INVITED COMMENTARY

HP TODAY

HYDROLOGICAL PROCESSES
Hydrol. Process. **19**, 331–338 (2005)
Published online in Wiley InterScience (www.interscience.wiley.com). DOI: 10.1002/hyp.5778

Looking for water quality

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Introduction

On the one hand the water quality field is increasingly diverse and complex, on the other hand there is an increasing demand from the public, water managers and all stakeholders for simplified water quality indicators integrated over time and space, and appropriate to specific issues. The evolution of water quality is also of concern at the global scale (Vörösmarty and Meybeck, 2004). Questions raised by this evolution are presented here in the hope of opening a forum on this topic.

Is Water Quality a Human Construction?

The appreciation of water quality is in constant flux. Water quality perception through its colour, turbidity, taste or effects on humans and animals is as old as water use, but the first water chemical analyses are as recent as 200 years ago. Between 1850 and 1900, regular monitoring was already being performed at water intake stations on the Thames and Seine rivers, focusing on a few descriptors such as resistivity, dissolved oxygen, ammonia and chloride.

Throughout the 20th century, water quality studies and monitoring have developed exponentially (Figure 1) according to: (i) *the water demand* (e.g. major ion analyses for irrigation needs in the USA since the early 1900s and in the Soviet Union since the 1940s, total suspended solids (TSS) surveys prior to river damming since the 1930s, faecal contamination surveillance at drinking water intakes); (ii) *the development of issues* (eutrophication since the 1960s, acidification in the 1970s); (iii) *new pressures* (radionuclides since the 1950s, pesticides since the 1980s, endocrine disruptors more recently); and, most of all, (iv) *the development of analytical chemistry*. There has been a stepwise development of indicators (i.e. the combination of several basic descriptors) in some periods, such as the standard 5-day biological oxygen demand (BOD_5) and chemical oxygen demand (COD) used for oxygen balance models since the 1930s and the eutrophication indicators developed by Vollenweider in the late 1960s.

In parallel with these developments, aquatic ecologists have produced ecological indicators of overall stream quality, such as the saprobic index, the Trent River index or the biotic index set-up by Woodywiss, which has been continuously used throughout the former Soviet Union for several decades (Kimstach *et al*., 1998). The quality of the physical habitat of aquatic systems has also been

considered, and ecohydrologists (Kundzewicz, 2002) now study the quality of whole river catchments.

From an initial definition of 'water quality' based on a few chemical descriptors on one sample or at one station, we have now shifted to an overall appreciation of the 'aquatic environment quality' based on chemical, physical and biological descriptors (Chapman, 1996), from the station to the regional sea basin. Whereas in the 1900s there were just one or two dozen potential water quality descriptors, the total number (including degradation products of some organic pollutants, specific metal forms, etc.) probably now exceeds several hundreds (Figure 1, trajectory A). The best-equipped monitoring stations (e.g. water intakes for major western cities) routinely consider up to 100 descriptors (trajectory B), while financial and technical constraints mean that monitoring stations in the least developed countries, when they exist, can still barely measure a dozen descriptors (www.gemswater.org/). *Our appreciation of water quality closely reflects the complex relations between man and water, for a given place, a given period and a given society.*

Our Biased Visions on Water Quality

Each hydroscience has a different interest in water quality; these visions are very rarely collected and synthesized.

Aquatic chemists establish the general laws that regulate the composition of any water from thermal springs to saline lakes, from rain to sewage. *Environmental chemists* track contaminant pathways everywhere in the aquatic system. *Geochemists* favour subpristine waterbodies, sometimes at a very fine scale, to define the natural controls of water and particulate composition across a range of geologic time scales. *Biogeochemists* concentrate their efforts on elemental cycles of carbon, nutrients or sulphur. *Ecologists* combine very simple descriptors (temperature, pH, conductivity, dissolved oxygen, hardness and nutrients) with complex indicators based on benthos, macrophytes, plankton, molluscs or fish. *Ecohydrologists* and *limnologists* rely heavily on

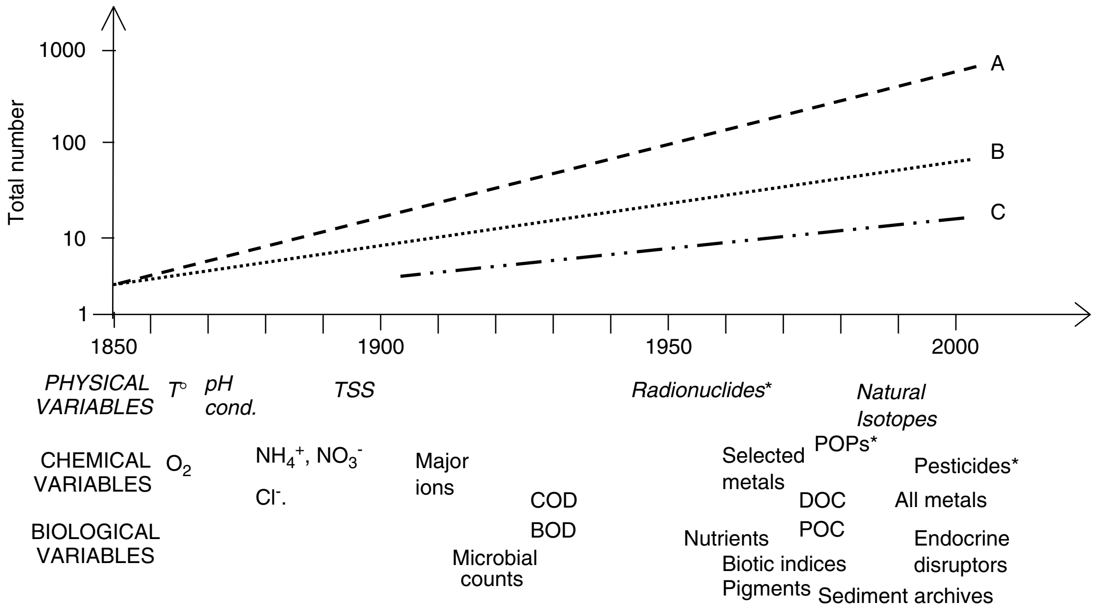

Figure 1. Exponential growth of water quality variables (physical, chemical, biological) and occurrence of their first analysis in regular surveys (asterisk indicates non-natural products). Trajectory A: total maximum number of variables that should be considered if all regulations were implemented. Trajectory B: number of variables actually routinely monitored in the first grade surveys. Trajectory C: monitoring capacities of least developed regions

measures of dissolved oxygen, nutrients, and carbon. *Palaeolimnologists* reconstruct the past quality of aquatic systems (environment archives) from sediment records. *Hydrologists* (*sensu stricto*) are using chemical tracers and isotopes (a rapidly evolving field) to study water pathways, decompose hydrographs, and estimate renewal times while being pressed by limnologists and coastal scientists to provide riverine fluxes of contaminants and nutrients. *Environmental engineers* develop techniques to treat wastewaters and distributed waters. *Hydropharmacists* are looking for peculiar water chemistries (that are sometimes considered as non-usable or even non-drinkable by other users) that may be applicable in the health sector. *Sanitary engineers* focus on all water-related diseases, particularly those related to microbial contamination. Finally, *water quality managers* should integrate all these aspects, making sure that water supplied to users is meeting all their water criteria and standards as traded by *environmental lawyers* between all stakeholders, from polluters to conservation groups.

Each of us is actually looking at different sectors of the expanding 'water quality universe' with different instruments and various focuses, claiming that his/her vision is the most important one, if not the only one.

Can Water Quality be Really Metered?

Many of us hydroscientists are producing factual observations such as chemical compositions, occurrence and abundance of aquatic species, fluxes, etc. that can be understood and interpreted by our scientific peers but are less usable for water uses, water quality assessments, management, and regulation; scales, ratings, criteria and standards are needed as metering tools (McCutcheon *et al.*, 1993; Chapman, 1996). Two main streams of water quality metering co-exist: referring to a hypothetical natural background and referring to potential water quality uses.

The *natural background* is often masked by the ambient contamination and its determination is difficult. A global-scale survey of major ions in pristine rivers shows ranges over two to three orders of magnitude (Meybeck, 2003a). We must face the fact that *water chemistry is not always fit for human uses in natural conditions*:

1. Natural environments unfit for given uses are sometimes declared 'naturally polluted', such as salt lakes and some groundwaters. This creates a lot of semantic confusion (sea water is saline, not polluted). The term 'natural impairment' for a given use (McCutcheon *et al.*, 1993) should be preferred.
2. Some mineral waters rich in salts, arsenic or fluoride are presently non-drinkable according to WHO standards, yet they are still sold commercially or used in spas.
3. Some deep lakes and groundwaters are naturally anoxic, rich in H_2S and yet in a pristine state.
4. Some extreme environments may have a very high conservation value. Unique waters, e.g. those with very high DOC contents (peat bogs), very low pH (pH 1 for Lake Kawah Idjen, Indonesia), very high pH (pH 12 in Lake Bogoria, Kenya) or hypersaline (Dead Sea, Kara Bogaz), may host very resistant and generally endemic species that hold intrinsic ecological value as well as potential uses for humans.

Conversely, anthropogenic impacts on chemistry may not always lead to a deterioration of the aquatic system. (e.g. a tenfold increase in K^+ or Cl^- from 2 to 20 mg l^{-1} has no biotic impact and does not limit water use).

Establishing reference water quality is not trivial and may have important socio-economic implications. The European Union has recently issued a directive to restore the EU aquatic systems to a 'good ecological state' by 2015. This important political decision is triggering a Brownian movement among managers, since: (i) so far, many countries have focused their monitoring where major water uses —and pressures—are occurring; (ii) the EU does not mention whether the reference period should be pre-industrial (*ca* 1800) or pre-agricultural (*ca* 1000); (iii) it is unclear how to deal with historical contaminations by ancient mining or industries still impacting present-day aquatic systems (problems of inherited contaminations); (iv) 'permanent' deterioration of aquatic systems may occur (contamination of soils, large aquifers, large lakes; dykes and dams), such that multiple exceptions will have to be made when the directive is applied; and (v) water quality issues, such as eutrophication, can be appreciated and metered in very different ways across the EU.

Establishing water quality meters for users is also a management decision. This is closely linked to the power balance among: (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; and (iv) dissemination of the technical and scientific knowledge.

The River Seine management is a good example of such complexity (Meybeck *et al*., 1998). For 30 years, the unique water quality criterion used for nitrate (NO_3^-) management in this basin was that for drinking water (Figure 2, scale C). For NO_3^- below 50 mg l^{-1} the river was considered as being in a perfect state (blue colour coded), but use was forbidden for NO_3^- above 50 mg l^{-1} (red colour coded). Observed NO_3^- distributions, considered in either spatial (scale B) or temporal (scale A) contexts, therefore, were always coded in blue. This management led to a steady increase in NO_3^- levels, some 20 times higher than natural background estimated from forested watersheds (scale E) due to intensive fertilizer use since the 1950s, and to coastal eutrophication, such as in Brittany. In the mid 1990s, a new scale for 'biological potential' (scale D) was added after a harsh bargain between the Ministry of Environment and farmers. This new national scale is more adapted to the river eutrophication issue, but it does not take coastal water eutrophication into account; an increase of natural levels of NO_3^- by eight times is still coded as acceptable (green).

The aquatic environment cannot be simply described by one or two emblematic descriptors, such as CO_2 for atmospheric chemistry or air temperature for climate. Vörösmarty (2002) has already observed that hydrologists were lacking a 'Mauna Loa'-like global reference for the global water balance; it is even worse for the water quality. *Multiple water-quality meters are needed and must be harmonized, agreed upon by stakeholders and regularly revised, particularly when sharing water bodies*.

What is the Basin Quality?

Space and time integrations of water quality remain very difficult. The 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. Yet the demand for water quality information requires much finer resolution.

Apart from colour, temperature, suspended solids and pigments, water quality can barely be appreciated from remote sensing, and we must rely on spatially and temporally discrete information obtained at stations. The efficiency of spatial integration from stations to reaches, subbasins, basins and regional seas depends on the station density. In developed countries, the density of water quality monitoring stations is similar to that of meteorological stations (about one 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 (www.gemswater.org/).

These spatial integration rules of water quality scales can be quite arduous and not always made explicit to stakeholders and decision makers (e.g. How do we handle isolated contamination hotspots when the rest of the basin has a fair quality?).

Let us use again the Seine basin (65 000 km^2, 17 million people) as an example of the spatial structure for seven water quality issues (Figure 3). Trends in water quality properties as stream orders increase from 1 to 5 are combined with a schematic longitudinal description across the Paris megacity (10 million people) to the freshwater estuary (orders 6 to 8; Meybeck *et al*., 1998; Meybeck, 2002). Forested headwaters (orders 1 and 2) provide a vision of natural water quality background (acidification is absent due to carbonated soils). In rural streams (orders 1 to 3), intensive agriculture is responsible for severe NO_3^- and pesticides contaminations. Contamination by metals and persistent organic pollutants increases with the population density from orders 1 to 6, then increases stepwise downstream of the Paris mega-sewer injection (8 million people, 70 km downstream of the Eiffel tower) where a first hypoxic reach is found. The second hypoxia, observed in the turbid macrotidal

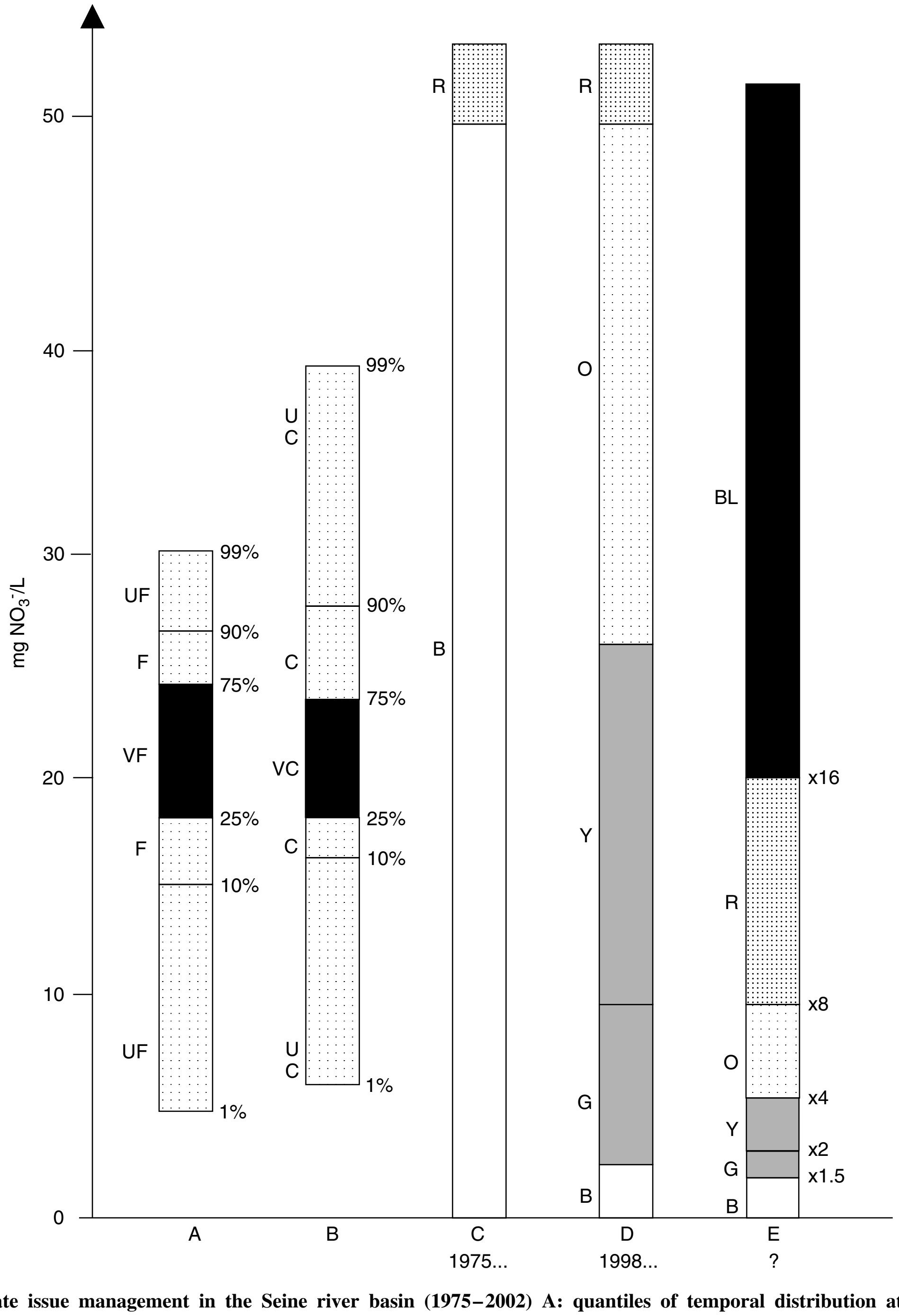

Figure 2. Nitrate issue management in the Seine river basin (1975–2002) A: quantiles of temporal distribution at river mouth (VF: very frequent; UF: unfrequent); B: quantiles of spatial distribution of NO_3^- medians at 52 stations (VC: very common; UC: uncommon); C: unique grid used from 1975 to 1998 based on drinking water criteria; D: added grid in 1998 for 'biological potential'; E: possible grid based on deviations (×1·5, ×2, ×4, ×8 and ×16) from estimated natural average nitrate background (1·25 mg l^{-1}). Colour code: blue (B), green (G), yellow (Y), orange (O) and red (R) plus added black (BL) stage. Depending on scales, the most frequent (F) and most common (C) waters can be coded blue (total absence of issue), yellow/orange or red/black (very severe degradation)

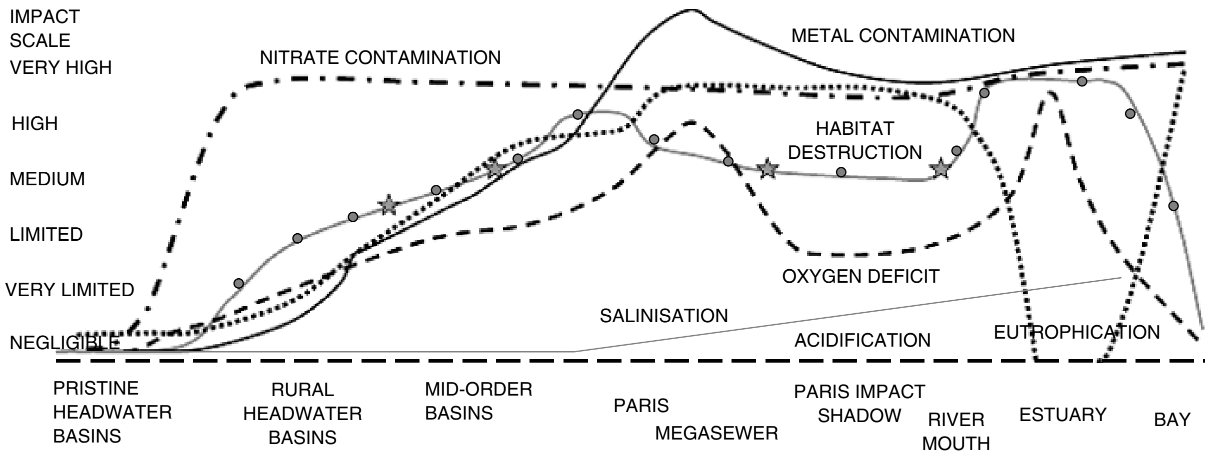

Figure 3. Distributions of seven water quality issues in the Seine river basin (1990–2000), combining stream order approach (left part) and longitudinal profile on river mainstream and freshwater estuary (right part). Paris impact is maximum downstream of the injection of one treated mega-sewer (8 million people). Stars indicate dams and locks

estuary, is mostly due to delayed nitrification of the sewer ammonia and to bacterial degradation of algal particulate organic carbon (POC) generated by river eutrophication in reaches 4 to 8. In others rivers, such as the St Lawrence, lateral variations in water quality due to poor mixing of tributaries and/or point sources of pollution exceed longitudinal variations. *The spatial description of a river basin needs more than an overall quality at the river mouth station.*

The temporal variability of water quality at one given station may also not be adequately addressed: continuous or very frequent observations, although technically feasible, are not made for lack of funds and manpower. The most common observation frequency is still monthly (www.gemswater.org/), and it is implicitly assumed that finer variations can be neglected. This is not the case, even in big rivers. Several types of diurnal variation (due to snow and ice melt, to phytoplankton development, etc.) are commonly described in rivers and lakes. For small- and medium-sized basins, floods also generate rapid variations of concentrations at hourly to daily time scales, which are very informative on water pathways and intensively studied by some hydrologists but rarely considered in regular monitoring. Fluxes of some materials, such as particulate nutrients, carbon and contaminants, can vary over one to three orders of magnitude during flood events. The establishment of yearly fluxes, as required by limnologists and by many coastal seas agreements, can be highly biased when based on monthly samples only.

Some human impacts may enhance the temporal variability of water and particulates chemistry. In eutrophied rivers, daily pH variation may reach 1·2 and daily oxygen cycles may reach 150% saturation, as in the River Loire. Odd cycles (xenocycles) at periods of 7 days or 1 month are also generated by such human activities as reservoir operation or waste releases from mines and industries (Meybeck, 2002). *Many statistical interpretations made in water quality assessments actually fail to take into account the fine temporal variability and the resulting uncertainties. Ecological approaches integrate temporal variations from weeks to years but are of limited interest for most water users.*

Perspectives

The water quality field is a puzzle: hydrologists and a dozen other hydrosciences are generally focused on one or a few pieces of the puzzle, whereas water management specialists (engineers, jurists, stakeholders and decision makers) are asking for a general view of the present picture and demanding a longer term vision. Several questions are now being raised.

Question 1. Is water quality a new multidisciplinary science?

Water quality is now intimately related to a socio-economic and cultural context, although this latter aspect might not be directly perceived by all hydroscientists. Should we keep any longer the historical differences between aquatic chemistry, biogeochemistry, hydrogeochemistry and hydroecology? If not, let us find a specific name for the water quality science and replace generic terms with multiple meanings, such as 'polluted', by specific terms (e.g. impaired, contaminated, acidic, acidified, salty, salted, rotten, altered, degraded, regulated, turbid, clarified, poisoned) that were used before the advent of modern science. Definitions of water quality are now so wide (Chapman, 1996) or multiple (Boon and Howell, 1997) that we need a greater involvement of our colleagues from the social sciences to clarify the situation.

Question 2. Are water quality assessments reliable, informative and equitable?

We must recognize that our vision of water quality, even with the best documented combinations of observations, will always remain partial due to the discrete nature of most observations at fixed dates and fixed stations; we will never fully capture the temporal–spatial variability of water quality. The necessary interpolation of observations should be based on explicit rules and/or realized through models.

The most developed monitoring may sometimes be built up on loose grounds, with inappropriate approaches (e.g. wrongly selected media), insufficient sampling frequency, wrong station selection or flaws in analytical procedures, even if the best available statistical techniques are used for interpretation. Agencies should regularly question and revise their databases and approaches.

Water quality information at the local to regional scale is not equitable: about 90% of the research and monitoring is performed by industrialized countries for 10% of the world's population (e.g. the Congo basin, the world's number two river, is still a *terra incognita* except for a few analyses made at the river mouth).

Question 3. Should water quality meters be unique or multiple?

Despite few universally used indicators and scales of water quality, there is a lack of commonly accepted meters for the multiple water uses and water-quality issues. Should they be defined at different scales (local level, basin level, country level, regional-sea level) taking into account the natural heterogeneities of water quality, of human pressures and of development, or should they be universal (e.g. drinking water)? We must also be aware that standards and indicators can be revised according to scientific knowledge evolution, to technical development, to water-literacy improvement or to socio-political changes.

Question 4. Is water quality another global change issue?

About half of the planet is now directly affected by such human pressures as wastes input, land-use change, river damming and regulation, application of agrochemicals, and use of xenobiotics. The remaining half may be indirectly affected by long-range atmospheric pollutants, by climate change or by sea-level rise. Human influences on aquatic systems have now equalled or exceeded the natural controls, thus defining a new epoch: the Anthropocene (Meybeck, 2002, 2003b; Vörösmarty and Meybeck, 2004).

Local to regional trajectories of water quality issues can be highly contrasted (Meybeck, 2002, 2003b). Fast impacts (i.e. years to decades) occur at rates much faster than those posed by atmospheric CO_2, as illustrated by the global increase of nutrients. Other rapid changes can occur in opposite directions, such as for suspended solids fluxes, which can experience a tenfold acceleration from changes in land use and then be trapped behind reservoirs. Slow impacts (decades to millennia) are also expected in water bodies with long residence times, such as large aquifers, deep lakes, and coastal zones, or will result from the new sedimentary balance of river reaches downstream of reservoirs. The global change of aquatic systems and their related land-to-oceans fluxes will impact the Earth system at multiple time scales (GWSP, 2004).

Despite the development of few global water quality models (Seitzinger *et al*., 2002; Green *et al*., 2004), which combine global water runoff models, global development scenarios and sometimes human responses scenarios, our knowledge of future water quality and its impact on the Earth system is still very limited. As climate scientists are looking in environmental archives to forecast the future changes better, the reconstruction of past water quality based on sedimentary archives, data mining, and historical records could help to validate these models for the Anthropocene (Vörösmarty and Meybeck, 2004).

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