Advanced water treatment as a tool in water scarcity management

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Abstract: The water resource is under increasing pressure, both from the increase in population and from the wish to improve the living standards of the individual. Water scarcity is defined as the situation where demand is greater than the resource. Water scarcity has two distinctly different dimensions: water availability and water applicability. The availability is a question of quantitative demand relative to resource. The applicability is a question of quality suitability for the intended use of the water. There is a significant difference in this regard with respect to rural versus urban use of water. In the former case, the water is lost by evaporation and polluted. In the latter case, the water is not lost but heavily polluted. With increasing scarcity, the value of water and the need for controls increase. In this situation, water reuse becomes an option that has been considered exotic until recently. This paper sets the stage with respect to perspective and management options related to implementation of water reuse. Water treatment has to be interpreted as the means by which to purify the water from any degree of impurity to any degree of purity that fits the desired use, including reuse. The historical distinction between processes used in water treatment for water supply versus processes used in water treatment of used water (wastewater) will fade, because it will all be unit processes and operations in combinations to fit the purpose of water use. Water can be purified to any degree of purity - except zero. The challenge of future reuse will be to account for the attitudes related to trace chemicals in water. How precautionary is it prudent to be? Risk analysis is no longer an elitist business. It will involve the perception of the public, politicians (and the press).

Keywords: Sustainability; water resource; water quality; water scarcity; water purification; precautionary principle

Introduction

During the last thirty years the basic attitude to the environment has changed. In fact the term “environment” has a totally different meaning. My institute dates back to 1865, when the motivation for water engineering was the cholera-epidemics in the European cities. That was successfully dealt with by centralised delivery of purified water. Since then and until the 1960s the problems of waste and pollution were considered the shadow side of society which nobody wanted to take seriously, until the detrimental effects became impressive and the whole development of society came up for scrutiny. That process is still going on and we have not seen the last of it. We have to be thankful to the public and to the pressure groups, because the fact is that it has been publicly driven in opposition to the establishment. By today’s standard, environmental issues have developed into basic concepts for the performance of society in line with resources, economy, social well being and concern for the next generations. In this regard water plays a central role, because it is an essential resource increasingly under pressure and scarcity is an expanding issue worldwide.

Water is a renewable resource

Water is a renewable resource. It is not limited in quantity, but in flow. Use of water within the available flow is one of the most sustainable resource exploitations that exist. It is too common to meet laymen and politicians who believe that we are mining a confined
resource that will be depleted some day. There is a challenge in educating the public on the factual matter of these issues.

Agricultural water use
It is also too common to experience situations and locations in the world where water is in fact mined, such that the reservoir is in fact being depleted. That is against the most fundamental principles of hydrology, which is taught in freshman courses in natural and engineering sciences. That is an example of violation of the concept of sustainability that does not require elaborate discussion of definition.

Water is withdrawn from the environment for use. In the case of agricultural use, it is characteristic that water is lost in the process to a significant degree, Figure 1. The world estimate is 60% (WMO, 1997) for irrigation. In this case, the water is in fact consumed from the point of view of the local user, because the water is evaporated and removed from the location. The fact that the water comes down somewhere else does not impress the local user. To him it is lost.

The fact that water is one of the limiting factors for food production and that the demand increases, makes demand control and loss control the most vital issues on the global scale. The example today is the disappearance of the Aral Sea. Upstream irrigation has diminished the flow to the Aral Sea, to the extent that one of the biggest lakes of the world is disappearing. That is misuse because the effect could have been foreseen on the basis of well known fundamental hydrological principles.

There are many examples of this. Examples can be taken from very small to large-scale projects. The engineers have to call attention to the fundamental hydrological principles at all stages and at all levels in order to avoid the small and the large scale disasters, including the stochastic properties of extreme events, whether floods or droughts. I define misuse in this context as the ignorance of or the disregard for well known, fundamental hydrological principles, such that the detrimental effects come as a surprise – including changing statistics of the extremes, whether droughts or floods.

Urban water use
While rural water use gives rise to a significant local loss of water, the urban use does not give rise to significant loss by evaporation. (A traditional use for cooling by evaporation will decrease due to increasing prices.) In the urban setting, water use is polluting the water, Figure 2. Water is used as a means of transport. That use of the water and the downstream consequences were ignored for generations. With the change of paradigm with respect to the environment, one of the first issues readily available for abatement was wastewater treatment. By modern concepts the used water has to be purified before discharge to the environment. In Denmark today, and soon in all of Europe, all wastewater will be purified.
Pollution

Urban and rural usage

Withdrawal Discharge

Aquatic ecosystem

Figure 2 Withdrawal of water for urban use leads to pollution

by removing suspended solids, biodegradable organic matter, nitrogen and phosphorus, (Harremoës et al., 1991).

In this respect it is worth while to emphasise some fundamental principles:

Any substance used in society will be present in wastewater

With the ever-increasing refinement of chemical analysis we are able to or will be able to detect even the smallest traces of any substance used by society. That poses a problem because the “zero standard” or the “non detectable standard” is simply a desirable, but unattainable goal. Society must come to grips with the reality that all residues from human activities are chemically traceable, against severe emotional blockages.

Water can be treated to any degree of purity at ever increasing cost. No matter how well treated, there will always be left a detectable residue.

In the 1970s the US Congress decided to demand a “zero discharge policy”. That is not feasible. It is common practice to demand “BAT: Best Available Technology”. That is not well defined. We have the technology to do better. It is a question of choosing a balanced solution in view of the totality of the system.

However, water is not suitable as a transport medium for all matter:

Some substances are suitable for removal at the treatment plants (e.g. organic matter, nutrient and bacteria). Others are not suitable and should be removed at the source.

The reason is that wastewater treatment plants treat the water, but also generate new pollution:

Wastewater treatment transfers pollution from one medium to another, solids and air

This reiterates the need for a more global view on the system:

Environmental problems can no longer be evaluated in isolation. They have to be looked at in total.

We have progressed beyond the point where we are satisfied to have treated the wastewater, cleaned the fluegas and composted the solid waste. These “end of pipe” solutions have their important role, but diffuse sources and non-technological approaches are indispensable to further progress.

However, in this context the main conclusion is, that it is not the quantitative withdrawal and use of water for urban use that is the problem with respect to sustainability. It is the use of other substances in the material flow through the city and the use of energy, which is the problem. There are detrimental effects associated with the re-routing of the water by withdrawal, urban use and subsequent discharge. These effects can be abated by the following actions:
• Decreasing the withdrawal by decreasing demand. That is happening today due to increased prices.
• Recycle internally in the city. That is happening in industries to an increasing extent. It will find wider application, especially in water scarce regions.
• Re-route to the locations near where it was withdrawn. That is considered in areas with quantitative water scarcity. It is of particular potential in case of marine discharge, which in this context can be considered lost.
• Desalination. At present, due to cost, desalination takes place under extreme scarcity only, e.g. Saudi Arabia.

Water as a resource is limited by its availability in quantity as a flow and by its applicability as a consequence of its quality. We purify the water for urban use, whether its quality is unsuitable as withdrawn from the environment or due to pollution. The problem with urban use of water is quantitatively the re-routing from the environment and qualitatively the pollutants that are discharged with the water, Figure 3.

The interesting aspect of this analysis is that the urban use of water by today’s standard involves purification at the water works and purification at the wastewater treatment plant. We approach the situation where the system can be interconnected, Figure 4. The ultimate potential is that water can be used in cities with hardly any withdrawal from, nor discharge to, the environment. In the long term, that might be one of the advantages of the centralised approach to management of urban water.

Short history of urban water management
In the first half of last century Europe experienced epidemic cholera; called the Asian disease, because it migrated in waves from Asia to Europe. E.g. in 1853 the epidemic reached Copenhagen, Denmark, with the result that 7% of the population died in two months. Nobody knew the real cause. Not until after the discovery of the bacteria (Pasteur, 1880s) did real understanding of the mechanisms of transmission of water borne diseases have an impact on the application of technology. Before that, the “experts” were divided into two camps: the two concepts were Miasma versus Contagoinism. Miasma was the belief that diseases were the result of a foul environment (mostly air). Contagoinism was the belief that some (as yet unknown agent) caused a contamination that could be communicated. Today, it is well known that John Snow during the cholera epidemic in Soho in London made one of the first real epidemiological investigations that indicated transmission via water (from the Broad Street pump); but it is also a fact that his approach was not recognised until much later. Many of the quarantine procedures still in effect today (e.g. with regard to ships entering foreign harbour) are from early last century and based on the concept of contagoinism. However, the concept of isolating the diseased did not work in practice, due mostly to
ignorance with respect to the real cause and the mechanisms of disinfection we know today. The concept of miasma prevailed: the cities had to be cleaned up. Clean water, air and food had to be provided and waste had to be carried out of the cities in an organised fashion. It is an interesting fact that the introduction of water supply and sewerage was based on a false concept, a misunderstanding of the issue.

But, it worked. The industrialisation during last century was the driving force with respect to expansion of the European cities, which were in the process of exploding within a confinement behind a ring of defence walls. The conditions had become a threat to the urban human health. At the same time a new concept of city cleanliness was introduced in order to make the expanding cities sustainable from a health point of view. It has to be understood that from the point of view of the city developer at the time, they introduced a new concept of “sustainability” in order to safeguard the health of the present and future urban population. On the basis of their paradigm, that development was highly successful: the cities of the developed world have been essentially free of water borne diseases since the introduction of centralised water supply and sewerage.

It should also be understood that the introduction of these new infrastructures was a phenomenal investment at the time. The cost can be compared in relative terms with the investments in the traffic infrastructure during this century. There is no way in which new paradigms can be analysed without taking these huge investments into account.

The inherited concepts
The management of water in cities has been based on the following basic concepts:
• prevention of water borne diseases
• use of water as a means of transport of waste out of cities
• the provision of water was supply driven

Prevention of water borne diseases
The prevention of water borne diseases was, and still is, based on two vital principles:
• Water should be withdrawn from the environment, purified and distributed from centralised waterworks
• Water should be distributed in a pressurised pipe system to prevent contamination of the purified water

It has to be borne in mind that it is the undisputed, world-wide experience, that if these two principles are violated, there is an immediate risk of outbreak of disease. That risk is not hypothetical, it is real. That is illustrated every year, even in well operated and well maintained systems.

In not so well operated systems the risk is eminent. Many cities in the developing world do not have well maintained systems and pressure drops and seepage into the distribution system is the rule of the day. The recommendation is not to drink the water from the tap, buy bottled water at a price two to three orders of magnitude more expensive per unit volume as compared to tap water.

Use of water as a means of transport of waste out of cities
Use of water in the city is frequently called “consumption” of water. That is a misnomer for use. The “consumer” does not consume in the conventional interpretation of the word. The “consumer” uses the water in order to pollute it! The function of water use in cities is to remove unwanted material from the location where the water is used: the toilet, the wash basin, the kitchen sink, the washing machine, etc. The function is to clean the thing, the fabric, the place, etc. In doing so the function is that the matter that is removed is transported away with the water. If changing paradigm, an alternative to this function has to be identified and implemented.
Provision of water was supply driven

Society needs water in order to function, as described above. The policy until now has been that development is good and that all demands should be satisfied. The use of water has been supply driven. This is where a new paradigm may change the heritage without sacrificing the established technical values. It is no longer a matter of course that water should be supplied in large quantities at a very cheap price. In fact, water has been supplied with a subsidy, because not all the cost of withdrawing, purifying, providing, collecting and again purifying water has been charged to the “consumer”. That is happening now, the price is increasing dramatically and the “consumption” is decreasing. The policy is changing from supply driven to demand driven.

The European urban wastewater treatment directive

Background

Eutrophication is a good example of a problem which requires a multi-disciplinary, multi-sectorial and multi-focal approach in order to reach abatement of the devastation caused by the development of society during the last century. It started out with growth of nuisance algae in lakes under heavy load from domestic wastewater. The problem was “solved” by adding a selective poison to the lake (copper sulphate) to remove the blue-green algae, 1930s. Then it was realised that the load of phosphorus was the cause and the world became divided into religions with respect to measures by treating the wastewater or banning P in detergents during the 1950s and 1960s. Then it was realised that nitrogen was limiting in estuarine and coastal waters and the world became divided into believers in P versus N as the limiting factor. In 1987, the Danish Government made a far-reaching decision. The experts could not agree on which nutrient is or can be made the limiting factor. In view of a political situation that called for action, it was decided to limit the pressure on the aquatic environment by reduction of the loads from Denmark of both P and N: P by 80% and N by 50%. Later this was converted administratively to a demand for effluent concentrations: totN < 8 mg/L and totP < 1.5 mg/L. This is an example of application of the precautionary principle: the uncertainty calls for preventive measures beyond what can be proved to be required. This was the inspired basis on which the European Commission (EC) adopted the “Urban Wastewater Treatment Directive” in 1991, described below.

The tradition with respect to approach varies significantly from country to country. This is illustrated for the Scandinavian countries in Figure 5. It is obvious that there are different traditions in the three countries.

Sweden started out in the 1960s with post-chemical precipitation with alum, soon to find out that nearly the same can be achieved cheaper with simultaneous precipitation. In Norway, pre- and direct precipitation is favoured due to many discharges to the ocean. In Denmark, simultaneous precipitation has been favoured, but the advantage of biological P-removal has dominated development over the last decade - with simultaneous precipitation as a backup or a supplement to achieve lower concentrations.

Figure 5 Phosphorus removal technologies in Scandinavia, 1990 (data from Henze, 1996)
The EU directive

The content of the directive is summarised in the text box below, copied from European Environment Agency (1998b)

Figure 6 illustrates the present status with respect to wastewater treatment in Western and Eastern Europe.

The Urban Wastewater Treatment Directive demands the following effluent concentrations: totN < 10 mg/L and totP < 1 mg/L. The statistical basis for compliance is very important for the evaluation of the consequences of the Directive.

Figure 7 illustrates the predicted situation when the Directive has been implemented, supposedly in year 2005. However, the present situation with respect to planning, design and construction makes it likely, that this deadline will not be met by all countries. Based on

The Urban Waste Water Treatment Directive defines standards for the collection, treatment and discharges of urban waste water and waste water from some industrial sectors. The Directive states that (with a few exceptions) all urban waste water discharges greater than 10,000 person equivalents to coastal waters and greater than 2000 person equivalents to freshwater and estuaries will be subject to secondary treatment by the year 2005. Furthermore, discharges from a list of industrial sectors with direct discharge (greater than 4,000 person equivalents) shall also respect the above regulation.

Member States have to classify their national water-bodies as sensitive, normal or less sensitive areas (eutrophication effects). In sensitive areas, discharges are subject to more stringent treatment with supplementary phosphorus and/or nitrogen removal, whereas in less sensitive areas less stringent treatment than the general secondary treatment prescribed is accepted. However, primary treatment is the minimum requirement in less sensitive areas.

All municipalities smaller than the lower threshold of 2,000 and 10,000 person equivalents should also be subject to appropriate treatment by the year 2005. However, no specific criteria are given in the Directive.

Waste water treatment

![Bar chart showing waste water treatment in the 1990s in three European regions. Rural population is the population not connected to sewers. EU North: DE, FI, NL, LU, UK. EU South: FR, IT, GR, ES, PT. AC10: Ten accession countries. Copied from: European Environment Agency (1998b)]](https://iwaponline.com/wst/article-pdf/42/12/73/39950/73.pdf)

Figure 6 Waste water treatment in the 1990s in three European regions. Rural population is the population not connected to sewers, EU North: DE, FI, NL, LU, UK. EU South: FR, IT, GR, ES, PT. AC10: Ten accession countries. Copied from: European Environment Agency (1998b)
the reporting from the EU-countries the result of compliance with the directive can be predicted, Figure 7.

It is clear that there will be a significant improvement in the situation in Western Europe over the next one or two decades.

The result in case the Eastern European countries were to comply has been estimated, Figure 8, option C.

Presently, there is a professional debate as to whether the Eastern European countries should take a traditional path and develop biological treatment first, in line with a Central European tradition, or whether they should go for direct precipitation, later to be followed up as pre-precipitation and downstream biological treatment, including nitrogen removal. Which approach best serves the environment? Which approach is the most cost-effective? Which is more sustainable? The discussion may resemble religious discussions. The result is the consequence of the basic axioms and not the arguments with which to derive the result.

The preferred choice of technology is a combination of biological and chemical treatment, much depending on local tradition. These technologies have become “Best Available Technology” – in spite of the fact that there are even better technologies to be added:
filtration, contact-filtration, disinfection, etc. The fundamental aim must be to include those processes that will achieve a balance between cost and quality of the environment.

Technical options and preferred technology

The basic motivation and demands

It is interesting to note the historical development of demands on wastewater treatment. When the water pollution issues were on the shadow side of society with little public attention and little political priority, the requirements were simple: removal of organic matter and suspended solids. With the development of environmental concerns the requirements have increased in spectrum and stringency, chronologically like this:

| Organic matter, settleable suspended solids, inhibitors to carbonaceous removal, odour, disinfection, phosphorus, ammonia, nitrogen, aerosols, metals, filterable suspended solids, ecotoxic chemicals, volatile organic chemicals. |

With this bewildering spectrum of demands, there is a need to consult the philosophers and stick to the basic concepts of integrated management. Otherwise, we end up in utter confusion in our role as engineers. We do not set the standards. Society does. We provide the spectrum of technologies that can solve the issues raised.

In this regard it is mandatory to identify which processes are suitable for treatment of domestic wastewater, and which are not. There are substances that may be removed from the water – just to end up in the sludge. That is not an end solution – unless we are prepared to contain that sludge for eternity at a landfill with no leakage! The sustainable solution is to reduce the contribution of metals and non-degradable organics at the source.

The choice of technology

A whole spectrum of technologies for cleaning wastewater is available. We have the technology to treat wastewater to whatever degree of purity we want – at a price. The willingness of the public and subsequently the willingness of politicians to prioritise the cost of environmental protection is constantly on the increase. In Denmark the cost of water has been increased by a factor of five over the last decade. That has been the most effective way of making industries save water, switch to cleaner production or purify in house before discharge. The attitude of industry has changed from hostile opposition to investment in pollution abatement during the 1970s, over reluctant allocation of funds in the 1980s to making environmental issues a question of public image in the 1990s.

We have the technology to remove organic matter, solids, bacteria and nutrients. I am not concerned with the detailed technical approaches, because basically they all play around with the same basic processes, Figure 9. The typical Danish approach is the alternating process – as opposed to the recycle process, (Harremoës et al., 1991). Instead of pumping the sludge around between the anaerobic, anoxic and the aerobic basins, the wastewater flows alternately to different basins. The basins change between anoxic and aerobic conditions, such that the water from the anaerobic basin always enters the anoxic basin for denitrification, utilising the organic matter available in the wastewater or the stored organic matter, PHA, in the bio-P-bacteria.

Wastewater characterisation

However, these processes cannot be designed without proper information as a basis for design and for operation.

It is still the basic concept of sanitary engineering that treatment plants can be designed on the basis of some scarce data on flow, BOD and SS, today supplemented with ammonia, totP and totN. That is combined with simple design rules that can be written on one page.
The fact is that the combination of processes may include oxidation of organic matter, nitrification, denitrification, biological removal of P (backed up by chemical precipitation as a safety measure), suspended solids removal and disinfection, all combined in one plant. This spectrum of processes can neither be designed properly nor be operated successfully without proper information about inflow and on-line performance.

In order to make a proper design, much more information is required with respect to the wastewater, its flow and fractionated components and the statistics of daily and extreme performance. Organic matter cannot be characterised just by BOD. Much more specific characterisation is required, for which purpose COD is much better suited, because of the mass and energy balances that can be established on this basis. There is no way in which biological P removal can be kept track of without monitoring “easily biodegradable COD”. There is no way nitrogen removal can be understood without accounting for “inert soluble organic nitrogen”, etc. Proprietors of treatment plant, designers and operators must get accustomed to much higher cost of monitoring and data analysis.

Technologies for reuse

Advanced treatment can be divided into categories as follows:

- Inactivation of infectious agents
- Further degradation of chemicals
- Removal of particles
- Removal of soluble chemicals

There is no clear demarcation between these four categories. The spectrum of processes is well known:

- Disinfection by chlorination, ozonation or radiation (UV)
- Chemical oxidation, e.g. in preparation for further biodegradation
- Anaerobic degradation, e.g. in preparation for further aerobic degradation
- Aerobic degradation
- Filter filtration, membrane filtration (ultrafiltration)
- Ion-exchange
- Adsorption on activated carbon processes
- Membrane (reverse osmosis)
- Distillation

A very clear demarcation can be made between low tech approaches and high tech approaches. The low tech approaches are mostly preferred because they are also low cost, as opposed to high tech, high cost approaches. There is a tendency that the low tech approaches are of low complexity as far as technological components are concerned, but are of complicated science (e.g. ponds). They are difficult to manage and have less reliability due to lack of basic understanding. The high tech solutions may be easier to operate individually due to more science based understanding, but the complexity may not provide the certainty of ultimate performance requested.

The advanced treatment for reuse is more a combination of a variety of operations and processes than a particular new technology. The fact is that we have the technologies for saving water by reuse at our disposal with the technologies available today. However, we lack experience with the performance of the individual operation and process and with the spectrum of combinations, in such detail that we can predict with sufficient certainty for distribution to any reuse. The combination of technologies has to match the water to be purified, the required quality of the water to be reused, the safety of performance, public perception and the economic constraints.

The development of a new attitude to water reuse is strongly influenced by the economy of reuse as compared to other options. The tendency is to charge the customers the full cost of provision of water and discharge of wastewater. That has increased the price of water significantly. In the context of water scarcity, Denmark has plenty of water. However, in order to save our groundwater resource, the price of water has increased 4–6 times over the last decade, from 0.7 to 3–4 USD/m³. That includes a “green tax” on water of some 0.7 USD/m³ delivered. That has decreased the water consumption in the city of Copenhagen by some 20%.

This price hike has to be compared to the cost of water reuse, e.g. in the order of 1 USD/m³ for distillation. No wonder that reuse has received increasing focus – even in a country with no substantial water resource problems, viewed in an international perspective.

Reuse of water re-emphasises the statement that water can be purified to any degree of purity, except zero. There will always be a residue in the produced water. No matter which technology is introduced, there will be no “guarantee” to the public that no contaminants are left in the water. There will always be a concern about exposure to residual concentrations. That concern is on the increase, exemplified by the increasing concern in Europe for the contamination of groundwater from agricultural application of pesticides to land and the subsequent migration to the aquifers from which the water is withdrawn for supply. Similar considerations apply to water withdrawn from surface waters, but the whole issue becomes much more apparent when water is reused directly, as compared to the rather fictitious reassurance associated with withdrawal from “natural” water courses. The following chapters will highlight the principles associated with these concerns.

The new paradigm

The introduction of technologies for reuse of water and the consequential changes to the mass flow of other materials through society has to be viewed in the much larger context of sustainability, (Harremoës, 1996).
The new paradigms for the environment have introduced new principles.

- The concern for the confined resources demands a decrease in the exploitation of the natural resources.
- The concern for the ecosystems has introduced new paradigms for the changes we make to nature, especially the burden of pollutants on the environment.
- The concern for the influence of contaminants on human health.
- The concern for the coming generations and their fulfilment of their wishes.

Philosophically this is nonsense, because it violates the thermodynamic principle of entropy. When mineral resources are mined and used, the result is a conversion from a concentrated to a dispersed state. It will require energy to re-concentrate the matter, which makes energy basically the ultimate measure of sustainability.

The practical solution is to approach the ideal. That makes sense in societies, which have violated the principle due to lack of concern in the past. Water and a few other substances are unique in making real sustainable operation possible.

The conflict is that the very basis for the success of man in a modern society is his ability to change the environment with the aim to sustain larger populations. The turning point is that man has pursued this track of development to the extent where the changes develop to the detriment of man himself.

Concern for ecosystems (the ecocentric attitude)
The effect of development on the ecological environment has reached proportions that question the sustainability of the development. The impacts from city development, industry, traffic, agriculture, etc. have reached the level where the detrimental effects make society respond with requests for a new paradigm with respect to economic development as the basic philosophy of the modern society.

This fear of the consequences is closely related to the use and misuse of chemicals in society. The ecocentric attitude puts emphasis on the effects on the ecosystem. Examples are too numerous to be mentioned here. However, in relation to water reuse the emphasis is on the detrimental effects of the withdrawal of water and the disposal of inadequately purified water to the environment. From this perspective, water reuse is a good technology, because it preserves water.

Concern for man and his health (the anthropocentric attitude)
The opposing attitude is the anthropocentric attitude according to which man is the centre of all concerns. In this perspective emphasis will be on the potential detrimental effects of water reuse. This will relate in particular to the concern for recycle of chemicals that may reach the consumer by reuse – directly or indirectly.

Concern for the welfare of coming generations
The real challenge of the sustainability concept is the concern for the welfare of the coming generations. The concern is a good one, too good to be disputed; but the interpretation and the implementation in any concrete situation is a real challenge. This can be illustrated with the city developers of the last century, who would no doubt have subscribed to the concept of sustainability in their development of water supply and sewerage. Could or should they...
have anticipated the criticism of today? The answer is “No, how could they”? Equivalently: “How can we”? The values change, the circumstances change. There is only one answer: “Analyse the issues on the basis of the most fundamental principles”. It is a reasonable assumption that they will be apply also a hundred years from now, like the law of thermodynamics, the constancy of mass of elements, basic physical, chemical and biological/ecological principles and fundamental philosophy. That is no minor challenge. The problem is to identify the current, opportunistic values, as opposed to the “eternal” values.

Water reuse should figure in the category of sustainable options - unless it will lead to excessive energy consumption and unintended and uncontrolled recycle also of chemicals, the ultimate effects of which are not yet clear. However, it is a new tendency to consider water reuse as a suitable high-tech solution, where low-tech was considered more sustainable.

Integrated environmental management
Many mistakes have been made because each environmental problem has been approached in isolation. It is classical to distinguish between the three media: water, air and soil. Often, treatment is just a conversion from one form to another and a transfer to another media, hopefully environmentally better. The example is sludge production, which is environmentally problematic, as opposed to N₂ -production by denitrification, which is environmentally as sound as you can get it. Second, the environmental issues have become so important that they have to be looked at in a social and economic context. Efforts are made to create a system by which to analyse the problems in total. The following is from an ongoing project within the European Environmental Agency to establish a commonly agreed concept and methodologies by which to assess integrated systems.

Cause-effect relationship
It is basic to all considerations that society shall act when there is a relationship between activities in society and detrimental effects in the environment.

In the European Environmental Agency the basic structure of the pollution of the environment fits into a formal structure called the DPSIR-approach to integrated environmental assessment. This is illustrated in Figure 10.

![Figure 10 The DPSIR-approach to integrated environmental management, modified from European Environment Agency (1998a)](https://iwaponline.com/wst/article-pdf/42/12/73/39950/73.pdf)
The structure is a formalisation of the interplay between the society and the environment with respect to Driving forces, by which Pressures are exerted on the environment. The Status of the environment is the basis for evaluating the Impacts due to the Pressures. That leads to Responses by society to the impacts, which requires identification of objectives and choice of tools by which to curb the pressures.

From pressures to impacts is in fact the cause-effect relationship, based on physical, chemical and biological mechanisms describing the relationship between pressures and impacts. This cause-effect relationship involves the natural sciences, while the driving forces and the responses involve the political, judicial and the social sciences.

Few options
From a global point of view, society has only a few options for handling material flow through society. These options can be listed as follows. Consider a chemical that is used in society: what options with respect to ultimate fate are available?

**No use:** We can stop using an unwanted substance, because the advantages of its use are overshadowed by the detrimental effects to the environment and to human health.

**Reuse:** We can decrease the amount reaching the environment by internally reusing the substances. This approach is under development and implementation is just at its beginning.

**Convert:** When a substance has been introduced, it is important to control the route of that substance such that the transport can be identified and the flow treated. Treatment mostly means converting the substance from an obnoxious form to a form acceptable for further transport by air or water or in solid form.

**Contain:** One of the ultimate fates is to contain the residues and leave it there forever.

**Disperse:** The only other ultimate fate is to disperse in the environment.

A more detailed analysis of this concept of only five options has been presented in Harremoes (1997).

In relation to water reuse, the “no use” option is really the option to be considered, because it is the only way in which no residual of a contaminant can be guaranteed. The other four options will leave a trace, some day to be detected and subject to public concern.

**Basic principles of environmental management**

Historically, the field of water and water pollution management was based on a command and control approach, but over the last decade it has developed to encompass more philosophical issues, as illustrated by the following list:

- **Command and control approach:** laws, directives, standards, norms, codes
- **Consensual approach:** hearings, consensus conferences, interests group meetings
- **Economic instruments:** taxes, levies, prices
- **Ethical approaches:** Ethics, attitudes, behaviour

The command and control approach was basically an elitist system, which has been modified by establishing procedures for reaching consensus among stakeholders before deciding on the “command”. That works for point sources of pollution, but it works poorly for the control of diffuse sources. That is where economic incentives come into the picture. However, no rule and no incentive works without a general acceptance by the public. The ethical values and the associated attitudes and behaviour are the foundation of a society that makes it work (Harremoes, 1996).

All four approaches come into play in relation to water reuse. Strict rules are indispensable in order to be persuasive that development is under control. Consensus is a must in
development of reuse. Economic incentives are the basis for the present development. The whole perception of the water resource and the environment plus the attitude to technology is changing.

Technical and environmental activities are governed by a set of approaches, from the very basic concepts of life to the detailed professional activities of the individual engineer and scientist and the activities of the public in their daily life. This is illustrated in the following list, ranked by order of importance or priority:

- Principles, ethics, moral
- Constitutions, laws, directives
- Precedent, set by courts
- Procedures, administrative, technical
- Substantial norms, administrative, technical
- Economics, taxes, prices
- Technical norms, written
- Technical norms, implied — Public norms, implied
- Technical activities — Public social and individual activities.

Our cultural heritage is the fundamental basis for our values and standards for proper conduct. That is expressed in our national constitutions and the whole law system; and in international law, like human rights, which is today’s expression of our most basic set of standards for humanity. This is interpreted by courts, who set the precedent for subsequent decisions. Laws are implemented by the administrative system, as expressed in guidelines, generically called substantial norms. Economic approaches to environmental regulation are based on the concept of the market-economy. Every professional society has as its ambition to regulate the professional activities in the form of codes. However, implied norms may be more important and the activities of the professional are even more important, because it is not possible nor desirable to regulate everything. In this regard, flexibility is a virtue, based on the well educated professional and his good common sense and judgement. In Europe, there are quite different ideas on how to balance between “command and control” versus “the professional know-how, skill and intuition of the individual”.

The principles declared to govern the environmental activities in the European Union (EU) are listed below:

- The Polluters Pay Principle
- The Principle of Full Cost Recovery
- The Principles of Proportionality
- The Subsidiarity Principle
- The Principle of Prevention
- The Precautionary Principle

The **Polluters Pay Principle** is an old principle from OECD in the 1960s. Generally agreed to in the market economies – but frequently exempted from in the planned economies (EU-agricultural policies). The **Principle of Full Cost Recovery** has become the principle of market economies as the way by which to obtain equity. In the past, the cost of water supply was a charge on water use, while the cost of sewerage and wastewater treatment was covered by tax. That has changed to become a water charge with increasing water price and decreased water consumption as a consequence. **Proportionality** is best explained by the opposite: a disproportionate verdict is one where the relationship between crime and punishment is not fair, reasonable, etc. **Subsidiarity**: decisions should be as local as possible, (frequently not lived up to).

**Prevention** is similar to “prophylactic” medicine, “prevention is better than cure”. This was the philosophy on which industry changed to cleaner technology in the late 1980s and
wastewater treatment was termed “end of pipe solution”. The essence is that emphasis changed from point source solutions to diffuse source solutions, because the point sources were either under control or in the process of becoming so.

The precautionary principle can be illustrated by a quotation from the “Declaration on sustainable development” (ECE 1990):

“Discharge of a substance which may have harmful effects shall be limited as much as possible – even though scientific evidence on the cause-effect relationship may not be available”

This gives rise to concern, because the statement calls for action even when there is no information available on a cause-effect relationship. That concern is a cause for further analysis. The Precautionary Principle relates to severe and irreversible damage:

- act on reasonable suspicion, do not wait for scientific proof
- the polluter should demonstrate likely non-harmfulness
- the consequences of being wrong should be analysed.

The principle is a weight in the balance between environmental concerns and concerns for human health versus benefits associated with the technology introduced and the saving of precious water resources.

Determinism and incertitude

How predictable is the performance of the technologies associated with water purification? How well can scientific understanding and/or experience provide sufficient assurance of reliability.

In the development of natural sciences since Galileo, Kepler, Newton, the deterministic description of cause-effect relationships has been the core of development. It is axiomatically assumed that there is a unique relationship between the action taken and the effects (in the environment or on human health). However, during the last century it has been realised that there are both inherited and practical uncertainties associated with this relationship and more recently questions have been raised as to whether there is such an identifiable, unique relationship at all. The precautionary principle is in fact a response to that realisation.

The cause-effect relationship can be written as follows:

\[ e = f(i_1, i_2, \ldots, i_n, p_1, p_2, \ldots, p_n) + \varepsilon \]

where:

- \( e \) is the effect
- \( f \) is a functional relationship
- \( i \) are input variables
- \( p \) are parameters
- \( \varepsilon \) is incertitude.

The functional relationship may be empirical in the form of correlations or theoretical in the form of generic relationships, based on \textit{a priori} knowledge of the phenomena involved. In relation to cause-effect relationships the phenomena are physical, chemical and biological.

The input consists of the variables associated with natural phenomena and the ethnopocentric pressures on the environment. The parameters characterise the functional relationship. In some cases such parameters are very well known from \textit{a priori} scientific knowledge, in many cases they have to be determined in each individual case by experiments and analysis of the phenomena involved.
The incertitude describes the extent to which it has not been possible to predict the effect on the basis of a deterministic functional relationship. That includes both the statistical uncertainty in cases where sufficient experimental data provide information by which to estimate the statistical error, but it also includes the incertitude associated with not knowing the essential phenomena and the lack of data by which to estimate the incertitude.

This has also been expressed by the following words: Determinism, Risk, Uncertainty, Ignorance, Indeterminacy. In the context described above, this is illustrated in Figure 11.

**Determinism** is an ideal that is never achieved. However, history has demonstrated beyond any doubt that determinism is worth striving for. Even with the best of determinism, the input variables show statistical properties. However, we have statistical instruments with which to handle variable input data and risk expressed statistically is a rational approach to description of variation. Still, there is always uncertainty involved, due to the mere fact that all relationships have to be calibrated with data. With a well known functional relationship and an adequate combination of number of parameters and number and character of data, the uncertainty can be expressed statistically and can be incorporated in the risk analysis.

**Ignorance** applies when we do not know essential functional relationships. They may become known later due to research and development on the issue, but they may not be known at the time when far-reaching decisions have to be made.

**Practical indeterminacy** is the situation where the functional relationships are so complicated and the number of parameters so large that neither determinism nor stochasticity is within reach. The functions and the parameters become unidentifiable. **Theoretical indeterminacy** is the situation where the relationships are inherently unidentifiable, e.g. due to chaotic properties that make predictions impossible.

The precautionary principle has been introduced as a way in which to formulate an approach to the situations where ignorance and indeterminacy dominate the cause-effect relationships. The importance is due to the realisation that many of the cause-effect relationships between the pressures from development of society and the environmental impacts are less than well known.

**The burden of proof**
It is a frequent interpretation of the precautionary principle that the burden of proof shall be shifted from the environmental stakeholder to the polluter. It is not that simple.

Imagine a situation associated with risk assessment of a chemical.
Imagine the claim that the chemical does cause harmful effects in the environment or to human health. If those adverse effects are well defined, the burden of proof can in fact be lifted. One example will prove the claim. It may be quite complicated to do so, but in principle it is feasible.

The opposing claim that the chemical does not cause harmful effects in the environment or to human health, cannot be lifted. There will always be situations which have not been covered with adequate investigations. The claim can only be evaluated by induction. The better and the more comprehensive the investigation, the more likely the claim is; but there can never be certainty. Just one example would falsify the claim.

The conclusion is that environmental and human health acceptance can only be demonstrated by induction and only by likelihood. In the end, it becomes a question of confidence. That confidence is based on evidence: have the authorities, or the polluter performed adequate investigations in order to establish a reasonable likelihood that the chemical is harmless according to acceptable criteria?

One interpretation of the precautionary principle is that it is the polluter who shall demonstrate by induction based on acceptable procedures that the chemical is acceptable according to agreed criteria.

Pro et con
Where adequate information on cause-effect relationships and acceptable effects is available based on determinism and uncertainty analysis, the political choice becomes a balancing act between opposing concerns: the benefit to society versus the acceptability of a level of effects in the environment and/or effects to human health.

It is frequently postulated that the public does not have a rational approach to the acceptable levels of effects, because it is a well known fact that people accept harmful effects with probabilities orders of magnitude apart (e.g. traffic, alcohol). However, people have a much better perception of the pro et con than understood by the specialists in risk assessment. It is when adequate information on the pro et con is unknown to the public that the reaction is fear and unrealistic wishes for action. Risk assessment is performed by an elitist profession. Public participation and stakeholder information have to be expanded and improved in quality, in order to improve the confidence in the system. Widespread introduction of water reuse will be no exception from this prediction.

In relation to the “pro et con” in evaluation of risk assessment, the precautionary principle is an expressed concern regarding uncertainties in favour of the environment and human health.

The risk of being wrong
In the weighting of concerns, the precautionary principle can be interpreted as an urge to evaluate the risk of being wrong. What are the consequences of not doing anything, in case the harmful effects are severe? The occupational health problems associated with asbestos are a striking historical example. In relation to the environment, the problem with mercury is a similar example. What are the consequences of an action, in case the action turns out to be not necessary or non-proportional?

Many issues fall into this category of concern for being wrong. At present, in Denmark, the hottest issue is the regulation, ultimately ban, of pesticides in agriculture. The very same issues will be faced with the introduction of water reuse – plus many more.

The no-know situation
The real importance of the precautionary principle is in the situation where either ignorance or indeterminacy prevails. However, still it is quite unexpected that actions should be taken...
in situations of no knowledge of a cause-effect relationship at all. There must be some reason on which to argue a reasonable suspicion, based on an expected cause-effect relationship – however uncertain. Otherwise the arguments change from a rational utilitarian concept to deontological dogmas or just superstition or non-structured empiricism. Water reuse for public consumption will be marred by dogmas against reuse, due to non-structured fear.

This situation is in fact not unfamiliar from engineering approaches. This can be looked at from two extreme points of view:

*The empirical, iterative approach*

*The predictive, scientific approach*

The empirical, iterative approach was the way in which craftsmanship developed before modern science provided much better means for design. That empirism did in fact thrive is visible from ancient and middle-age structures, e.g. cathedrals. However, it was the Greek heritage of logic and scientific development that created the basis for modern technology after the renaissance. This is in particular visible by comparison between two cultural developments in parallel: the European development on the basis of science versus the Chinese development on the basis of an empirical correlation philosophy and technology, which worked extremely well by comparison until the scientific break-through in Europe. In fact, the Chinese had cast iron, pumps, suspension bridges, china, etc. long before Europe.

In case of ignorance and indeterminacy as described above, the precautionary principle comes in as an approach, which combines with an empirical, iterative approach, where a predictive, scientific approach fails or suffers from a predominance of incertitude. In relation to risk assessment, the chemical properties to be concerned with are:

- Persistency in the environment
- Bio-accumulation in the environment
- Severity of toxicity to humans
- Irreversibility

The greater the suspicion of harmful effects to the environment and/or to human health is, the more pre-emptive measures are called for. In view of the level of ignorance and indeterminacy, it is important to make development in the right direction in a stepwise fashion, because the risk of being wrong must be counter balanced by the advantages of water reuse. At the same time, it is urgent to increase research on the issues of concern. It must be in everybody’s interest to improve the knowledge of the cause-effect relationship (remove the ignorance) and to decrease the uncertainty (provision of more and better data and establishment of safe procedures for implementation) associated with design and operation of technologies for water reuse.

**Conclusions**

Technologies for water reuse are available, but there is a lack of experience with the spectrum of suitable combinations of operations and processes. The change of cost policies from subsidies to real and full cost recovery has increased the cost of water considerably. That increase in cost will affect the demand for water and will in itself provide an incentive to decrease water consumption. The general change of attitude towards the environment and sustainability will further increase control of demand. The increased price of water will increase the potential for introduction of water reuse as an economically viable option – even in countries without water scarcity. With the technologies available today, water can be purified to any degree of purity. However, there will always be a residue of contaminants
in the purified water. That will pose an issue related to the perception of risk in relation to
the use of reclaimed water. No guarantee can be stated to the public. The development of
water reuse must rest on development of reliable technologies and good procedures for the
introduction – such that the public, politicians and the press feel assured that the risks have
been reduced to reasonably low levels.

In the industrialised cities, the inherited infrastructure weighs heavily in favour of con-
tinuation of centralised management of water in urban areas. Many options are available for
more attractive handling of water in the urban setting, but the basic application of water for
cleaning the city and for conveyance of polluting matter out of the cities will prevail. It will
be supplemented with economic demand control of water use and better handling of materi-
al flows through the city, chosen on the basis of integrated analysis to be evaluated on the
basis of the new paradigms associated with sustainability. In principle, the options in the
developing cities are many, but lack of control of the urban development, lack of economy
and lack of political priority will not favour adequate solutions.

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