On the Relation Between Urban Wastewater Management Needs and Receiving Water Objectives

WOLFGANG SCHILLING, NTNU, Trondheim, Norway; WILLY BAUWENS, Free University Brussels, Belgium;DIETRICH BORCHARDT, University Kassel, Germany; PETER KREBS, EAWAG, Switzerland; WOLFGANG RAUCH, University Innsbruck, Austria; PETER VANROLLEGHEM, University Gent, Belgium

INTRODUCTION

In the past, the growth of urban agglomerations in Europe caused major disruptions in basic needs such as public health, hygiene, and safety against flooding. Starting in the last century, large scale urban drainage systems were implemented to tackle the worst water related problems in urban areas. Subsequently, flood protection and public health improved dramatically. At the same time, the quality of receiving waters deteriorated as a result of the increased and more polluted discharges. Wastewater treatment schemes were implemented to alleviate this problem. Today, among urban drainage engineers the concept still prevails that "receiving water protection is equal to pollution discharge reduction".

While the engineer traditionally focuses on water quality and its improvement, biologists claim that the ecological quality of a receiving water is determined by numerous factors of which many are only poorly understood. A reasonable water quality is merely a necessary but not a sufficient criterion for ecological quality.

The receiving water regulators are in a particularly uncomfortable position, as their task is to define and control the ecological quality standards which receiving waters should fulfill. They have to call for action, but their demands can only be based on uncertain cause-effect evidence and are furthermore constrained by the needs and priorities of society. As a consequence, the receiving water protection standards in most countries are simple and uniformly applied regulations focusing on pollutant discharges reduction by end-of-pipe engineering measures.

There appears to be a widening gap between the increasing scientific knowledge on receiving water quality on the one hand, and the simplistic regulatory framework for receiving water protection on the other hand. Suspicion is rising that this gap leads to decreasing cost-efficiency of engineering measures for receiving water protection.

The classical urban drainage system was implemented in Europe in the last century and continues to serve its purpose until today: collect all wastewater, polluted or unpolluted, transport it as quickly as possible out of the urban area, and treat it as good as possible, before it is discharged into the receiving water. The physical means are a combined sewer system in which all types of sewage are collected, mixed and transported, and a wastewater treatment plant (WWTP) in which various physical, chemical and bio-chemical processes are applied to remove a large part of the pollutants. During rainfall very high flow rates occur that exceed the capacity of WWTPs. Hence, a fraction of the sewage cannot be treated and is directly discharged into the receiving water (combined sewer overflow, CSO).

Solutions to reduce receiving water pollution from urban discharges are 1: to reduce the amount of sewage (e.g. by infiltration of stormwater into the soil), 2: reduce CSO (e.g. by implementing storage), 3: increase WWTP capacity (e.g. by volumetric expansion), and 4: increase treatment efficiency (e.g. by process control).

IMPACTS OF URBAN DISCHARGES ON RECEIVING WATERS

Urban wastewater discharge impacts on receiving waters can be grouped into chemical, bio-chemical, physical, hygienic, esthetic, hydraulic and hydrologic. These impacts can be further classified in terms of duration as acute, delayed or accumulating.

The immediate oxygen depletion in the receiving water passing a sewerage discharge point is considered the dominating acute effect in running waters. E.g., during CSO events large amounts of oxygen-demanding substances may be discharged. Easily degradable, dissolved organic substances cause an immediate oxygen demand in the water phase by suspended bacteria and through direct absorption by benthic organisms. A delayed oxygen depletion is caused by sedimentation of particulate, slowly degradable organic matter. On longer term, low oxygen concentrations may result as a consequence of eutrophication, caused by the accumulation of nutrients released by the WWTP, successive CSO events and from diffuse sources.

Toxic pollutants (heavy metals, pesticides, oil-derivatives,…) can result in immediate impacts to the receiving water biota when released in high concentrations. Of particular interest are short duration ammonia discharges, as the unionized form of ammonia is a strong fish toxicant. Long term exposure of toxicants due to adsorption and accumulation may have chronic effects to aquatic life (i.e. carcinogenic or mutagenic), even at low levels. Bio-accumulation effects, synergetic effects and the creation of degraded products that may be more harmful than the original pollutant impede a straightforward assessment of the impacts of many toxic pollutants.

Important problems - as seen by the general public - relate to esthetic pollution due to the discharge of trash, debris and oil, and to hygienic pollution due to pathogenic (fecal) bacteria and viruses. The discharge of sewage with high concentration of suspended solids inhibits biological activity by reducing light penetration and coats the substratum with an anaerobic layer of fine sediment.

Urban discharges result in significant changes in local hydraulic flow conditions. Acute effects on the organisms living near the river bed and banks might be caused by increased shear stress. Discharge of settleable solids through CSO and WWTP effluents might proliferate sealing of the substratum from the water body and thereby destroy the habitat of macroinvertebrates. On the long run, the morphology of the river may be affected by the changes in the hydraulic regime. Table 1 summarizes the most relevant effects of urban wastewater discharges on receiving waters.

An analysis of the impacts mentioned above shows that they originate from different causes (i.e. hydraulic, chemical, physical, bio-chemical,…) that act on different temporal and spatial scales. Moreover, the assessment of the overall impact has to consider synergetic effects between the impacts of urban discharges as well as conditions of the receiving water itself. The latter include the hydrologic regime (e.g. floods, droughts, regulated flows), the morphology of the receiving water (e.g. shape and stability of the river bed), the climatic and the ecological characteristics of the river basin.

Table 1: Impacts of urban discharges on receiving waters

time scale	characterization	indicator variable
acute	hydraulic	flow, shear stress, bed erosion
(hours)	chemical	toxic substances (NH_3)
	physical	suspended solids
	bio-chemical	oxygen depletion in the water body
	hygienic	bacteria, virus
	aesthetic	floating material, odor
delayed	hydraulic	sediment carrying capacity
(days)	chemical	toxic substances (NH_3, NO_2)
	bio-chemical	oxygen depletion in the sediments
	hygienic	bacteria, virus
	esthetic	floatables, debris, oil
accumulating	hydologic	flow regime, morphology
(weeks, years)	chemical	heavy metals, persistent organics,
		inorganic and organic sediments
	bio-chemical	oxygen depletion (eutrophication)

CHARACTERISATION OF RECEIVING WATERS

In the majority of current legislation, the goals for receiving water quality are characterised by threshold values of a variety of chemical and physical water quality parameters. Usually, no distinction is made between different types of receiving waters. Neither are criteria included that refer to biologic, hydraulic, morphologic, and hydrologic characteristics or indicator variables describing these characteristics. However, they may be as crucial for the ecological quality of the receiving water than physical and chemical water quality parameters. To assess the ecological quality of a receiving water, a wider perspective is needed, that takes into account, both, the different types of receiving waters and their spectrum of characteristics.

Table 2 relates the most important types of receiving waters to their characteristics mentioned above. The importance of various characteristics for the ecological quality is indicated as a function of the receiving water type. High ecological quality is only attained when the requirements of the most important, if not all, characteristics are fulfilled. Table 2 shows, for example, that a small river is obviously sensitive with respect to more quality indicators than an inland sea and therefore requires a more detailed evaluation.

If such a table shall be used as an operational tool, the individual cells consist of some type of evaluation system that may vary as a function of site specific conditions, such as the ecological characteristics or the type of water use. While to maintain the level of ecological quality is the goal, the various water uses must be taken into account as boundary conditions or constraints. These include water supply, recreation, irrigation, shipping, fishery, cooling, waste disposal, and hydropower. The required ecological quality is defined by the use as such and does usually not depend on the type of receiving water.

Table 2: Importance of indicators characterising ecological quality of receiving waters.

Type	Running waters			Stagnant waters			Tidal waters	
	creek	small river	large river	mixed	stratified	inland sea	estuary	coast
Phys.-chem.	+	++	++	++	++	+	+	++
Biologic	++	++	+	++	+	+	++	+
Hydraulic	++$^{1)}$	++$^{1)}$	+$^{1)}$	+$^{2)}$	+$^{2)}$, +$^{3)}$	-	++$^{3)}$	++$^{3)}$
Morphologic	++	++	+	+	+	-	+	-
Hydrologic	++$^{4)}$	++$^{4)}$	+$^{4)}$	-	-	-	-	-

$^{1)}$ e.g. velocity, shear stress; $^{2)}$ e.g. retention time, water level variations; $^{3)}$ e.g. mixing characteristics, turbidity currents; $^{4)}$ e.g. flow distribution, floods, droughts

Table 3 presents an example on what is to be included in a cell of the matrix shown in Table 2. Here, for a small river the criteria for quality classes with respect to the most relevant physical-chemical parameters are given. If the river is additionally used for a specific purpose, further parameters must be added that might either harmonise, compete or conflict with the ecological quality goals. Table 3 adopts the trend in many European water quality assessment systems towards setting 4 quality classes, rather than differentiating only between “good” and “bad” quality.

The values in Table 3 indicate the required criteria for achieving a certain quality class. In case of a small river, acute problems are most pertinent. Those can be appropriately described with extreme value statistics. For example, in order to be rated having “sufficient water quality”, the small river must not have: a minimum oxygen concentration below 3 mg/l, during one hour, more often than once per year.

Likewise, cells in Table 2 may be defined for other types of receiving waters. In stagnant waters, for example, it is more relevant to limit accumulative pollution. Here, more appropriate indicator variables may be total nitrogen N_{tot}, total phosphorus P_{tot}, and heavy metals.

In order to develop appropriate management decisions it is necessary to distinguish objectives that describe (1) a reference state, (2) the present situation and (3) the achievable state of the receiving water. The reference state is equal to the best ecological quality. The present ecological state (usually a deteriorated state) may be identified from the difference to the reference state of the variables in Table 2. The achievable state in terms of ecological quality and other uses is the necessary compromise between the reference state and the human impact that cannot be avoided. This compromise includes socio-economic constraints. Therefore, it is necessary to define the matrix in Table 3 site-specifically and according to the local interests. These should be related to appropriate temporal and spatial scales as indicated in Table 1.

Table 3: Example of a cell in the matrix shown in Table 2 (shaded). Receiving water type: "small river". Physical-chemical characteristics described by 3 relevant indicator variables "dissolved oxygen", "unionised ammonia", "water temperature".

Cause	Parameter	Required value for level of ecological quality			
		good	sufficient	insufficient	bad
Toxic effects	DO (mg/l), duration 1 h return period 1 year	4	3	2	1
	NH_3 (mg/l), duration 1 h, return period 1 year	0.1	0.2	0.3	0.4
Tempe-rature	dev from reference (ºC) annual change (ºCd)	1 0-5%	2 5-10%	3 10-20%	4 >20%

Special attention must be paid to dynamic conditions, both, in time and space. For example, in a small river that is heavily influenced by an urban drainage system, short duration ammonia concentrations are important. The outcome of field measurements are depending on the season and the day time of sampling. Diurnal variation of ammonia concentrations in sewage can be in the range of 1:10. The base flow in the river may be increased in the spring due to snow melt or high groundwater table and thus dilute the concentrations as compared to late autumn. Due to the kinetics of the biochemical processes, the critical concentration might be observed far downstream of sewage discharge as well as delayed in time. To handle these problems, field sampling must be augmented with dynamic modelling and statistical analyses to describe the sensitivity and the behaviour of the receiving water.

In the real world, conflicts between the aspired ecological quality (objective) and the various water uses (boundary conditions) exist. Trade-offs must be defined based on political priorities and subject to local conditions. An operational advantage of the proposed approach is the possibility to resolve problems arising from conflicting receiving water objectives: The 'fuzzy' formulation of required indicator variables within a decision support system allows to find best compromise solutions without compromising the scientific relevance of the receiving water assessment.

CONSEQUENCES FOR URBAN WATER MANAGEMENT

In the past, the bad physical-chemical quality of the receiving waters overpowered most other detrimental effects on their ecological quality. Today, the level of treatment of urban wastewater discharges in some West European regions is so high that other parameters become relatively important, too. From Table 2 it is obvious that most of these parameters cannot necessarily be correlated to effects from the urban drainage and wastewater system. Cause-effect relations seem to exist but, apart from the physical-chemical water quality they cannot be quantified yet. This does not mean, however, that improvement of the ecological quality can only be achieved by means of uniformly applied end-of-pipe measures in WWTP's and CSO's.

On the other hand, there is still a long way to go when trying to comprehensively predict the effects of engineering solutions within the urban wastewater and drainage system on the receiving water ecosystem. The attempt above is a step towards closing the gap between engineering pragmatism and scientific rigor. Cause-effect relations are qualitatively known, but it will require a number of case studies and further basic research to derive quantitative relations and to validate the usefulness of the approach above. A prerequisite for progress is the sheer existence of an approach that, both, engineers and scientists can agree upon.

The bottleneck with respect to the operational application of the approach is the lack of quantitative cause-effect relationships in the "receiving water" system. Two strategies seem to be worthwhile for further development. One is based on a "black-box" data-driven approach similar to the RIVPACS system developed for natural waters (Wright et al., 1993). The aim is to mine the immense databases collected by environmental agencies for relationships between physico-chemical and morphologic descriptors of receiving waters and their ecological quality (e.g. quantified by invertebrate communities).

The other approach is more pragmatic. Cause-effect relationships might be established between urban drainage related descriptors (e.g. predicted using urban drainage models) and biological water quality descriptors typically used by the scientist and/or public opinion. The aim would be to identify the most important cause-effect relationships for different receiving waters (type and current state) and subsequently to establish relevant characteristics as suggested in Table 3.

In the past, wastewater treatment was necessary to restore the water quality in receiving waters, because wastewater discharges were primarily responsible for the receiving water deterioration. Today, having reached a high efficiency with respect to physical-chemical purification, it is debatable whether not a mix of, both, physical-chemical pollution abatement, morphologic restoration and hydrologic management measures would yield a higher ecological quality of the receiving water, than focusing solely on pollution abatement.

The pragmatic assumption of the past was that improved wastewater treatment is cost-effective to yield better ecological receiving water quality. In the future this might become an expensive misconception. If investments continue to focus on wastewater treatment, and leave out other aspects of receiving water quality, we might get nowhere at great expense. We might even compromise possibilities for more effective solutions in the future. However, our limited knowledge should obviously not be used as an argument to scale down efforts for achieving a better quality of our receiving waters.

REFERENCES

Lijklema, L.; Tyson, J.M., Le Souef, A., "Interactions between sewers, treatment plants and receiving waters in urban areas", Proc. IAWPRC Conf.INTERURBA ´92, Wageningen, the Netherlands, Water Science and Technology, Vol. 27, 1993.

Wright, J.F., Furse, M.T. and Armitage, P.D. (1993) "RIVPACS - A technique for evaluating the biological quality of rivers in the UK". Eur. Wat. Poll. Cont., 3(4), 15-25.

ACKNOWLEDGMENT

The paper was inspired by discussions during a workshop sponsored by the European project COST 682 "Integrated Wastewater Management", held 20 - 23 October 1996 in Trondheim, Norway.