

Waste design and source control lead to flexibility in wastewater management

T.A. Larsen and W. Gujer

Swiss Federal Institute for Aquatic Science and Technology (EAWAG) and
Swiss Federal Institute of Technology (ETH), 8600 Dübendorf, Switzerland

Abstract The concepts of *waste design* and *source control* are introduced as contracts between wastewater handling agencies and consumers and consumers and industry respectively. Waste design serves to produce waste streams that are optimized in composition and time sequence for easy transport and treatment. Source control makes services and installations available, which allow the consumer to adhere to the specifications of waste design. Increased delegation of responsibility to the consumer is expected to result in more flexible wastewater handling systems.

Keywords Source control; waste design; wastewater management; flexibility; consumer preference; sustainable development; combined sewer system

Introduction

With the Brundtland report in 1989 and the Rio conference in 1992, sustainable wastewater treatment has become an important focus. Typical driving forces for new ideas are:

- the fact that phosphorus is a limited resource with known reserves for approximately 150 yrs (U.S. Geological Survey, 1999);
- the rising awareness for the costs of urban water management;
- the difficulties of exporting the concepts of western urban water management technologies to the rest of the world (Larsen and Gujer, 1997).

A recent element of discussion in water pollution control is the discovery that micro pollutants (endocrine disruptors, residual pharmaceuticals, pesticides, fuel additives etc.) are much more abundant in the aquatic ecosystems and even in drinking water resources than previously anticipated (Buser *et al.*, 1998; Halling-Sørensen *et al.*, 1998; Ternes, 1998; Ternes *et al.*, 1999). New analytical methods are able to detect biologically highly active compounds in extremely low concentrations and indications are found that these compounds may threaten fish populations (Frick *et al.*, 1998; Renner, 1998). Although the concentrations of micro pollutants found in drinking water are extremely low, Ternes *et al.* (1999) consider the building of antibiotic resistance to be a problem of direct relevance to human health. The problem of resistance building stems from the presence of resistant microorganisms in wastewater as well as from the exposure of natural microorganisms to residual antibiotics in wastewater.

Closing nutrient cycles, reducing the load of anthropogenic micro pollutants and lowering the costs of wastewater management are all elements calling for a more active attitude towards wastewater management. Recently Henze (1997) introduced the concept of waste design referring to the idea of a proactive attitude towards wastewater treatment. Rather than passively accepting the wastewater as it happens to be produced, it is anticipated that we actively start to influence its composition by means of segregation, retention, water saving measures etc., with the goal to alleviate the task of wastewater treatment.

In this paper we will discuss possibilities to deal with today's major problems in wastewater management and we will identify possibilities to develop the existing systems into a more diverse and flexible future.

Definitions

The terms *source control* and *waste design* will be used in the following way in this paper (Figure 1).

- *Waste design* stands for the interaction of the consumer (or the producer of wastewater) and the agencies that provide the services required for dealing with wastewater. This interaction consists of a contract, which specifies the duties and the rights of the consumer on one side and the duties and the rights of the wastewater agency on the other side. The consumer may accept restrictions with regard to the composition of the waste and possibly the time when she can discharge this waste, and the agency accepts the liability to correctly handle the waste and to provide efficient and economic service. The details of this interaction must be dealt with in view of the desires and possibilities of the consumer and the technological and economic possibilities of the agency.

Examples of waste design are: (i) The fact that legislation in Switzerland demands that rainwater collected from new urban developments can only be discharged to the sewer if local infiltration is not possible (e.g. due to local hydrogeological limitations) or (ii) that an enterprise which uses heavy metals in galvanic surface protection must pre-treat its waste to certain standards before it can be discharged to a sewer.

- *Source control* stands for the interaction of the consumer with industry that provides the services and goods the consumer desires. These goods and services must allow one to fulfill the waste design restrictions the consumer accepted (or had to accept). Given the (enforced) restrictions from the waste side, the consumer will demand that whatever she is buying from the market must allow her to fulfill her duties.

An example for source control is the way washing powders have evolved. First hard, non-biodegradable detergents had to be replaced with biodegradable materials, later (in some countries) the phosphates had to be substituted with alternative complexing and softening agents.

Today's problems – an analysis

The combined sewer system (CSSs) is the most frequently used system for wastewater management in western countries. Even though alternatives to this system exist, they are minor deviations and improvements rather than true technological alternatives. In order to remain concise we will concentrate on the analysis of CSSs but most arguments may equally be applied to alternative systems employed today.

Table 1 is a summary of some defects of today's system. These defects have three main causes.

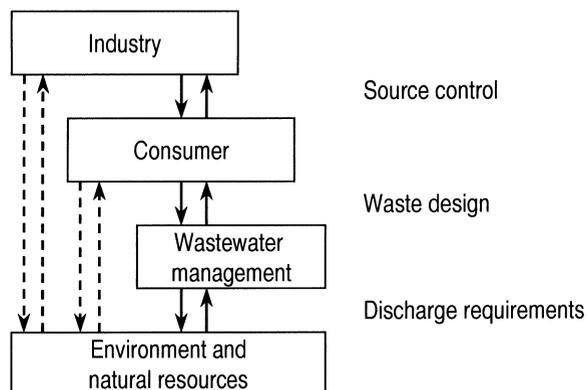


Figure 1 Source control, waste design and discharge requirements relate to different interfaces between the relevant systems. This paper deals with source control and waste design

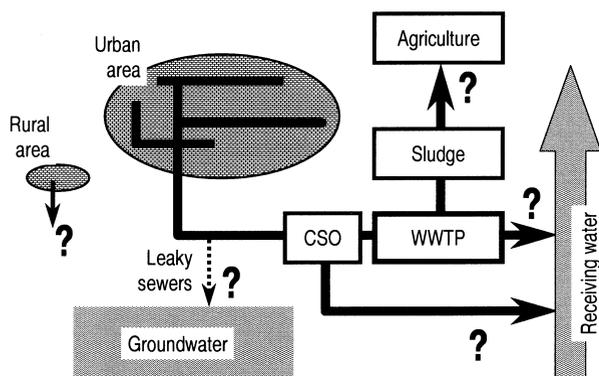


Figure 2 Today's wastewater management systems have many leaks. Only a limited fraction of the pollutants reach the treatment plant and residual pollutants are discharged to the environment

Points 1 to 3 (Table 1) relate to the source of the wastewater: CSSs are designed to accept just about any wastewater produced. Only few restrictions are enforced, the pretreatment of industrial and trade waste being the most important one. In addition, some specifications with regard to the composition and properties of consumer chemicals exist.

In general, anthropogenic organic chemicals are metabolized to a polar water soluble form to allow excretion by the kidney (Sheldon *et al.*, 1986). Informally, experts estimate that 70–80% of the pharmaceuticals in today's wastewater originate from urine. It is unrealistic to demand that these pharmaceuticals should not be used any more or that only pharmaceuticals should be allowed which have a very short half life in the environment: Here source control is obviously difficult. However it is realistic to introduce waste management systems which can separately deal with urine (Waste design, Larsen and Gujler 1996).

Points 4 to 7 relate to the technological possibilities of the system. Figure 2 identifies that not all pollutants and pathogens released by consumers reach the wastewater treatment plant. Unconnected waste sources and leaks from sewers of unknown magnitude introduce pollutants into the environment and endanger e.g. drinking water resources. CSOs lead untreated combined waste to the receiving water. Sewage sludge and treated wastewater contain residual pollutants. Clearly even well maintained and fully developed systems will only reduce the load of the environment to a limited degree.

In Switzerland where the construction of the infrastructure is well developed, some 6% of the consumers are not connected to public sewers and have only marginal wastewater handling facilities. Recently a shortcut between a leaking sewer and a groundwater pumping station caused a major breakout of *shigella* (several thousand cases). Further the ban of phosphates in washing powders in 1986 resulted in a reduction of lake eutrophication which was far better than predicted. Predictions did not take the leaks from sewers and unconnected consumers into account (Siegrist and Boller, 1999).

Points 8 and 9 relate to the fact that today's CSSs are extremely inflexible and lead to a natural monopoly (A natural monopoly describes the situation where the average cost per unit of production falls sharply over the entire range of output of a firm or industry. Thus a single firm, a monopoly, can supply the industry output more efficiently than can multiple firms. Samuelson and Nordhaus, 1995). For CSSs, capital costs by far exceed the operating costs. The long economic life of the sewers (in Switzerland typically 80 yrs) together with the fact that CSSs have grown over the last century lead to a classical technological lock-in. We have to maintain the function of all elements (sewers) if we want to "use up" the investment into more recently built elements of the system. However, sewer renovation is expen-

Table 1 Problems of Today's Wastewater Management System (Combined Sewer System)

1. Disposal of sewage sludge	Due to the content of heavy metals and anthropogenic organic substances, recycling of nutrients into agriculture is difficult. Incineration is expensive and produces solid residues, which have to be disposed of.
2. Nutrient cycles	At the present level of consumption, known resources of phosphorus exist for only 150 years (US Geological Survey, 1999). P-extraction from sewage sludge is attempted, but is resource consuming and expensive (Brett <i>et al.</i> , 1997). Direct recycling of sludge is difficult. In the present system, significant recycling of nutrients other than P is only possible if wastewater effluent is used for irrigation.
3. Micro pollutants	Until now, micro pollution primarily posed problems for the disposal of sewage sludge (see 1). In the last years, an increasing number of studies have documented that a large range of micro pollutants are present in detectable amounts in aquatic ecosystems and in ground water (e.g. Buser <i>et al.</i> , 1998; Halling-Sørensen <i>et al.</i> , 1998; Ternes, 1998). It is suspected that micro pollutants are co-responsible for observed damage to fish populations in rivers and lakes (Frick <i>et al.</i> , 1998; Renner, 1998).
4. The system leaks	Even with well developed combined sewer systems, an estimated 20% of the pollutants do not reach the treatment plant and get lost directly to the environment via unconnected wastewater sources, leaks in sewers, and CSOs. Overall treatment efficiency is therefore always less than 80%!
5. The system causes hygienic problems	Leaks of untreated sanitary wastewater, treated effluent and sewage sludge are the cause of many hygienic problems in surface and groundwater as well as in agriculture.
6. The system drains off ground water	In many non-arid countries, groundwater infiltration into poorly maintained sewers accounts for as much as 50% of the combined wastewater, often more than the total water consumption. This results in a local loss of groundwater and dilutes the wastewater.
7. Sewer maintenance	In urban areas, sewer maintenance and renovation is an important economic burden and is frequently neglected. Additionally, construction sites are a nuisance in cities.
8. The system is inflexible	The sewer system is one of the most inflexible systems, one can imagine. Thousands of elements (sewers) with different age, all with life-expectancies from 50 to more than 100 years must function as a whole. Rapid reaction to new problems is not possible.
9. The system is not suited for privatization	The combined sewer system results in a natural monopoly that requires a high degree of regulation if this service is to be provided by the private sector. This slows innovation and does not allow for a free market situation.

sive and demands an additional long economic life span of renovated elements... A vicious circle.

Flexibility of public services is a new idea, influenced by present developments, and the spirit of our time. In water supply systems, the change from ever growing demand to stagnant or even shrinking water consumption is one example why flexibility comes up as an important issue (Tillman *et al.*, 2001). For urban wastewater management systems, it is striking that fundamental methodologies have remained relatively stable for more than a century while consumer behavior and production technologies have evolved dramatically. In an environment of rapid technological progress, it is difficult to understand – and to accept – that an industry, which in western economies consumes approximately 2% of GDP, is hardly changing.

According to most economic theories (see e.g. Samuelson and Nordhaus, 1995), the market is a driving force for innovation, a force which for obvious reasons is lacking in a natural monopoly. Privatization is only possible with a high degree of regulation and in our opinion, urban water management does not work in a fundamentally different way in countries which have privatized these services.

Waste design

Waste design is a concept where the interface between the consumer and the agency responsible for waste handling is defined. Ideally this definition considers the utility function of all stakeholders involved. An ideal situation could look like this.

- The *consumer* knows what service the waste handling agencies can provide reliably and economically. She can invest in source control technology, which allows to fulfill the requirements of waste design. Since the interaction of the consumer with the waste agency is based on a rather long-term contract, economic depreciation of her investment is possible.
- The *waste agencies* have clearly defined duties and do not have to adapt their investment to new trends at ever-increasing pace. By this their capital is protected even if the economic service life of their infrastructure is very long. These agencies can therefore provide their service rather economically.
- *Industry* is interested in producing source control procedures and apparatus because it can expect that there will be a long-term demand for such goods.

In order to achieve this situation, explicit contracts between the population (politics) on one hand and the engineers responsible for wastewater handling on the other hand are necessary. At the moment, this contract is only available in an implicit form. Research may have an important role to play in the mediation of such contracts on the basis of transparent and un-biased assessment of different possibilities. Given clear and explicit boundary conditions and as much freedom as possible, we expect that the three stakeholders will together optimize the system and thereby gain increased flexibility.

Waste design is limited to the specification of the composition of different segregated waste streams and to the time sequence of when these waste streams can be discharged to which system. According to Henze (1997), the goal of waste design is to produce a waste with an optimal composition for further treatment and disposal. He considers flexibility and adaptivity to be essential for obtaining sustainable solutions.

In the field of solid waste handling the concept of waste design is increasingly practiced worldwide and has led to many economic and environmental improvements. In many countries with well developed infrastructure, several solid waste streams are separated and it is

Table 2 Possible "milestones" for waste design

	Advantages as compared to today's conventional system (CSS)
1. No source control	Does not exist in Western Europe.
2. As today (regulation)	Regulation prevents clogging of sewers, contamination of sludge, poisoning of the biocenosis in wastewater treatment plants, etc.
3. As today minus rainwater	Infiltration results in fewer storm water retention basins and/or fewer CSO events. With time, the diameter of sewers will decrease. Groundwater is replenished to a certain degree, depending on local infiltration possibilities.
4. As today minus faeces	If the feces are kept out of the system, the organic loading of the treatment plants is reduced by a third. The hygienic problems caused by wastewater will be drastically reduced.
5. As today minus urine	With urine separation, nutrient control at the treatment plant will be obsolete. Nutrient recycling to agriculture will be facilitated. Emissions of pharmaceuticals and hormones from human metabolism to the combined sewers will be drastically reduced.
6. Only gray water collection	This solution combines the advantages of 4 and 5.
7. Production of "un-polluted" wastewater only	Unpolluted wastewater may be disposed of together with storm water. Storm sewers or infiltration possibilities have to be provided anyway in non-arid areas. There will be no use for the rest of the CSS.
8. No export of wastewater	In non-arid parts of the world, this is comparable to 7

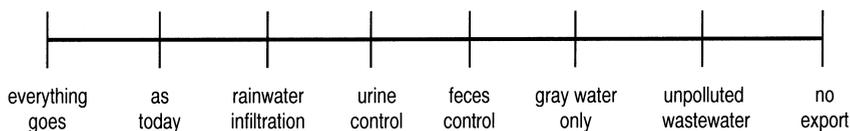


Figure 3 The span of waste design for households. For more details, see Table 2

specified when (weekday, date, ...) and where (central collection station, in front of the house, ...) these streams can be handed over to the waste handling agencies. Clearly this concept is easier to enforce for solid waste which is transported in digital form by truck rather than for wastewater which is transported in analog, continuous form in sewers.

In the wastewater field the possible span of waste design is wide (Figure 3). It extends from today's restrictions (we cannot dispose off solvents or oil or ...) to total on-site waste handling as practiced on many North American rural properties.

It is important that we do not specify the technology to be used for waste segregation and possible on-site treatment. Rather we should specify what properties the waste streams must have in order to be accepted. This will spur competition in industry in order to develop alternative possibilities to deal with new problems. For instance we could drastically reduce hygienic problems with CSS if hygienic on site solutions for the handling of faeces were mandatory. Whether this goal will be reached with an improved compost toilet or in an ingenious device, which results in a handful of nutrient-rich ashes, will largely depend on the technological ingenuity of industry and the preferences of the consumer.

Waste design is expected to lead to restrictions for the consumer that will initially be a nuisance. Still, if the concept of waste design is well applied, the consumer will profit in the long run from the fact that environmentally satisfactory services will be provided more economically. Further, if the requirements are formulated in a reliable long-term fashion, industry will respond and start to provide solutions, which will serve the consumer. It may be necessary to speed up such developments by providing economic incentives in an initial phase. Temporarily reduced connection fees for complying customers are a possibility. Similar concepts have been used to speed up the introduction of catalysts in cars when taxes for new cars with this technology were reduced in Germany.

Since the economically driven time frames in industry are much shorter than in public services, waste design will specify what the industry has to solve on site and what residual pollutants the public utility can accept from industries without adverse consequences. Typically it takes several years to design and construct a public wastewater treatment plant whereas industries barely know what they will produce in a few years – and definitely the economic service life of these public works is beyond the time scale of any planning horizon of an industry.

Source control

Source control should be driven by consumer demands and a market which provides the desired services within the limitations of waste design. Source control practice is a very broad approach to accommodate the requirements of waste handling and consumer utility, and will contain one or more of the following elements:

- substitution of chemicals not wanted in the waste streams;
- enhancement of the treatability (degradability) of user chemicals without losing the characteristics desired by the consumer;
- on-site treatment of concentrated industrial and trade waste with problem specific technology;
- development of new appliances which will save water or segregate waste streams in the desired way;

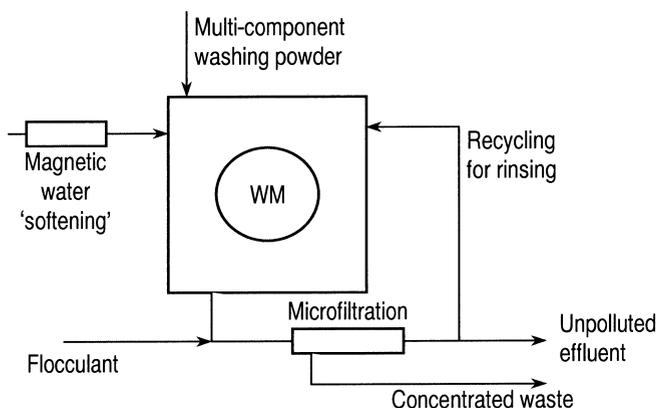


Figure 4 Hypothetical invention, a water saving, non polluting, self-controlling washing machine

- development of waste handling processes for individual households;
- etc.

There are a number of examples in the literature for the implementation of the source control measures listed above. Here, we will give an example of a possible development for waste handling processes for individual households. Normally, such solutions rely on extensive biological processes. However, for obvious reasons, high-tech physical-chemical processes are easier to mass-produce and incorporate into home appliances than biological processes.

Figure 4 illustrates some of the theoretical possibilities for source control, offered by high-tech physical-chemical treatment methods. We “invented” a non-polluting, water saving, self-controlling washing machine in order to illustrate the principles and challenges of applying source control in households. Important are the following points.

- The washing machine, as well as the chemicals used in the process is optimized, not only for the washing process, but also for the waste handling process.
- Synergies are found between waste handling and water saving measures: the desired amount of water saving becomes possible only due to the waste handling system. And the water saving minimizes residual pollutant flux in the wastewater.
- The recycling of effluent for rinsing is essential for the self-controlling aspect: only if the waste treatment module works, will the washing machine work!
- Partial recycling of washing chemicals may be possible.

Not only the advantages, also the problems of source control in households become clear in this example. There is a clear trade-off between energy consumption and use of chemicals (chemicals for flocculation/precipitation allowing one to use micro-filtration versus the use of energy consuming reverse osmosis technology); traces of pollutants in the effluent may still require further treatment (possibly in extensive, biologic filters or centralized polishing technology). The “concentrated waste” is another problem for which a solution must be found. Transport with the solid waste is one option, but concentrated liquid or humid solid waste may cause problems elsewhere.

Introducing our hypothetical washing machine would be in competition with using the services of a public or industrial laundry, which already today may have significant on site treatment of its waste and could possibly become an economic alternative. The consumer must have the choice.

System size and flexibility

Today’s CSSs are inflexible because the many elements of the system (sewers) can provide their service only as a collective. If each individual house or firm could solve its waste

problem independently, new technologies could rapidly be introduced as seen e.g. with the introduction of the catalyst in private cars where 10–15 yrs after the introduction of this new technology sale of leaded gasoline could be stopped.

The advantage of large wastewater collection systems results from the statistics of single polluting events. In a large community where the wastewater takes hours to reach the treatment plant, individual behavior cannot be identified in the influent of the treatment plant. The leveling out of the load of the treatment plants led to the development of technologies, which heavily rely on biological processes. Microorganisms are efficient waste handlers as long as they are continuously supplied with a stable mix of pollutants.

In Switzerland, the historic argument to combine the treatment of domestic, trade and industrial wastewater was that this combination would reduce problems to deal with nutrient limited wastewater. The leveling out of pollutant loads leads to decreasing design values for the solids retention time (SRT) of activated sludge systems for large treatment plants (ATV, 1991)

Wastewater handling systems for individual houses or industries suffer from the fact that they must deal with individual polluting events. Consider e.g. an individual, which for medical purposes must use some antibiotics, of which a large fraction will be released to the waste stream. Definitely such events result in extreme variations of waste composition and their biological effects. Biological systems, which can deal with such variations, require considerable buffer capacity and invariably depend on the availability of large land areas resulting in very extensive treatment units. Space saving high-tech solutions would have to rely on physical chemical processes that today are less energy efficient than modern large-scale biological treatment systems.

Flexibility can be gained by introducing small to very small systems that handle the waste of a few individual sources. It is important that these small systems are installed as one unit such that the entire system maintains equal economic age and may in the future be adapted as an entire unit. However such small-scale systems must after a period of technological maturation be able to compete with large-scale systems in view of economy and resource efficiency (LCA).

Conclusions

Micro pollutants (residual pharmaceuticals, products for body care, fuel additives, washing powders, etc.) and pathogens (hygiene) are rapidly recognized to be a major threat to the environment and to the quality of water resources. Today's waste handling systems are not designed to deal efficiently with these problems.

Large amounts of essential nutrients such as nitrogen, phosphorus and potassium are lost from today's combined sewer systems (CSSs).

These systems (CSSs), as we predominantly use them today, have many defects that in densely populated areas result in unacceptable environmental conditions. These defects relate to the fact that today's CSS have many leaks which are inherent in the system and can only be closed at extreme expense. Today an estimated 20% of the pollutants do not even reach the treatment plant.

At the same time, today's CSSs are extremely inflexible and lead to a classical technological lock-in and a natural monopoly. Therefore CSSs in their present form do not allow for significant innovation.

More flexible systems may be obtained if more responsibility is delegated to the producer of the waste (the consumer of the waste handling services). This can possibly be achieved with the concept of waste design. In this concept we clearly prescribe the properties (composition and time sequence) of segregated waste streams which will be accepted by the public utility and will be disposed of reliably, economically and environmentally acceptably. It

is the responsibility of the consumer to deliver a waste, which is within the boundaries of what is acceptable.

Industry has the task to provide options for source control, which allow the consumer to adhere to the waste design prescriptions. In densely populated areas, we expect high-tech physical-chemical processes to be superior as compared to biological processes.

Concepts of waste design and source control may well become essential tools, which will help to release today's technological lock-in, will lead to more flexible systems and will spur innovation.

References

- ATV (1991). *Bemessung von einstufigen Belebungsanlagen ab 5000 Einwohnerwerten*. Arbeitsblatt A 131. Ein Regelwerk der Abwassertechnischen Vereinigung e.V. (ATV). In German.
- Brett, S., Guy, J., Morse, G.K. and Lester, J.N. (1997). *Phosphorus removal and recovery technologies*. Environmental and Water Resource Engineering Section, Imperial College of Science, Technology and Medicine, London.
- Buser, H., Müller, M.D. and Theobald, N. (1998). Occurrence of the pharmaceutical drug clofibric acid and the herbicide mecoprop in various Swiss lakes and in the North Sea. *Environmental Science and Technology*, **32**(1), 188–192.
- Frick, E., Nowak, D., Reust, C. and Burkhardt-Holm, P. (1998). Der Fischrückgang in den schweizerischen Fließgewässern. *Gas, Wasser, Abwasser*, **78**(4), 261–264. (In German).
- Halling-Sørensen, B., Nors Nielsen, S., Lanzky, P.F., Ingerslev, F., Holten Lützhøft, H.C. and Sørensen, S.E. (1998). Occurrence, fate and effects of pharmaceutical substances in the environment – a review. *Chemosphere*, **36**(2), 357–393
- Henze, M. (1997). Waste design for households with respect to water, organics and nutrients. *Wat. Sci. Tech.*, **35**(9), 113–120.
- Larsen, T.A. and Gujer, W. (1996). Separate management of anthropogenic nutrient solutions. *Wat. Sci. Tech.*, **34**(3–4), 87–94.
- Larsen, T.A. and Gujer, W. (1997). The concept of sustainable urban water management. *Wat. Sci. Tech.*, **35**(9), 3–10.
- Renner, R. (1998). Human estrogens linked to endocrine disruption. *Environmental Science and Technology*, **32** (1), Environmental News, p. 8.
- Samuelson, P.A. and Nordhaus, W.D. (1995). *Economics*. 15th edn., McGraw-Hill, NY.
- Sheldon, L., Umana, M., Bursey, J., Gutknecht, W., Handy, R., Hyldborg, P., Michael, L., Moseley, A., Raymer, J., Smith, D., Sparacino, C. and Warner, M. (1986). *Biological monitoring techniques for human exposure to industrial chemicals*. Noyes publications. US.
- Siegrist, H. and Boller, M. (1999). Auswirkungen des Phosphatverbots in den Waschmitteln auf die Abwasserreinigung in der Schweiz. *Korrespondenz Abwasser*, **46**(1), 57–65. (In German).
- Ternes, T.A. (1998). Occurrence of drugs in German sewage treatment plants and rivers. *Wat. Res.*, **32**(11), 3245–3260
- Ternes, T.A., Hirsch, R.W., Stumpf, M., Eggert, T., Schuppert, B.F. and Haberer, K. (1999). *Nachweis und Screening von Arzneimittelrückständen, Diagnostika und Antiseptika in der aquatischen Umwelt*. ESWE-Institut für Wasserforschung und Wassertechnologie GmbH, Wiesbaden. (In German).
- Tillman, D., Larsen, T.A., Pahl-Wostl, C. and Gujer, W. (2001). Interaction analysis of stakeholders in water supply systems. *Wat. Sci. Tech.* **43**(5) 319–326 (following paper)
- U.S. Geological Survey (1999). *Mineral Commodity Summaries* (<http://minerals.usgs.gov/minerals/pubs/commodity>)

