Interactions between Global Change and Human Health
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GLOBAL CHANGES IN AQUATIC SYSTEMS AND THEIR INTERRELATIONS WITH HUMAN HEALTH

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Aquatic systems are commonly considered to be essential determinants of human health, for example through multiple water-related diseases that affect the lives of some hundred million people or through their impact on food supplies, water-related safety, personal hygiene, etc. (Unesco, 1992; McMichael *et al.*, 1996; Gleick, 1993; McMichael, 2003). Continental aquatic systems (CAS) include streams, rivers, wetlands, lakes, ground waters, coastal wetlands and estuaries in their broader sense (e.g., deltas, tidal estuaries). These systems are regarded by economists and water sector industrialists as essential water sources for most human needs and activities. For Earth System scientists, CAS are also looked at in terms of fluxes, reservoirs and cycles of materials, such as water, carbon, nutrients, ions, metals, sediments, shaping the surface of continents and feeding the coastal zone (Garrels *et al.*, 1973; Berner and Berner, 1987; Steffen *et al.*, 2004). These cycles are controlled by processes such as water balance, atmospheric inputs, soil leaching and erosion, chemical weathering, biological uptake, flow routing, food web cycling, and particulates retention (Berner and Berner, 1987; Schlesinger, 1997; Meybeck and Vörösmarty, 2005).

Continental aquatic systems have gradually changed since the very early development of humanity, with the first irrigated fields and their related dams and reservoirs, and with the first agricultural drainage. In addition to water use in agriculture, most other human activities use continental waters and in return are impacting them at the local to regional scale in quantitative ways (e.g., water balance, river discharge) or in qualitative ways (e.g., pollution, habitat change, aquatic biota modification). Pristine CAS are now seldom found, as less than 17% of the present-day continental surface can be considered to be without a direct human footprint (Sanderson *et al.*, 2002). Most of this pristine land is actually found in desert regions, where CAS are actually very limited, as in the Sahara, Central Australia, Central Asia and the Kalahari. Pristine river basins are limited to some boreal regions of Siberia and North America, and to the Amazon and Congo basins.

These local to regional impacts are now combined with global environmental changes, such as climate change and sea level rise, which both occur at the global level and which have begun to influence all aquatic systems on land (Kabat *et al.*, 2004) and those at the land/sea interface (Crossland *et al.*, 2005). Although the present extent of climate change impact on river basins is difficult to establish and to differentiate from direct human impacts such as damming (Dynesius and Nilsson, 1994) or irrigation (Gleick *et al.*, 2001), most scientists are convinced that the next 20 to 50 years will see major changes of the water balance at local to global scales due to climate change, and that sea level will gradually rise (Kabat *et al.*, 2004; Steffen *et al.*, 2004).

In addition to global environmental changes, the last one or two hundred years have also been characterized by accelerated human changes across the planet such as population development, economic changes, technical innovations, and social and political changes (Steffen *et al.*, 2004). In the human health sector, other major global changes should also be considered, such as human behavior, health care, public infrastructure, global circulation of humans, animals, food, and their related diseases. All these changes are now considered as part of global change, which has been accelerating over the last fifty years. Recently Paul Crutzen (2002) defined this present-day Earth System as the Anthropocene, the new geologic era following the Holocene (the last 10,000 years), in which human control on Earth Systems dynamics, particularly climate, is now equal to or exceeds the natural forcing, e.g., solar radiation and the internal heat of the Earth.

Many aspects of climate change and health have been extensively treated within the IPCC and by UN agencies such as WHO, WMO and UNEP (Unesco, 1992; McMichael *et al.*, 1996; McMichael, 2003), and by Gleick *et al.* (2001) and will be summed up in Section 6 of this paper after a short presentation (Sections 1-3) of health issues related to aquatic systems. The core of this paper is devoted to the direct influence of humans on aquatic systems, which is far more important and which proceeds faster than climate change impacts (Meybeck and Vörösmarty, 2005; Vörösmarty and Meybeck, 2004). The quality of water and of aquatic systems is specifically addressed (Sections 4 to 6) although its global assessment is difficult due to lack of relevant data. Finally, in Section 7, I am proposing some possible scenarios for the future evolution of aquatic systems in the Anthropocene, particularly for water quality, in relation to various human responses to changes.

1. Health Issues in Natural Aquatic Systems

Under natural conditions, aquatic systems do not always facilitate human development and good health. Three major types of health issues are identified here (Table 1, Figure 1): (i) problems related to chemical composition of water resources in natural conditions; (ii) problems related to the occurrence of illness vectors such as insects, snails, bacteria, viruses and other microorganisms; (iii) problems related to drought and flood risks, which will be addressed in the next section together with droughts and floods generated by climate change.

The natural water chemistry of continental waters can be very variable (Meybeck, 1998, 2003a). The total dissolved solids (TDS sum of major ions) may range from 0.1 to 10 g/L in streams and rivers and reach up to 400 g/L in saline lakes such as the Dead Sea. However, most rivers and open lakes have a TDS content much less than 3 g/L, which is fit for human consumption. Exceptions are noted for springs and small river basins (Figure 1, b) underlain by rare rocks types such as pyritic shales, gypsum and rock salt; for these waters the dominating Ca^{2+} and HCO_3^- ions may be replaced by Na^+-Cl^- or Mg^{2+}-SO_4^{2-} ionic associations, which are much less appropriate for drinking. In semi-arid and arid regions, the surface waters are gradually evaporated (Figure 1, c). This results in an increase of TDS and enrichment of Na^+, Mg^{2+}, Cl^-, and SO_4^{2-} which sometimes exceeds the WHO water quality criteria. Some extreme water bodies do not allow most water uses, including use as drinking water, and yet have a very high conservation and biodiversity value. Unique waters, with very high dissolved organic carbon (DOC) contents (peat bogs), very low pH (pH 1 for Lake Kawah Idjen, Indonesia), or very high pH (pH 12 in Lake Bogoria, Kenya) or hypersalinity (Dead Sea, Kara Bogaz), may host very resistant and generally endemic species.

Groundwaters are generally more mineralized than surface waters, consequently water quality criteria are more often exceeded. In some groundwaters, fluoride or arsenic-containing rocks may release these elements when pumped at the surface. These water quality issues are found at the regional level and may affect hundred of thousands to a million people as in Tanzania, Senegal, and Rajasthan for fluorosis, and in Chile and Bangladesh for arsenic poisoning (Chilton, 1989).

In regions far from the inputs of marine aerosols that naturally provide iodine, deficiencies of this element in water may put hundreds of millions of people at risk of goiter, as in Central China (Meybeck *et al.*, 1989). In contrast, the marine intrusion of sea salt into coastal aquifers, particularly in deltas, is a natural limitation of most water uses, including drinking (Figure 1, d).

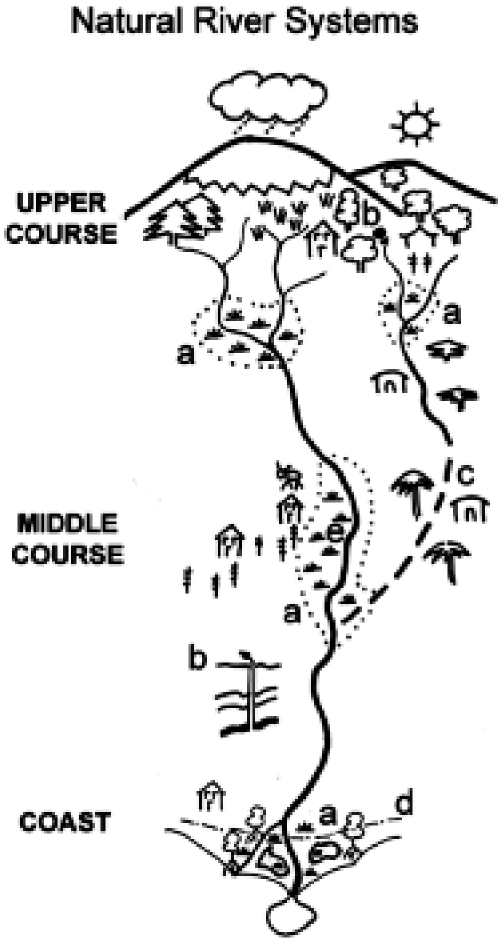

Figure 1. Schematic landscape view of continental aquatic systems and related health issues in natural conditions (# a to X, see Table 1).

TABLE 1. HEALTH IMPACTS INDUCED BY AQUATIC SYSTEMS IN NATURAL CONDITIONS (Coding refers to Figure 1 and Table 1).

Aquatic System (Coding)	Description	Vectors and/or issues	Health impact and Population affected[1]
Wetlands and lakes occurrence (a)	lowland humid regions	• Mosquito occurrence	Filariasis: 117 million infected per year
			Yellow fever: epidemics in tropics
			Malaria: 2.4 billion at risk
			Dengue: 50 million infected per year
		• Snail occurrence	Schistosomiasis: 200 million
		• Cyclops (crustacean) occurrence	Dracunculiasis: 100 000 infected per year
Running waters	Tropical regions (Africa)	• Simulium (Black flies)	Onchocerciasis: 18 million infected per year
Evaporated surface and groundwaters (c)	arid regions	• saline waters (Na^+, Cl^-, SO_4^{2-}, Mg^{2+})	dozens of millions worldwide
Specific surface and groundwaters (b)	occurrence of F^-, Arsenic	• fluorosis (Senegal, Tanzania, Radjasthan)	
	high levels of dissolved salts	• saline waters (arid belt)	
Inland waters	lack of iodine	• iodine deficiency (China)	Goitre: millions in China
All waters	tropical regions mostly	• infective bacterial agents (*Salmonella, Vibrio cholerae, Leptospira*)	
		• Viral agent (hepatitis A, poliomyelitis)	
		• Parasites (*Amoeba, Giardia*)	
		• Enteric diseases (diarrhoeas)	
Coastal groundwaters (d)	marine intrusion (salt wedge)	• Saline waters	

(1) 1990s statistics (Unesco, 1992 with update according to McMichael *et al.*, 1996)

Most vectors of water-related diseases are found in humid tropical regions and, less often in temperate regions (McMichael *et al.*, 1996). Mosquitoes which are the vectors of filiariasis, malaria, yellow fever and dengue (Table 1) can be found in all types of wetlands, either located in the upper course of a river basin, the middle course or in the coastal zone (Figure 1, a). Freshwater snails that host schistosomiasis-transmitting trematodes are commonly found in tropical ponds and irrigated areas. Black flies that propagate onchocerciasis were common in West African middle sized rivers until a major WHO sponsored program limited their development. Cyclops, a tiny crustacean propagating dracunculiasis, is common in Africa. There is also now growing evidence that cholera outbreaks are linked to the development of multiple *Vibrio cholera* hosts in some aquatic systems such as blue-green algae and coastal copepod zooplankton (see next section on meteorological extremes). Further information can be found in the reports by Wilson (2001) and by McMichael (2003).

2. Health Issues Induced by Climate Change and Sea Level Rise

Climate change and health issues have been extensively reviewed in the last decade particularly within the Intergovernmental Panel on Climate Change (IPCC) and at WHO (McMichael *et al.*, 1996; McMichael, 2003). I focus here more on (i) the gradual changes of the water balance and its related impact on land cover and (ii) on extreme meteorological and hydrological impacts.

The longest records for river discharge reach back 100 years. While direct impacts from water use are evident for this period (see next sections) (Vörösmarty and Meybeck, 2004), it is difficult to draw a global picture of hydrological changes due to climate change. For instance, the analysis of very diverse rivers such as the Athabaska (N.E. Canada), N. Dvina (European Russia), Lena (Siberia), Niagara (N. America), Parana (S. America), Congo and Amazon does not show definite trends for the 1900-1990 period. In dry and semi-arid regions, cyclic natural variations are observed, as for the Niger River discharge (W. Africa) (Laraque *et al.*, 2001), Lake Chad levels (Central Africa) (Lemoalle, 2004), and Moroccan Rivers discharging SE to the Sahara. The Central Asia regions from the Gobi desert to the Caspian also show very variable runoff with relatively limited climate variability over the last hundred years: the Gobi was drained by the Kerulen River in Mongolia, which was connected to the Amur River basin in the 1900s, and the Amu Darya river had been connecting the Aral and Caspian Seas through the Uzboi channel some 3000 years ago (Aladin *et al.*, 2004). Both river basins had very different and more humid waterscapes from what was observed in the 20th century.

The expected hydrological changes linked to climate change and their impact on human health and on Earth System functions (e.g., carbon balance, fluvial morphology, and aquatic biodiversity) are presented in Table 2 and in Figure 2, using a river basin structure identical to the one of

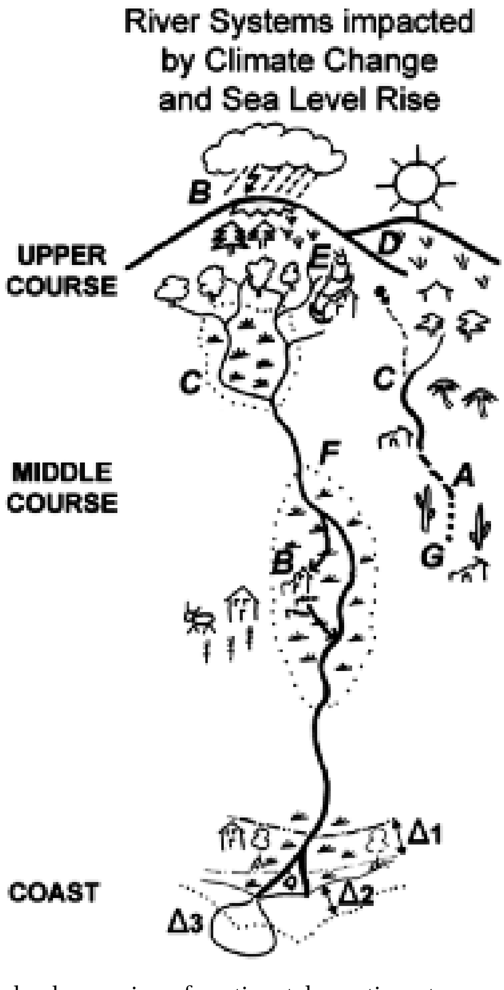

Figure 2. Schematic landscape view of continental aquatic systems and related health issues with Climate Change (# A to G) and Sea Level Rise (Δ1 and Δ2) impacts (see Table 2).

TABLE 2. MAJOR HYDROLOGICAL CHANGES DUE TO CLIMATE CHANGE AND SEA LEVEL RISE, AND THEIR RELATED ISSUES

Environmental changes	Local to regional changes	Global Impacts						
		A	B	C	D	E	F	G
Climate variability and Climate Change	A Development of non-perennial rivers	•	•	•	•	•	•	•
	B Development of extreme flow events	•	•			•	•	•
	C Changes in wetland distribution	•	•	•	•		•	•
	D Changes in chemical weathering				•			•
	E Changes in soil erosion	•			•	•		•
	F Changes in flow regimes	•	•			•	•	•
	G_1 Salinization through evaporation	•	•	•			•	
Sea Level Rise	Δ_1 Salt water intrusion	•		•			•	
	Δ_2 Coastal erosion					•	•	

A: human health, B: water availability, C: water quality, D: carbon balance, E: fluvial morphology, F: aquatic biodiversity, G: coastal zone impact. Only the major links between issues and impacts are listed here (Meybeck *et al.*, 2004; adapted from Meybeck, 1998) (Codes refers to Figure 2).

Figure 1. Increased droughts will lead from seasonal to permanent river dryness – river and lake desiccation – (A, Figure 2, Table 2), which affects all river functions within the Earth System and leads to severe health issues. These aspects are developed further with other extreme events such as floods. The major impact of climate change is probably the shift in wetland distribution (C). Some dry regions will be exposed to more humid climate and new wetlands will develop, while in other regions they will decrease (see Steffen and Lambin, 2006).

In subarctic regions, permafrost melting due to global warming will leave millions of hectares of new wetlands, although their direct impact on human health may be more limited than the occurrence of new wetlands in the tropics. Changes in chemical weathering (D) and in soil erosion (E) due to warming, land cover change and water runoff change will impact the Earth System functions more than human health except for the development of extreme storm events that increase landslide occurrence, particularly in coastal regions. The gradual evaporation resulting from drier climates will lead to the extension of regional salinization (G1).

The specific issues in the coastal zone include the intrusion of sea salt into aquifers and coastal erosion, both related to sea level rise (Figure 2, Table 2).

In addition to these permanent changes, climate extremes will generate specific hydrological events that have an extreme impact on societies, particularly on human health (Hales *et al.*, 2003) (Table 3). They can be expressed at various temporal scales from very short (hourly and daily rainfall) to seasonal and decadal. During El Niño years, the hydrological balance of the Earth System is very much affected from the local to the global scale but changes of climate extremes may also be related to local and regional events as hurricanes and typhoons (Kabat *et al.*, 2004). Many studies have found some correlations with extreme events generated by the El Niño Southern Oscillations (ENSO events) or by the Southern Oscillations Index (SOI) with the expansion of malaria and dengue epidemics, however in most cases these correlations are very local and not yet fully explained (Hales *et al.*, 2003).

During the extreme events, surface hydrology may be greatly modified and social and economic infrastructures can be completely altered leading to catastrophic events, essentially defined by their socio-economic impacts: the same hydrological extreme may be mitigated very differently in different locations, as is regularly observed for Caribbean Hurricanes. WHO has defined a catastrophic flood or drought as an event that is (i) affecting more than 200 people, or (ii) killing more than 10 people, or (iii) requires assistance from a central or provincial government.

Both floods and droughts can be associated with the development of enteric diseases. In the tropics, diarrhoeal diseases typically peak during the rainy season. Extreme floods could help propagate the pathogens, while drought conditions lead to an increase of hygiene-related diseases (Hales *et al.*, 2003).

During heavy rainfall, surface water supplies and even some karstic-groundwater supplies can be more turbid, even after treatment to meet drinking water quality, and contain clay-sized particles with cryptosporidium, giardia, shigella, typhoid, and viruses that cause diarrhoea. *One important and long-term impact of extreme events is the destruction of sanitation infrastructures during floods or landslides, and the contamination or destruction of drinking water systems and subsequent fecal contamination.*

The fine scale mapping of the climate change impacts on human health, such as the geographic distribution of malaria, schistosomiasis, dengue and other vector-borne diseases, will be very difficult due to the multiple factors that have to be predicted at this scale, such as temperature, seasonal pattern of rainfall, and occurrence of new wetlands, which are still very much debated among modelers (Martens *et al.*, 1995). For instance, there is growing evidence of correlations between heavy rainfall and inundations during El Niño years and cholera outbreaks, as in the Ganga-Brahmaputra delta and in the

Amazon floodplain. However, the links between the multiple controlling factors such as river pH and phytoplankton blooms are not yet fully understood (Pascual *et al.*, 2002; Colwell, 1996; McMichael *et al.*, 2003). Another major difficulty in assessing the impact of climate change is taking into account the current dynamics of aquatic systems exposed to direct human impacts.

TABLE 3. HEALTH IMPACTS INDUCED BY AQUATIC SYSTEMS MODIFICATIONS DURING EXTREME EVENTS (modified from Kovats R., 1999; and Hales *et al.*, 2003; McMichael *et al.*, 1996; McMichael, 2003) (Coding refers to figure 2 and table 2).

EVENT (Coding)	**TYPE**	**DESCRIPTION**	**POTENTIAL HEALTH IMPACT**
Heavy precipitation (B)	Meteorological	Extreme rain	Increased leaching of soil microorganism (*Cryptosporidium, Giardia*) (W_B)
	Geomorphological	Wetlands formation	Increased water-related vectors (mosquitoes…) (W_B)
		Landslide; mud slide	Break of drinking water and sewage collection systems; pathogens contaminants (W_B)
Flood (B, E)	Hydrological	Over bank flooding; temporal wetlands	Water-related vectors (mosquito abundance; cholera hosts) (V_B)
	Social	Property damage	Contamination of water supply with faecal matter and rat urine (W_B)
	'Catastrophic event'		multiple drowning; respiratory infection; diarrhoeal disease; population displacements (W_B)(1)
			Crop losses and famine (PP)
Drought (B, C)	Meteorological	Riverbed dried up	Development of some disease vectors (V_B)
	Social	Reduction of water supply; reduction of sewage dilution	Water quality degradation (W_B)
	'Catastrophic event'		Water-washed diseases spreading (PP)(2)
			Population displacement; crop losses and famine (PP)

WB: water-borne diseases; VB: vector-borne diseases; PP: Person to person diseases; (1) e.g. outbreaks of hepatitis A, leptospirosis, typhoid (McMichael *et al.*, 1996); (2) e.g. outbreaks of scabies, conjunctivitis.

3. Health Issues Induced by Direct Human Impacts

Direct human impacts on aquatic systems have been, so far, much more important and faster than the gradual climate change impacts we are experiencing now. In a few millennia, the land cover change due to agriculture and global human settlement has reached about 80% of the Earth's surface (Steffen and Lambin, 2006). In the last 50 to 100 years, the river hydrological network has been completely fragmented and regulated by dams, dikes and levels, reservoirs, water diversion and irrigation practices (Dynesius and Nilsson, 1994; Gleick, 1993; Gleick *et al.*, 2001; Vörösmarty and Meybeck, 2004). The changes generated by water uses have now reached a level similar to those induced by slow climate variations that occurred over the last 20,000 years since the Last Glacial Maximum (Meybeck and Vörösmarty, 2005).

Most human activities, for example mining, smelting, industries, urbanization, and intensive agriculture, have generated an enormous amount of wastes, which are dumped, leached or eroded into aquatic systems and slowly carried by river networks to the coastal ocean. Other human activities such as transportation and hydropower generate a profound modification of river course morphology and aquatic habitat. These processes can be regarded as an acceleration of transfers at the Earth's surface for organic carbon, nutrients, metals, sediments, and some hydrocarbons. Water quality surveys also reveal the occurrence in aquatic systems of new materials that do not exist in natural conditions, such as pesticides, polychlorinated-biphenyls, solvents, and drugs, which are termed *xenobiotics* and are harmful for animals and humans.

These impacts are generally made at the local to sub-regional scales, but they are occurring now on all continents and can be regarded as a global scale issue (Cole *et al.*, 1993; Seitzinger *et al.*, 2002; Meybeck, 2003b; Steffen *et al.*, 2004; Vörösmarty and Meybeck, 2004). They are presented in Figure 3, using the same schematic river network, from headwater to coast, as in Figures 1 and 2. The alteration of Earth System functions together with the health issues in association to these human pressures are presented in Tables 4 and 5.

Most human pressures on aquatic systems have some potential health impacts, and produce a combination of several types of Earth System alteration. This results in a growing complexity of the interrelation between humans and aquatic systems. It is important to note that some physical alterations of natural systems are targeted to facilitate human settlements and agriculture, and/or to safeguard crops and properties. They can also lead to important Earth System dysfunctioning, which in turn may have an impact on human health, for instance through the modification of aquatic habitats and their related biodiversity. Intensive irrigation and reservoir flooding are often associated with new wetlands that favor disease vectors such as mosquitoes and freshwater snails. In semi-arid regions, irrigation may result in a marked increase of the dissolved salt content in irrigation returns and in groundwaters that can exceed WHO criteria for drinking water. Groundwater pumping in Bengal and Bangladesh has modified the chemical equilibrium of arsenic species that are naturally present in this aquifer leading to massive As poisoning in this region.

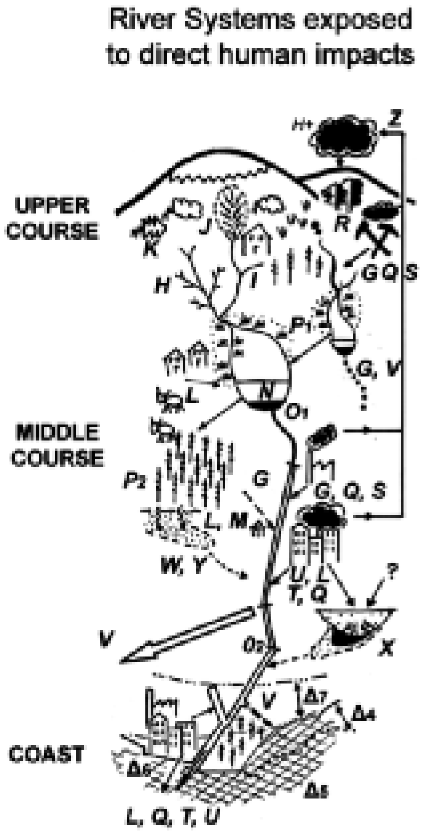

Figure 3. Schematic landscape view of continental aquatic systems and related health issues and degradation of Earth Systems functions under direct Human pressures (# H to Z, see table 3; Δ3 to Δ7, see Table 5).

TABLE 4. MAJOR LOCAL AND REGIONAL PRESSURES ON CONTINENTAL AQUATIC SYSTEMS AND RELATED ISSUES. A: human health, B: water availability, C: water quality, D: carbon balance, E: fluvial morphology, F: aquatic biodiversity. Only the major links between issues and impacts are listed here (Meybeck *et al*., 2004; adapted from Meybeck, 1998) (Codes refers to Figure 1, right).

Pressures	Local to regional changes of environmental states	Global Impacts					
		A	B	C	D	E	F
Land use change	H Wetland filling or draining	•	•	•	•		•
	I Changes in water pathways and water balance		•	•			
	J Change in sediment transport				•	•	
	G Salinization	•		•			•
	K Alteration of first order streams					•	•
	L Nitrate and phosphate inputs	•		•	•		
	M Pesticide occurence	•		•			
	W Groundwater contamination (NO_3^-, pesticide)	•		•			
River damming and channelisation	N Nutrient, carbon and particulates retention	•			•	•	
	O Loss of longitudinal (O_1) and lateral (O_2) connectivity						•
	P Creation of new wetlands	•		•	•		•
Industrialisation and mining	Q Inputs of heavy metals and POPs	•		•			
	R Acidification of surface waters	•		•			•
	G Salinization	•		•			•
	S Inputs of particulates			•		•	•
Urban wastes	L Nitrate and phosphate inputs	•		•	•		•
	T Faecal contamination	•		•			
	U Carbonaceous	•		•			•
	Q Inputs of heavy metals and POPs	•		•			
Irrigation/water transfer	V Partial to complete decrease of river inputs	•	•		•	•	•
	G Salinization (evaporation and percolation)	•	•	•			
Groundwater changes	W Infiltration of contaminated waters	•		•			
	X Wastes dumps leakage	•		•			
	Y Overpumping groundwaters	•	•	•			
Atmospheric pollution	Z Emission of atmospheric pollutants	•		•			

The coastal zone (Table 5) is very sensitive to Global Change (Crossland *et al*., 2005). The effects of this zone encompass (i) upper river course and middle course impacts through river flow modification, (ii) direct specific impacts such as groundwater pumping and oil extraction in coastal alluvial aquifers (Δ7, Figure 3), coastline artificialisation (Δ6) (e.g., dredging navigation channels; digging canals in deltas that modifies the water dynamics) and (iii) sea level rise impacts (Δ1 and Δ2, Figure 2 and Table 4). Wetland

TABLE 5. MAJOR LOCAL PRESSURES AND GLOBAL CHANGES IN COASTAL SYSTEMS AND RELATED ISSUES. A: human health, B: water availability, C: water quality, D: carbon balance, E: fluvial morphology, F: aquatic biodiversity. Only the major links between issues and impacts are listed here (Issues linked to Sea Level Rise: see Table 2).

Pressures	Local to regional changes of environmental states	Global Impacts					
		A	B	C	D	E	F
Coastal Issues	V Partial to complete decrease of river inputs		•		•		•
	_3 Enhanced sediment input				•	•	•
	_4 Sediment starving and erosion					•	•
	_5 Coastal eutrophy, Harmful algal blooms	•			•		•
	_6 Coastline artificialisation and wetland filling				•	•	•
	_7 groundwater overpumping, oil extraction, salt intrusion, subsidence		•	•			
	L, Q, T, U Coastal contamination	•		•	•		•

drainage and filling (Δ6) is another important pressure in coastal regions, sometimes carried out for mosquito control, but most of the time for agricultural development and urbanization.

Where nutrient inputs to the coast increase either through direct release from cities and agriculture, or through river inputs (L), coastal eutrophication may occur, resulting for some deltas in the destruction of the oxygen balance and severe modification of the food-web (dystrophy) (Rabalais and Turner, 2001) or in development of harmful algal blooms that can be associated with high levels of toxins in filtering mollusks (oysters, clams, mussels) (Chorus and Bartram, 1999; Anderson *et al.*, 2002). After a drought in February, 1996, all 126 patients in a haemodialysis unit in Caruaru, north-east Brazil, developed signs and symptoms of acute neurotoxicity and subacute hepatotoxicity following the use of water from a lake with massive growth of cyanobacteria (blue-green algae) (Pouria *et al.*, 1998). Other specific impacts on the coastal zone concern the sediment inputs that can be markedly increased in smaller river basins (Δ3) after land use change such as deforestation and farming, particularly in the humid tropics, which can 'blanket' the coral reefs with fine mud (Syvitski *et al.*, 2005). Conversely, the damming and reservoir construction that has been exponentially increasing at the global scale since the 1900s, and the water diversions that are common in some regions, result in a decrease of all river inputs (V) to the coasts particularly for water and for sediments (Δ3), i.e., the sediment 'starving' of the coast. These impacts are modifying the Earth System balance (e.g., inverse sediment balance in some deltas with the dominance of coastal erosion), yet their relation with human health requires more study, particularly in the long term (50-100 yrs). In addition to these quantitative human impacts, from headwaters to estuaries, on the continental aquatic systems, the water quality is impacted by anthropogenic sources of contaminants (see Column C, Table 4).

The transfer of these contaminants in aquatic systems is not straightforward and depends on

(i) the water residence time in the different water bodies of the river basin;

(ii) the reactivity of contaminants in these water bodies;

(iii) the trapping of particulates in the system.

The transit time of surface waters in big rivers ranges from a few weeks to nearly a year for the longest ones. River aging due to reservoir construction can increase these figures by an order of magnitude (Vörösmarty *et al.*, 1997; Vörösmarty and Meybeck, 2004). In addition, it must be considered that surficial aquifers which contribute to river base flow during dry periods have a much larger residence time, from years to decades as is the case for many large lakes. Once these water bodies are impacted, their restoration will take 2 to 3 times longer than the residence time, due to multiple environmental inertia in soils, sediments and to their non-piston flow renewal.

The reactivity of water borne material and the trapping of particulates within aquatic systems is also very variable. Fluvial filters (Meybeck and Vörösmarty, 2004), which include mountain slopes and piedmonts, headwater wetlands, floodplains, lakes, and estuarine systems control the fluxes of particulates and their attached contaminants, nutrients and pathogens, as well as many fluxes of dissolved and/or reactive nutrients and contaminants. Each river system can be described by its specific assemblage of fluvial filters, which is now changing fast as a result of water engineering and land use change. *It is estimated that more than 90% of suspended matter derived from erosion is naturally retained in large systems, and up to 99.9% is retained by large reservoirs, while only 18% of total nitrogen inputs to river basins to river basins (natural and anthropogenic) are exported to oceans* (Vörösmarty *et al.*, 2003; Green *et al.*, 2004).

Determining the direct impact of human activities on aquatic systems with regard to health issues is complex and involves water quality issues, the positive impacts of flood and drought regulation, settling and processing of particulate contaminants, and attached pathogens in reservoirs. Although the global picture shows an overall degradation of water quality from natural conditions, there are striking differences in time and space for each type of issue as presented in the next sections.

4. Defining and Assessing Water Quality at the Global Scale

The perception of water quality through its color, turbidity, taste, or effects on man and animals is as old as water use: water quality management rules existed in most ancient hydraulic civilizations from Mesopotamia to Egypt. The first chemical analyses of water were performed following the development of analytical chemistry some 200 years ago. Since that period, water quality perception and definition has constantly evolved with societal development. Water quality is a rapidly evolving field with multiple metering approaches (Meybeck, 2005). Unlike many other Global Change impacts, it is very site specific.

4.1. *Water Quality: a Fast Evolving Field*

The first major water quality surveys were performed on the Thames and Seine rivers following cholera outbreaks in the mid 1800s with only a few descriptors such as resistivity, dissolved oxygen, ammonia, chloride and fecal contamination indicators (fecal coliforms). Throughout the 20th century, water quality studies and monitoring grew exponentially in step with water demand, the occurrence of problems (eutrophication since the 1960s, acidification in the 1970s, endocrine disruptors more recently, radionuclides since the 1950s, pesticides since the 1980s) and the development of analytical chemistry.

'Water quality', initially defined by sanitary engineers and hydrologists using a few chemical descriptors in one sample or at one station, has now shifted to an overall appreciation of the 'aquatic environment quality' based on chemical, physical, and biological descriptors (Chapman, 1996). Water quality monitoring is getting very complex (Chapman, 1996; Mc Cutcheon *et al.*, 1993) and the total number of potential water quality descriptors probably now exceeds several hundred, while in the 1900s they were just one or two dozen (Figure 4, Trajectory A) (Meybeck, 2005). However, due to financial and technical constraints, the best-equipped monitoring stations consider routinely one hundred descriptors at best (Trajectory B), while in the Least Developed Countries, monitoring stations, when they exist, can still barely measure a dozen descriptors (Trajectory C).

In contrast to the situation in atmospheric chemistry, the aquatic environment cannot be simply described by one or two emblematic descriptors such as CO_2, which is continuously measured at the Mauna Loa observatory in Hawaii. The increase in global CO_2 measured at this station triggered the climate change concern in the 1960s (see Steffen *et al.*, 2004). Global warming can be also tracked on the basis of one simple indicator, average air temperature, commonly measured for 200 years and now widespread at tens of thousands of meteorological stations. Sea level rise is also based on one indicator. Yet evaluating water quality involves dozens of descriptors and their evolution is station specific. Vörösmarty (2002) observed that hydrologists were lacking a 'Mauna Loa'-like curve as a reference for global water balance. It is even worse for water quality, for which no 'Mauna Loa' curves can be established.

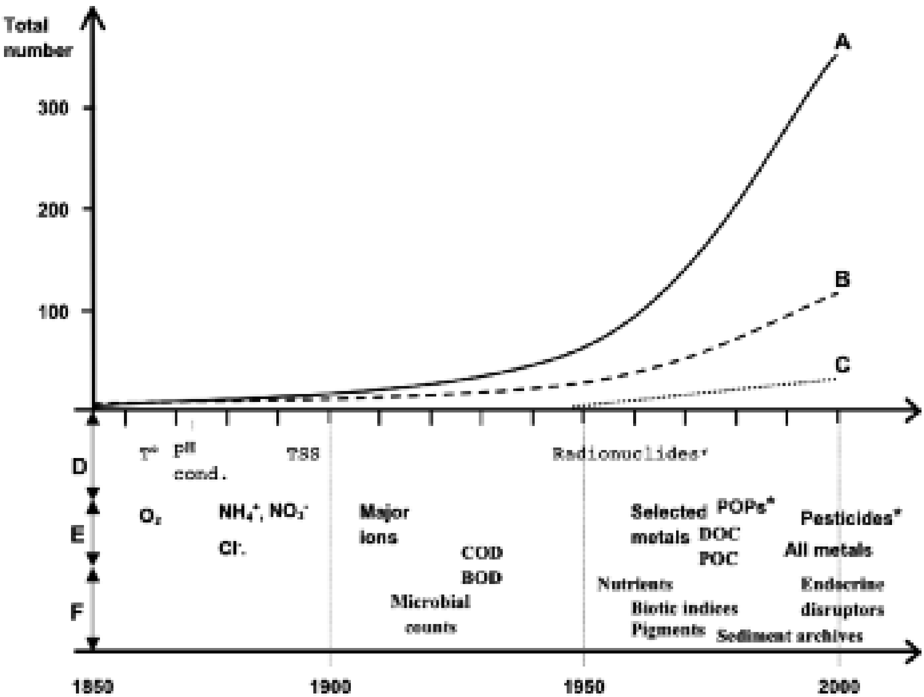

Figure 4. Exponential growth of water quality descriptors since 1850 and occurrence of their first analysis in regular surveys. Trajectory A = total maximum number of variables that should be considered if all regulations were implemented. B = number of variables actually routinely monitored in the first grade surveys. C = monitoring capacities of Least Developed regions. D = Physical descriptiors. E = Chemical descriptors. F = Biological and Ecological descriptors (*: non natural products) (adapted from Meybeck, 2004).

4.2. *Assessing Water Quality is Complex*

Each water user and each hydroscientist is interested in different aspects of water quality; these are very rarely collected and synthesized (Meybeck, 2005) and may lead to multiple definitions of water quality (Boon and Howell, 1997). Two main streams of water quality assessment co-exist: one referring to a *hypothetical natural background*, which is a common vision among Earth system scientists, and the other referring to *potential water uses*, which is the vision of all water users; particularly for drinking.

Establishing water quality metrics for users is an important part of water management. The drinking water criteria as established by WHO are probably the only universal criteria accepted by countries, which generally transcribe these criteria into legal and regulatory thresholds such as for chloride, nitrate, lead or arsenic. These criteria are not the only ones. In most cases, the water quality metrics used in management result from political decision balancing: (i) socio-economic activities responsible for pressures; (ii) socio-economic activities impacted by water-quality degradation; (iii) perception of water-related issues by societies through the media; (iv) dissemination of technical and scientific knowledge. *Multiple water quality metrics are needed and must be agreed upon by stakeholders and regularly revised, particularly when sharing water bodies.* These scales may evolve: even the most widely used reference, the WHO drinking water standard, is periodically revised on the basis of new scientific knowledge and, probably, on new levels of risk acceptance.

4.3. *Water Quality Issues Depend on Water Bodies*

The occurrence and extent of major water quality issues depend on the nature of the water bodies (Meybeck *et al.*, 1989; Chapman, 1996). These issues are listed in Table 6 and their location in continental aquatic systems is schematically indicated on Figure 3. Their relevance to direct health impacts is evaluated at three levels. Pathogens and vector-borne diseases are associated with communicable diseases (C, Table 6). However, most water quality issues correspond to non-communicable diseases (NC). Some issues such as eutrophication and suspended solids occurrence only occur in surface waters, others are primarily observed in groundwaters, such as salinization and high nitrate levels. The occurrence of fecal pathogens is observed more often in running waters than in other water bodies. The range of water residence time in lakes, reservoirs and groundwater is from weeks to hundreds of years while in streams and small rivers, it is days, thus permitting a higher spread of fecal pathogens.

TABLE 6. WATER QUALITY ISSUES AND HUMAN HEALTH

Issue		Health relevance		Water body			
	Coding[1]	Importance[2]		Rivers	Lakes	Reservoirs	Groundwaters
Faecal pathogens	T	+++	C	♦♦♦	♦	♦	♦
Suspended solids (as host of pathogens)	S, U	+	C	♦♦	na	♦	na
Decomposable organic matter	U	+	C	♦♦♦	♦	♦♦	♦
Eutrophication	L	+	NC	♦	♦♦	♦♦♦	na
Nitrate	L	+	NC	♦			♦♦♦
Salinisation/salt contents F^-	G	++	NC	♦	♦	♦	♦♦♦
Trace metallic elements + Arsenic	Q	+++	NC	♦♦	♦♦	♦♦	♦♦
Organic micropollutants	Q	+++	NC	♦♦♦	♦♦	♦♦	♦♦♦
Acidification	R	++	NC	♦	♦♦	♦♦	?

[1] See Figure 4 and Tables 4 and 5; (2): + (low) to +++ (high); Importance: C = communicable, NC = non communicable; Occurrence: ♦ (low) to ♦♦♦ (high); na: non applicable.

4.4. *Water Quality is Site Specific*

River water quality measured at one station is actually a spatial integration of the multiple sources, sinks and controls occurring in the intercepted drainage area (Figures 1, 2 and 3 combined). In Earth System Science, global scale scientists have often only taken into consideration the riverine fluxes of material to the oceans based on a dozen of well-documented major rivers (Meybeck, 1982; Seitzinger *et al.*, 2002; Caraco, 1994; Ludwig *et al.*, 1996). Yet the users' demand for water quality information is of course very different from global geo-chemistry and requires much finer resolution.

Water quality cannot be detected by remote sensing apart from color, temperature, suspended solids and pigments. Therefore we must rely on *spatially discrete information performed at stations*. Usually, stations are located where water is most used but the risks associated with water quality must be assessed everywhere.

Spatial integration and interpolation rules must be applied from stations to reaches, subbasins, basins, and depend on station density. In developed countries, the density of water quality monitoring stations is similar to that of meteorological stations (circa 1 station for 250 km^2 and 25,000 people in France), but it is between one and two orders of magnitude lower in the least developed countries. Spatial representativity also depends on the mixing state of the water body: a few stations may be adequate for a large lake, while a large aquifer may need hundred of stations. Conversely, the survey frequency should be high for rivers, medium in lakes and reservoirs, but can be low (yearly or less) for groundwaters.

Our appreciation of water quality closely reflects the complex relations between humans and water, at a given place, a given period, and for a given society. It is now based on dozens of indicators. Many of them cannot be afforded by the least developed countries and are still barely documented in some developed countries. In addition, water quality and its trends are often site-specific. The next section will address the diversity of human responses to water quality degradation and to its socio-economic and health impacts.

5. Societal Responses to Water Quality Issues

The response of societies to environmental changes depends on many factors such as the identification of an issue, the recognition of its links with human pressures, the consensus that can be built to define adequate measures, and the availability of financial, technological, technical or regulatory means. The study of water quality issues provides good examples of the combined inertia of societies and of water bodies, which generally extends over decades.

5.1. *Timing of Societal Responses: Example of a Restoration Cycle*

The full restoration and stabilization cycle of a water quality issue presents a good example of societal responses, depending on intensity of human impact, time constants and varying societal conditions (Meybeck, 2003b, 2002). The start of human impact is set at time T_0. Then, the following stages can be distinguished (Figure 5):

(i) *hydrosystem reaction to contamination* (T_0-T_1), depending on system size and contaminant pathways (e.g., dissolved vs. particulate transfer): this process depends on water and particulates residence time in hydrosystems;

(ii) *impact detection* (T_1-T_2) of hydrosystem changes by water users, scientists, specific citizen groups ('sentinels');

(iii) development of *societal awareness* (T_2-T_3): time for the development of general knowledge and understanding of the issue, sometimes delayed by lobbying from various social or economic groups;

(iv) *policy lag* (T_3-T_4): time for authorities or politicians to decide on the appropriate action; such decisions can be reached through environmental awareness of all stakeholders (bottom-up consensus) or obtained and imposed by political decision (top-down);

(v) *financial and technical lags* (T_4-T_5): time to fully implement and enforce the decisions;

(vi) *hydrosystem reaction to restoration and remediation measures* to limit (T_5-T_7) or decrease the environmental and societal impacts (T_{6A}-T_{6B}).

Depending on the timing of impact detection, impact duration and remediation effectiveness, various threshold levels can be reached. If the environmental control is not delayed and is sufficiently effective, a limited

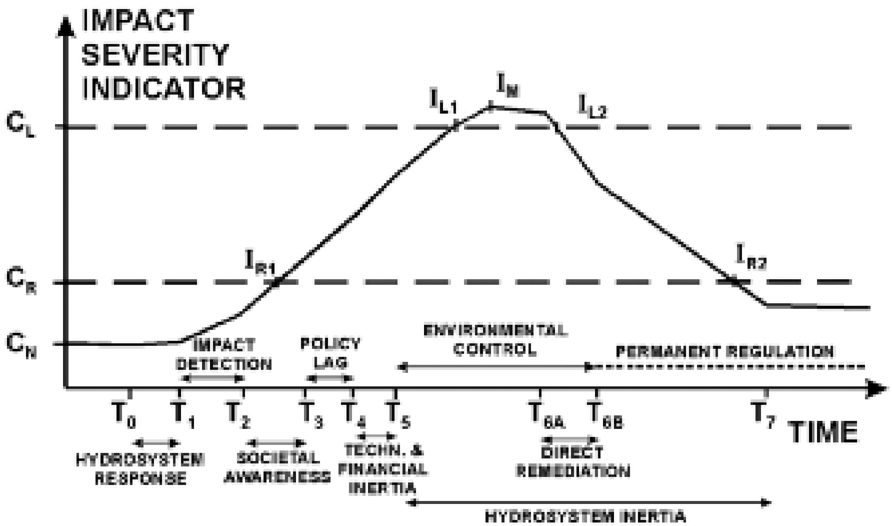

Figure 5. Successful restoration of water quality in an aquatic environment illustrated by a bell-shape trend in water quality. C_N, C_R, C_L: natural, recommended and limit concentrations of water quality indicator. T_0: start of environmental pressure, T_1: first change of water quality, T_2: detection of change, T_3: established societal concern on issue, T_4: political decision concerning the issue, T_5: start of implementation of environmental measures, T_M: time of maximum impact, T_{6A-6B}: direct remediation measures, T_7: new steady state. Time scale (T_0-T_7) varies according to issues and basin sizes (generally expressed in decades) (Meybeck, 2002).

level of maximum degradation is reached, followed by an improvement phase. If not, it can exceed the critical level C_L. In many examples of successful CAS restoration it has been necessary to perform a direct remediation of the aquatic system (dredging the contaminated sediments, inactivation of sediments below a layer of new sediments, direct chemical treatment of water or contaminated soils etc.). *The restoration cycle of a small to mid size catchment (1,000 to 100,000 km^2) is generally a few decades*.

5.2. *Recent Trends of Water Quality in Impacted Rivers*

This bell-shaped successful evolution of a water quality issue (Figure 5) is not often actually observed in rivers. Multiple trend patterns are documented (Anderson *et al.*, 1996; Foster and Charlesworth, 1996; Meybeck, 2002). As concentration measurements may not always fully represent the evolution of river systems, fluxes of riverine materials are also often considered as an alternative metric. They are the product of concentration and water discharges. In the great majority of documented cases, flux trends are linked primarily to changes in concentrations, few are linked to river flow changes only. To allow for their inter-comparison and typology, they are here normalized to the beginning of impacts (time T_1), (Figure 6) (Meybeck 2002).

Flux trends are contradictory: many fluxes increase due to rising concentrations (types B, D1, D2, D3, F, H, I, J, K, Figure 6) but some of them actually decrease (types C, E, G) owing to a decrease of water discharge due to water use, water diversion or to the biogeo-chemical and physical retention in an impoundment. Three types of flux decrease can be defined:

(i) the hydrological changes caused by water diversion or use, mostly for irrigation, result in a *gradual decrease* of all water-borne fluxes (type G, Figure 6). This is the case for many impounded basins in arid and semi-arid zones;

(ii) *complete retention* caused by the settling of all particulate matter including attached pathogens in reservoirs (type E), which exceeds 90% when the water residence time exceeds two months and might be responsible for trapping at least 30% of river particulates (Vörösmarty *et al.*, 2003);

(iii) *partial retention* resulting from degradation of organic matter including its pathogens and from the uptake of nutrients (type C) in reservoirs. In eutrophied and/or impounded rivers the Si/N ratio may decrease markedly and cause severe degradation of coastal-zone food webs and development of harmful algal blooms (Turner *et al.*, 2003).

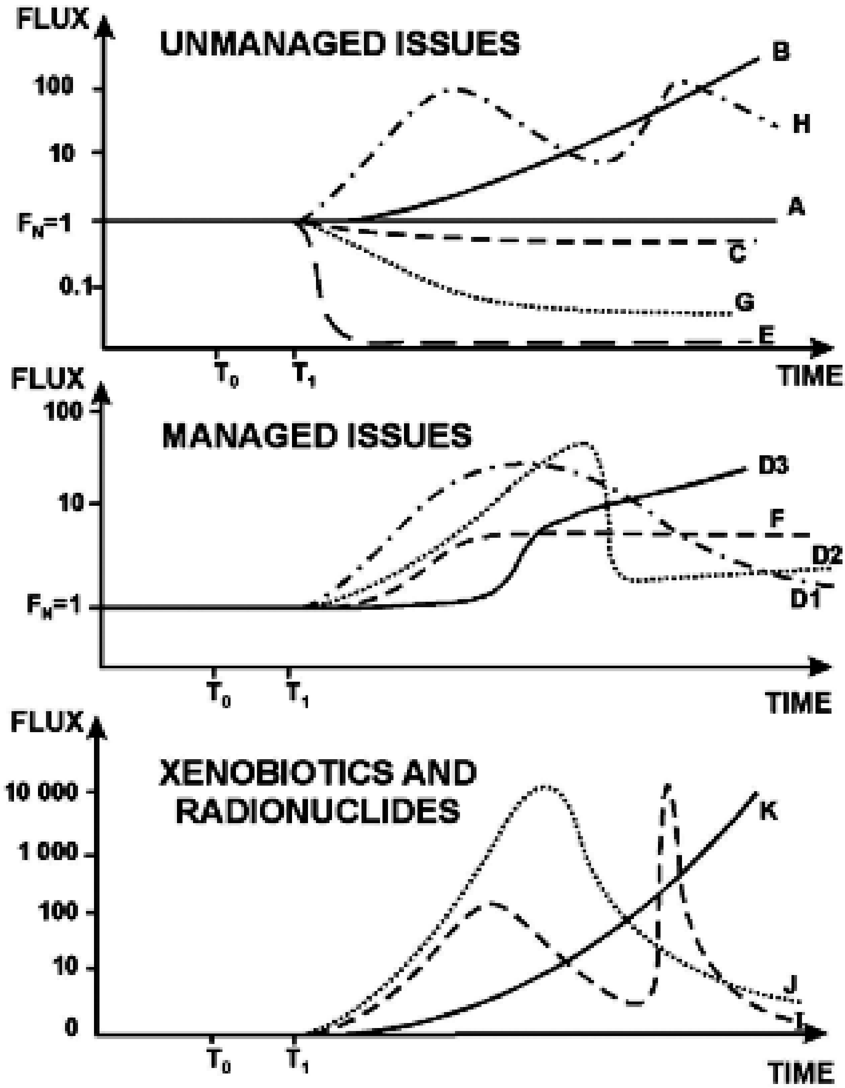

Figure 6. Types of river flux trends normalized to pristine fluxes (F_N) since the beginning of impacts (T_1) related to human pressures (T_0) (Meybeck, 2002).
– Unmanaged issues: A: stable evolution, B: gradual increase, C: partial retention, E: complete retention, G: gradual retention, H: multiple cycles (e.g. BOD_5)
– Managed issues: D1: bell-shaped control, D2: stepwise improvement, D3: stepwise degradation, F: stabilized contamination.
– Xenobiotics products: I: multiple cycles of some radionucleids, J: total ban (as for DDT), K: gradual xenobiotic contamination.

Very few chemical elements are barely affected by human activities and present a stable evolution (type A): most of them are not very related with health such as Ca^{2+}, Mg^{2+}, HCO_3^- or particulate Al, Fe, or Si. The *gradual increase* (type B) of many water-quality indicators corresponds to the development of pressures, for example, Na^+, Cl^-, K^+, NO_3^-, SO_4^{2-}.

Bell-shaped control (type D1) characterizes a successful and gradual control.

Stepwise improvement (D2) is characteristic of a sudden decrease of contaminant concentrations (dissolved and/or particulate) in river systems. These trends are essentially caused by a drastic reduction in contaminant point sources such as that caused by the construction of urban or industrial sewage treatment plants, or by the reduction or closure of economic activities during economic crises.

Stepwise degradation (D3) is the symmetric evolution corresponding to the installation of major industries, collection of urban sewage without subsequent treatment or to sudden change in land use.

Multiple cycles (type H) of contamination/improvement are often observed in very long series, as in sediment archives of metal contamination (e.g., Bronze Age, Roman and Renaissance).

Stabilized contamination (type F), i.e., very limited change over decades despite pressures, may result from long-term water quality protection, e.g., from international treaties for shared water bodies.

Xenobiotic pollutants have specific trends. The DDT evolution in the Northern Hemisphere CAS presents a gradual increase from flux zero, a marked peak, then a decrease after its ban in the early 1970s, but can still be detected in trace amounts in some rivers due to its great environmental persistence (*total ban*, type J). Herbicide contents, such as that of atrazine, increase generally (*gradual xenobiotic contamination*, type K) until they are finally regulated or the product is banned. For these less persistent products the decline may be rapid (a few years). Artificial radionuclides are often characterized by multiple cycles, as for the artificial radiocaesium in the Northern Hemisphere (*radioactive contamination*, type I) which peaked in 1962-1963, following trends of inputs into the atmosphere from nuclear tests, then again in 1986 after the Chernobyl accident.

Trends of river fluxes are very variable with patterns of both increase and decrease. A similar typology can also be used to describe concentration trends in rivers, lakes and reservoirs, estuaries, and, apart from trend types E and C, to describe groundwater contamination.

5.3. *Water Quality Management: Indicators of Societal Responses to Environmental Issues*

Riverine trends illustrate very different types of water quality management. They are a good example of complex and various societal responses to environmental change (Meybeck, 2002) from the absence of management to full management.

– *Unnecessary management*: water quality is not affected by human pressures; environmental or economic impacts are minimal and the rates of change are slow and predictable.

– *Unplanned improvement*: unexpected and/or unplanned decrease of contamination linked to the reduction of human pressures: closure of mines and industries, changes in technologies, economic crises.

– *Unperceived issue*: deterioration of water quality and/or its link to human pressure is not detected or perceived. Water-quality improvements are unplanned and result from the balance between pressure and natural river basin response. The scientific and technical progress of analytical chemistry has been a major regulator of the detection of water quality problems (Meybeck, 2005). The endocrine disruptors originating from drug residues in domestic wastes, hospital wastes, and veterinary wastes are now beginning to be detected in specific river surveys (Trajectory A, Figure 4), they will probably be regarded soon as an important issue.

– *Natural pressure endurance and suffering*: in some rarely-found geological and climatic conditions (see Section 1). Depending on the availability of alternative water resources, the uses of such resources may lead to limited or to severe health and/or economic impacts.

– *Precaution management*: environmental, health and economic impacts are kept to the minimum acceptable level. If action is taken too late, the level may first exceed the management target then is reduced, such cases are found in highly developed and environmentally aware countries. This type is still rarely found on the planet (Gilbertson, 2001).

– *Maximum impact management*: targeted at the maximum acceptable limit, commonly chosen in international treaties (e.g., salinity in the Rhine and Colorado).

– *Total ban*: ban on manufacturing and/or use of products; usually targeting xenobiotics only after severe problems have been detected, demonstrated and recognized by all stakeholders.

– *Delayed pollution regulation*: established after a period of lack of management and subsequent severe impacts; targeted levels are usually the maximum acceptable ones for economic reasons.

– *Laissez-faire*: although its severity is now well established and even studied, the situation has not yet been adequately tackled for multiple reasons: lack of environmental awareness or societal consensus for the level of severity, shortage of financial means, lack of environmental regulations or of political will to enforce them.

– *Natural pressure remediation*: direct treatment of unsuitable natural water resources (desalinization, defluorization, removal of arsenic).

– *Remediation of ancient contamination*: in most cases there is no present-day economic or administrative entity directly linked to the contamination ('orphan pollution'), which often occurred at times of 'unperceived issues' or of 'laissez-faire'. The corresponding restoration measures are very costly and rarely set up since they require environmental knowledge, societal consensus and financial means (Hines *et al.*, 2001).

– *Cyclic management*: over the very long term (50 to 100 yrs) water-quality presents multiple cycles of deterioration and improvements resulting from the complex interactions of human pressures, environmental impacts and human responses.

Water quality trends result from a combination of human pressures, hydrosystem responses to human pressures, development of social and societal awareness, advances in environmental science and in analytical techniques, political decision processes, financial, technical or policy means and finally, from the hydrosystem response to environmental control. Most of the documented trends concern the last 30 yrs only.

6. Global Assessment of Water Quality Issues

The global assessment of water quality is regularly required by international health programs as well as by Global Change programs (Vörösmarty *et al.*, 2005), although it remains very limited due to the type of information available. There is only one program, launched by UNEP and WHO in 1978, devoted to monitoring harmonization, analytical quality control, data collection and assessment at the global scale: the GEMS-Water program (www.gemswater.org; Robarts *et al.*, 2002). However, despite continuous efforts, the GEMS-Water database is insufficient for global analysis of many issues. Expert judgment based on dozens of country and regional reports and hundreds of publications must be used. However, there are structural limits to our knowledge of water quality: (i) the density of water quality stations is one to two orders of magnitude inferior to hydrological stations (river gauging and groundwater levels); (ii) the quality of the information is extremely variable ranging from a few basic parameters of limited relevance for human health to several dozens of chemicals including trace contaminants (see Section 4); (iii) survey frequency can limit the assessment of water quality.

The extent of water quality issues may be quite variable, even within one type of contaminant, as demonstrated below for the heavy metals. A tentative global analysis of issues is then proposed.

6.1. *Metal Pollution in River Particulates, an Example of Global Contamination Ranking*

Metals are identified as one of the most dangerous substances found in the environment for their toxic properties and their sensitivity to human pressures. When metals contaminate aquatic systems, they can affect humans through drinking water, aquatic biota and food. Cadmium intoxication (Itai-Itai disease) through contaminated rice, and mercury intoxication (Minamata disease) through contaminated coastal fish are some of the worst environmental issues ever reported and had a great impact on the creation of UNEP in 1972.

A global survey of metal contamination in river basins remains to be established (Salomons *et al.*, 1995). Even at the regional scale, as for Europe, the relevant data to assess the status of contamination are still very limited (Stanner and Bourdeau, 1995). Some synthetic assessments are made for some regions as in the USA (Rice, 1999) or for some specific elements such as cadmium (Cd), mercury (Hg) or arsenic (As). A global vision for other metals, copper (Cu), nickel (Ni), lead (Pb), zinc (Zn), chromium (Cr) and metalloids such as antimony (Sb) and tin (Sn) is difficult (Foster and Charlesworth, 1996; Salomons *et al.*, 1995). Finally, it must be noted that the analysis of metals in dissolved form is very difficult and the analyses from unfiltered waters, often used in the water quality industry, have little environmental meaning (Horowitz, 1995; Meybeck, 2005).

As a first global estimate, I am using here a set of analyses made on river basins from 10,000 km^2 to more than one million km^2 (Meybeck, in preparation). These analyses have been essentially published since 1980 and multi-elemental analytical techniques are used after a complete digestion of the river material. Several sets of stations have been used: (i) natural background stations (BGR) for which there is no or very limited human impact (they also include analysis of pre-industrial river deposits, from sediment archives); (ii) impacted stations (IMP) for which there is a known human pressure and (iii) undetermined stations (UND). Their combination constitutes the general set (GEN) which holds from 100 to 500 different analyses for a given element. In addition to the most toxic elements, I am also using silver (Ag), lithium (Li), beryllium (Be), barium (Ba), titanium (Ti), strontium (Sr), molybdenum (Mo) and phosphorus (P) for comparison. I also include a set of 10 to 15 multi-elemental urban sewage particulate analyses from all continents (SEW).

Using the medians (GEN_{50}, BGR_{50}) and upper deciles (IMP_{90}, BGR_{90}), I construct three indicators of global scale contamination (i) $I_A = GEN_{50}/BGR_{50}$ for the global sensitivity to contamination; (ii) $I_B = SEW_{50}/BGR_{90}$ for the global occurrence of a metal source in urban sewage and (iii) $I_C = IMP_{90}/BGR_{90}$ for the local occurrence of marked contamination. The three indicators are very convergent although they also express specificities for some elements (Table 7).

Many elements such as Ag, As, Ba, Be, Co, Li, Mo, Sr, Ti, and V are not globally affected by human activities. Human impact on Cr, Ni, P (particulate) and Sb is still very limited. This does not mean there is no impact at all at the local scale: the I_C indicator shows that the upper arsenic and phosphorus deciles of the general distribution are 3 to 5 times higher than high background values (upper decile of BGR set).

The elements that show the most evidence of environmental contamination are mercury, cadmium, possibly tin (to be confirmed on a larger data set), then copper, lead and zinc. These elements are also found at very high levels in at least 10% of documented stations, exceeding ten times the extreme background values ($I_C > 10$). Silver and copper are also often found locally at very high levels.

The analysis of sewage particulate matter (sludge) provides some clue to the origin of elements. Urban sources are very likely for silver, mercury, cadmium, zinc, copper, lead and phosphorus. Urban sludge is not a major source of contamination in rivers since it is actually diluted for As, Ba, Co, Li, Mo, Ni, Sr and V with regard to background levels in river particulates, probably due to the presence of large amounts of sewage organic material.

Other major sources of metals at the global scale include ore extraction and processing in mines and smelters (e.g., Pb, Zn, Ti, Cd) and plating (Cd, Cr, Hg) (see Figure 3 and Table 4). The assessment of the inorganic contamination should now be refined at the regional scale: the contamination orders may be different from those presented on Table 7 depending on the

TABLE 7. GLOBAL SCALE CONTAMINATIONS OF RIVER PARTICULATE MATTER FOR 19 ELEMENTS BASED ON THREE INDICATORS (IA, B, C). Statistics based on 100 to 500 river stations (Meybeck, in preparation).

A – Global sensitivity to contamination ($I_A = GEN_{50}/BGR_{50}$)

I_A	< 1.1	1.1 – 1.25	1.25 – 1.5	1.5 – 1.75	> 1.75
	no effect	some effect	low contamination	medium contamination	high contamination
	Ag	Cr	Cu	Cd	Hg
	As	Ni	Pb	(Sn)	
	Ba	P	Zn		
	Be	Sb			
	Co				
	Li				
	Mo				
	Sr				
	Ti				
	V				

B – Occurrence of metal source in urban sewage ($I_B = SEW_{50}/BGR_{90}$)

I_B	< 1	1 – 2	2 – 5	5 – 10	10 - 20	> 20
	no source	limited source	some source	important source	high source	essential source
	As	Cr	(Sn)	Cd	Hg	Ag
	Ba	Sb		Cu		
	Be			P		
	Co			Pb		
	Li			Zn		
	Mo					
	Ni					
	Sr					
	V					

C – Local occurrence of marked contamination ($I_C = IMP_{90}/BGR_{90}$)

I_C	< 1.5	1.5 – 3	3 – 5	5 – 10	10 - 20	20 - 50	> 50
	not likely	very limited	limited	common	very common	common hotspots	very common hotspots
	Ba	Co	As	Cr	Cu	Hg	Ag
	Be	Ni	P	Sb	Pb	Zn	Cd
	Li	Ti					Sn
	Mo	V					
	Sr						

Note: Sn on 60 rivers only; As contamination is better assessed on dissolved As.

human pressures ratio mining:industrial:urban. This can only be done on the basis of systematic sampling of river particulates such as has been done for the past twenty years for the conterminous USA (Rice, 1999; Horowitz *et al.*, 2001).

6.2. *Global Ranking of Water Quality Issues Based on Regional Assessment*

The first global assessment of water quality (Meybeck *et al.*, 1989) already pointed out our fragmented information on water quality at the global scale. A second attempt has been made with the Dublin International Conference on Water and the Environment (ICWE) (Meybeck *et al.*, 1991). It has been recently updated for the Millennium Assessment (Vörösmarty *et al.*, 2005).

Eleven variables are considered and ranked: fecal pathogenic agents, organic matter (oxygen-consuming, also termed carbonaceous pollution), salinization, nitrate (as a contaminant), fluoride (mostly from natural sources), eutrophication (and/or nutrient levels), pesticides, industrial organics (PAH, PCB, petroleum products, etc.), heavy metals, suspended sediment (as limiting water uses), and acidification (may occur only if the natural buffering capacity of soils is low). The scoring ultimately reflects the aggregate impact of human pressures, natural rates of self-purification and pollution control measures (Figure 7).

Updated results show that *pathogens and organic matter pollution are still the two most pressing global issues* (Figure 7), reflecting the widespread lack of waste treatment. As water is often used and reused in a drainage basin context, a suite of attendant public health problems arise, thus directly affecting human well-being. At the other extreme, acidification is ranked #10 and fluoride pollution #11 on the global scale.

At the regional scale, any issue can be important or severe, e.g., acidification in Northern Europe and Northeast North America, salinization for the Arabian peninsula, fluoride in the Sahel or the African Great Lakes (see maximum scores reached on Figure 7). Fluoride and salinization issues are mostly due to natural conditions (rock types and climate), but mining-related salinization can also be found (e.g., W. Europe), and salinization can be enhanced by irrigation returns to CAS as in the Aral Sea basin (Aladin *et al.*, 2004). Other issues are directly caused by human impacts. It is important to note that in many regions of the world still under limited human pressures, many of these issues have been judged as negligible.

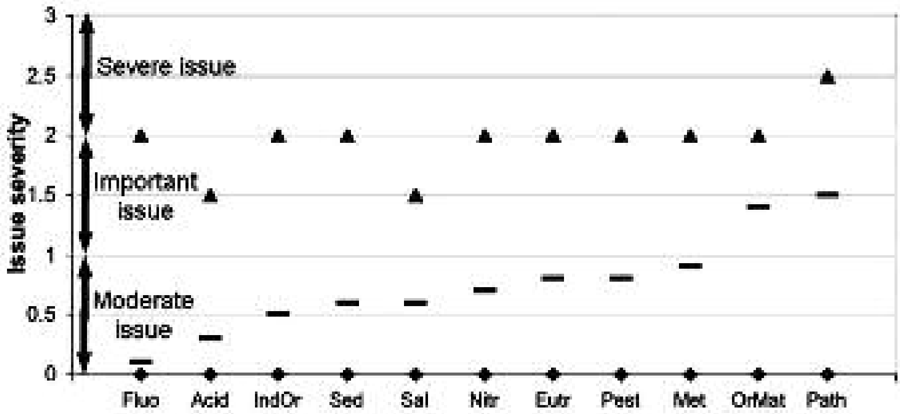

Figure 7. A tentative ranking of globally significant water quality issues based on expert judgement for ▬ regional assessment (typically 108 km²). (The information base upon which to quantify the degree to which water supplies are compromised is currently insufficient). (Fl = Fluoride; Acid = acidification; IndOr = industrial organics; Sed = suspended sediment; Sal = salinisation; Nitr = nitrate as a contaminant; Eutr = eutrophication and/or nutrient levels; Pest = pesticides; Met = heavy metals; OrMat = organic matter; Path = pathogenic agents). (Issue severity rank: 0= No problem or irrelevant, 1= Some pollution: water can be used if appropriate measures are taken, 2= Major pollution: impacts on human health and/or economic use, or aquatic biota is important, 3= Severe pollution: impacts are very high, losses concern human health and/or economy and/or biological integrity, ND= Could not be assessed (mostly for industrial pollutants). ▲ Maximum issue severity reached at the regional level, ◆ Average issue level at global scale, ▬ Minimum issue severity observed (modified from Revenga *et al*., 2005).

6.3. *Human Impacts on Continental Aquatic Systems within an Earth System Analysis; the River Syndromes*

Changes occurring in continental aquatic systems will also generate indirect effects on human health through their participation in global environmental change, i.e., river fluxes and concentration of carbon, nutrients and contaminants in aquatic systems (Tables 2, 4 and 5, columns B to G). Human activities are generating fast impacts, which can be organized into 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 10 river syndromes (Meybeck, 2003a,b): flow regulation, fragmentation of river course, riverbed silting, desiccation, chemical contamination, acidification, eutrophication and microbial contamination, and to land subsidence and groundwater over-pumping in deltas. Other syndromes, such as thermal regime alteration, radio-nuclide contamination, and biological invasion, are likely to occur, but will not be discussed here. Each syndrome is defined by a set of symptoms and causes and can be illustrated from well-studied river basins. The desiccation syndrome (originally termed neoarheism by Meybeck, 2003b) corresponds to the drastic reduction of river flow and/or lake area due to water diversion and water use, particularly for irrigation as observed in the Amu Darya basin (Kayunov, 2004). It is here understood as a flow or area reduction of at least 50% with regards to previous average.

The modification of river systems, either natural or anthropogenic, can be analyzed from both Earth System's and water resources' perspectives, including health aspects. River syndromes affect:

(i) 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 up-welling, and deep ocean water formation;

(iii) carbon balance, 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), and CO_2 release by wetlands and large rivers;

(iv) the nutrient balance of nitrogen, phosphorus and silica species which control level and type of aquatic primary production (e.g., diatoms vs. cyanobacteria);

(v) emission of green house gases; and

(vi) the aquatic biodiversity and trophic balance of continental and coastal systems.

The ecological responses of continental aquatic systems to these syndromes are not developed here, except for eutrophication, although their extension and importance is now more and more established (Revenga *et al.*, 1998; WCMC, 1998; Rabalais and Turner, 2001).

The syndromes are examined in Table 8, where example rivers and the relative alteration of Earth System functions are given. They generally occur at medium (10-50 years) to long-term time scales (> 50 years) (with reference to 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 (teleconnections over 1,000 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 maximum with a 50 to 100 years time-lag after construction of the reservoir and last as long as the reservoir, i.e., hundreds of years. The response of river bio-coenoses and of its biodiversity, therefore of diseases vectors, to changes may be rapid (i.e., damming effect on migratory species) or slow (e.g., species invasion through 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.

Desiccation is one of the most spectacular syndromes (more than 90% flow reduction for the Colorado, Nile, and Amu Darya, 80 % reduction for the Indus, seasonal desiccation of the Huang He, etc.). It is caused by consumptive water use, especially in large-scale irrigation in arid and semi-arid areas, estimated to be *ca.* 4,000 $km^3.y^{-1}$ (Gleick *et al.*, 2001), i.e., *ca.* 10% of the natural river water flux to oceans, and should be considered in Global Climate Models.

Both positive and negative impacts are noted for human health (Table 8). The positive impacts essentially concern water quantity: water storage for drought protection, reduction of extreme flows and increased flow regularity have been permanent targets for civil engineers for millennia. Some water-related health hazards have also been reduced by land use changes such as wetland reclamation and pesticide use against malaria or onchocercosis (Holland and Peterson, 1995). The trapping of contaminated particulate matter in river systems can be also regarded as positive if permanent. The negative impacts of river syndromes on aquatic resources mostly concern water quality (see Table 4).

The direct impacts of human activities on aquatic systems with regards to health issues are very diverse, mixing negative impacts, mostly a degradation of water quality and a loss of river dilution power, with positive impacts such as flood and drought regulation, settling and processing of particulate contaminants, and attached pathogens in reservoirs. Impacts on Earth System functions are multiple and occur sometimes at very broad temporal and spatial scales. The present global distribution of these river syndromes will have to be established.

TABLE 8. MAJOR SYNDROMES OF CHANGES IN AQUATIC SYSTEMS AND RELATED HEALTH ISSUES (modified from Meybeck, 2003b).

Syndrome(1)	Coding (2)	Examples	Health issues	Global Health impacts
Acidification(*)	R (Z)	Scandinavia, Kola P., E. Ontario, Quebec, Pennsylvania	• increased Al^{3+} and dissolved heavy metals	*
Faecal contamination	T	Most W. Europe rivers in mid 1900's; Brazil (Piracicaba), India (e.g. Yamuna); populated China, etc.	• Waterborne pathogens	+++
Chemical contamination(***)	U	as for faecal contaminants	• Anoxic waters; ammonia; H_2S	***
	Q	Most W. Europe rivers (1950-1980), Kola peninsula rivers, Don	• Increased metals contents	0 to ***
	L	W Europe, China, India; many aquifers	• Nitrate contamination	***
	M, Q	W. Europe rivers, Mississippi	• Xenobiotics occurrence	** to ***
	Q, X	Idrija R., Rio Tinto, Coeur d'Alene L., Love Canal	• Persistent pollutants; leaks from Historical pollution	*
Salinization(**)	G	Amu Darya, Syr Daria, Colorado, Murray Rivers	• Increased salt contents	**
	G (Q)	Rhine, Weser, mining districts		
Eutrophication(**)	L, Δ5	W. Europe rivers (Rhine, Seine, Loire), Volga; Mississippi, Danube deltas; North Sea, Brittany coastal zones	• Harmful algal blooms	*
Flow regulation(**)	C	Most European and US rivers, most dammed rivers (Moscowa, Nile, Indus, Parana, Murray Rivers)	• Flood plain area reduction: loss of vector-borne wetlands	++
	O_1-O_2	Colorado, Rio Grande, Columbia, Missouri, Volga, Dniepr, Murray, Bay James, Orange, Sao Francisco Rivers	• Reduction of flood/droughts hazards	+++
Damming and fragmentation(***)	H	Colorado, Rio Grande, Columbia, Missouri, Volga, Dniepr, Murray, Bay James, Orange, Sao Francisco Rivers	• Trapping of microorganisms attached to particulates	+++
	H	Colorado, Rio Grande, Columbia, Missouri, Volga, Dniepr, Murray, Bay James, Orange, Sao Francisco Rivers	• Trapping of particulate contaminants	+++
	P_1	Colorado, Rio Grande, Columbia, Missouri, Volga, Dniepr, Murray, Bay James, Orange, Sao Francisco Rivers	• Creation of new wetlands	*
Change of sediment balance(**)	J	Huang He, Kotri (Nepal); Madagascar rivers; most small tropical island rivers; Queensland rivers; New Guinea rivers	• Accelerated erosion and transfer of microorganisms	*
	Δ3	many tropical islands; Queensland	• Coastal silting and coral die out	?
	B	Huang He	• River course shifting: flooding hazards	**
Dessication(**)	A	Huang He; Amu Darya; Syr Darya	• Shift from permanent flow to seasonal drought; major reduction of annual flow: loss of dilution power	**
	V	Colorado, Rio Grande, Nile, Indus, Huang He, Amu Darya, Syr Darya, Shattal Arab, Ebro, Orange	• Marked to total reduction of material fluxes at river mouth: trapping of contaminants on land	++
	P_2	Lake Nasser; L. Kariba; L. Volta	• Creation of wetlands in irrigated area	*
Delta subsidence(*)	Δ7	Mississippi, Rhone, Indus	• Salinization	*
Groundwater abstraction(*)	Y	Bengal aquifer	• Remobilisation of arsenic	**

Health issues degradation: * locally important, ** regionally important, *** globally important; Health issues improvement: + (some improvement) to +++ (major improvement) (1)Global impact on Earth System functions: * locally important, ** regionally important, *** globally important (2)Coding refers to Figure 1 and Tables 1, 2, 3.

7. Future Evolution of Aquatic Systems

The global picture of aquatic systems in the next 50 or 100 years is still very fuzzy. There are now growing efforts to model some issues or syndromes at the global scale as is done for nutrients and carbon river fluxes. These models are originally based on multi-regression analysis linking human pressures and the resulting state of river quality. Mixed models now integrate pressures, river basin filters and water routing (e.g., Green *et al.*, 2004). A new generation of process-based models is now developed at the basin scale for nutrients (Billen *et al.*, 2001) but their application at the global scale will be difficult for lack of basic data at the appropriate resolution. As for the Global Climate Models (GCM), these models will be our tools to explore the future of aquatic systems. They should be validated first on the present situation. Yet the available data on aquatic systems is often relatively short-term, particularly concerning water quality. Considering the scales of responses of aquatic systems to climate variations during the last thousand years and to human activities, long-term evolutions (> 100 y) are also needed to validate the river basin models. They will have to be established using a combination of methods now developed by the paleohydrology community (PAGES-LUCIFS, 2000). Once these models are validated they will be used to explore the future, combining GCM scenarios, scenarios of water use, and scenarios of human responses to changes. The validity of the prediction will greatly depend on the model resolution (2° for most GCM, 0.5° for most river flux models).

7.1. *General Evolution of Human Pressures and Responses*

The timing of global human pressures, environmental impacts and societal responses is schematically depicted in Figure 8 (Meybeck, 2003b and Meybeck *et al.*, 2004).

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, but there are growing efforts in reconstruction of historical land use 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. An 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 kilometers away from emission sources. These statements should not imply that all riverine impacts are now globally significant (see previous section). In fact, most well documented impacts on aquatic systems are local to regional. Since the majority of human induced sources of pressure on the CAS have had an exponential rate of increase over the last two hundred 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 8.

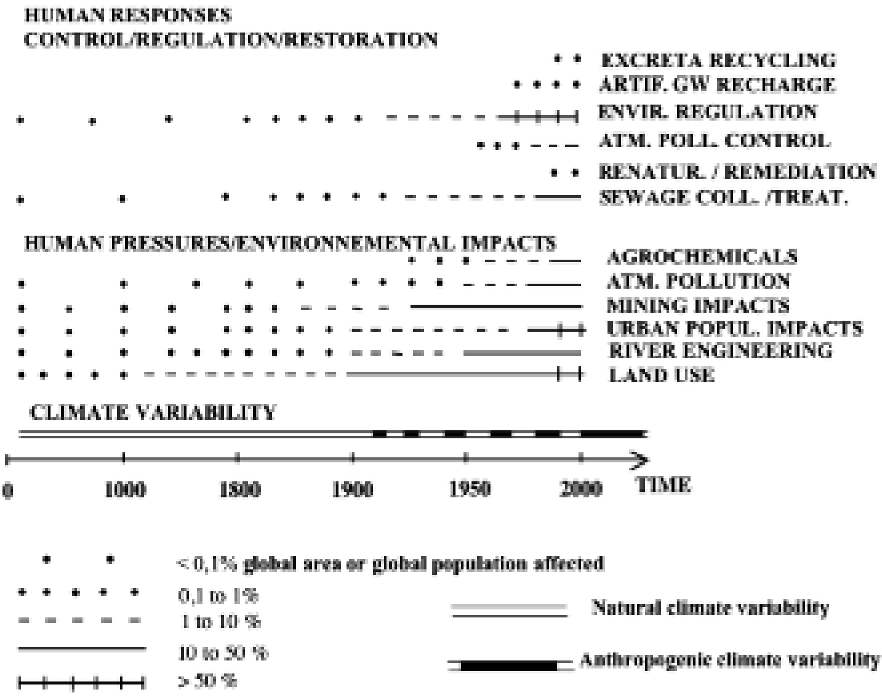

Figure 8. Working hypotheses on the occurrence of some major pressures on continental aquatic systems at the global scale and related environmental remediation responses (accelerated time scale) (Meybeck, 2003b).

The key-control of river impacts is the relative timing of human pressures and societal responses, such as policy and regulation, emission control, and restoration, as has been developed for chemical contamination. As seen before, these responses have generally been developed with a considerable lag related to pressures.

7.2. *Contrasted Historical Evolution of Continental Aquatic Systems*

The past evolution of CAS may be very different from one region to another. The reconstruction of trajectories of these environmental changes is essential to avoid present-day mismanagement, and to consider environmental issues on a long-term basis, i.e., more than 50 years (Harremoes *et al.*, 2001). River basin evolution has been rarely addressed so far (Schwartz *et al.*, 1990; Messerli *et al.*, 2000; Vörösmarty and Meybeck, 2004), although this field is now covered by the IGBP-PAGES programme (PAGES-LUCIFS, 2000).

Reconstruction of historical interactions between human and aquatic systems is based on four types of information:

(i) *Sedimentary archives (10^2 to 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) as performed at the global scale by the IGPP-PAGES LUCIFS project (Meybeck *et al.*, 2004). More recent archives (10-100 yrs) can be obtained from reservoirs;

(ii) *Archaeological and historical archives* give valuable information on river systems and their uses and on societal responses to river basin changes (Guillerme, 1983; Schwartz *et al.*, 1990). The longest and most promising historical records of man and river interactions are probably found in China (Elvin, 1993; Elvin and Liu, 1998) and in Egypt;

(iii) *Direct observations*: date back to the early 1800s, and the earliest regular river surveys started before the 1900s;

(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 (Billen *et al.*, 2001).

Two examples of working hypotheses for past river evolution are presented here (Figure 9) for Western Europe, an example of very ancient impacts, and South America for recent ones (Meybeck, 2003b). Four river quality indicators specifically related to health issues are proposed here, using an accelerated time scale, reflecting the evolution of some human impacts: organic and fecal contamination (Figure 9, 1), heavy metals (2), nitrate (3), and pesticides (4). As in Section 5, a simplified issue severity scale in three steps is used here, where C_N is the natural or pristine concentration, C_R a first threshold above which environmental impact, health issues, cultural or economic loss are occurring, and C_L a second threshold above which severe impacts are occurring.

In Western Europe (Figure 9), the earliest changes in river chemistry and assumed severe impacts have been recorded for metals in mining districts (4) as early as the Bronze age period (~4500 yrs B.P.) as in the Rio Odiel, Spain (Leblanc *et al.*, 2000), with maximum levels of Hg, Pb and Zn equivalent to those found presently in some highly contaminated European rivers. Such mining impact is likely to have been very localized: larger basins were probably much less contaminated. Other examples of metal contamination from mining are documented for Roman times (Wales rivers and Humber catchment, England; Macklin *et al.*, 1997), the Middle Age in Central Germany (Goslar), and in the 1700s in Brittany. Modern contamination peaks have been observed in the mid-19th century then in the 20th century as in the Rhine and Meuse rivers (Middlekoop, 1997). The most recent metal contamination generally peaked in most Western European rivers between 1950 and 1980.

Organic and fecal contaminations (1) can be multi-cyclic as is well documented for the last 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 European rivers, the maximum general contamination was noted in the 1950s and 1960s when the sewage collection rate increased, yet without appropriate waste water treatment which was generalized in the 1970s and 1980s. This evolution is well documented through oxygen demand, ammonia and fecal coliforms, which peaked during the 1950-1970 period.

Nitrate contamination has gradually developed after World War II following the general use of fertilizers in intensive agriculture (Cole *et al.*, 1993). In Western Europe, it is now approaching the severe impact level (50 mg NO_3^-/L) set by WHO 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, had already been exceeded in the 1960s to 1970s. As a consequence, severe coastal algal blooms 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 (4) has been rapidly growing since the 1970s and, in a given medium-sized basin such as the Seine's, over 100 different active molecules might be used (Chevreuil *et al.*, 1998). The use of such xenobiotic substances is now more and more regulated in Western Europe and North America.

In South America, the expected evolution of river chemistry is somewhat different (Figure 9, lower part). Riverine quality is not likely to have changed much prior to the arrival of European settlers, except for limited

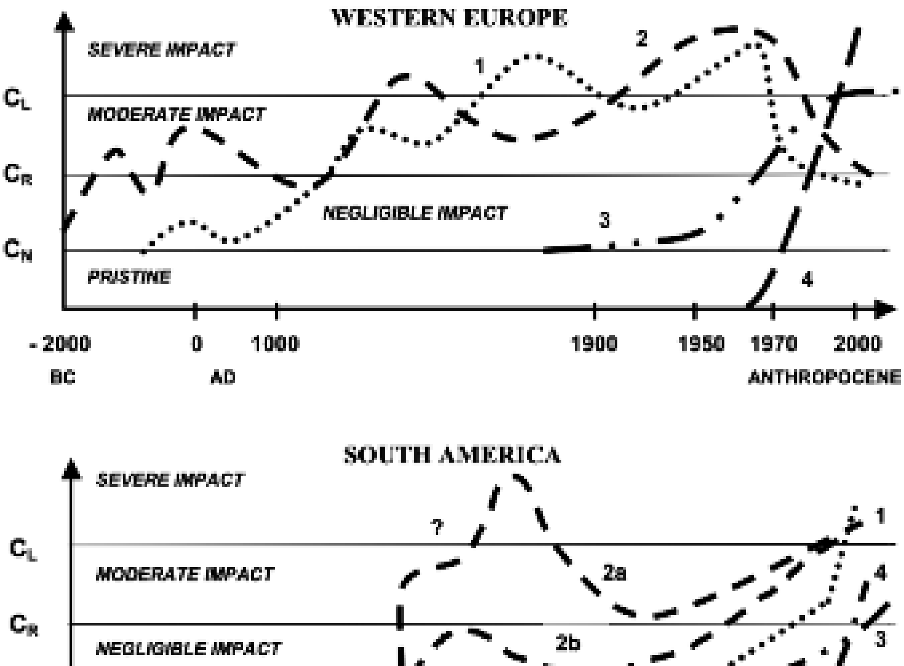

Figure 9. Working hypotheses on the evolution of some chemical contamination indicators in medium-sized Western Europe and in South American river basins. (1): organic and faecal contaminations. (2): metal contamination. (3): nitrate contamination. (4): pesticides. Accelerated time scale. C_N, C_R, C_L: natural, recommended and limit levels for related uses. South America: 2a = evolution of basins affected by Colonial American mining, 2b = other South American rivers (Meybeck, 2003b).

agricultural land-use impacts from Pre-Columbian civilizations for example on river sediment fluxes. A very slight atmospheric lead contamination during the Roman times is theoretically possible since 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), although less likely to have impacted the Southern Hemisphere. The most striking possible feature of human impacts on South American rivers can be found in Peru and Bolivia (2a): the gold and silver mining and the mercury amalgamation performed by the Spanish settlers since the mid-1500s (Brading and Cross, 1972) have probably generated an enormous direct and indirect mercury contamination via atmospheric pathways (Lacerda *et al.*, 1999), which remains to be validated using sediment archives.

In other South American regions, riverine changes are likely to have occurred mostly over the last 50 yrs but will probably be much faster than in Europe. Organic pollution, toxic metals, and xenobiotics contamination are probably now reaching their maximum levels, due to the growing imbalance between pressures and environmental regulation. Examples are the Piracicaba River in Sao Paulo state (Mariely *et al.*, 2002) and other Brazilian rivers (Knoppers *et al.*, 1999).

7.3. *Possible Scenarios for the Future Contamination of Rivers*

The evolution of rivers over the past 2,000 years can help us to foresee some possible future scenarios of water quality for the next 50 years. Although the precise evolution of rivers will be basin-specific, a schematic trend is proposed here as a working hypothesis and illustrated for chemical contamination (Figure 10). It is probably valid for other river syndromes.

Human pressures have started at a very local scale. There is an inverse relationship between the impact severity and the spatial scale of contamination (Meybeck *et al.*, 1989, 2004). Chemical contamination was still very limited some 2,000 years ago and likely occurred at the local scale only ($< 10^4$ km^2). Two hundred years ago, most chemical contamination symptoms were moderately developed at the regional scale. In the mid-19th century, chemical contamination reached a moderate to severe level in some regions of Western Europe and in parts of the Eastern USA, but was still negligible on many continents, while the transfer of atmospheric pollutants over long distance was already limiting the occurrence of truly pristine basins. In the present Anthropocene period, river chemical contamination is now widespread and the occurrence of very severe contamination levels at the local scale is well documented as has been demonstrated for some metals (Table 7) (mega-cities, historical pollutions, mining and smelting districts, etc).

Three main future scenarios (2000-2050) are envisaged here (Figure 10):

(i) *Business as usual and Laissez-Faire* (Figure 10, Curve A): although regulation/restoration responses may be developing on all continents, human pressure is still increasing rapidly. The global contamination and the artificialization of continental aquatic systems accelerate, leading to a generalized degradation of aquatic habitat and an expected response of aquatic biota, 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 and in the Former Soviet Union (Kimstach *et al.*, 1998), and in most fast-developing countries such as in China (Wang *et al.*, 2000), Brazil, and India (Meybeck *et al.*, 1991);

(ii) *Priority reduction of river impact hot spots* (Figure 10, Curve 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 10, Curve C): in addition to the previous management rule, human impacts, either direct or indirect, are generally limited to the lowest acceptable impact. This type of policy is now being developed by the European Union in its new Water Framework Directive. It has been favored for two to three decades by some countries such as the Scandinavian countries, Switzerland, and Canada. However, in such a scenario, some moderate and even severe impacts are likely to remain at the local level due to structural factors (e.g., a mega-city located on a small watershed with limited dilution power). This policy requires a combination of citizen awareness, water literacy, scientific and technical knowledge, political will and financial means, which is unlikely to be found everywhere.

These scenarios should now be combined with water runoff and river flow scenarios resulting from Global Climate Models (GCM), and with water use and water engineering scenarios. The occurrence and future development of dams, water diversions and irrigation will greatly influence the dis-

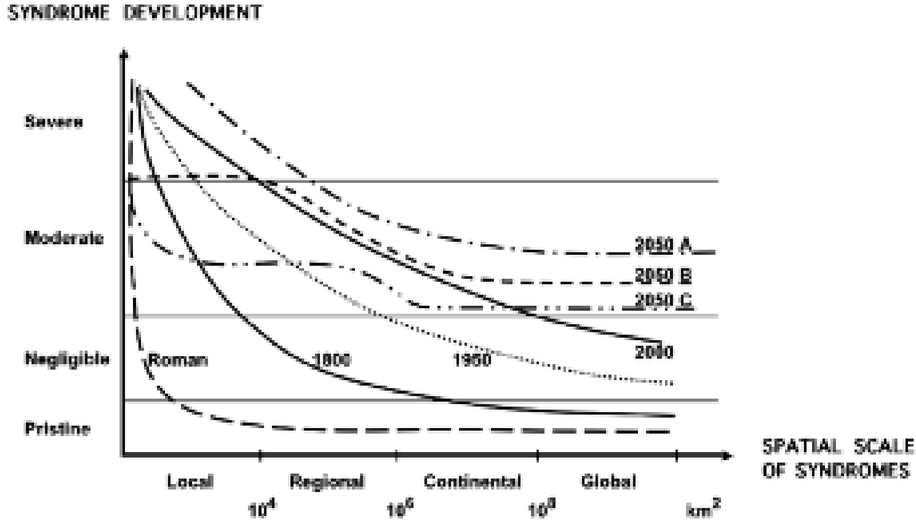

Figure 10. Schematic evolution of the chemical contamination from point sources at different space scales from Roman period to contemporary. Scenarios for year 2050 correspond to (A) business as usual, (B) priority reduction of the most polluted sites, (C) a general application of precaution principle (Meybeck, 2003b).

tribution types of water bodies, their ecological functions (Petts, 1984) and quality, as well as river fluxes. Some fluxes of materials (nitrogen, phosphorus, mercury, cadmium) across river systems and to oceans have increased already much beyond the natural Holocene variations. Others, such as sediments, are probably stable (Walling and Fang, 2003) despite an acceleration of sources, due to a simultaneous acceleration of retention in riverine filters principally reservoirs. A global decrease of silica concentration levels and fluxes to the coastal zone is now likely. These changes are resulting in marked impacts on coastal biogeochemistry (Rabouille *et al.*, 2001) and food webs (Rabalais and Turner, 2001). These contrasted Earth System modifications will have long-term impacts on both water resources and human health although these cannot yet be assessed.

The continental aquatic systems are now shared by the natural and human components of the Earth System (Crutzen, 2002; Steffen *et al.*, 2004; Meybeck, 2002, 2003b). Their analysis can be made using the OECD Driver-Pressures-State-Impact-Response (DPSIR) already used in some environmental studies such as coastal zone management (Turner and Bower, 1999; von Bodungen and Turner, 2000; Crossland *et al*., 2005).

Natural Earth System drivers are climate change and sea level rise, natural climate variability and tectonic forcings (Figure 11, right part). Human drivers such as population increase, economic and technical developments, lead to the increased exploitation of natural resources generating multiple pressures such as water use, waste release, land use, biomass use, increasing development of xenobiotics, and river flow regulation. These pressures modify the state of the Earth System and, in turn, have multiple impacts on water resources. The combined changes of aquatic systems are part of the general modification of the Earth System through alteration of water fluxes, both vertical and lateral, green house gas emissions and river borne fluxes. They occur at various time scales from years or shorter (vertical fluxes to the atmosphere) to hundred of years and more (lateral fluxes of particulates). The coastal response to modified river fluxes may also range from decades to a hundred years and more.

On the human side (Figure 11, left part), these modifications of Continental Aquatic Systems are generating both negative impacts (Figure 11, lower left) and positive impacts (water supply security and drought control, secured communications through waterways, decrease of water-borne and water-related diseases, flood control). The assessment of the evolution of continental aquatic systems (CAS) under Global Change combines multiple degrees of complexity, which are just beginning to be addressed (GWSP, 2005). The health issues related to the evolution of aquatic systems must be addressed at sub-regional to local scales due to their spatial heterogeneity and to the variety of human responses, which can take decades in most cases. The first global scale models of water quality now established for nitrogen and phosphorus at 30’x30’ resolution (i.e., 50x50 km at the equator) already show an enormous heterogeneity. This scale is sufficient for global assessment but not for local management. The analysis of water quality trends and the construction of hypotheses about their historical variation also reveal the complex interactions of humans and water bodies, which vary from one river basin to another although regional patterns are likely.

The future of human development will greatly depend on how we will balance these negative and positive aspects. This will require new approaches (e.g., the Earth System analysis with its teleconnection and delayed impacts should now be considered in the Integrated River Basin Management) and new concepts such as hydrosolidarity and water literacy will have to be considered (Falkenmark, 1997; Lundqvist and Falkenmark, 2000; Falkenmark and Lundqvist, 1998). This multidisciplinary field is now wide open.

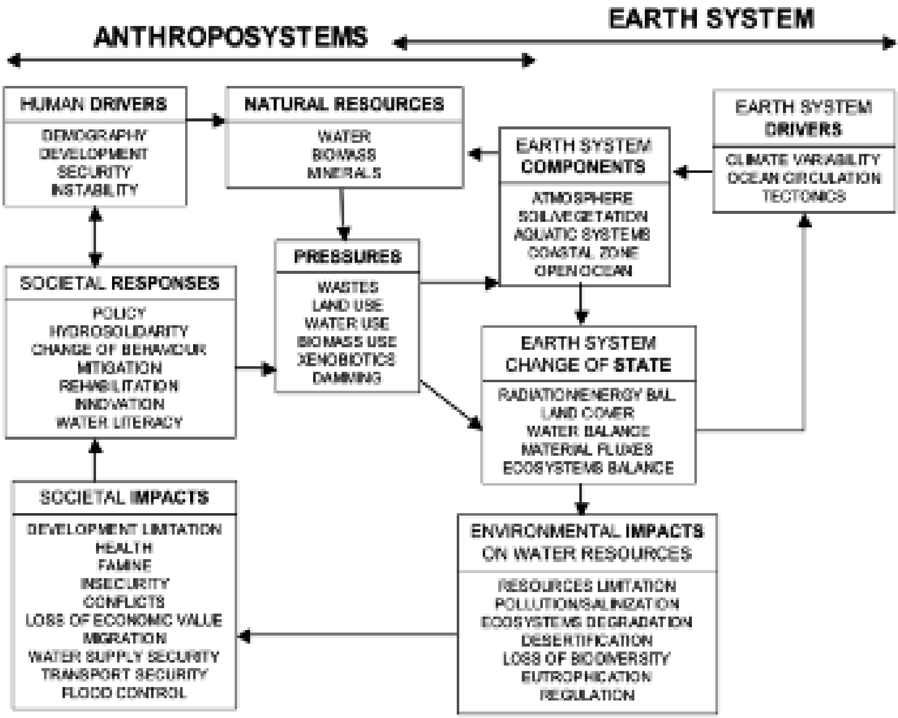

Figure 11. The Driver-Pressure-State-Impact-Response cycle on continental aquatic systems (modified from Salomons *et al.*, 1999 and Falkenmark *et al.*, 1999).

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