

## The global change of continental aquatic systems: dominant impacts of human activities

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**Abstract** Continental aquatic systems, particularly rivers, are exposed to major changes due to human pressures. Some changes are voluntary such as flow regulation and the fragmentation of river courses, both due to damming, or the water consumption particularly in dry regions, which results in a partial to complete dry-up of some rivers (neo-arheism). Other changes result from indirect impacts of other human activities, and include: sediment unbalance of river systems, chemical contamination, acidification, eutrophication, thermal unbalance, radioactive contamination, microbial contamination, and aquatic species introduction/invasion. These changes can be regarded as syndromes which have now reached a global amplitude, even in less populated regions, as the result of damming, mining and of long-range atmospheric pollution, thus defining a new era, the Anthropocene, where continental aquatic systems are no longer controlled by earth systems processes but by human activities. Each region of the globe has developed specific patterns of syndromes trajectories that can be reconstructed from historical analysis and through environmental archives. These trajectories reveal multiple types of human responses to aquatic environmental issues (e.g. water quality), usually lasting 10 to 50 years for the successful ones. The reactions of the earth system to such major changes of fluxes (water, energy, nutrients, carbon, pollutants) via the continental waterscape, the land-ocean interactions, the water bodies-atmosphere interactions, are likely to take place over a longer time scale (100–1,000 years) yet are poorly addressed by scientists and not considered in Integrated Water Management, particularly as concerns the coastal zone.

**Keywords** Anthropocene; aquatic systems; global change syndromes; neo-arheism; rivers

### Introduction

Human pressures on aquatic continental systems (rivers, lakes, wetlands, soil-groundwaters, coastal marshes and estuaries) have resulted in a set of global scale syndromes of changes. These changes greatly affect the water resources, particularly the water quality and the aquatic biota. They are also modifying, generally over longer time scales, the functioning of the earth system in which riverine fluxes of water, materials and energy are playing an important role. The consideration of both water resources and water as a key element of the earth system should now be taken into account in integrated water management from local to regional scales. The relationship between humans and water is a complex one that started 5,000 years ago in some hydraulic civilizations in the Nile, Huang-He, Indus valley and in Mesopotamia, while in some other regions of the world the impact of human activities on continental aquatic systems has just started. The syndromes of global river changes are fully developed in Meybeck (2003); examples of the complex relations between humans and aquatic systems have been presented previously (Meybeck, 2002) with a focus on the Seine basin. This paper is a summary of both approaches and also refers to two concepts: the Anthropocene and the Anthroposphere.

In more than half of the world the human pressures are now the major drivers of the functioning of aquatic systems. The term **Anthropocene** has been recently reused in earth system science by Crutzen and Stoermer (2000) to qualify this new era, following a proposition made by Vernadski, a Russian scientist, in 1926. The **Anthroposphere** is here understood as “man’s sphere of life, a complex system of energy, material and information

fluxes. It is part of the Earth's biosphere and (behaves) as a living organism. It includes the uptake, transport and storage of all substances, the total chemical transformation within (this) organism, the quantity and quality of all refuses" (Baccini and Brunner, 1991, p.1).

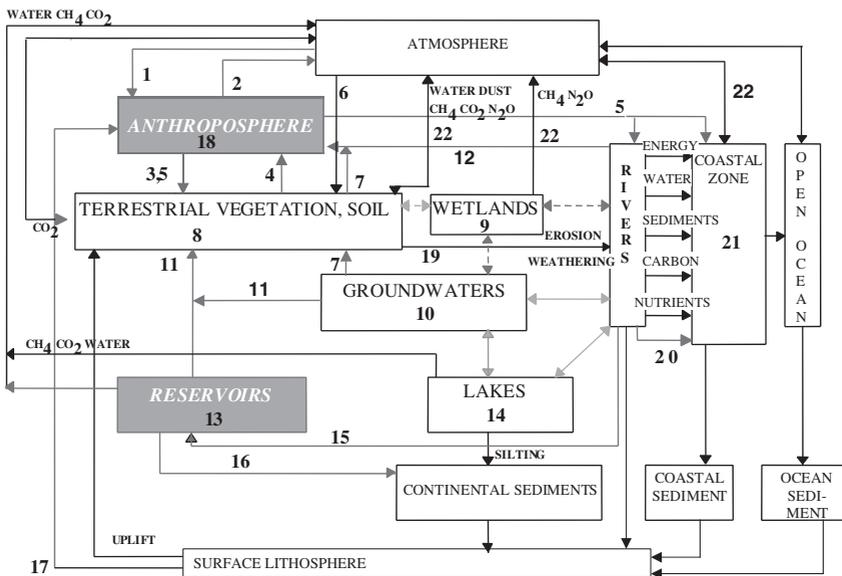
### Continental aquatic systems in present day earth system

The indirect human pressures on aquatic systems are multiple: land use (agriculture, forestry), mining and energy production from fossil fuels, urbanisation, industrial transformation of material resulting from earth mining, agriculture, and from nitrogen fixation (ammonia chemistry as N fertilisers). All these activities greatly modify the water quality and, for some of them, the water cycle. Another set of human activities is directly targeted at aquatic resources such as the construction and operation of dams, the irrigation from surface and groundwater, the channelization and dredging of waterways. Human activities have also greatly modified the wetlands in many parts of the world and have created artificial water bodies such as reservoirs and canals. These changes are schematised in Figure 1.

The Anthroposphere should now be the central component of the multiple controls on continental aquatic systems, and most fluxes of water, dissolved and particulate matter across river systems and from rivers to oceans and internal seas have been greatly modified regionally and, for some water-borne materials, globally. These changes can be described by a set of syndromes of river changes.

### Syndromes of river changes

The concept of global syndromes has been developed by the German Advisory Council on Global Change (GACGC, 2000) as "typical patterns of problematic people-environment interactions which can be identified as regional profiles of damage to human society and



**Figure 1** Continental aquatic systems in present day earth system. In black: natural fluxes and pathways of material. In grey: major impacts of human activities. 1 = N fixation, 2 = water consumption, 3 = fertilisation, 4 = food and fibre consumption, 5 = waste release, 6 = atmospheric pollutants fallout, 7 = water abstraction and diversion, 8 = land use (deforestation, cropping, urbanisation), 9 = draining, 10 = salinization, contamination, depletion, 11 = irrigation, 12 = diversion, 13 = evaporation, regulation, eutrophication, 14 = eutrophication, 15 = damming, water storage, diversion, 16 = silting, 17 = mining, 18 = industrial transformation, 19 = enhanced soil erosion, 20 = xenobiotics fluxes, 21 = changes of inputs to coastal zone, 22 = changes in greenhouse gases emission (Meybeck, 2003, © Royal Society, with permission)

ecosystems". This concept can be extended to river changes for: flow regulation, fragmentation of river course, sediment unbalance, neo-arheism, chemical contamination, acidification, eutrophication, microbial contamination, thermal unbalance, radio-active contamination, and biological introductions and invasions (Meybeck, 2003). The last four syndromes will not be developed here although the microbial contamination from human and/or animal faeces is probably the number one water quality issue at the global scale.

**Flow regulation** is a major target of water management. It is generally achieved through the construction of dams and reservoirs and sometimes through water diversions. Flow regulation has a major impact on river sediment fluxes and river bed morphology. The ultimate flow regulation can dramatically change the seasonal hydrological regime, as for the Moskva River in which the water discharge is rigorously stable for 11 months per year (Chernogaeva, 1998) with the exception during the April snow melt. The ecological impacts of such extreme regulation can be important.

**River fragmentation** is generally associated with the previous syndrome: in a majority of rivers of the northern hemisphere river courses are now interrupted by multiple dams and reservoir cascades that greatly limit their longitudinal connectivity (Dynesius and Nilsson, 1994). Another type of fragmentation of the aquatic habitat is the change in lateral connectivity due to channelization, levees and embankment construction. Such fragmentation also results in major changes of the aquatic biota particularly fish (e.g. migratory species) and interstitial fauna.

**Neo-arheism** is the dramatic reduction of river flow due to consumptive use of water and/or to diversions (Meybeck, 2003). As for the two previous syndromes neo-arheism is usually a planned river change due to water engineering and water use, particularly resulting from irrigation, but it may also be related to urban water demand in some dry regions. As a result the river basin becomes gradually disconnected from its river mouth, first with seasonal droughts, then with near-complete reduction (>90%) of flow to the natural receiving coastal zone. This trend is already widely observed on all continents, e.g. the Colorado and Rio Grande (North America), the Nile and Orange, the Indus, Amu-Darya and Huang-He, and the Murray Darling. The impacts of neo-arheism are mostly observed in the coastal zone which is no longer supplied with fresh water, thus changing the salt balance, as is occurring in the SE Mediterranean Sea, with essential nutrients, organic matter and sediments.

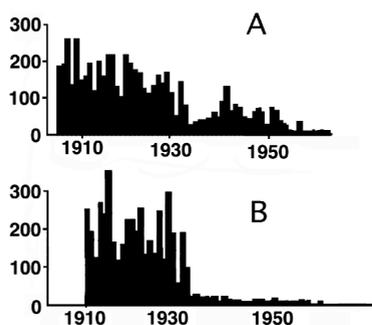
**Sediment unbalance** is the gradual or rapid change of sediment transfer, suspended matter or bedload in river systems due to land use changes and to reservoir building. Land use change, particularly deforestation in mountain regions of the world (e.g. Himalayas, Madagascar, Pacific Islands) results in accelerated soil erosion, sometimes by a factor of ten. This results in gradual changes (generally over decades and more) of the river bed. In the upper reaches of mountain rivers (e.g. Kosi and Kotri tributaries of the Ganges), in highly erodible regions (e.g. Huang-He basin) and in small river basins of the West Pacifics (e.g. Taiwan), the increase of sediment transport due to land use change has resulted in dramatic river bed silting, in changes of river course (Kosi, Kotri) and/or in silting of coral reefs for the tropical regions. Reservoirs add another essential impact on river systems: they store the bedload material (sand and gravel) and they may store more than 90% of the suspended matter when the water residence time exceeds 2 months (Vörösmarty *et al.*, 2003). The construction of reservoirs by humans, which has been termed "neo-castorization" (Vörösmarty *et al.*, 1997), has added 500,000 km<sup>2</sup> of new water bodies, of which more than 90% correspond to the large reservoirs associated with high dams (exceeding 15 m, ICOLD, 1994) but hundreds of thousands of small reservoirs are already built, but not registered at the global scale as in India, China, USA, NE Brazil, W Africa and other regions of the world. In addition to sediment storage, reservoirs also store particulate nutrients,

particulate organic matter and particulate pollutants, thus having multiple effects, both positive and negative, on the quality of rivers downstream. As the result of multiple particulates sinks in river systems, increased fluxes are barely observed at the mouths of large river systems (Walling and Fang, 2003) as most of the generated material is redeposited in foothills, river beds and floodplains and, more recently, in reservoirs. Figure 2 illustrates the impact of reservoirs for the Colorado River (USA-Mexico) where flow regulation, fragmentation, sediment unbalance and neo-arheism syndromes have been developed over the last 50 years.

The **salinization** of the world's rivers is worldwide and generally gradual. It results in the release of dissolved salts ( $\text{NaCl}$ ,  $\text{KCl}$ ,  $\text{CaSO}_4$ ,  $\text{MgSO}_4$ ...) from industrial and urban sources. The concentrations of  $\text{Na}^+$ ,  $\text{Cl}^-$  and  $\text{SO}_4^{2-}$  in the world's rivers had already increased by at least 50% when compared to their pristine values in the 1970s (Meybeck, 1979). Regionally these increases are much higher and can reach a factor of 10 and even 100 for those rivers affected by coal, salt and potash mines (e.g. Pennsylvania, Rhine, Weser, Vistula). In semi-arid regions, the salinization process is general and occurs when river water is actively used for irrigation as in the Colorado, Amu Darya and Syr Daria, and Murray-Darling. Since total dissolved solids are already naturally high in these river basins the salinization process may result in severe limitations of water uses.

The **chemical contamination** syndrome is multiple and is related to most human activities such as mining and oil extraction, industries, urbanization and transport, agriculture. Most concentrations of natural and potentially harmful chemicals are enhanced (e.g. heavy metals, nitrates, polyaromatic hydrocarbons) and new molecules that do not exist in natural conditions are generated (xenobiotic compounds). The global status of chemical contamination is still very difficult to assess (Meybeck *et al.*, 1989, 1991) due to the great complexity and variety of chemical indicators that should be considered (Robarts *et al.*, 2002). Only the major ions, the nutrients, the indicators of oxygen balance (i.e. organic matter) are commonly measured, toxic substances are much less monitored and their status at the global scale cannot be assessed (Robarts *et al.*, 2002): there is an urgent need for the promotion of regional to global water quality databases.

**Acidification** of continental waters is related to atmospheric fallout of sulphuric and nitric acids, generally generated by smelters, industries or megacities far away from their impact locations where the acid fallout is deposited on non-carbonated rock types. Acidification has been a severe regional issue in NE North America, in Scandinavia, Central Europe and could now develop in parts of China and in Africa. The current water quality network in Africa is unable to account for this river syndrome in this continent at risk of acidification.



**Figure 2** Evolution of annual water discharge (A, in  $\text{km}^3/\text{year}$ ) and of annual sediment load (B, in M tonnes/y) for the Lower Colorado river (from Meade and Parker, 1985) illustrating gradual syndromes of flow regulation, sediment unbalance and neo-arheism due to dam construction (fragmentation syndrome) and water withdrawal

**Eutrophication** is actually an excess of algal development in water bodies due to nutrient enrichment, mostly phosphorus for rivers and lakes, and commonly nitrogen for the coastal zone. This algal unbalance results in an excess production (P) vs the bacterial decomposition or respiration R with  $P/R > 1$  as observed in lake epilimnions and in some slow river courses such as in Western Europe, or in East Europe impounded rivers such as the Volga (Drabkova, 1998). The corresponding algal organic matter, very labile, is eventually decomposed in the deepest parts of lakes and reservoirs, and in turbid estuaries, thus resulting in severe oxygen consumption ( $P < R$ ) that can reach total anoxia. Another type of nutrient unbalance has been recently described. It is due to the marked decrease of the Si:N ratio in some rivers. The dissolved silica may be partially retained by multiple reservoirs where diatoms are developing, while nitrate is progressing in all impacted rivers. In the Mississippi, for instance, the Si:N ratio was close to  $50 \text{ g.g}^{-1}$  at the beginning of the 20th century. It is now close to 1 or below 1: under this threshold value the diatom community of the coastal zone is replaced by cyanobacteria which are not consumed by the zooplankton grazers, thus resulting in marked seasonal hypoxia over hundreds of  $\text{km}^2$  of Louisiana coast (Rabalais and Turner, 2001). Such evolution has also been described in the Danube Delta and is feared in other regions such as in Western Europe.

**Thermal unbalance** is a term probably more appropriate than “thermal pollution” for two reasons: (i) the term “pollution” remains very vague and has multiple definitions, (ii) in some impounded rivers, as for the Colorado, the water temperature can actually be seasonally decreased due to the reservoirs’ operation (bottom water release). It will not be developed here although its impacts on the aquatic biota may be important.

**Biological introductions** have been voluntary and common for a least 2,000 y, e.g. carp fish farming in the Roman Empire. Biological invasions in aquatic systems (e.g. water hyacinth, zebra mussel, crayfish) result mostly from the very rapid increase of fluvial transport and of ocean transport through ballast waters, particularly between central Europe and the North American Great Lakes. Biological introductions and invasions may have exponential and dramatic impacts on water resources (e.g. clogging of water intakes by zebra mussels) and on aquatic ecology.

### Historical development of river syndromes and human responses

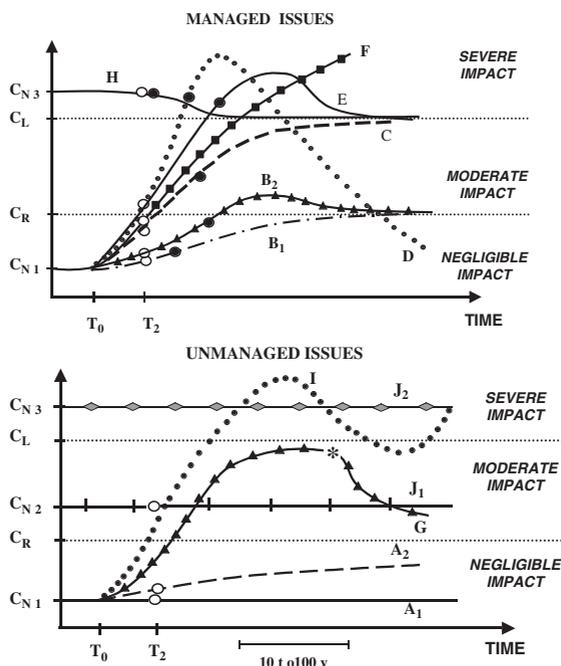
Each syndrome can be described by a set of symptoms of changes based on specific indicators. For example, the percent reduction of annual flow and of peak monthly discharge and the percent increase of annual low-flows are appropriate to characterize the flow regulation. Similar indicators for the suspended sediment load plus river bed profile variations are good descriptors of sediment unbalance. When chemical contamination is described in all its aspects (oxygen balance, heavy metals, xenobiotics...) the detailed monitoring of water quality may exceed one hundred analyses (Chapman, 1992). Such monitoring is very rare and is generally used to assess the present state of river water quality. Environmental archives such as chemical analyses of sediments core (metals, persistent organic pollutants, nutrients, pigments) can be used to reconstruct the past riverine evolution from sediment taken in lakes, deltas and flood plains. Biological approaches such as diatom assemblages can also be used to reconstruct the oxygen balance, the pH and the salinity of aquatic systems over centuries to millennia (PAGES-LUCIFS, 2000). Sedimentary archives in flood-plains and comparison of early maps are also used to reconstruct the evolution of river systems and to decipher the impacts resulting from land use changes (e.g. deforestation, cropping) from the impact of past climate variability such as during the Little Ice Age in Western Europe (Petts *et al.*, 1989).

The interaction between humans and their environment can be described through the complex fluxes of materials and/or elements over a given space as for a city (Baccini and

Brunner, 1991) or a river basin (Meybeck *et al.*, 1998). The evolution of river quality presents multiple patterns that reflect these interactions: development of pressures, their perception, natural inertia of the aquatic systems (e.g. longer responses in groundwaters and large lakes; intermediate storage in soils), and multiple inertia of the society (impact detection, societal awareness, consensus building, political decision, financial and technical implementations of the decisions) (Meybeck, 2002). For water quality evolution, which combines most symptoms related to salinization, eutrophication, acidification, chemical and microbial contamination, the time-lag between the change of state and the implementation of environmental measures, successful or inoperative, is commonly a generation. In most cases the deterioration of the aquatic system is not detected until a first threshold is reached where some water demands are not satisfied or imply additional economic cost to treat the water. In some cases the issue is not addressed before the aquatic systems are so degraded that severe economic losses, serious human health damage and/or serious and irreversible ecological damage occur.

Several types of unmanaged and managed water quality situations (Figure 3) can be described and illustrated by trends of water quality indicators. The major managed situations include (Meybeck, 2002):

- Precaution management (Figure 3, B1) in which environmental and economic impacts are kept to the minimum acceptable level of water quality indicator (here schematically represented by a recommended concentration  $C_R$ ).
- Maximum impact management (Figure 3, C) targeted at the maximum acceptable limit ( $C_L$ ).



**Figure 3** Typologies of river basin management strategies for water quality illustrated by trends in water quality: ( $C_{N1}$ ,  $C_{N2}$ ,  $C_{N3}$ ), natural, ( $C_R$ ) recommended and ( $C_L$ ) limit concentrations.  $T_0$  = start of environmental pressures,  $T_2$  = environmental impact detection (○), start of environmental measures (●), unplanned decrease of environmental pressures (\*).  $A_1$  and  $A_2$ : unnecessary management,  $B_1$ : precaution management,  $B_2$ : delayed precaution management, C: maximum impact management, D: total ban, E: delayed pollution regulation, F: laissez-faire, G: unplanned improvement, H: natural pressure remediation, I: unperceived issue,  $J_1$  and  $J_2$ : natural pressure endurance and natural pressure suffering (Meybeck, 2002, © EAWAG, Dübendorf, with permission)

- Total ban (Figure 3, D) which occurs generally after severe problems have been detected, demonstrated, and recognized by all stake-holders (e.g. DDT, PCBs, Atrazine).
- Delayed pollution regulation (Figure 3, E): it is established after a period of non-management and subsequent severe impacts; targeted levels are usually the maximum acceptable ones.
- Laissez-faire (Figure 3, F): the severe impact level is reached, detected but not adequately addressed (lack of environmental awareness, lack of consensus, lack of regulation enforcement, shortage of financial means).

The major unmanaged issues are:

- Unnecessary management (Figure 3, A) when the water quality is not affected by human pressures.
- Unplanned improvement (G): closure of mines and industries, changes in technologies of pollutants emitters, economic crises (e.g. Eastern European rivers after 1989).
- Unperceived issues (I): a general type prior to the development of analytical chemistry, often with multiple contamination-decontamination cycles.
- Natural pressures endurance (J1) and suffering (J2) when the natural water quality exceeds the recommended or the severe levels (often found in groundwaters or in extreme environments).

Depending on the management and non-management of water quality issues and on the development of human pressures very diverse patterns of environmental indicators can be found. Each of them is characteristic of the trajectories of a given syndrome concerning the water quality indicators, such as organic and faecal contamination, nitrate contamination, metals and pesticides; they are likely to be very different from one region of the globe to another, depending on their stage of development, their environmental concern, their human and technical resources (Meybeck *et al.*, 1991; Meybeck, 2003).

### Future development of global river syndromes

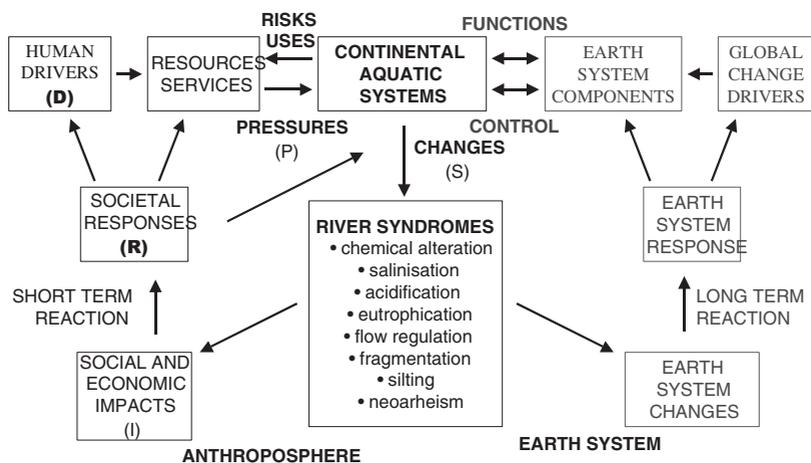
Continental aquatic systems have been considered since the early civilizations by water managers in terms of water resources. In the late 20th century, the demonstration of major changes of these resources at the global scale has been gradually made for river connectivity, river regime, river chemistry, river sediment transfers, aquatic biota (Dyneius and Nilson, 1994; Vörösmarty and Sahagian, 2000; Meybeck and Helmer, 1989; Vörösmarty *et al.*, 2003; Seitzinger *et al.*, 2002; Revenga *et al.*, 1998). The natural functions of aquatic systems in the earth systems such as the water, materials and energy storage and transfers from headwaters to the coastal zone, sometimes as far as 6,000 km for the Amazon and Nile rivers, have therefore changed as well. The original aquatic biota in some regions such as Western Europe and North America has already changed dramatically and similar changes are likely to occur in other regions such as in China and the Indian subcontinent.

The management of aquatic systems in the 21st century will have to take into account, on one hand the local to regional impacts of river change syndromes on the human societies living within basins and on their coastal zones and, on the other, the long term regional to global reaction of the earth system to these changes (Figure 4). The continental aquatic systems are commonly described by water managers in terms of the DPSIR approach (Von Bodungen and Turner, 2001) (Figure 4 left). Drivers (D) of economic activity (such as demography, technical progress, markets) are related to multiple uses of water resources and other aquatic system resources (such as food, fibre, sand, clay). The continental aquatic system also provides free services for humans such as flood control, water storage, pollutant retention and degradation. These services have been recently recognized in environmental economics (Costanza *et al.*, 1997). Another essential relationship between humans and continental aquatic systems concerns the water-associated risks, particularly floods

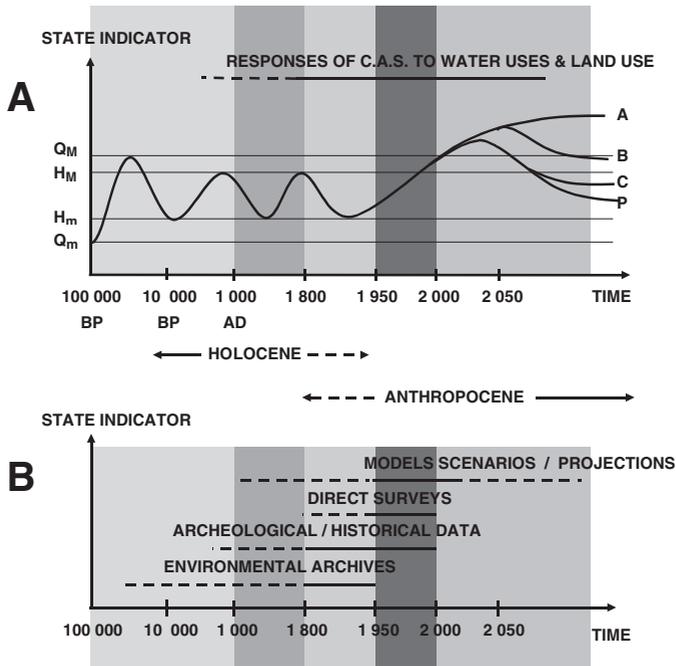
and the related management (e.g. reservoir building). Water health risks (e.g. malaria) have been until now essentially controlled in the most developed countries. Multiple pressures (P), such as water uptake, river engineering, species introduction, waste release and use of agrochemicals, induce multiple changes that have been described here in terms of global syndromes commonly qualified by environmental scientists as impacts, or by economists as a change of state (S). Social and economic impacts (I) include economic losses, health issues, limit to development etc. The societal responses (R) are also multiple, including passive suffering, immigration, regulation of pressures (e.g. biofarming, ban of chemicals), regulation of drivers, direct remediation of aquatic systems (e.g. soil cleaning, dredging of contaminated sediments, injection of O<sub>2</sub> in hypoxic waters etc.).

On the right side of Figure 4, the continental aquatic systems are presented as they are still conceived in some earth science text books, i.e. without any human impact. River systems, including lakes and groundwaters, are still fully connected to the coastal zone, they are not regulated and their biogeochemical functions are still pristine; they provide fluctuating fluxes of water, energy and materials from headwaters to the coastal zone and their aquatic biota diversity is also pristine. More and more scientists, however, consider that aquatic systems are now very much affected and sometimes fully controlled by human activities (Vörösmarty and Meybeck, 2003). They understand that river syndromes are now gradually affecting the whole continental waterscape, the coastal zone, and eventually the whole ocean (e.g. through the marked changes in nutrients balance, the possible changes of river carbon inputs, the changes in aquatic biodiversity). The long-term impact of river syndromes on the ocean system then on the earth system is still rarely addressed (Ver *et al.*, 1999). It is likely to be much slower (100 to 1,000 years) than the impacts of river syndromes on human societies and their related responses, generally between 10 to 50 years. The world's regional seas that are connected to about half of the human pressures exerted on the continents will react to earth system changes much faster than the open ocean, and this reaction will affect first their coastal zones.

General models of the evolution of aquatic systems and their impacts are needed to give precise answers. They should be validated either on relatively short term direct observations of river changes (10 to 30 years in most cases) or on the reconstruction of river evolution from historical data, when available, and from environmental archives (Figure 5). There is evidence of past natural variations of aquatic systems for both quality and quantity due to past climate variations since the Last Glacial Maximum and particularly for the last



**Figure 4** Schematic relations of continental aquatic systems within the Anthroposphere, according to the Driver-Pressure-State-Response-Decomposition approach, and within the earth system



**Figure 5** Schematic responses (A) of continental aquatic systems to climate variability, land use change and direct human impacts, such as water use, from Holocene to Anthropocene. State indicators (B) are obtained from short modern observation, historical records, environmental archives and backcasting modeling. The Anthropocene era is counted since 1950. Anthropocene variations now exceed the natural Holocene range ( $H_m$ - $H_M$ ) and even the Quaternary range ( $Q_m$ - $Q_M$ ) caused by past climate variability. A, B, C, and P correspond to possible future scenarios

10,000 years (Holocene period) (Steffen *et al.*, 2002). Since 1950, a date conventionally used to start the Anthropocene era (Meybeck, 2002), as the result of accelerated direct human pressures (urbanization, reservoir construction, fertilizer use, species introduction, irrigation, etc.) the aquatic systems have changed at a rate probably an order of magnitude faster than during the Holocene.

There is now an urgent need for local, regional and global river basins databases for model validations, then for model comparison as has been done in the last 20 years for the climate and the land cover changes. Once these models are adequately validated it will be possible to use them to explore possible scenarios. The combination of future human responses and earth system reaction to river syndromes should be addressed jointly as many syndromes are interconnected.

The return to a pre-Anthropocene level (Figure 5, scenario P) is very unlikely in the near future, particularly when considering that most of the water-engineering structures are designed to last 100 years and possibly more. The stabilized level scenario (C) where the changes are kept to a minimum risk while ensuring a maximum benefit for human development (enhanced water resources security) together with minimal earth system changes, would imply joint efforts in all regions of the globe i.e. (i) the richest countries should provide assistance and funds for the environmentally sound development of the poorest ones and (ii) the fast developing countries should not target the past/or present environmental misbehaviours of the past or present industrialized countries. This is still not yet envisaged on the international agenda. Therefore, when considering the present evolution of aquatic systems, the scenario of stabilized level (B) with both maximal acceptable risk for human development and marked earth system change is more likely, although such an option is not

clearly stated in international conferences. Such a policy is hazardous, there is a risk that scenario A may be realized: in many regions, the future aquatic resources would not sustained and an irreversible earth system change, unmanageable for human development, would occur. Such a catastrophic scenario has already occurred in the Aral Sea basin. Global analyses of continental aquatic systems combining all syndromes of changes, their trajectories and their distribution is an urgent task, however barely developed so far on most international agendas.

### Acknowledgement

This work has greatly benefited from discussions with my colleagues from several international programmes such as BAHC/IGPB, and EUROCAT (EU project EN.1-2000-0044) and from the French Piren-Seine programme.

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