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Sustainability indicators for river water quality management in urban areas

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Abstract: In developed countries, the main problem of water management is the incompatibility between the average water quality, on the one hand, and the needs for ecosystem protection and the desirable water use or uses (i.e. recreation, water supply, agriculture, etc.), on the other. To achieve qualitative levels compatible with these two objectives, engineering controls are devised; such water quality criteria are often expressed by acceptable values of the parameters which represent health condition for the ecosystem. This is also taken into account in European and National legislations. These parameters could be easily linked to the concept of *sustainability*. Sustainable water management is a multidimensional approach to the issue of interdependency between the natural, social and economic variables that play a part in different water uses. In the analysis of sustainability of river water quality in urban areas a key point is represented by the adoption of suitable indicators. This paper suggests an integration between the outputs from river water quality models and the sustainability concept. Thus, after a presentation of five widely applied water quality models, sustainability indicators for river water quality in urban areas are discussed pointing out both their strengths and limitations. Finally, a list of suitable indicators to be applied in sustainability case-studies is proposed.

***Keywords**: water quality; sustainability; river water quality models; urban areas; sustainability indicators.*

1 INTRODUCTION

Environmental Fluid Mechanics (EFM) is the scientific study of naturally occurring fluid flows of air and water on our planet Earth, especially of those flows that affect the environmental quality of air and water [Cushman-Roisin et al. 2008], with scales of relevance, which are ranged (i) spatially from millimeters to kilometres, and (ii) temporally from seconds to years. So the EFM must be distinguished from both classical fluid mechanics and hydraulics. Moreover, EFM is aimed at prediction and decision. Indeed, typical problems in EFM concern the prediction of environmental-quality parameters on different scales ranged from (i) short to long term (temporal) and (ii) small to large (spatial) that depend on natural fluid flows, such as bedload transports, pollution levels and climate change. So EFM deals with several different and complex processes, that are basically transport and transformation processes, such as advection, molecular and turbulent diffusion, and physical, chemical and biological transformation phenomena.

In water systems, the study of the above EFM processes is aimed to gain a better knowledge about how the introduction of pollutants of different kind and nature in a water body will produce the ultimate levels of quality in the aquatic environment. In fact, in developed countries, the main problem of water management is the incompatibility between the average water quality, on the one hand, and the needs for ecosystem protection and the desirable water use or uses (i.e. recreation, water supply, agriculture, etc.), on the other. To achieve qualitative levels compatible with these two objectives, engineering controls are devised; such water quality criteria are often expressed by acceptable values of the parameters which represent health condition for the ecosystem. This is also taken into account in European and National legislations. The EC-Water Framework Directive [WFD 2000, 2008] has the objective of an integrated catchment-oriented water quality protection for all European waters with the purpose of attaining a good quality status by the year 2015. The water quality evaluation for surface waters shall rely mainly on biological parameters (such as flora and fauna) − however, aided by hydromorphological (such as flow and substrate conditions) and physico-chemical quality components (such as temperature, dissolved oxygen or nutrient conditions) − and on specific pollutants (such as metals or synthetic organic compounds). A good chemical quality status is provided when the environmental quality standards are met for all pollutants or pollutant groups. A significant aspect of the EC water policy is the *combined approach*, i.e. both limitations on pollutant releases at the source due to promulgation of *emission limit values* (ELVs) as well as the establishment of *environmental quality standards* (EQSs). Releases of pollutants, especially from point sources, must meet both requirements. For most European member countries this policy introduced a considerable deviation from current water quality management practice by which the releases of pollutants has been controlled by either one of these two control mechanisms, but usually not their combination. The issue of ELVs and, especially, EQSs in natural water systems could be easily related to the concept of *sustainability*. This concept is at the core of the water management model that the WFD puts forward. Sustainable water management is a multidimensional approach to the issue of interdependency between the natural, social and economic variables that play a part in different water uses [Menciò et al. 2010]. In the analysis of sustainability of river water quality in urban areas a key point is represented by the adoption of suitable indicators. They should be also related to the predictions obtained from river water quality models that simulate, in quantitative and qualitative form, cause-effect relationships between pollutants sources and water quality. These models are also as tools in the management of river water quality.

This paper suggests an integration between water quality models and the sustainability concept. Thus, five widely applied water quality models are presented and considered under the point of view of their complexity. Second, the application of sustainability concept to river water quality management is discussed. Finally, a list of suitable indicators to be applied in sustainability case-studies is proposed.

2 RIVER WATER QUALITY MODELS. A SHORT REVIEW

Nowadays the analysis of water quality issues is very often carried out using water quality models. They are simulating the movement of precipitation and pollutants from the ground surface through pipe and channel networks, storage treatment units and finally to receiving waters. In doing that, they are able to represent the interaction between pollutants and aquatic environment due to transport and transformations and ultimately can be used to better understand pollution phenomena and to choose among different, alternative management strategies.

The different complex physical, chemical and biological phenomena simulated by a water quality model are related to the characteristics of the pollutants taken into consideration; particularly, toxic substances differ from conventional pollutants in that they are partitioned into two different forms, dissolved and particulate, i.e. associated with solid matter in the water column and in the bed sediments [Chapra 1997]. This distinction has an impact on toxicant transport and fate in the sense that certain removal mechanisms act selectively on one or the other of the two forms; in fact, particulate fraction may be exchanged between water column and sediments through settling, resuspension and burial processes, while dissolved fraction could be subjected to volatilization and diffusion [Gualtieri 1999].

In the analysis of conventional pollution, dissolved oxygen (DO) has been recognized since long time as a key-parameter, which could be used to comprehensively represent the health condition for the ecosystem. Hence, DO analysis is, historically, the first water quality problem which has been studied by mean of mathematical models; Streeter-Phelps equation in 1925 could be considered as an attempt to model in simplified conditions DO profile in a river. Later on, the modeling efforts have been refined to gain insight into kinetic processes and has been developed to encompass different and more complex hydrodynamic, environmental and loading conditions. However, in general, a modeling approach starts from the analysis of the main components of DO mass balance, i.e. sources and sinks, such as atmospheric reaeration, oxidation of carbonaceous and nitrogenous waste material (BOD), photosynthetic oxygen production and respiration of aquatic plants and sediments oxygen demand (SOD). Each one of these phenomena can be expressed through a different kinetic equation. Therefore, most DO models are based on DO mass balance equations for each of the control volumes that together represent the physical configuration of the water body being modeled; each equation contains all the sinks and sources processes kinetic expressions. These equations are then solved in order to provide DO concentrations in each control volume. Fig. 1 presents the historical evolution of water quality models.

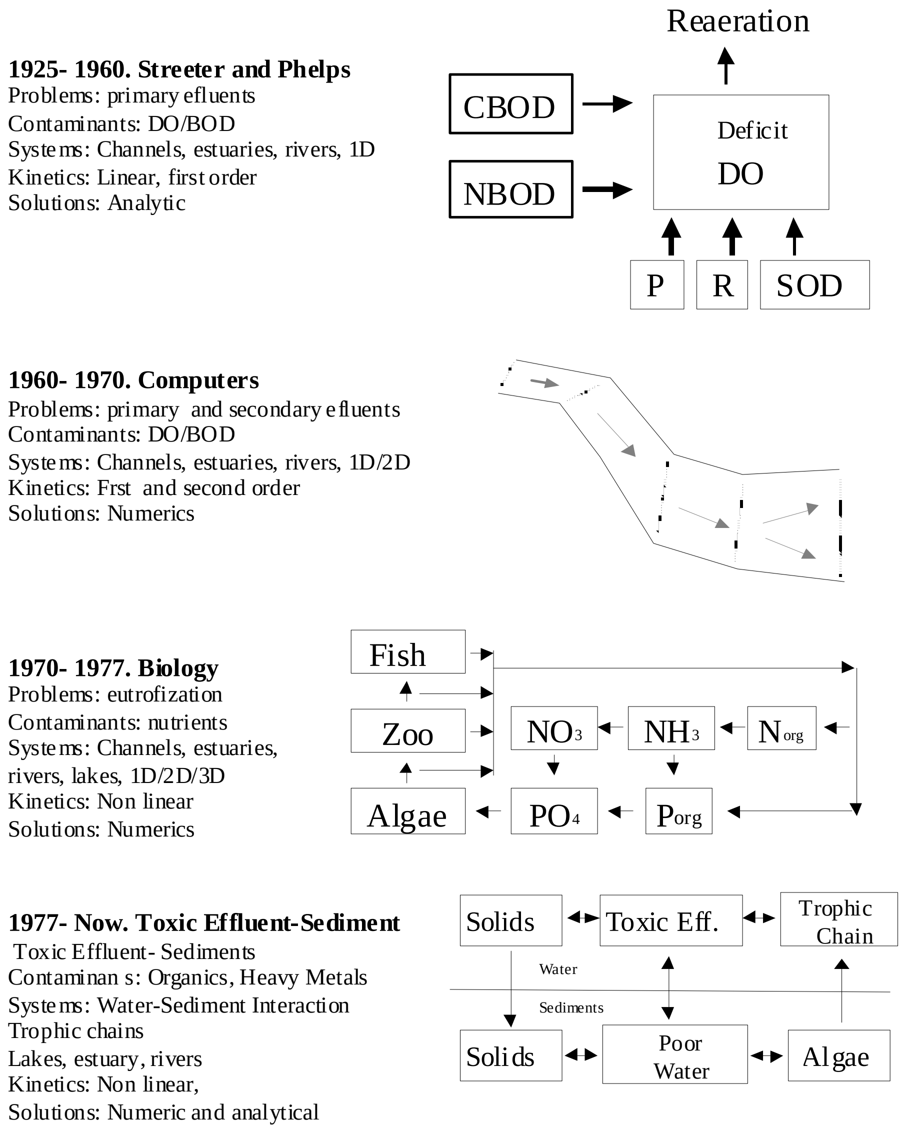

Figure 1. DO Models evolution. Adapted from Chapra, 2006.

Several water quality models have been proposed in the literature [Chapra 1997, Cox 2003, Kannel et al. 2011]. Some of these have been produced for commercial purposes and are running under license, while others are of public domain. In this Section, five widely used and mostly freely available water quality models, namely QUAL2EU, QUAL2Kw, WASP7, EPD-RIV1 and RMA-11, will be considered and their potential for use in applications will be presented.

The QUAL2E [Brown and Barnwell 1987] is public domain model for conventional pollutants in branching streams and well-mixed lakes. The QUAL2E is the result of a historical development of DO, nitrogen (N) and phosphorus (P) models [Rauch et al 1998] since the classical Streeter and Phelps model and it was first released in 1985 by the United States Environmental Protection Agency (USEPA) and subsequently improved. The QUAL2E model is a 1D, steady-state model of in-stream flow and water-quality. It simulates DO and (up to 15) associated water quality determinants along a river and its tributaries. As a steady-state model, it is limited to periods when the stream flows and any discharges are essentially constant. However, the model is able to account for the effects of meteorological diurnal variations (e.g. radiation) on certain water-quality determinants such as DO and temperature. After the addition of an option allowing uncertainty analysis (sensitivity analysis, first-order error analysis, and Monte Carlo simulation) and some enhancements, the model was renamed QUAL2EU. QUAL2EU has been extensively applied in several countries [Barnwell et al. 2004].

Recognizing several limitations of the QUAL2E/QUAL2EU, Park and Lee [2002] and Pelletier and Chapra [2006] developed an enhanced version, QUAL2K and QUAL2Kw, respectively. The QUAL2Kw included several changes both the reaction kinetics and in the simulated processes. Sediment-water fluxes of dissolved oxygen and nutrients as well as water exchange between surface water column and hyporheic zone and sediment pore-water quality are simulated. It also includes a a genetic algorithm to automatically calibrate the kinetic rate parameters.

The WASP7.5 [Ambrose and Wool 2009] is an enhancement of the original WASP [DiToro et al. 1983]. It is a dynamic compartment-modeling program for aquatic systems, including both the water column and the underlying benthos. The time-varying processes of advection, dispersion, point and diffuse mass loading and boundary exchange are represented in the basic program. WASP7 allows the user to investigate 1, 2, and 3 dimensional systems, and a variety of pollutant types. It can be used to analyze a variety of water quality problems in such diverse water bodies as ponds, streams, lakes, reservoirs, rivers, estuaries, and coastal waters. WASP also can be linked with hydrodynamic and sediment transport, such as DYNHYD and EFCD (Environmental Fluid Dynamics Code) models that can provide flows, depths velocities, temperature, salinity and sediment fluxes. WASP includes two sub-models, EUTRO and TOXI, which can be used to simulate two of the major classes of water quality problems: conventional pollution (involving DO, BOD, nutrients and eutrophication) with EUTRO and toxic pollution (involving organic chemicals, metals, and sediment) with TOXI.

The EPD-RIV1 is a system of programs based upon the CE-QUAL-RIV1 model developed by the U.S. Army Engineers Waterways Experiment Station (WES) and developed for the Georgia Department of Natural Resources and USEPA, Region IV. EPD-RIV1 is a one-dimensional (cross-sectionally averaged) hydrodynamic and water quality model. It consists of two parts, a hydrodynamic code (EPDRiv1H) which is typically applied first, and a water quality code (EPDRiv1Q), which uses the results of the hydrodynamic code. It may perform waste load allocations in complex systems incorporating wastewater discharges, tributary inflows, water withdrawals, and power plant heat load. The water quality code can simulate the interactions of 16 state variables, including water temperature, nitrogen species (or nitrogenous biochemical oxygen demand), phosphorus species, DO, carbonaceous oxygen demand (two types), algae, iron, manganese, coliform bacteria and two arbitrary constituents. In addition, the model can simulate the impacts of macrophytes on dissolved oxygen and nutrient cycling. The model was designed for the simulation of dynamic conditions in rivers and streams for the purpose of analyzing existing conditions and performing waste load allocations, including allocations of Total Maximum Daily Loads (TMDLs).

RMA-11 is a finite element water quality model for simulation of three-dimensional estuaries, bays, lakes and rivers. It is also capable of simulating one and two dimensional approximations to systems either separately or in combined form. It is designed to accept input of velocities and depths calculated with hydrodynamic models to be applied in the solution of the advection diffusion constituent transport equations. Additional terms for each constituent represent source or sinks and growth or decay. The model operates independently of the time steps in the hydrodynamic model, input velocities and depths are automatically interpolated. RMA-11 could simulate 15 state variables, such as DO, BOD, nitrogen species (Org-N, NH_3, $N0_2$, NO_3), phosphorus species (Org-P and PO_4), algae as Chlorophyll a, Temperature, Cohesive and non-cohesive suspended sediments, salinity, coliform and up to 5 arbitrary non-conservative constituents.

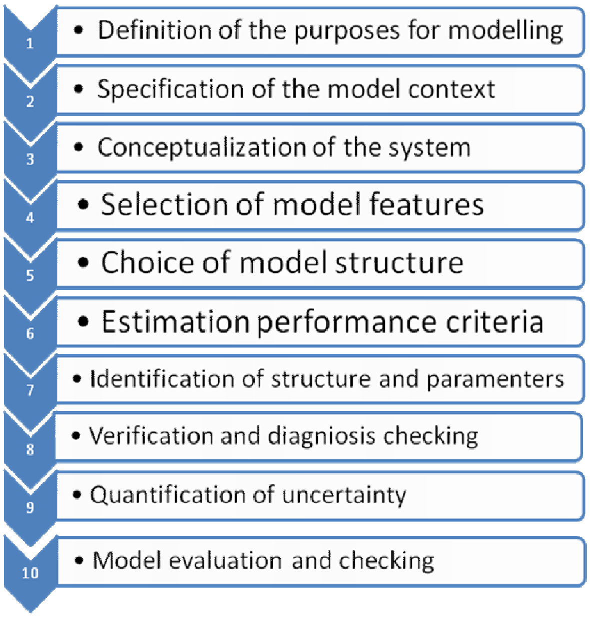

Figure 2. The ten-steps approach [Jakeman et al. 2006]

The issue to suggest guidelines for model development and evaluation for a wide range of model types was addressed by Jakeman et al. [2006], while more recently Blocken and Gualtieri [2012] proposed an application of the ten-steps approach to computation fluid dynamics (CFD) methods for EFM. This approach may be also applied to water quality models, which share basic equations, typically conservation law for mass, both for the fluid and the water quality variables, momentum and energy, with CFD models.

Two steps of the above approach will be shortly discussed here in the context of the above water quality models. The first one is *Specification of the modeling context: scope and resources*, where the specific questions and issues to be addressed by the model are identified, as well as the available resources, the forcing variables (drivers), the required outputs, the spatial and temporal scope, scale and resolution, the model flexibility and the users of the model. The second is *Conceptualization of the system, specification of data and other prior knowledge*, which refers to the definition of the data, prior knowledge and assumptions of the processes, based on the prior identification of model purposes. These steps suggest to consider the five above water quality models under the point of view of their level of complexity and their requirement of input data. Which level of complexity is required in a model aimed at the simulation of water quality in a river ? It is very likely that a model considering several physical processes affecting water quality involves a high number of data, whereas a model which includes only basic processes needs a limited number of data. Hence, the complexity of any model should be consistent with the quality and quantity of data available for its application. Furthermore, the financial cost of these models must also be considered. Coming back to the five considered water quality models, i.e. QUAL2EU, QUAL2Kw, WASP7, EPD-RIV1 and RMA-11, the QUAL2EU has been widely applied but it has lack of provision for conversion of algal death to CBOD being inappropriate where macrophytes play an important role on DO balance.

QUAL2Kw has an higher level of complexity as it includes automatic calibration system and new constituent interactions, such as algal BOD, denitrification, DO change caused by fixed plants, hyporheic exchange and sediment pore-water quality. WASP 7.5 requires a large amount of data but it allows the simulation of toxic pollution. EPD-RIV1 has the limitation of one-dimensional hydrodynamics simulation but it allows the simulation of a large number of water quality parameters, while RMA-11 it is fully three-dimensional but requires to be linked to a hydrodynamics model for the transport input data and it is not of public domain.
After all, it might be a useless exercise to try to identify the best water quality models, but the choice of a model depends also upon time, cost and requirements of the specific application, that is on the *Specification of the modeling context*.

3 SUSTAINABILITY INDICATORS FOR RIVER WATER QUALITY IN URBAN AREAS. A PROPOSAL

It is important to relate the traditional conceptualization of the water quality model with a more wide term of sustainability indicator proposal. For many years, a limited number of key measures have been used to judge how systems are performing, i.e. in economy: level of employment, rate of inflation, balance of payments, public sector borrowing, etc. These key numbers are Indicators of how well (or bad) the system is doing. Indicators are then quantified information which help us to explain how things are behaving. The variation of these indicators along time will inform modelers about how the key parameters of the system are changing. These information will give an overall picture of the performance of the system, but they must be quantified and compared to standard in order to assess the whole performance. Reliable indicators will alert the modeler about a problem before it gets too bad and they help managers to recognize what needs to be done to fix the problem.
In terms of sustainability, indicators are mainly related to natural resources; and they involve quite complicated assessment. Air quality, water quality and materials used for production have an effect on health and also on economics profits: if a process requires clean water as an input, previous water depuration is an extra expense, which reduces profits; and involves energy incomes and can have health consequences if it fails. Thus, sustainability requires this type of integrated view of the world: multidimensional indicators will be defined linking a community's economy, environment, and society. Also, sustainability indicators have basic functions of: simplification, quantification, and communication. All these functions must be represented in simple expressions. This is a difficult task, especially when dealing with urban waters, in which many agents are implicated. Particularly, sustainability indicators for river water quality modeling in urban areas will be related to sustain and improve water quality and the aquatic urban environment. Other aspects observed will be the management of the discharge of waste water, the instruments to control pollution, to ensure adequate water resources of sufficient quality available for abstraction for treatment as drinking water, and the elements which facilitate the recreational use of water where appropriate in the city.
The only way to quantify these key aspects include chemical and biological ratios of freshwater quality: concentrations of important pollutants, water pollution incidents, and expenditure on water supply and treatment. A list of indicators that could be proposed in this sense is:

- Dissolved Oxygen (mg/L);
- BOD (mg/m^3);
- COD (mg/m^3);
- Ammonia – Nitrite − Nitrate concentration (mg/L);
- Phosphorous − Nutrients (mg/L);
- Pesticides (mg/m^3);
- Metals (mg/m^3);
- Algae presence (mg/m^3);
- Pollution incidents (Number of incidents/year/inhabitants);
- Expenditure on water treated in cities for reuse and Amount of treated water for

reuses (Cost/inhabitant or m³/inhabitant);

- Expenditure on sewage treatment, Amount of sewage water, and Water treated per inhabitant (Cost/inhabitant or m³/inhabitant);
- Presence of marine outfall. Wastewater thrown to the sea (m³/inhabitant);
- Energy used in pumping/treating water in the city (Kw/m³/inhabitant);
- Rate of drinking water supplied/waste water treated (m³/m³).

Some of these indicators are related to modelling because the concentrations can be calculated or even measured by the modellers. Nevertheless, the interdisciplinary character of the sustainability indicators take other implications: more social or economical determinations must be considered and the traditional models are not suitable to be used as a complete tool for evaluation of sustainability in the city. As presented in Figure 3, water has a deep cycle in the urban environment and many economic and social agents are involved.

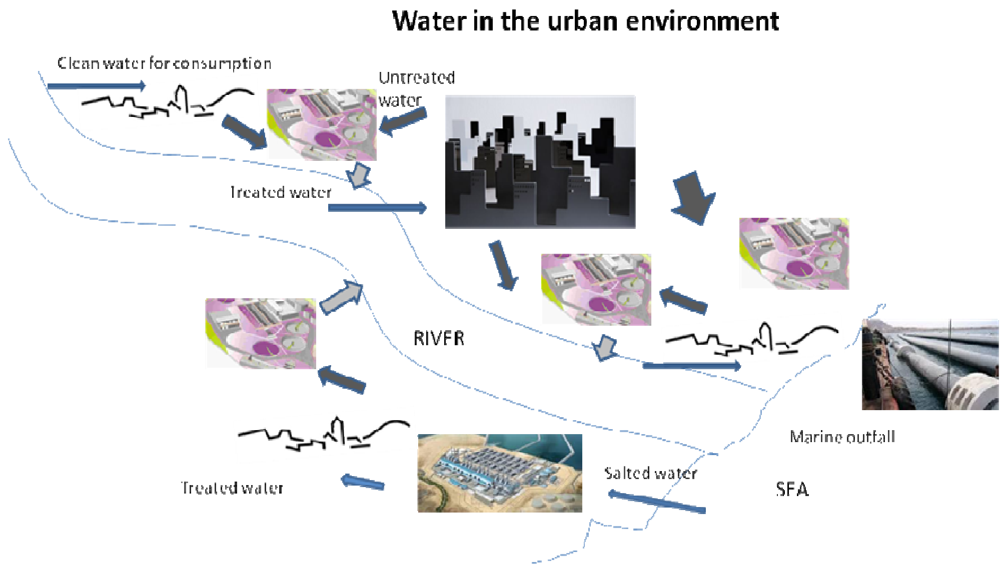

Figure 3. Water in the urban environment

4 CONCLUSIONS

Sustainability is a wide concept but necessary to be applied nowadays in all the processes involving resources wasting. One of the more important of these processes is the water cycle in the cities, where water quality issues are very frequent. River and sea water have many implications in this urban context from the primary moment of treatment, in river, bell or sea water, till the last moment of disposal as treated water; again in river or sea. Even the reuse of water is a possibility that must be considered within the whole management options in the urban environment towards sustainability.

The paper presented a short review of existing water quality models to be also applied in river management. First this review suggested that the specification of the modeling context and the conceptualization of the system allow to consider these models under the point of view of their level of complexity and their requirement of input data. Second, it was stressed that the approach to urban river management based on water quality models should evolve into one considering the concept of sustainability which involves a number of new issues and processes to be considered. However, despite urban development involves a large knowledge of all the technical, social, economical and environmental aspects of water management, a comprehensive model for sustainability of river water quality is currently missing. Hence, a list of potential, despite not exhaustive, indicators of sustainability was finally proposed.

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