MONITORING AND MODELLING – A QUESTION OF BALANCE

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Introduction

Effective management of an urban drainage network, whether for wastewater or storm water runoff, depends on a holistic appreciation of its performance. The engineer needs information on how the asset behaves for transient events, whether from historical records of flooding, the impact on receiving waters of discharges from overflows, from data generated by level or flow monitors, or from properly constructed computational models.

Historical performance data of flooding or the impact of overflows on receiving waters are of direct relevance to the engineer, in that he is primarily concerned with the impact that the drainage may have on the total environment. The reduction in the frequency of surface flooding and/or of overflow discharges can only be addressed if the engineer understands why these situations occur and how they may be reduced. This involves knowledge of the behaviour of transient flows within the network. Without this knowledge, flooding and overflow discharge data are strictly dependent data that can only indicate what might have been happening within the network. Monitoring, however, provides data on levels and flows directly from the real world network. In this sense monitors are 'first hand' data generators for the real world asset. Their data alone are adequate for decision making by some management functions though such data is invariably limited, and accurate data over a long period of time is often viewed as expensive to obtain. However if the cost is viewed on a per metre (or linear foot) basis it is still one of the lowest cost forms of data collection, well below that for CCTV.

Another attractive form of data generator is a computational model of the asset. Such a model is normally deterministic in that it sets out to reproduce the primary physical processes describing the flow in the network. The instantiation of a model for a particular network is based on the concept of links and nodes, representing the pipes or channels that make up the network and the junctions between them. There is therefore a direct, if limited, physical correspondence between the model and the real world asset. In effect, the model becomes a virtual laboratory of the asset in which the engineer can conduct various experiments to improve his understanding of the behaviour of flows in the asset and to test what happens when changes are made to the asset data or transient inputs.

It is vital that monitoring and computational modelling of the real world asset are seen as complementary rather than competing. There is, in fact, a strong interdependence between these forms of data generation. Successful, efficient and effective management of an urban drainage asset depends on making maximum use of generated data both from monitoring and modelling.

The technology for developing the asset management plans in the UK has been focused on 'verified' simulation models to assess the performance of an existing network and to identify the optimal engineering option for upgrading the system. Here, 'verified' means confirmation of the asset data as used in the model rather than 'verification' to confirm a calibration. The issue affecting calibration is explored further below. At this stage it is important to recognise that there are two major variables, the rainfall-runoff relationship and the asset data. In the UK one of the variables has been removed as existing practice first assumes the availability of a pre-calibrated rainfall-runoff model for any UK sub-catchment and therefore the asset data as used by the model becomes the focus of attention. It should be pointed out here that 'verification' is a word that is entirely inappropriate to use in describing how well a model can reproduce the behaviour of the real world system. As Oreskes et al (1994) point out, computational models as used in open channel hydraulics can never be verified; they can at best be 'confirmed'. A model is s form of highly complex scientific hypothesis which we can never verify in the strict sense of the word.

In order to confirm the model, that is, to confirm the asset data as used by the model, monitored flow data from the real world asset is required. The process of correction depends crucially on the ability of the Engineer to interpret the flow data and its variance from the modelled data, to pinpoint particular forms of discrepancy so that targeted surveying of the network and the above-ground catchment can take place, rather then arbitrarily adjusting the data. This way the physics, and therefore the determinism of the runoff and flows in the network is preserved.

The confirmation procedure raises a number of questions about the reliability of the resulting model. Invariably a short term flow survey captures records for only a small number of storm events, and it is rare that events with frequency less than once every two or three months are included. This means that the confirmation of the model is limited to the monitored event frequency. Often, however, the model will be used to assess the performance of the real world asset for events of up to 30 years return period. In short, the determinism of the model has to be suspect outside the range for which the confirmation has been done. So, what is a reasonable duration of a flow survey given the cost of installing, servicing and maintaining equipment in the harsh sewer environment? To what extent can a confirmed model be used with confidence outside the range of the flow survey events? These are questions of increasing importance as ever more critical management decisions are made on the basis of monitoring and modelling.

The relationship between monitoring and modelling becomes even more of an interdependent one as we turn from planning and design to real time control. Where pro-active RTC is shown to be beneficial then opportunities exist for using 'grey' models that combine the best of both simplified deterministic ('white') modelling and stochastic ('black box') input. This permits the use of monitored data to be used directly with the model in real time. Flow data rather than "depth-only" data is essential for input into this type of model.

The governing principle is to make maximum use of all available data whether from monitoring or modelling. The questions raised here concern how monitoring and modelling may be most effectively integrated to provide the maximum amount of information for reliable real time control.

Before we address these issues, we now focus on a separate, more detailed examination of monitoring and modelling before attempting to produce a synthesis of the two approaches to data generation for urban drainage networks.

Monitoring

Monitoring is used to study the operational functionality of a network, including diagnostics and inflow and infiltration. It is also used to assist in calibrating models and confirming predicted performance. The simplest application is for billing, however this is also the area often requiring the greatest accuracy. By its very nature, monitoring is limited to the recording of performance directly in the existing network. This is the strength of the approach: the resulting data tells us how the flows in the network have behaved in the past since installation up to the present, or does it? This premise only holds true if the data are of good quality, otherwise it can lead the Engineer into erroneous beliefs about the way the system is operating. Even a good flow monitor does not guarantee good data. Just as critical are good site selection, good installation, good hydraulic and equipment calibration, good QA/QC and good analysis.

Although monitoring has a vital role in these functions it does, however, have a number of limitations and problems. For example, most monitoring technology is restricted to measurements made at discrete points. This reinforces the fact that any data is usually collected with a particular purpose in mind. Data monitored at one point may be suitable for the specific purpose for which it was collected, but it does not necessarily mean that the same data is appropriate for a different purpose, or that the measurement point is adequate for another application. There is also the issue that the installation, servicing and maintenance of a monitor in such a harsh environment as a sewer is very difficult and can entail high costs. This implies that there is normally a limit on the number of points which can be monitored in the network. The shortness of many flow surveys and the difficulties, inherent in most flow monitoring technology, of sustaining the reliability of long term monitoring in the hostile environment means that transient effects in the network may not be identified for all different flow states and therefore accuracy may be compromised. This puts an emphasis on the quality of the monitoring system used and how it is serviced. Too often a low cost, low quality system fails at the crucial moment when data are most needed. Storm conditions often present the greatest challenge to both the monitoring system and its installation and service. An additional problem can be the need for an experienced analyst in order to interpret the data reliably. An experienced, well trained analyst can examine data collected at a single point and deduce information about the performance of the network remote from the monitoring site, thus reducing the restrictions of the single point monitoring phenomena mentioned earlier.

In addition to the uses already described are two further purposes that are assuming a growing importance. The first is for real time monitoring and control. This cannot be achieved without continuous monitoring, usually of water level, but increasingly of flow also. In this case there is a very important need for monitors to be reliable, robust and accurate over long periods of time in order to maintain the reliability of the real time control, to minimise risk of failure and to reduce maintenance costs. Such constraints make high demands on existing monitoring technology, and on-going research and development is needed to continually improve the equipment. Where real time monitoring is done, there is then the possibility of detecting stochastic events within the network, such as sewer collapses or blockages and providing valuable information to managers of the network for the purpose of planned, rather than reactive, maintenance.

The second purpose is for water quality monitoring. Much has been done on improving instrumentation to measure pollutographs at overflows and to treatment, but in-situ, direct monitoring of particular determinands in the flow cannot yet be done other than for turbidity and suspended solids. Until more appropriate monitors exist it is unlikely that water quality modelling, which depends for its confirmation on water quality data, will take on the routine nature that now exists for hydraulic modelling.

In this respect modelling has advanced far beyond monitoring capabilities. Water quality samplers have seen some improvement over the past few years, and many of the manufacturers who do not have Zone 0/Zone 1 Intrinsic Safety certification are working towards this aim. However, sample collection and consequent laboratory analysis is both very expensive and unacceptable from a time delay aspect. If flow monitoring in the sewer environment is difficult, real time sewage quality monitoring is several orders of magnitude more complex. Even where quality measurement technologies exist for certain determinands, their ability to operate in such a harsh environment for any prolonged period, without the need for excessive maintenance is a long way in the future. Fortunately, a number of private companies are making serious R&D investment in this area. It is important that the UK Water Service PLCs appreciate the need for commitment to these companies if significant progress is to be made in order to meet the needs of future quality monitoring and modelling.

Modelling

To date, the use of deterministic models based on a solution of the full, time-dependent Saint Venant equations for gradually varying flow in open channels, has been primarily for planning purposes and detailed design. Unlike monitoring, a model has no direct link with the real world asset other than through the asset data and the confirmation process that must be used to ensure a reasonable match between the prediction of the model and the performance of the real world network.

Like the monitoring process the model can be used to reproduce historic events and the present performance of the network. Its primary advantage however is that it may be used to examine what might happen for arbitrary rainfall-runoff and wastewater inflows and to deduce what effect changes to the asset data will make to the performance in the real world network. The model can be used therefore to identify flows and performance throughout the modelled network, not just at a limited number of monitoring points. It is also used to provide answers to the "what-if?" questions that the manager needs to ask in order to make responsible decisions.

In this sense the model becomes a virtual laboratory for reproducing the behaviour of the real world network, whether for events recorded in the past or for hypothetical events, and for describing the behaviour of an adjusted network. It can fill out missing monitored data, corroborate flooding reports, identify where flooding occurred that was not reported, deduce the magnitude of pollution spills, evaluate the use of storage, and so on. As a laboratory tool or piece of equipment it becomes a generator of data on which new knowledge can emerge about the model and therefore the real world network.

A computational model is therefore a very flexible and valuable asset management tool for evaluating options and optimising the performance of a network, especially with static controls but also for implementing or developing the rules to operate and control flows in the network in real time.

There are of course particular problems and limitations with modelling. These include the need for good quality input data for both the asset and the temporal inputs, the neglect of less important physical processes that may on occasion have greater importance than expected, the inherent assumptions in the conceptualisation of the physics, the network, the above-ground model and the reliability and computational speed of the software. There is also the high cost of data acquisition, and the shortage of skills to build, confirm, understand and interpret the results and apply them to the real world network. The importance of interpretation of results should always be highlighted in respect of the sizeable uncertainties in all data classes and types, and in the modelling algorithms

Synthesis

There is little doubt that monitoring and modelling have both competing and complementary advantages and benefits. In some applications monitoring gives adequate information for particular purposes without requiring modelling. In others, monitoring is too limited and modelling is required. However, any model is dependent for its success on the asset data and the monitored performance data, whereas monitoring is completely independent of asset data, which only becomes important according to the application.

There are at least three applications where the synergy between monitoring and modelling needs to be stressed. The first is in model confirmation. The success of the procedure for hydraulic analysis depends on the availability of a pre-calibrated rainfall-runoff model applicable to the whole of the UK. There is little doubt that the availability of such a model has been extremely valuable in that it speeded up the process of model building and confirmation. However, it is well known, though rarely acknowledged, that the UK calibrated runoff-model explains only about 50% of the variance on what is in effect a limited set of rainfall-runoff data from a comparatively small number of catchments. Additionally the original model is strictly limited to a small sub-catchment, typically of 1000 m^2. Although there are now variations of the basic rainfall-runoff model for larger sub-catchments there remains considerable uncertainty about the accuracy of the calibrated UK rainfall-runoff model.

It is therefore important to consider how monitored data on a catchment acquired during a flow survey may be used to both calibrate the network model, that is, to deduce the values of the parameters that cannot be measured directly, particularly for the rainfall-runoff where there is sizeable uncertainty, and to confirm the model asset data as done currently. One consequence of this requirement is that there is almost certainly a need for a greater number of monitored events and careful and appropriate location of monitors. This would require the lengthening of the duration of a traditional short term flow survey. Automatic calibration of the rainfall-runoff model is now feasible with present techniques. It is therefore possible to calibrate on some monitoring data and to confirm the asset data on others.

This still leaves the other problem of confirming the model asset data for the more rare events than may occur during a short term flow survey. It is the authors' view that short term flow surveys should be complemented by limited long term monitoring, particularly at outfalls and at strategic points within the network as identified by known flooding or significant spills, in order to confirm the model for at least the one year event.

Current UK practice appears to be such that because of the five yearly periodic review by OFFWAT, the UK Water Service PLC's do not know what income they might reasonably expect to receive during the next quinquennium. This, together with the practice of back end loading of spending with the view that it maximises profitability, leads to an undesirable compression of the planning, design and construction of a major scheme. Inevitably the project is rushed in order to meet certain compliance deadlines and the optimum solution is less likely to be found. The graph (fig. 1) illustrates the benefits of long term planning and design by VBB Viak for Halmstad in Sweden. It can be clearly seen that the continual refinement of the model and the use of long term flow data, continuously reduces the spill to receiving waters whilst at the same time reducing the capital costs for the proposed scheme.

The critical events for flooding should strictly be in terms of return periods of a number of years. In many catchments, however, the return period of flooding may only be one or two years. Whether the critical event has a return period of one or 30 years, the need to upgrade networks with poor performance will mean that accurate and reliable models will be needed for the rarer events. This will be more expensive to achieve than the current practice of short term surveys.

The experience of many UK engineers who develop models for drainage area plans to assess the frequency of flooding throughout a catchment is that the short term flow surveys provide data that may be adequate to give a qualitative assessment of performance, but are far from satisfactory where detailed design is concerned. There are, however, serious questions that have to be asked, firstly about the appropriateness of such models for the detailed design of civil engineering works, and secondly about the reliability of models for water quality prediction through combined sewer overflows. This is because of the sensitivity of predictions of pollutographs to network geometry, particularly in connection with the level of overflows and the calculation of water levels through the network. It is argued therefore that water quality modelling in particular requires a mixed short term flow survey and long term flow monitoring to improve the accuracy of predictions and to ensure ongoing compliance.

The third application of modelling and monitoring that should be considered is real time control. In a network that is controlled in real time, the modelling is strictly less important than monitoring since without monitoring there can be no reliable knowlege of what is actually happening in the network at the present time. It is true that the model could be used to predict what is happening from rainfall input and assumed wastewater inflows, say, depending on the degree of confidence that can be put into the model predictions. However, the model cannot deduce the consequences of an unforeseen blockage or sewer collapse in the network. Such a circumstance could be identified by appropriately located monitors that are working reliably. It would still require a model in order to deduce the control rules for this case.

Following the principle that all data, whether from monitors or a model, should be used to maximise the information for decision making, then it is logical to synthesise the benefits of modelling and monitoring and to integrate a model with the monitoring system, particularly to reduce inaccuracies in data or predictions. This leads to the concept of 'grey' models as explained above.

Any monitoring depends on the reasons for which it is carried out. Both the collection of data and its interpretation depend on the purpose for which the data is collected. In particular, the interpretation depends on a concept in the mind of the collector to justify the monitoring and to deduce information for the application. Similarly, computational models are also developed for a particular purpose; they may be simplified to improve speed of calculation. The risk of inappropriate use of models is reduced if the models include details of all the 'significant' pipes and structures in the network, but again the user should question the nature of the confirmation of the model asset data and the calibration, if relevant. Considerable care is needed to ensure that both data and models are used responsibly if they are applied to problems or situations other than for which they were intended.

Both monitoring and modelling in the UK are applied in the context of particular engineering procedures. These procedures have been significant in influencing the development of sewerage in the UK, especially since the reorganisation of the Water Industry in England and Wales in 1973. There is a need however to move away from sole dependence on short term planning responses to perceived problems and to invest adequately in the initial modelling and ongoing monitoring to reduce the total cost. This is because it is in the implementation of these complementary functions that the greatest savings can be achieved. Such savings need to be sought particularly in the area of water quality where the accuracy of monitoring and modelling is presently poor compared with that for quantity.

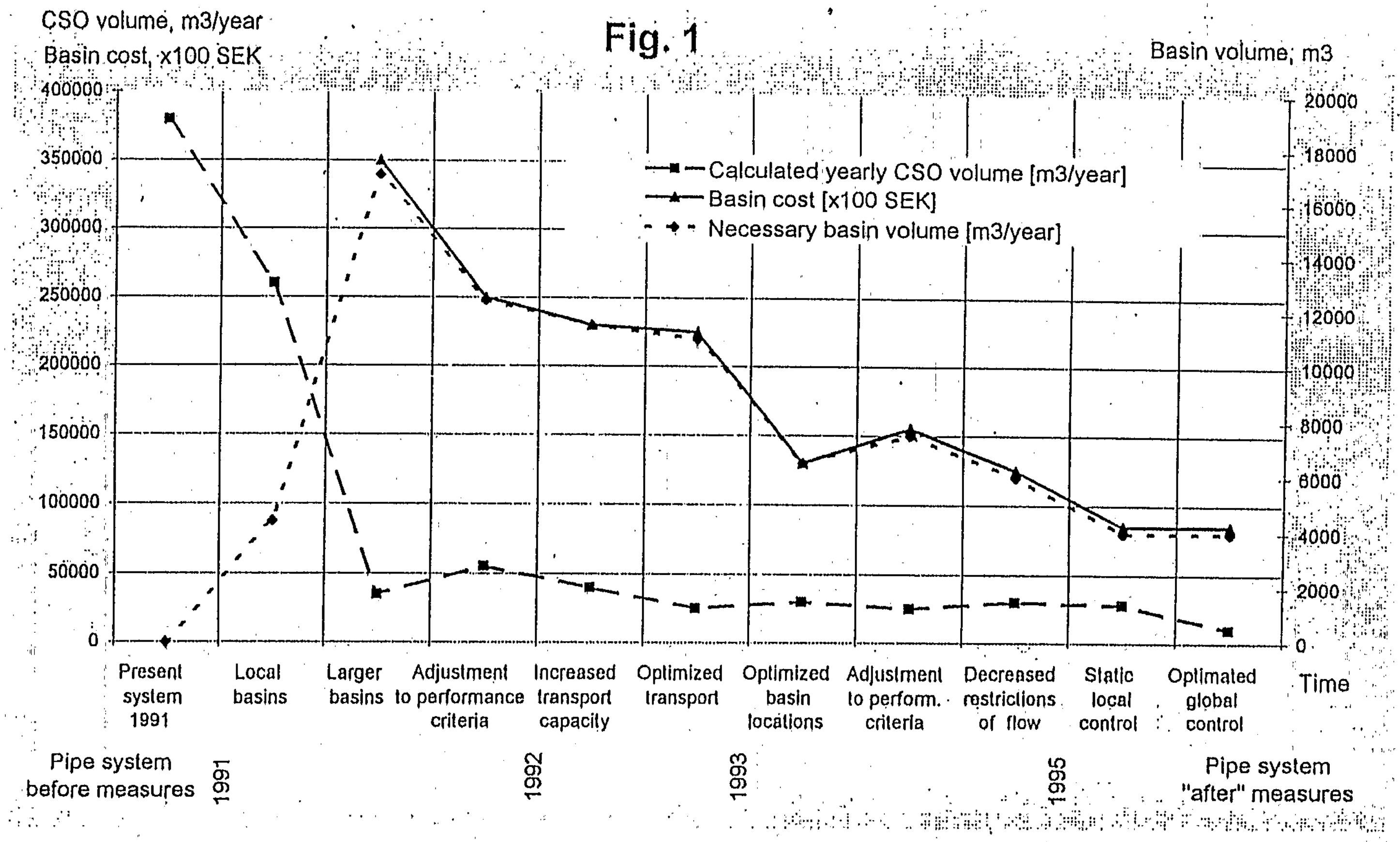
Conclusion

Monitoring has been demonstrated in the USA to be very useful on its own without modelling, though it is limited to the study of problems in which the system is returned to its original or intended state. Only modelling, however, can be used to plan for structural changes to the network and to predict the effects of those changes on present performance. Models are only as good as the data on which they are built, and good quality monitored data is essential for calibration and the confirmation of the asset data used by any model. Finally, it is concluded that present UK management practice militates against the optimisation of networks and therefore for the achievement of optimum value for money.

References

Oreskes, N. Schrader-Frechette K, and Belitz K. Verification, validation and confirmation of numerical models in the earth sciences, Science, Vol 263, 4 Feb 1994.

Fig. 1


CSO volume, m3/year
Basin cost, x100 SEK
Basin volume, m3
400000
350000
300000
250000
200000
150000
100000
50000
0
20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
Calculated yearly CSO volume [m3/year]
Basin cost [x100 SEK]
Necessary basin volume [m3/year]
Present system 1991
Local basins
Larger basins
Adjustment to performance criteria
Increased transport capacity
Optimized transport
Optimized basin locations
Adjustment to perform. criteria
Decreased restrictions of flow
Static local control
Optimated global control
Time
Pipe system before measures
1991
1992
1993
1995
Pipe system "after" measures

Monitoring and Modelling - A Question of Balance

Gareth Catterson — ADS
Roland Price — Wallingford Software Ltd

Question - Richard Ashley, University of Abertay Dundee
I agree that short term flow monitoring is invalid and that there is a need for longer term monitoring. You have talked about black box models and grey models for the hydraulic aspects, but do you think we should be using grey models for water quality modelling.

Answer - Gareth Catterson
As you know the modelling aspect is my co-authors field, rather than mine, and unfortunately he is not here to answer your question directly. However, in my opinion it is too early to talk about using grey models for water quality. We haven't even got the data collection right for the hydraulic aspects and, until such time as we achieve that basic goal, we can't realistically proceed with grey hydraulic models. Water quality is a whole order of magnitude more difficult, particularly for data collection, it would be absurd to consider grey models for water quality until we can collect water quality data on-line and in real time without the need for the enormous cost of analysis and maintenance that currently exists.

Question - John Turner, Leeds City Council
First a comment to support your stance on the need for quality data. You said that models are not being used for design however, we use models all the time for design. What is most important is not to take results at face value but to examine them very carefully to ensure that you arrive at the correct conclusion.

Answer - Gareth Catterson
Thank you for giving me the opportunity to clarify any misunderstanding that I may have caused. What I mean was that models are rarely used for design in the context of green field sites. The vast majority of modelling is carried out on established networks where existing system performance is analysed together with the design of system enhancements.

I would agree that it is essential to study results very carefully, whether they are from data collection or generated by the model to ensure that they make sense and that they are a sound base on which to make investment decisions.