Integrated urban drainage, status and perspectives

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Abstract This paper summarises the status of urban storm drainage as an integrated professional discipline, including the management-policy interface, by which the goals of society are implemented. The paper assesses the development of the discipline since the INTERURBA conference in 1992 and includes aspects of the papers presented at the INTERURBA-II conference in 2001 and the discussions during the conference. Tools for integrated analysis have been developed, but there is less implementation than could be expected. That is due to lack of adequate knowledge about important mechanisms, coupled with a significant conservatism in the business. However, significant integrated analyses have been reported. Most of them deal with the sewer system and the treatment plant, while few incorporate the receiving water as anything but the object of the loads to be minimised by engineering measures up-stream. Important measures are local infiltration, source control, storage basins, local treatment and real time control. New paradigms have been introduced: risk of pollution due to system failure, technology for water reuse, sustainability, new architecture and greener up-stream solutions as opposed to down-stream concrete solutions. The challenge is to combine the inherited approaches with the new approaches by flexibility and adaptability.

Keywords Integrated management; real time control; sewerage; sustainable drainage; urban drainage; wastewater treatment; water quality

Introduction
The present concept of urban sewerage and drainage dates back some 200 years. The European cities grew at a rate and to an extent that was no longer sustainable, due to an internal handling of water and waste in a way that created foul conditions in general and unacceptable risk of waterborne diseases in particular. The development of communal, centralised approaches to handling of water in cities has been an indisputable success according to the paradigms governing city development for more than a century. The cities became well regulated. A certain standard with paved streets, gutters and sidewalks, subterrain water supply and drainage pipes, nicely contained rivers and lakes with stone or concrete walls were the standard that still dominates the appearance of the European city. But above all, the communal approach to handling of water became the successful basis for the decline in waterborne diseases in cities. This is the heritage that set the primary stage for the first INTERURBA conference (Lijklema et al., 1993), which dealt with the opportunities derived from integrated analysis of the design and operation of sewer systems, treatment plants and receiving waters. “The spirit of the time” had changed. Society has developed demands on the performance of the systems for handling of water in cities and new tools have become available to the profession. The follow-up conference INTERURBA-II, 2001, is an account of the status of knowledge, tools, managerial approaches and new paradigms developed since the first conference.

Development versus paradigmatic change
The concept of paradigmatic change was introduced in 1964, see e.g. Kuhn (1970). Science develops according to an accepted paradigm, which constitutes a commonly accepted interpretation and a tacit understanding that is taken for granted. Within a given paradigm,
development takes place in an evolutionary fashion, called “normal science”, or just “development”. That may become challenged by revelation of “anomalies”; like data, that does not fit the established concepts. This creates paradigmatic instability, building up to a new concept, that fundamentally changes the basic, established concepts. Paradigmatic change may be caused by the following, illustrated by environmental examples:

- new understanding (realisation that marine eutrophication is limited by nitrogen, 1980s)
- new theories (Monod bacterial growth kinetics, 1940s)
- new data (pH-measurements in rain, discovering acid rain in Scandinavia, 1960s)
- new tools (computer capability to solve well known equations, 1970s)
- new policies (sustainability, 1980s).

The INTERURBA concepts did in fact not constitute a new paradigm, but a development based on the recognised potential of methods known in 1992. Before then, significant changes in paradigm had taken place within the field of urban drainage:

- new public attention to pollution and policy of abatement in the 1960–70s, e.g. nutrient removal in wastewater treatment
- new understanding of basic phenomena in runoff, treatment and receiving waters and new theories
- development of models and computer programmes by which to simulate, analyse and predict performance
- new data on performance, e.g. pollutant discharge from separate rain runoff.

The aim of INTERURBA was to develop the concepts, tools and approaches that permit an integrated analysis and design of urban drainage, in order to remove the inconstancies, irrationalities and costs of non-integrated engineering.

**Basic approaches to design and operation**

There are two basically different approaches to design and operation. In the extreme, the approaches can be characterised as follows (Harremoës and Madsen, 1999):

- the empirical iterative approach, also called “trial and error”
- the deterministic predictive approach, also called “modelling”.

Remarkable engineering accomplishments have been achieved by the empirical iterative approach: Roman aqueducts still standing, drainage in ancient Athens, middle age gothic cathedrals and many other famous structures. Many mistakes paved the road to these successes; not the least in the field of environment, e.g. introduction of chemicals that mistakenly were regarded as harmless, but turned out to be harmful (CFC, PCB, MtBE, etc., EEA, 2001). The empirical iterative approach is still a valid approach. Those favouring this approach tend to pride themselves by calling themselves: “practitioners”.

In the other end of the scale is the deterministic predictive approach, which favours developing an understanding of all elements in the structure, so that the performance of the structure can be predicted. On that basis the structure can be designed to meet predetermined requirements. The enthusiasts of this approach will be called “theoretists”.

In philosophical terms the empirical iterative approach reasons by “association”, i.e. by similarity from one case to another. The danger is, that the cases may not be similar – and there is little way of knowing, except by “induction”, i.e. experience. In philosophical terms the deterministic predictive approach reasons by “causation”, i.e. the belief that there is a cause-effect relationship to be unravelled by scientific investigations and monitoring. However, in the end also the deterministic predictive approach cannot avoid significant elements of pragmatism, because investigations and monitoring provide the empirical basis for the structure of reasoning and the parameters of the models.

In principle, the deterministic predictive approach has a much better chance of having a universal applicability, in so far as the structure of thinking is based on an adequate, natural
scientific knowledge base. That principle has been verified again and again since natural science became the basis of thinking in the 16–17th century. However, it has to be reckoned that recent experience has also shown that system complications may be so intricate that the knowledge base is insufficient for reliable predictions. Furthermore, it is well established that in the social sciences the same rigour cannot be identified and other approaches have to be implemented. Then, there is no other approach than the empirical iterative approach to design and operation.

The status of knowledge on urban drainage

Most sewers and wastewater treatment plants are still designed and operated on an empirical basis and permissible discharges from the system to receiving waters are still formulated much on an equally empirical basis. This is not only due to lack of knowledge, but also due to a significant conservatism in the profession. However, the following knowledge, based on basic understanding of the mechanisms associated with cause-effect relationships, has found significant application in practice:

- simulation of the hydrology and the hydraulics of sewer systems has been well accepted and is routinely applied, especially with respect to flooding and hydraulic loads on the treatment plant and on the receiving waters;
- simplified simulation of pollutant transport and pollution discharged from combined sewer overflows;
- simulation of wastewater treatment plants has found wide application in analysis of performance, but less so in design, where old design methods still prevail;
- simplified simulation of sewers systems and treatment plants for real time control.

The best results by comprehensive comparison between simulation and actual performance have been obtained for hydraulic simulation and for simulation of wastewater treatment plants. However, it has to be reckoned that the uncertainty associated with such simulations is still very significant, and will remain uncertain, except in case of comprehensive investigations that are intensive beyond the level of practical application. That is due to the uncertainty associated with input functions and parameter calibration characteristic of the local situation (Henze et al., 2001; Harremoës and Madsen, 1999; Rauch et al., 1998; Arnbjerg-Nielsen and Harremoës, 1996).

The development of these tools goes hand in hand or one development creates demands on the other. A significant example is the demand for better wastewater characterisation as input to wastewater treatment models as a consequence of requirements for nutrient removal from treatment plants. That has inspired a whole new concept of sewer simulations: “The sewer as a bioreactor”, to which INTERURBA II have significant contributions, e.g. Vollertsen and Hvitved-Jacobsen (2002) and Hvitved-Jacobsen, Vollertsen and Matos (2002). There is a growing realisation that analysis, design and operation of treatment on the traditional basis cannot live up to the demand for adequate information on crucial variables of unquestionable importance to the performance, essentially the fractionation of the load of organic matter in the influent. This applies under dry as well as wet weather conditions. It is essential to get a qualitative understanding of these processes, even though they may be difficult to simulate with accuracy, or predict with precision.

The need to understand and an acknowledged difficulty in simulating can be illustrated with pollutant transport during rain runoff (Harremoës and Madsen, 1999; Ashley et al., 1999). It is now well documented that the parameters governing pollutant transport vary significantly from event to event and from one sewer catchment to another. The general mechanisms are known, but the parameter variation cannot be universally described. This very point is highlighted by David and Matos (2002), who found a discrepancy between the
efforts required and the results obtained from comprehensive studies. However, statistical descriptions in combination with simple deterministic models can be applied successfully to design. In the case of real time control, the problems can be overcome by on-line measurements and on-line up-date of the most essential model parameters, applied for short term predictions and optimised control (Harremoës and Rauch, 1999; Rauch and Harremoës, 1999).

The difference between reasoning by “association” as opposed to reasoning by “causation” can be illustrated by the following example. It is “well known” in the profession that treatment plant performance can deteriorate during increased loading due to rain runoff. An investigation was performed in order to establish an empirical basis for such a relationship (Ronen, 2000). Association between the suspended solids in the effluent from the treatment plant of The City of Copenhagen and the hydraulic load on the biological treatment compartment was analysed by time-series-analysis. There was only vague interrelationship and much noise. However, establishing continuous sludge mass balance inventory revealed a relationship. Whether sludge overflow occurred or not depended entirely on the sludge conditions in the plant during the rain event – and that depended on the sludge handling practices of routine operation: heavy rain on Fridays did not cause sludge overflow, but the plant was vulnerable to such overflows on Mondays. That is due to the sludge wastage routines. Low sludge before weekend, increasing sludge during weekend due to no sludge treatment during weekends, and high sludge concentrations Monday morning, before wastage was resumed on the first weekday after the weekend. Reasoning by “association” can be transferred to reasoning by “causation” on the basis of better understanding. This is essentially what research is all about.

However, there is a limit to the success of the “causation” approach. Cause-effect relationships between discharge and receiving water quality illustrate the problems encountered when the system becomes so involved that it is difficult to identify the essential phenomena. Eutrophication of lakes is an example to be noted (Scheffer, 1998). Eutrophication was believed to be controlled by a unique relationship from “below”, i.e. by the load of nutrients and the build up of biomass in the lake. It turned out to be controlled as much from “above”, i.e. by the higher order fauna, which controls the grazing on the algae biomass – and the whole mechanism shows fractal properties, which may prevent a unique causal relationship between load and effects.

Another example is the relationship between intermittent loads on rivers due to rain runoff and the resulting effects on the ecosystem. That is still a controversial issue, but the realisation is that even though such a relationship may exist, it has not been possible in practice to unravel the causation sufficiently well to make modelling tools reliable for practical purposes. On that basis, it is the realisation in Denmark that CSOs will have to be designed on the basis of empirical iterative approaches – much to the regret of the engineering community, who hate to admit the limitations of the deterministic predictive approaches. The idea is to design on the basis of the best available information, to realise from the outset that the predictive reliability may be low and to choose robust and flexible solutions accordingly. The logical step is to follow up with systematic monitoring in order to check compliance and enforce abatement where compliance has not been met. This realisation must significantly affect the managerial approaches, not the least in view of the EU Water Framework Directives, which change the emphasis from chemical quality to ecological quality of the receiving waters.

Only one paper deals explicitly with pollution in the environment, a combined pond and river system (Marsalek et al, 2002). The study is a much needed contribution to the information on the effects of separate system discharges and the accumulation of pollutants in the sediments and resulting toxicity. The effects of pollution from upstream catchments...
were noticeable, but not severe. The issue is of importance to selection of up-stream BMP-structures and the impact runoff may have on the amenity and the local ecosystem.

Analysis of the integrated system

Before the 1992 INTERURBA conference, only a few pilot investigations of the integrated system had been performed and mostly as university type trials. In the mean time, integrated model-complexes have become available on a commercial basis, mostly by combining existing models of sewer system, treatment plant and receiving water (mostly river). An educational package is now available as an internet course given at DTU for students from both EU and from USA (Warnaars et al., 1999). The question is, to what extent the knowledge base is sufficiently developed for use on integrated problems, to what extent these tools have been developed to an adequate state of application and to what extent they have been applied in practice? This issue is addressed comprehensively and in detail by Rauch et al. (2002).

The invitation to the INTERURBA II conference demanded contributors to bring examples of applications which as a minimum involved two of the three components. The result is that rather few of the contributions describe situations involving more than two of the components. The tendency is that it is the receiving water component that is missing from the investigation. Where receiving waters are incorporated in the analysis, it is mostly based on highly hypothesised models with little calibration/verification of the water quality impacts. This is not surprising, because that is where the models have proven difficult to fit in situations with extensive data on performance (e.g. Andersen et al., 1996; Harremoës et al., 1996; Harremoës and Rauch, 1999).

Only four contributions to INTERURBA II deal with the receiving waters with respect to the cause-effect relationship between discharge and resulting water quality on the basis of monitoring the effects in the receiving water and the use of calibrated/verified models, in one case only as a “semi-hypothetical” model and ammonia-measurements at the point of discharge. One case study is a detailed investigation of the effects of discharges from separate sewer systems. One study relates to six months of results of monitoring of DO and ammonia. Only compliance figures are shown, no calibration/verification is reported. On this basis, some concern has to be expressed as to the reliability of model predictions, in view of the fact that it is difficult to simulate impacts in receiving waters with a reasonable degree of fit, even for the conventional parameters like DO and Ammonia. It may even be prudent to question the qualitative conclusions relative to the tendencies derived from non-calibrated/non-verified models on hypothetical affects of different up-stream, engineering measures that are quoted in a much greater number of investigations. It should be considered to change attitude from pretending to simulate a reality to admittance of ignorance and on that basis advocate an empirical iterative approach to design. The deficiency of research and development is highlighted by Rauch et al. (2002).

Most studies deal with the interrelationship between the sewer system and the treatment plant, while the receiving waters are incorporated only as the receiving component to which the loads are minimised/optimised. These contributions leave no doubt that there is a significant potential in analysing the sewer system and the treatment plant as one unit. This can be argued on the mere fact that the receiving water will experience the combined load, not the load from each system independently. Second, there is such a well established linkage between the sewer system and the treatment plant that integrated design and operation has a lot of merit. Several case studies show this. The following options are available to the engineering manager:

• infiltrate locally
• change to separate systems
• build storage basins
• provide local treatment at CSO
• improve sludge properties
• increase final clarifiers
• real time control
• combinations of these options.

These options have been investigated in the total catchment of The City of Copenhagen (Harremoës et al., 2002). The most cost-effective option was a combination of storage tanks and local treatment. A comprehensive analysis of the entire Ruhr-catchment has revealed similar results, based on presently 500 storm water detention facilities (Bode and Weyand, 2002). The empirical basis for the result is acknowledged with the statement: “... if the positive pollution load balance is to be upheld or even enhanced, it is necessary to carefully monitor all operations ...”. Real time control is used to optimise storage and even out loading, but the concluding argument is based on a wish to “optimise manpower planning”. Several papers describe analysis of combinations of effective storage basin design and optimal control of their performance. This is undoubtedly a field for much development and abatement in the future – a real playing ground for engineers.

The models used vary from detailed deterministic models to simplified models and to combinations of deterministic and stochastic models. This is a complex issue with no easy solutions, but the tendency is that simplified models are used for integrated planning and for real time control. The very detailed models are associated with detailed studies of individual components in the system, e.g. flooding studies, troubleshooting of treatment plant performance. In integrated planning there is no need for great complexity. The very detailed models will hide the issues in the complexity. The data required for detailed modelling is excessive and not required. For real time control the issue is different. The need for detail is not there because the simple models can be adapted on-line. Second, the time constraint of real time calls for fast models, to the extent that deterministic models may be overtaken by empirical models with on-line up-date, e.g. neural networks. The key is that a spectrum of adequate models will be available for use in practice, among which the practitioner can choose for adaptation to the problem in question.

Management, risk and sustainability
The concept on which the INTERURBA conference is based is essentially to optimise the established system with respect to performance within the paradigm inherited from past generations.

One of the important extensions of the old concept is the introduction of risk associated with uncertainty of modelling and decision making as a significant component (Hauger et al., 2002). That should be combined with a component in risk assessment, which is frequently ignored: the risk of failure in the operation of the system. This has turned out to be a risk of significance as compared to the detrimental effects associated with discharges from CSO during rain. In Denmark, a failure of an unattended pumping station has caused more dramatic damage to a river than any CSO-event recorded. The probability of power break in Denmark is 0.7 events per year per installation. The “storm of the century” on the 3rd of December 1999 caused extensive power shortage at many locations. The pollution effects derived therefrom are not spoken of, because it is considered “force majeure”, but it is no more force majeure than extreme rains. This issue requires more attention.

The inherited concepts are challenged by new concepts, which break with the very paradigm of the basic approach: optimisation of centralised sewerage and large scale wastewater treatment (Otterpohl, 2002). This is an interesting development that cannot be overstated, though the heritage, the inertia associated with investments already made and
simple engineering conservatism is always an obstacle to easy implementation of new paradigms.

The general idea is presented in the paper by Otterpohl (2002). It is too early to evaluate how the new and the old will combine. The important point is to keep an open mind to the “pros and cons” in the analysis of options. Too frequently does it become a bias with preconceived ideas and no room for compromise between opposing views. The point has to be to extract the best of the options for further analysis and for implementation. In this respect there are mistakes made on both sides of the issues. The reason is that the ultimate evaluation is not based on science nor engineering considerations, but is based on personal and social values, which is hard to discuss in an engineering context. It has to be discussed in a social, economic and ethical context. If the basic thinking differs in this respect, it is difficult to find grounds for compromise.

An example will illustrate the point. Distributed, in-house reuse of water shall be analysed with respect to “pros and cons”. In doing so, it should be a matter of course that the health risks associated with such technologies have to be analysed in a proper fashion. Here, and in other instances, it has been considered critical even to suggest such an analysis, because it is interpreted as a sign of “being against”. The ideal is “Integrated Environmental Management” in which it is the deliberate attempt to analyse all options, cover all media (air, water and soil), take uncertainty and ignorance into account and to evaluate on the basis of values of all stakeholders (Harremoës, 2000).

In relation to rain runoff, Clifford and Martin (2001) point out that traditional urban pollution management and sustainable urban management systems are complementary to each other. The sustainable approaches are new options by which to achieve the original objectives, plus new objectives that encompass new paradigms and new criteria for performance. The new tools are called “Best Management Practices”, in short BMP. The new objectives are:

- less use of resources, including the water resource
- local infiltration
- up-stream source control
- solutions closer “to home”, and thus apparent to layman
- a new architecture, more green solutions and improved amenity, as opposed to concrete structures.

Such new approaches call for new information, in order not to repeat the mistakes potential to all new approaches on which experience is limited. This raises a number of issues, some of them also dealt with in the contributing paper to INTERURBA II. Marsalek et al. (2002) raise the issue associated with contaminants accumulating in up-stream ponds and infiltration sites. The claims of potentially detrimental effects appear to be overrated, but the approaches and the proximity “to home” calls for adequate source control; a policy of increasing priority anyhow. The same applies to the risk of infiltration of contaminants, potentially contaminating groundwater. There are serious cases reported on contamination of groundwater and water supplies, e.g. with MtBE, but mostly from point sources (spillage from gas stations) and not from disperse sources associated with urban drainage – so far. The objective is to be flexible, to aim at cost effective solutions and to prevent the new paradigms introducing new, unforeseen problems in attempts to reach new ideals. The lack of fundamental knowledge and lack of extensive experience calls for an empirical iterative approach and for robust, flexible solutions adaptable to new insights and new paradigms.

With respect to both the heritage and the new paradigms, the development of urban drainage can be fulfilled in the best interests of the urban population and the environment.
Discussion

Development

The development of the discipline has provided new knowledge, and new tools available to the urban water scientist and engineer:

- new knowledge on the cause-effect relationships within the integrated urban drainage system, predominantly regarding processes in the sewer system
- development of modelling techniques and computer simulation tools. Integrated tools are now available for engineering application
- new monitoring tools, including analytical tools for a new spectrum of chemicals
- new database technology, including GIS (geographical information systems).

It is noteworthy that the new integrated tools were not developed at an earlier stage after 1992 when the concept was introduced. This is caused by the slow pace of commercial software development, required to provide reliable products for application. University models and programmes have been there all the time. On this basis, integrated approaches have not found wider application in practice. However, the potential is there and applications will develop. It is equally noteworthy that real time control has not found wider application. This is due to smaller benefits than originally anticipated, greater complexity in operation, increased risk of technical and software failures and conservatism in the practitioner community.

Modelling of receiving water has been a partial success. The success is due to the rationale of the approach, based on predicted performance with respect to compliance with water quality standards on oxygen, ammonia and loads of total P and N. The limitation of the success is due to significant residual uncertainty of prediction and the lack of predictability with respect to ecological criteria. This last feature will be consequential in relation to the new Water Framework Directive.

New paradigms

The following issues have been subject to changes of paradigm – in the sense that they dramatically alter the foundations on which the INTERURBA concepts were based.

Incertitude, risk and failures. The environmental issues have been marred by scientific and engineering surprises due to ignorance regarding basic phenomena, uncertainties unaccounted for and risks of technical failures. This is in particular related to uncertainty of predicted performance, lack of knowledge regarding effects of chemicals used in society and lack of attention to technical risk assessment versus risks associated with rain runoff.

Ecology of receiving waters. Prediction of ecological effects of urban drainage is not possible by modelling, because of lack of knowledge related to the cause-effect relationships. The policy has to be based on the empirical-iterative approach. That approach may in its first iteration be based on the present procedures, but it has to be followed up by dedicated monitoring and analysis.

Decentralised techniques. The common denominator for this new paradigm is “sustainability”. However, it is not entirely clear what the criteria are for this characterisation. The established and the new approaches can be combined with success when accounting for both the heritage and the potential of the new approaches. New approaches require good professional analyses and designs in order not to make new mistakes based on new uncertainties. The new approaches have a significant potential for use in the developing countries, where the solidity of the established techniques is less of a barrier.
**Widening the scope**

It is clear from the papers and it came out clearly from the discussion that there is a need for widening the scope of integration. Urban drainage is of too narrow a scope for further development and new paradigms.

The issue has to incorporate groundwater and water supply, leading to *urban water management*. In that context, it is paramount that the social-economic aspects play a role. This calls for widening to incorporate new disciplines, which is a major endeavour. Furthermore, water and its pollution is just a sector of the whole mass balance of cities (Harremoës, 1997). Interdisciplinarity related to the three media, water, air and soil, is becoming mandatory, in order not to repeat some of the dramatic mistakes of the past.

“Integrated Urban Drainage” is just a sub-sector of the new discipline of “Integrated Environmental Assessment”, which consists of: integration among disciplines and media, technical and chemical risk assessment, analysis of alternatives and life cycle analysis, with the aim to address the science/engineering-policy interface. The discipline has to be expanded to include: incertitude, all stakeholder values, all information from all sources, early monitoring and research based on suspicion of failure, “pros and cons”-analysis (incorporating not just costs and benefits in economical terms; but all factors, including perceptions) and land use aspects.

Each of these items constitutes a significant development potential, but put together it constitutes a significant change of paradigm for the profession, the managers and the politicians. The challenge is to combine the heritage with the new approaches, such that development moves in a sustainable direction by transparent and accountable procedures and by robust and flexible means, which are adaptable to new changes in “the spirit of the time”.

**Conclusions**

New tools for analysis, design, operation and real time control of the integrated urban drainage systems have been developed and some implementations have been recorded, but there appears to be a significant conservatism in the profession with respect to application of new tools. Few investigations include the receiving water aspects, which indicates the dilemma in decision making associated with relations to the ultimate goal and the rationale behind engineering solutions. However, this is the effect of the lack of adequate knowledge regarding even basic mechanisms in receiving waters. Accordingly, an empirical iterative approach is recommended. The importance of integrated analysis with respect to optimisation of design and operation of storage basins, local treatment and treatment plant operation is well documented. The implementation of new paradigms: accounting for incertitude, sustainability, new architecture and greener up-stream solutions is an important new component in design of urban drainage. The development of centralised systems, which advantageously can be optimised as an integrated system, can beneficially take place in combination with new approaches, involving infiltration, storage basins, local treatment and real time control. With respect to both the heritage and the new paradigms, the development of urban drainage can be fulfilled in the best interests of both the urban population and the environment. However, the scope of integration has to be widened in order to cope with the mass flow of matter in cities, the land use and the social-economic aspects of urban drainage.

**References**
