Hydroinformatics and urban drainage: an agenda for the beginning of the 21st century

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ABSTRACT

The developing insights of hydroinformatics have much to offer the water industry, and particularly urban storm and wastewater drainage. This paper reviews aspects of data mining and knowledge discovery of large asset databases, the complementary nature of both physically based and data-driven modelling of drainage network performance, and the roles of decision support systems and knowledge management. It concludes with the presentation of ten agenda items that would benefit research and practice at the beginning of the 21st century.

Key words | data mining, decision support systems, physically based modelling, urban drainage, urban wastewater

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INTRODUCTION

Confident predictions are being made that by the year 2050 as much as 80% of the world's human population will live in urban areas. This has serious implications for society. Whereas people have lived for centuries 'cheek by jowl' in towns and cities, the prospect of many millions of people in close proximity and with increasing competition for physical and psychological space raises numerous sociological issues. In addition, there are many concerns about developing and maintaining the physical infrastructure. Whereas sustainability is not a principle that can be advocated for the urban area alone, in that it is extensively dependent on resources from outside, there is a need to pursue some form of sustainability on the larger scale. Sustainability will be severely tested during the inevitable period of urbanisation during the next 50 years. This places an increasingly heavy burden on planning at all levels. Utilities, for example, face a number of challenges to ensure that their levels of service are sustainable and, in many cases, can be improved. The management of water in conurbations raises its own issues, whether in terms of water supply, treatment and distribution, storm and wastewater collection, sewage treatment, or disposal of treated and untreated effluents to receiving surface waters and groundwater. Increasingly, urban planners are having to recognise that they must plan for a larger area than they are immediately concerned with. And this is just as valid for water as it is for any other resource.

Proper management of water in urban areas becomes more complex as the size of the conurbation increases. There is a commensurate increase in information associated with the water utilities and their interaction with the immediate environment. Such information involves not just data on the physical domain: the networks, inputs, demands, performance, and so on, but also on management procedures, such as designs, operational rules, standards, legislation, finances and customer services. The effective and efficient management of this information is becoming important as we move more towards a 'soft' rather than a 'hard' engineering approach. For example, accurate information on the assets and their value is vital for a privatised water company that seeks to attract investment. The handling of information has, of course, been revolutionised by the emergence of computing during the last half of the 20th century. Indeed, information and communication technologies have brought enormous benefits to the water industry ranging from improved design and analysis through simulation modelling of performance to far more efficient and effective customer services. There have been improvements in such areas as billing, customer care, operations and maintenance, planning and rehabilitation. In short, the combination of information and communication technologies with urban water management is a prime example of the activity known as hydroinformatics.

This paper explores urban water management, and specifically urban drainage, from a hydroinformatics point-of-view. Here the phrase 'urban drainage' is taken to embody the whole process of collection, treatment and disposal of storm and wastewater. The objective is to propose an agenda for renewing urban drainage in the 21st century, keeping in mind the huge demands that will be made on water as a resource for the conurbations of the future. A hydroinformatics point-of-view may be new to some, particularly those who come from a hard engineering background in the water utility area. So the paper first addresses what hydroinformatics is and what it, as an area of activity, provides to urban water management. Then the paper explores the application of hydroinformatics to urban drainage in particular, and concludes with a presentation of the key agenda issues and opportunities.

HYDROINFORMATICS

Hydroinformatics is about making effective use of advanced information and communication technologies to handle information concerning natural or artificial water-based systems so that we can improve our understanding and management of those systems. Information here should be viewed as having the sense of the *capacity to impart knowledge* rather than the more narrow sense of classical information theory (Abbott 1999). Urban storm and wastewater drainage are two major forms of water-based systems that have benefited in recent years from a hydroinformatics approach. Whereas traditionally both forms of utility have been viewed primarily as activities in civil engineering structures and hydraulics, we are now accustomed to other stakeholders seeing the utilities from a quite different point-of-view. For example, the privatisation of the water industry in the UK means that urban water supply and drainage have become profitable businesses. The Stock Market looks at the water companies as valuable investments. It is not surprising therefore that with advances in information and communication technologies there should be considerable investment by the water industry in these new technologies to improve efficiency and therefore their attractiveness to investors. And such investment is only secondarily for engineering purposes: the business and financial management of the water companies is leading to considerable expenditure on customer services, billing, and other similar functions.

There is, however, considerable investment in information technology for engineering purposes. And this is the primary focus of hydroinformatics; see Price *et al*. (1998). But to discuss this we have to be aware of the four dimensional nature of hydroinformatics. The first two dimensions concern the traditional mix of mathematics and the physical sciences that form the basis of engineering hydraulics. The third dimension is associated with informatics, that is, the handling of information through information science and technology. What is now increasingly apparent is that there is a fourth dimension involving human culture. As Abbott (1999) states, hydroinformatics is a socio-technical enterprise. The strong emphasis on the human dimension is highlighted by concern over the *communication* of information, not only internally within an organisation but also between an organisation and its customers and stakeholders. Issues such as how knowledge and information are acquired and shared, how people can work more effectively together, what it means to be innovative, how learning takes place in an organisation, are as much the concern of hydroinformatics as technical solutions to engineering problems. It is not without good reason that we are now accustomed to speaking about information and communication technologies together.

Reference to communication highlights the importance of the Internet. Increasingly, it is expected that the Internet will be used to facilitate decision making by an increasingly wider circle of stakeholders in a given asset. This will mean that consumers will have more power in determining the strategy and development of the water utilities; see, for example, Abbott and Jonoski (1998). A more detailed discussion of the issues here is beyond the scope of this paper.

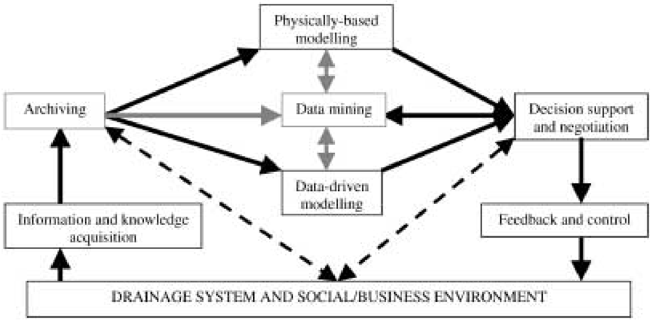

Figure 1 | Information process.

INFORMATION MANAGEMENT

To enlarge upon this point-of-view of hydroinformatics consider first the handling of information needed to manage, say, the water distribution or urban drainage network infrastructure. We can identify a number of different aspects; see Figure 1. Firstly we have to *acquire* information about a network. This involves not only data concerning the physical domain in terms of the network, customer demand, the above-ground catchment, its development, and the historical performance of the network, but also the human dimension: the historical, sociological, legal, economic, management and even political aspects. Much, though not all, of this information is geographical and therefore lends itself to inclusion in Geographical Information Systems (GIS). We are seeing the emergence of comprehensive and detailed asset databases linked to the powerful querying facilities of GIS. Besides having large amounts of data *archived* in databases and documents, even more knowledge and information resides in the heuristics and experience of the engineers ‘on the ground’. One of the growing concerns in human resource management is how to map and access this ‘tacit’ knowledge along with the knowledge already made explicit in the form of documents, databases and modelling systems.

A major task of the managing organisation is to *analyse* the information it has available and to determine what new information needs to be collected, archived and made *accessible*. Much can be deduced from the raw, historic data. Increasingly we are now seeing data mining techniques, originally developed for business and commercial applications, being applied to large asset databases. The opportunities in the future for knowledge discovery from such databases will do much to improve the information available in our water utilities. Data on the performance of an asset will, however, continue to be difficult to collect in sufficient quantities and reliability. In addition such data can only record what has happened in the past. Invariably therefore, some form of *modelling* is required to make sense of the acquired data and to generate new data representative of an improved network, particularly for possible future scenarios. Whatever data is collected or generated, or new knowledge and information deduced, decisions have to be made by people in management. Inevitably the information on which decisions are made has a degree of uncertainty. In some cases the uncertainty can be large. Unfortunately in many cases the degree of uncertainty is not even known. This can place the decision-maker in a difficult position. A person who has learnt by experience from the consequences of decisions made previously is in a better position to make decisions than others without such experience. Making such experience explicit is however dependent not only on deducing the heuristics under which the ‘expert’ works but also in explicating the chain of assumptions and approximations made by other human beings throughout the information cycle. Where such knowledge can be made explicit it can form the basis of systems for *decision support*, such as to assist in rehabilitation of sewerage networks. These systems involve a number of people with different roles. This emphasises again the need for the sharing of knowledge between people and for effective working together in a collaborative manner. Finally, there is the need to *communicate* decisions at all levels and to *disseminate* information back to the real world, including amendments to the network and advice to the community served by or affected by the network.

ASSET AND DATA MANAGEMENT

The urban water utilities possess valuable man-made assets in the form of pipe networks and treatment works. A realistic assessment of these assets is vital if they are to be properly managed. Commercial water companies, through their drive to increase profitability, are concerned to operate their networks more efficiently. This can be expressed in colloquial terms as 'making the assets sweat' (Sharman 1998). There are a number of different aspects. For example, planning involves such diverse tasks as forecasting financial returns, assessing water demand, and improving effluent quality. The determination of the costs associated with an asset revolves around such items as capital revenue expenditure, optimising design and construction, making finance available and attracting investment. Similarly, the control of an asset is concerned with process control and the efficiency with which the asset is operated. Then again there are levels of service requirements that include compliance with regulatory standards, improving customer service, identifying customer perception, and dealing with defects, such as in hydraulic capacity or flooding, structural integrity and water quality. There is the whole aspect of knowledge about an asset and its performance. This can involve maintaining an asset register, assessing the condition of the asset, forecasting its useful life, applying appropriate rehabilitation techniques, and acquiring structural and hydraulic data, CSO emission data and a documented account of the history of the asset. All of these tasks place a heavy requirement on the utility for good quality data and the means to acquire it.

Increasingly, municipalities are investing in the acquisition of the necessary structural and performance data for their water networks. Investment is made also in monitoring to record asset performance (rainfall, demands, flows, pressures, leakage, flooding, etc.) as well as collecting economic indices and news events relating to the asset. Documents are archived electronically for automatic retrieval. Because so much of the data that is archived in an asset database is geographically referenced there is usually a direct link to a GIS which in turn is connected to a digital terrain model. So, for example, a query can quickly determine the houses served by a particular water main, or identify the sewers draining a factory. A GIS can be used for such tasks as discriminating various types of pervious and impervious areas for a drainage network, analysing the digital terrain model to identify possible surface flow patterns and routes, and to delineate the drainage catchment into sub-catchments based on identification of land features.

Once the databases are set up a range of data mining techniques can be used to analyse the data for different purposes. For example, an asset database can be mined for information to predict when and where water distribution pipes are likely to need rehabilitation. This can be done, for example, using Kohonen mapping techniques to discern patterns in the data; see Velickov *et al*. (1999). As yet these techniques have barely been used by the water industry, largely because it is only comparatively recently that well populated databases for the assets have become available. The potential to extend data mining to knowledge discovery, that is, the automatic search for new knowledge in databases, has yet to begin in earnest.

NEED FOR MODELLING

The growing demand by society for fresh water is being frustrated by the deteriorating quality of both surface and groundwater. The cost of reclaiming polluted water for consumption is of the order of 10 times that of providing water from natural, unpolluted sources. The need to conserve water resources has been emphasised by the Stockholm, Dublin (ICWE 1992) and Rio (UNCED 1992) conferences. These have given an international imperative for action. Concern has been politicised such that action is supported by legislation. In the European Union this has given rise to the Urban Wastewater Treatment Directive (1991), among a number of other related Directives. Attitudes towards implementing these Directives through regulation vary throughout the EU, but in general there is a movement towards setting goals and meeting targets.

A number of problems arise when trying to implement the Directives. For example, there is poor understanding of the science of water quality at each phase (collection–treatment–disposal) of the drainage process. This is improving through extensive research programmes in each phase. Part of the difficulty is in monitoring water quality determinands and collecting data. Because of the shortage of good data there are corresponding difficulties in defining responsible water quality standards. Quantifying the water quality in each phase with reasonable accuracy is difficult. This is compounded by the separation of the phases in operational terms. This is not helped by the separate approaches to water quality management by engineers concerned with each phase. The observed systems can be so complex that in order even to understand the inter-relationship between the performance of the different processes it is necessary to conceptualise some form of model.

As an activity modelling has a number of benefits to an organisation. For example, it requires the assembly of existing knowledge with proper formulation of data collection programmes, it leads to the generation of new knowledge, and it helps identify deficiencies in knowledge. Models also help in reproducing historical events, quantifying the consequences of design events and analysing the response to changes in the asset. They enable the assimilation of complex issues, the design or implementation of real time operations and help in asset planning.

Such models for the separate phases in urban drainage then become the basis of communication between individuals and groups, and may eventually be expected to form the basis for planning and design. Where an integrated physically based modelling system can be developed it provides a means of understanding the inter-relationships between the different phases, designing improvements to the overall system and arranging to meet regulatory standards.

ENGINEERING CONTEXT OF MODELLING

Engineers have quite rightly therefore seen the model as a tool to use rather than an end in its own right. Consequently, there is a valuable tradition in a number of countries, particularly the UK and USA, of developing engineering procedures for drainage-related issues that encapsulate the use of models. These include, for example in the UK, the TRRL method (the first drainage design procedure that made use of computing), the Wallingford Procedure from HR Wallingford (1982), the Sewerage Rehabilitation Manual (SRM) from WRc (1983, 1986, 1994), and the Urban Pollution Management (UPM) manual from FWR (1994). The USA has invested heavily in the development of ‘best management practices’ (BMPs) in this area. Such procedural approaches bring together a task structure that contains important generic knowledge (’how’ to do something rather than just ‘what’ to do) and the active involvement of the engineer with his or her own experience.

One of the reasons for the development of these procedures is the existence of a large number of drainage networks (more than 10,000 in the UK alone). In turn this implies a potentially large number of separate studies that need to be completed whether for design or rehabilitation. These studies can only be completed with any modicum of efficiency and effectiveness if procedures are in place to guide engineers through the finer details. Because modelling has been recognised as an important way of improving the hydraulic analysis of sewerage networks this has meant the inclusion of modelling system performance within the procedures. From experience largely gained in the UK, but also augmented by insights developed in other countries (in particular, see Vanrolleghem *et al*. (1998)), a generalised procedure for the rehabilitation of networks would appear to take the form:

1. Define receiving water uses/ecological state
2. Evaluate societal pressure
3. Define objectives
4. Identify problems (involving ‘critical’ structures)
5. Generate potential solutions
6. Acquire and archive asset and historical performance data
7. Monitor (short term) existing system
8. Select (hydraulic analysis) modelling tools
9. Build model
10. Confirm model performance
11. Establish base performance
12. Evaluate alternative solutions
13. Select preferred solution (‘optioneering’, a term used by North West Water, UK)
14. Implement solution
15. Audit post-implementation situation

It can be seen that models in some form or other form an important part of the investigation process prior to

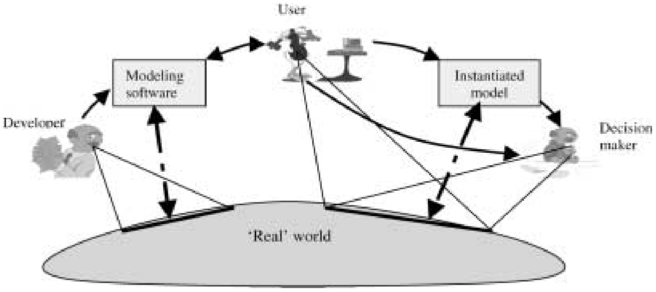

Figure 2 | Modelling relationships.

decision making on engineering options (see items 8–12 above).

PHYSICALLY BASED SIMULATION MODELLING

Before we go any further it is as well to ask what sort of models are being used for the performance of a network. Traditionally, these are simulation models that are *physically based*; that is, they are based on a conceptualisation of the perceived physical situation, such as using the Newtonian laws of physics to describe the flow. In this way particular scientific knowledge is built into the model. It is customary to write the software for the model in a generic form such that it can be *instantiated* for a given situation. The value of such specific software is that it includes generic knowledge of the physical processes and the domain, such that it becomes considerably easier for the engineer to insert his own data, whether for the structural domain, or the time-dependent boundary conditions. What is more, the user can have some confidence that a confirmed model (see Oreskes *et al*. 1994) will reproduce the performance of the network over a range of input conditions. The actual degree of confidence depends, of course, on a variety of factors.

Software for physically based computational modelling of urban drainage systems is a tool that is generated by the 'developer' who has a particular perspective of a real-world asset (a particular set of existing drainage networks); see Figure 2. The developer hopefully includes the best science, makes a sensible conceptualisation of the physical network, formulates the right mathematical equations (often with arbitrary parameters that need to be adjusted for a given instantiation), provides an accurate and stable numerical solution, and produces software that is as free as possible of 'bugs'. The user, on the other hand, has necessarily a different (though hopefully not too different) view of what it means to model his particular drainage network. What he hopes is that with all the knowledge encapsulated in the software (over which he has no control), his appreciation of the *context* in which the developer wrote the software, and the inclusion of the asset and performance data for a particular network, he can produce a reliable model. The purpose of the instantiated model is to generate new knowledge about the drainage network; in particular, about its performance. In turn, the user will normally transfer conclusions based on the results of the model to the decision-maker. Obviously, good communication between these three parties (and other supporting parties) is critical if good decisions are being made.

INTEGRATED MODELLING

Although the type of procedural approach above has its critics, not least because of the difficulty of implementing it and the large measure of uncertainties generated, it has formed a rational basis for decision making. As already commented on above there are various pressures that are directing us to make, at least, the attempt at a more comprehensive analysis of the collection–treatment–disposal process for urban storm and wastewater. Besides the societal awareness of pollution problems in our natural waters generated by industrial and domestic waste, especially from urban areas (this is not to neglect the serious problems of pollution from certain agricultural practices), there is a trend towards a more holistic approach to problem solving. This is assisted by the recognition that impacts 'downstream' are due to 'upstream' influences. In addition, there are bewildering advances made in IT hardware and software engineering, such that what was deemed fantasy 15 years ago is now commonplace. Consequently the integration of models for the separate phases is now being done, even if with limited success; see Dudley and Tomicic (1998). The use of GIS linked to flexible databases is the norm for some organisations. We can even see the use of the Internet opening up radical new ways of operating software remotely in conjunction with on-line monitoring; see Velickov *et al*. (1998).

And this is not just a European enthusiasm, it is shared worldwide, as shown by the number of successful international conferences held on a regular basis (NOVATEC, PULLUTEC, AQUATEC, ICUSD, UDM, to mention but a few!) What is more there is growing awareness that integrated modelling of the urban storm and wastewater process is but part of a larger move towards a holistic urban water management. The trend here is being set by the merger of IAWQ and IWSA. The Urban (Storm) Drainage Committee has for many years had both the IAWQ and the IAHR as its joint parents. This movement towards greater co-operation is reflecting the need for the different specialists (researchers and practising engineers) to talk with each other and to work together. Each group has its own particular views and philosophy about the particular process it has taken responsibility for. Such views have evolved over many years and are part of the tradition. The insights gained are valuable and important, and yet they have to be shared with, reinterpreted for and appreciated by the other groups. In England and Wales these groups were all in the same organisations between 1973 and 1989. With privatisation river management was passed to the National Rivers Authority (now the Environment Agency), while ownership and responsibility for the collection and treatment phases were passed on to the privatised water utility companies. Different ways of administering the urban storm and wastewater processes have evolved in different countries. It is apparent that the success of being able to carry out integrated management of the urban storm and wastewater process does depend on the prevailing administrative structure. (This is not to say that the UK model is the best; it simply means that local legislation, standards, regulation, and communication between engineers planning, designing, implementing and operating drainage systems, will have to be adapted to the local structure. It is the effectiveness of these business processes in each case that is at issue.) In other words, we have to admit that socio-technical, socio-economic and political–national differences are important when considering the possibility and effectiveness of integrated modelling.

A YET WIDER VIEW OF INTEGRATED MODELLING

But there are also physical–geographic factors to consider. Why stop at collection–treatment–receiving water? What about integrated modelling of urban *water* systems? What about infiltration to sewers and the interaction of sewerage systems with groundwater? How does local groundwater affect urban structures? What is the link with leakage from water distribution networks and interaction with urban surface waters? And how do we model the urban storm and wastewater process within the context of river basin management when there may be several major conurbations in the basin, and when the quality of surface waters have significance for water supply? The importance of such questions varies between situations. Certainly groundwater is more important a consideration in flat areas such as The Netherlands and Flanders as compared with the traditional reasonably steep catchments in the UK and other EC countries

DANGERS OF MODEL CALIBRATION

Detailed physically based models do provide a means of understanding the complex interactions and processes that occur in urban storm and wastewater systems. The danger comes when they are pressed beyond what they are designed for and what they are capable of. Calibration happens to be one of the danger points; see Cunge (1998). Many of the physically based models include parameters whose values, it is claimed by the developers, have to be adjusted to improve the match of the model predictions and observed data. The problem with this approach is that the calibration of the parameters can take account of physical (chemical and biological) processes that have either been improperly specified or not even included. It is interesting that the original Wallingford Procedure for urban storm drainage design and analysis focused on verifying the asset data for a model rather than calibrating surface runoff or pipe roughness. Admittedly this was because the surface runoff model had already been calibrated *nationally*, so there was strictly no need to spend more time in refining the calibration for a specific application. Also, the use of a roughness length for the pipe roughness meant that usually it could be estimated accurately from observations of the boundary texture. The engineer could then place his effort into ensuring that the asset data (including above ground surface and land use data, and surface connections) were correctly defined. This is a fundamental aspect of the application of the SRM and UPM procedures in the UK. It is therefore argued here that it would be wrong to force a physically based model any further through calibration in the traditional sense. If there is a desire, nevertheless, to refine the model then the way forward should be to deal with the residual difference between the physically based model and observations. This could be achieved *at the observation sites* by training an artificial neural network on the residual difference. Although this method is strictly a 'black-box' method, it has the advantages that it replicates non-linear functional relationships and there is growing research evidence that the internal weights of the artificial neural network (ANN) can be interpreted to give knowledge on how to improve the physically based model; see Dibike (1999).

The approach advocated here places greater emphasis on measured data. We need to work closely with those developing monitoring equipment to ensure that the increased demand for data can be accommodated.

UNCERTAINTY IN MODELLING

This leaves open, of course, the possibility of starting with much simpler conceptual models of the different processes and being prepared to calibrate these against observed data, possibly introducing the same ANN approach to explain what cannot be modelled with precision by the simplified model. In terms of gaining a first order estimate such models may be very convenient. What is needed however is a better understanding of the uncertainty associated with these and the physically based models. Practising engineers continue to be happy when a model gives a specific result, and often continue to use that result without concern for the uncertainty associated with it. Safety factors may be introduced based on 'rules of thumb'. But these can often be far from what is needed. Instead there should be a more formal way of estimating uncertainty associated with any model prediction. The problem is, of course, that uncertainties are introduced at every level of the modelling process, and therefore the overall uncertainty is extremely difficult to estimate. Some automatic tests can be run on a completed model to determine the sensitivity of model results to certain input parameters or data. There is considerable effort being made to try and improve on this situation by going back to theory to try and work out a methodology for including uncertainty directly in the model calculations. This research is still in its infancy however.

DATA-DRIVEN MODELLING

ANNs, fuzzy logic generators, genetic algorithms, chaos theory, and cellular automata are technologies originally developed in other areas. These are now being brought into drainage modelling, not only for straightforward linking of input (say, rainfall) to output (discharges at outfalls or CSOs, levels of flooding, etc.) but also to replicate physically based models. Such replication speeds up the computations so that very long time series and Monte Carlo analyses can be done quickly and efficiently. See for example, Abebe (2000), Gautam (1998), Khindker *et al*. (1998) and Liu and Lin (1998). They also show considerable promise for efficient real time control in which optimised scenarios can be selected at any stage depending on rainfall or other types of forecast (such as given by chaos theory); see Bazartseran (1999) and Rahman (1999).

INCORPORATION OF ASSET AND BUSINESS PROCESS MODELLING

The integrated modelling that we are talking about is concerned with the hydraulic, chemical and biological

Table 1 |

Collection network		**Treatment works processes**		**River impact**	
HydroWorks (InfoWorks)	Wallingford Software, UK	GPSX	Hydromantis, Canada	MIKE 11	Danish Hydraulic Institute, Denmark
Mouse (Trap)	Danish Hydraulic Institute, Denmark	STOAT	WRc, UK	ISIS	HRWallingford/Halcrow, UK
SOBEK-Pluvius	Delft Hydraulics, Netherlands	EFOR	Kruger, Denmark	ISIS	HRWallingford/Halcrow, UK
CANOE	Sogreah, France	SIMBAD	CGE, France	SOBEK	Delft Hydraulics, Netherlands
SIMPOL	WRC, UK	WEST + +	University of Ghent, Belgium	SIMPOL	WRc, UK
MicroDrainage	MicroDrainage, UK	SIMBA	Ifak, Germany	DMZ	RIZA, Netherlands
SWMM	USEPA, USA (with interfaces from commercial organisations)			MCARLO	UKEA, UK
ILSAX	University of Technology, Sydney Australia			DUFLOW	STOWA, Netherlands
KOSIM	Institut für technische-wissenschaftliche Hydrologie, Hannover, Germany			MIKE-SHE	Danish Hydraulic Institute, Denmark
				SIMCAT	Thames Water, UK

performance of an urban storm and wastewater system. But why not go further and model the *state* of the asset? At the moment we ‘freeze’ the asset and determine the (statistical) performance of the ‘snap-shot’. Our sewerage rehabilitation engineering procedures are geared towards asset management. The question ‘when to invest in what?’ is as important as ‘how much to invest?’ And what about the larger view of the business processes associated with the management of the asset (see Tillman *et al*. 1998)? Should we even now be concerned with including these in our integrated modelling? At the very least we should be aware of the software developer–model user–decision-maker relationship.

COMMERCIAL SOFTWARE

Table 1 is a summary of some of the *commercial* software available for modelling the different phases in the urban storm and wastewater process. (It is acknowledged that a number of other products are referred to in the literature, but most of these are not available commercially and are largely university-based.)

The number of commercial software products in the table reflects the importance of the wastewater management market. The commercialisation of software is regretted by some, in that it tends to restrict access to what is contained in the software. This has often been exacerbated by developers who have been unnecessarily secretive over the content of their modelling 'engines'. Such secrecy has now lost its value in the light of the growing expenditure on user friendly interfaces for such modelling software. What these attitudes have engendered, however, is a separation between research (into largely the science), engineering practice and software development. There are advantages and disadvantages to this separation. It can be argued that, provided there is healthy competition, the exigencies of the market will encourage rather than discourage the software suppliers to provide what their customers want. This assumes that the practising engineers 'close the circle' by being in touch with what the researchers are doing, or should be encouraged to do, by the practising engineers. There is little doubt that these engineers have an important influence on what products reach the marketplace. In view of the huge capital investment in urban storm and wastewater management in Europe there should be ample opportunity to see a regular improvement in modelling products through a proper appreciation and control of the market by the end-users. See Dee (1993) for a framework in which modelling software can be validated for end-users.

DEFICIENCIES IN COMMERCIAL MODELLING PRODUCTS

Although there have been huge advances made in simulation modelling of the urban storm and wastewater system, there are still considerable deficiencies. For example, chemical and biological processes in sewers are modelled in a crude manner, if at all. Similarly there are no commercial software products modelling the interaction of the hydraulics of the flow and the dynamic changes in sediment depths on the bed of a conduit generated by the flow. Again, there are some fundamental differences in approach between the contained bacterial populations in the treatment works processes and the unconfined populations in natural surface waters. The latter is made even more complicated by the interaction of pollutants with sediments in the river, say. In addition river modellers have adopted BOD_5 as the main determinand for carbonaceous pollution whereas treatment process modellers have focused on COD. There is a need for transformations to map the determinands used in each phase to those for the next downstream phase. A number of studies are now being done on the best ways of bringing consistency to the modelling of biological processes in the three phases; see, for example, Fronteau *et al*. (1997) and Rauch *et al*. (1998).

Some of these deficiencies have been avoided for a variety of reasons. In some cases the science is still immature. In others there are considerable problems of data collection and monitoring. Another problem is the entrenched approach adopted by developers, often for good reason, because of the nature of the process and historical developments. But it would be wrong to paint too gloomy a picture in that considerable advances have been made in physically based modelling. What modellers must do however is to recognise and take advantage of new developments and understanding of the role and value of simulation modelling, particularly in regard to the treatment of uncertainty.

Interestingly, a number of countries are beginning to become somewhat wary about the use of different modelling products, and have consequently begun to lay down guidelines for an acceptable product. Typical of this approach is that of the UK WaPUG Modelling Code of Practice (1994) and of The Netherlands; see Mamerens and Clemens (1996).

DEVELOPMENT OF SOFTWARE

There is little doubt that modelling software for the urban storm and wastewater process will continue to be developed and marketed commercially. This is ensured by the size of the market. What is more, the commercial modelling products will increasingly be embedded in asset management systems. The commercial software developers will only develop what their customers want. For example, larger organisations are moving towards networked modelling systems that are linked to corporate asset databases and a corresponding GIS; see, for example, InfoWorks from Wallingford Software. Interestingly, as yet, the (commercial) demand for properly integrated modelling of collection–treatment–river impact is still muted.

Despite the public interest in the impact on the environment and the efforts being made by the wastewater managers the commercial demand is limited. Therefore most integrated modelling is being done with separate products for each phase. We have yet to see a formal commercial product that is integrated at each level: database, model building, process interpretation, etc. (though see advances made in The Netherlands: Gijsbers (1998), Schuurmans and Nelen (1998) and Waveren (1998)). Perhaps because of the present wide range of views of the different phases and how they should be modelled, the need for better scientific knowledge of the processes involved, and the weakness of commercial demand, a truly integrated model addressing the *detailed* physical, chemical and biological aspects and which is accepted internationally may not emerge for several years. When it does it will not look like the commercial models of today. It is likely that it will be fundamentally object-oriented, have a consistent *federated* database, be dependent on short and long term monitoring systems, be driven through a much more user-friendly interface, be linked with other processes in the urban water cycle, including groundwater, and form part of an overall asset management system. What is more, the whole use of the modelling system will be complemented by an evolving knowledge base that will support the user(s) in generating and applying safe and reliable instantiated models; see Ahmad and Price (1998). In other words, the design of the software will be driven by end-user requirements and how the results from the models will be used in decision making in ways that previous generations of simulation models have not. In the meantime we will be making more extensive use of much simpler, integrated models and making better use of sensitivity and uncertainty analysis to overcome the considerable deficiencies of these models. Their simplicity will enable us to do time series analysis and to gain an understanding of how the integrated system works and its operation improved (even in real time).

DECISION SUPPORT

Much of this paper has focused on modelling. But it was pointed out above that from an engineering point of view modelling is primarily a tool to assist the engineer in making decisions for planning, design, operations, maintenance, and so on. Increasingly computers are being seen not simply as number crunchers but as knowledge processors and communication devices. This brings in the notion of assistance to engineers for reasons other than data archiving and analysis, modelling and data and results visualisation.

Expert systems and rule-based systems with reasoning capabilities have been around for some time. These failed to fulfil their early promise and engineers have resorted to more generalised decision support systems. Typical of recent developments was Safe-DIS (Ahmad and Price 1998), which sought to provide engineers with a range of supporting tools for sewerage rehabilitation. The essence of this particular system was the task structure revealed by the SRM. Actually the SRM, despite its length as a printed volume, contains only some of the task structure: the rest resides in the experience of engineers who regularly work with the procedure. A little more of this experience was captured during the SAFE-DIS study to illustrate how such a system could be implemented in practice. Once in place such systems become the basis of accelerated learning at an individual and organisational level, based on analysis of accumulated experience in the use of the DSSs.

Other decision support systems in drainage tend to be focused on related activities. They are being used to optimise the performance of a network; see, for example, Yorkshire Water. Another system provides access to modelling system software over the Internet. This is a throw-back to the old days of large mainframe computers, but now individual clients working on their PCs can link to a more powerful server that provides simulation software; see Velickov *et al*. (1998). Various commercial and technical advantages result from this configuration. At the heart of such a system is a decision support system to assist clients in identifying their problem, selecting software, and instantiating models; see www.eltramos.com.

The growing identification of real-time control by many researchers and practising engineers in North America and Europe as a means of improving existing system performance without having to construct large capital works has led to considerable investment in decision support systems for control.

A further area for decision support is with emergency management of flooding in urban areas. In this instance the project focus is not strictly on UK conditions but applies to areas where there are rapidly developing storm events with insufficient time to identify them from rainfall monitoring whether from gauges or radar, and where there is a short lag time between peak rainfall and runoff. Rapid and reliable forecasts are needed for flood warning purposes when the data for decision making contains many uncertainties. In this case a decision support system appears to be an important component of the overall system, especially as it has to work with a range of different data. For further information see www.telefleur.com.

KNOWLEDGE MANAGEMENT

Hydroinformatics was defined above as an area of activity in which information is handled using advanced information and communication technologies for better understanding and management of the aquatic environment. If we regard knowledge as that which provides meaning to information then hydroinformatics is an activity concerned with knowledge management to do with the aquatic environment.

Knowledge management is now big business as many major companies are recognising that their knowledge, and particularly the knowledge residing in the minds of their employees, is their primary capital. These companies are racing towards a knowledge economy and developing a variety of ways to acquire, archive and analyse knowledge for market advantage.

The question then arises as to what this means for the civil engineering industry. Is it just a passing phase that may leave some residual value like expert systems in the 1980s? Or does it have far reaching implications that will change the way business, research and education are carried out in the future? Many pundits would give a positive answer to the latter question. For them the consequences are far reaching such that even our culture will be profoundly affected. So we should at least give it some serious attention.

A detailed study of knowledge management for civil engineering hydraulics and sewerage is beyond the scope of this paper. However some brief points can be made here. The first is that better knowledge management in the water industry gains enormously from the informatics developments identified above. However, it is also apparent that some of the key issues affecting good knowledge management, even with the benefit of advanced informatics facilities, involve the cultural working practices of practising engineers. Without effective sharing of knowledge and collaborative working there can be little innovative application and individual and corporate learning. The difficulty with Western culture is that the primary goal is to pursue the fulfilment of the individual at the expense, if necessary, of others. So ‘knowledge is power’, and the retention of knowledge is seen as a defensive ploy in securing jobs and careers. Consequently, for knowledge management to function effectively there have to be changes in working practices. Informatics tools can assist in creating a better environment for these changes to take place, but the onus is always on the people involved.

The Dutch government is funding a long-term research programme into sustainable infrastructure for densely populated delta areas, called ‘Delft Cluster’. A major part of this programme is knowledge management, in terms of promoting innovative research and effective dissemination of acquired and generated knowledge; see Delft Cluster (1999). A model of knowledge management based on the notion of ‘communities of practice’ is being developed, with common facilities made available through a corporate knowledge platform. The idea is that engineers in particular tend to work in groups focused on one or more tasks. They share common objectives and appreciate and respect the skills held in common and separately. Knowledge sharing takes place within the communities of practice, while knowledge is disseminated across the boundaries of the communities of practice such that the context of the knowledge is appreciated. This model, while being developed for civil engineers working on a wide range of topics within a research environment, appears to offer benefits to engineers working in the different phases of urban drainage. It is expected that closer attention to the specifics of knowledge management will do much to improve the internal workings of the water industry.

CONCLUSIONS AND AGENDA

This paper has tried to elucidate what hydroinformatics is in the context of urban drainage, and to identify key agenda points for urban drainage from this point of view.

Obviously, as with any water-based asset, little can be done without data defining or describing the asset. Data is important, not only as a resource from which to discover new knowledge through data, but also for simulation modelling. Whereas this modelling is largely and traditionally physically based, a range of other technologies, similar to those used in data mining, are available for *data modelling*. The scope and range of modelling has therefore increased, as has the way in which knowledge is acquired, analysed and applied.

There are also other consequences for urban drainage. Besides new ways of generating decision support systems, hydroinformatics raises awareness on the potential and use of the Internet, and how decisions may be made more effectively in collaboration with others. Underlying the whole subject is the growing use of the phrase ‘knowledge management’ as a catch-all for the fact that we are switching (already) from an information to a knowledge economy. The things we ‘know’ are becoming more important than the things we make or construct. Whether this will ever receive more than just a healthy scepticism from the practising engineer remains to be seen. The fact is though that radical changes are taking place in our society and the way we manage our assets. We can no longer manage our urban drainage networks in isolation: we have to recognise the interdependence between our physical and social environments. As a consequence the integrated system is far more complex to understand in its behaviour and consequently to manage.

It is claimed here therefore that the traditional way of pursuing urban drainage needs to change. The following are ten agenda issues that are being and should increasingly be taken up by the water industry if it is to take advantage of the new opportunities for improving effectiveness and efficiency.

1. *Holistic, integrated modelling*
   There is a need for this both on the collection–treatment–impact level and the river basin level in which there may be a number of separate conurbations.
2. *Modelling of water quality*
   This needs better science and a willingness to work more directly with data, where it is available, using data modelling techniques.
3. *Hybrid physically based and data driven modelling*
   The value of integrating physically based and data driven modelling is that the resulting modelling systems take advantage of both the encapsulated knowledge of the physically based part and added value of having good quality data from the real world system.
4. *Inclusion of uncertainty and risk assessment into model predictions*
   Considerable research is now being done into quantifying the uncertainty in model predictions. This information is urgently need by decision-makers to improve the confidence of their decisions.
5. *Data driven real time control (RTC) with network performance optimisation*
   Much still needs to be done to identify the most appropriate and efficient way of controlling complex water networks. The new data driven modelling techniques open up such a way, provided of course the performance of the network is being effectively optimised without and with RTC.
6. *Data mining and knowledge discovery of large asset databases*
   The acquisition of large asset databases opens up the possibilities of mining the data for new information and knowledge. In particular, knowledge can be gained on the rehabilitation prospects for the system and therefore long-term capital investment.
7. *Modelling of asset state*
   Whereas the physically-based models are focused on hydraulics or water quality performance of the drainage systems there is also a need to model the

state of the asset, such that better predictions can be made about when and where improvements to the asset should be made.

8. *Task-based decision support systems for best management practices*
   The existence of engineering procedures and best management practices within urban drainage offers an effective basis for decision support, enhanced by tacit knowledge of engineers made explicit through the application of such decision support systems.
9. *Decision support systems for decision making under uncertainty*
   Decision-makers are often faced with making decisions while taking into account the uncertainties involved in a wide range of factors, from model predictions to engineering and political criteria. They need better tools and support to make more reliable decisions.
10. *Integrated knowledge management within the water utilities and with other urban utilities*

Given the growing importance of knowledge sharing, collaborative working, innovation and corporate learning, knowledge management theory and practice offers much to the collection–treatment–impact process and the improvement in working practices within urban areas through different utilities working more closely together.

Obviously there are other agenda items that can be postulated, depending on the point-of-view. Here the emphasis has been on looking at urban drainage through the opportunities provided by developments in hydroinformatics. It is claimed that by following the above agenda items there will be radical improvements, not only in engineering research but also in practice.

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