed for chemical contamination (Meybeck 2002). Although some responses can be traced back to several thousands of years ago, as for waste disposal to rivers, they have generally been developed with a considerable lag related to pressures for multiple reasons: (i) lack of impact awareness; (ii) lack of scientific knowledge and of technical solutions; (iii) lack of societal concern or consensus and/or of political will; and (iv) lack of financial means. In addition to growing regulation, as contaminated water recycling and/or treatment, new technical responses, such as artificial groundwater discharge, ecological farming, renaturalization of river courses or remediation of con-

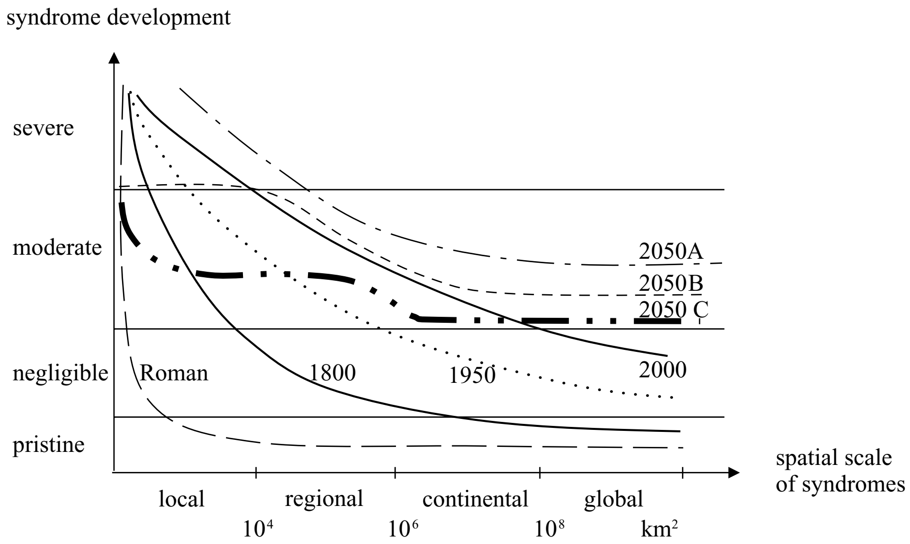

Figure 4. Schematic evolution of the chemical contamination syndrome extension at different space-scales from the Roman period to contemporary. Scenarios for the year 2050 correspond to: A, 'business as usual'; B, priority reduction of the most polluted sites; and C a general application of precaution principle.

taminated sites, are now developed although they are still experimental at the global scale (figure 3).

These social and societal responses to river changes should now be established for each syndrome according to the various stages of human development and natural continental aquatic system conditions.

(d) *Future evolution of river syndromes*

The past evolution of rivers over 2000 years can help us to foresee some possible future scenarios for the next 50 years. Although the precise evolution of river syndromes in time and space remains to be established, a schematic trend is proposed here as a working hypothesis and illustrated for chemical contamination (figure 4).

The chemical contamination syndrome was still very limited some 2000 years ago and likely to be occurring at the local scale only (less than 10^4 km^2). Two hundred years ago, most chemical contamination symptoms were moderately developed at the regional scale. In the middle of the nineteenth century, the chemical contamination syndrome had reached a moderate to severe level in some regions of western Europe and in parts of the eastern USA, but was still negligible in many continents, whereas the transfer of atmospheric pollutants over long distance was already limiting the occurrence of truly pristine basins. In the present period, the river chemical contamination syndrome is now widespread and the occurrence of very severe contamination levels at the local scale is well documented (mega-cities, historical pollutions, mining and smelting districts, etc).

Such an evolution will have to be set up for all other syndromes. For instance, there is evidence of important river engineering between the Huang He and Yang–Tse–Kiang rivers at the regional scale (10^4–10^6 km^2) in China 2000 years ago (Elvin 1993; Elvin & Liu 1998), and in the Huang He Basin (0.7×10^6 km^2) the sediment imbalance syndrome was already reaching a severe level 2000 years ago. The flow regulation and the river-course fragmentation syndromes may also have a different time and space pattern (a dramatic increase of damming over the past 50 years and, probably, a wider and more severe impact than the chemical contamination shown on figure 4). The neoarheism syndrome has essentially developed since the 1950s.

The future evolution of river systems is highly uncertain and cannot be predicted, but scientists and managers are now proposing various possible scenarios such as for river network artificialization (Petts 1984). Three main future scenarios (2000–2050) may be looked upon for the chemical contamination syndrome (figure 4) at the global scale.

(i) 'Business as usual' and laissez-faire (figure 4 line A): although the regulation/restoration responses may be developing on all continents, human pressures are still progressing fast. The global contamination of continental aquatic systems accelerates, leading to a generalized degradation of water resources and an expected response of the Earth system, particularly in the coastal zone. From the analysis of recent river evolution, it can be assumed that such a policy has been applied until the end of the 1980s in eastern Europe, as in the former Soviet Union (Kimstach *et al.* 1998) and in most fast-developing countries such as China (Wang *et al.* 2000), Brazil and India (Meybeck *et al.* 1991).

(ii) Priority reduction of river pressure hot spots (figure 4 line B). Such a scenario applies mostly to the water quality issues. Environmental management is here targeted to the most severe pollution issues, either contemporary or historical (remediation of polluted sites) according to a cost/benefit analysis. This policy has been applied in the past in most western European countries and the USA in the 1960s to 1980s. In such a scenario, the biggest point sources of pollution and the most contaminated sites are cleaned up first, but there is a gradual shrinking of the remaining sub-pristine river basins and a homogenization of river conditions towards a mediocre quality.

(iii) Precaution management (figure 4 line C): in addition to the previous management rule, human impacts, either direct or indirect, are generally limited to the least acceptable impact. This type of policy is now being developed by the European Union in its new Water Framework Directive. It has been favoured for two or three decades by Scandinavian countries, Switzerland and Canada. However, in such a scenario, some moderate and even severe impacts are likely to remain at the local level owing to structural factors (e.g. a mega-city located on a small watershed with limited dilution power, even with a waste treatment efficiency reaching 90%; unremediated historical contaminations). This policy requires a combination of citizen awareness, scientific and technical knowledge, political will and financial means, which is unlikely to be found everywhere.

6. CONCLUSIONS AND PERSPECTIVES

The continental aquatic systems are naturally controlled in the Earth system by multiple physical, biological and chemical processes regulating water transfers, particulate and dissolved material concentrations and fluxes. These transfers are naturally heterogeneous at the global scale and have varied in recent Quaternary history. Human activities have greatly modified the continental aquatic systems through land-cover and land-use change, water engineering, release of waste to aquatic systems, and introduction of exotic aquatic species. The anthropogenic control and/or pressures on river systems has accelerated in the past 50 years and is now balancing the Earth system controls, as for the nitrogen and phosphorus inputs to oceans and the sediment transfer. Crutzen & Stoermer (2000) have referred to this new state as the Anthropocene, the new era that follows the Holocene, and they have proposed Watt's invention of the steam engine in 1784 as a symbolic start for this period. Another conventional date, 1950, corresponding to the acceleration of many anthropogenic pressures (population, atmospheric pollution, water pollution, land-use change, river engineering, loss of biodiversity) and being also the reference for ^{14}C dating (Before Present ages), has also been proposed for the Anthropocene (Meybeck 2001*a*,*b*, 2002).

The Anthropocene transformations of river systems are here described in a set of river syndromes, which have gradually developed on all continents. This set should now be complemented by additional syndromes, such as the change of the thermal regime of rivers, the contamination by radionuclides, the development of water-borne diseases and the introduction of exotic species. The syndrome analysis should be based on specific indicators defining each symptom for comparing basins, scaling, timing, mapping, and for future scenario analysis. For many syndromes, such as chemical contamination, acidification, salinization or eutrophication, chemical or biological indicators have already been proposed for CAS monitoring (Chapman 1992) although seldom accepted at a global scale, except for lake eutrophication (Vollenweider 1968). Flow regulation and river-course fragmentation indicators have also been defined (Dynesius & Nilsson 1994).

Each syndrome should be addressed at the short- to long term through a cause–effect analysis including the cost for human societies and the impact on the Earth system, particularly as concerns the relationship between water and agriculture (Tilman *et al.* 2001; Wallace & Gregory 2002). Such analyses have already been performed for the acidification syndrome, which has led to a marked reduction of SO_2 and NO_x emissions since the early 1970s. These analyses, which can use the DPSIR approach (Turner *et al.* 2001; von Bodungen & Turner 2001) or others (Baccini & Brunner 1991; Vellinga 1996; Costanza *et al.* 1997; Rotmans & De Vries 1997; Postel & Carpenter 1999; Wilson & Carpenter 1999), should also be made at the most relevant spatial and temporal scales.

The regionalization of river syndrome analysis is critical for the resolution of water-related issues. Each region of the world had a different Earth system history (e.g. glaciation–de-glaciation, land-cover change) and a different human development history. The future human drivers (population increase, education, economic development, environmental regulations) and Earth system controls (global warming, climate variability) will be very different from one region to another. In particular, the natural sensitivity of river systems to develop syndromes should be addressed. For instance, the presence of carbonated rocks or soils greatly limits the development of acidification; semi-arid regions are very sensitive to salinization and neo-arheism; mountainous catchments, volcanic area and loess-covered regions are more sensitive to the sediment imbalance. Regional studies may also provide surprises: an unexpected improvement of the northwest Black Sea has recently been observed 10 years after the reduction of the Danube River nutrient inputs following the 1989–1992 economic crisis in this basin (Kideys 2002). If confirmed, this would mean that some systems could recover faster than expected.

International treaties on shared rivers (Wolf 2002), or regional seas, such as the Rhine, Nile, Colorado, Danube and Parana Rivers have, as early as 1820, first set up international borders, permitted navigation and decreased flood risk, shared hydraulic power resources and water supply for drinking and irrigation in the first half of the twentieth century, then in the 1960s to 1990s have limited salinization (Rhine River) and controlled other water quality issues (in many European basins). Forthcoming European treaties will concern the maintenance of good ecological quality, i.e. including aquatic habitat. Although they could not completely eradicate water conflicts, which still occur in many regions, such treaties have been a basis for economic development and regional stability. In the 1980s and 1990s, chemical contamination, eutrophication and sediment imbalance have been considered in some international treaties or international conventions for regional seas (e.g. the Oslo–Paris Convention for the North Sea, Helsinki Convention for the Baltic Sea). They are also well analysed by the scientific community, as for the Black Sea (Mee 2001; Lancelot & Martin 2002), the Baltic Sea (Ozsoy & Mikaelyan 1997; Elmgren & Larsson 2001), the Pohai Sea (Milliman *et al.* 1987) or the Louisiana coast (Turner *et al.* 2001). Other regional seas are probably much affected by river changes, like the White Sea (river contamination (Kimstach *et al.* 1998)), the Caspian Sea (contamination, flow regulation, fragmentation, neo-arheism), the Gulf of California (neo-arheism of the Colorado River), the Persian Gulf (neo-arheism of the Shatt el Arab River), the North Arabian Sea (neo-arheism of the Indus River), the East Mediterranean Sea (neo-arheism of the Nile and of Turkish rivers), the James Bay (flow regulation and fragmentation), the South China Sea (silting due to land-use change), etc.

The study of river syndromes at the global scale is still limited by the available information. The only programme collecting yearly information on continental water quality, GEMS-Water (100 to 500 stations depending on descriptors; GEMS-Water 2002; Robarts *et al.* 2002) is now being rejuvenated after a period of financial constraints in the late 1990s. The original GEMS-Water target of 1200 water quality stations collected and processed worldwide in rivers, lakes, reservoirs and groundwaters should be achieved, and UNEP programmes related to trans-boundary water quality issues and/or land/coastal interactions, such as the Global Environment Fund, should contribute to this global water quality database. Concerning the river water discharge, the situation is also degrading: the number of active gauging stations stored in the Global Run-off Data Centre in Koblenz should be augmented, particularly through better transmission and access to run-off data generated by countries (Vörösmarty 2002*a*,*b*). The global register of large dams (ICOLD 1994) only considers the largest and highest ones and is missing the small ones representing at least 80% of world reservoirs in number. No global spatialized register of urban and industrial sewage collection and treatment is presently available, and even the river temperature has not been properly collected (Webb 1996). The first global groundwater register has only just been established at UNESCO. In contrast to these limited field data, satellite imagery has made the development of global datasets possible on land use, land cover and population at fine resolutions (0.5° and less). These datasets are now used to address the future water supply and demand, which were considered until recently only at the aggregated country levels (Vörösmarty *et al.* 2000). Spatialized river nutrient models are now also benefiting from these datasets (Garnier *et al.* 2002).

The global climate change impacts and the impacts of some river syndromes on aquatic resources are already considered as a first priority (Zebidi 1998; Lundqvist & Falkenmark 2000; World Commission on Dams 2000); the impacts of the river syndromes on the Earth system should now also be considered on the global environmental agenda (Steffen *et al.* 2001; Pahl-Wostl *et al.* 2002).

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GLOSSARY

CAS: continental aquatic systems
DDT: dichlorodiphenyltrichloroethane
DOC: dissolved organic carbon
DPSIR: driver pressures state impact response
GACGC: German Advisory Council for Global Change
PAH: poly-aromatic hydrocarbon
PCB: polychlorinated biphenyl
POC: particulate organic carbon
POP: persistent organic pollutant
TSS: total suspended solids
UNEP: United Nations Environment Programme
WBD: water-borne disease