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PREFAZIONE AL VOLUME

Il LARA (**LA**boratorio **R**egionale a rete per le **A**cque) è un laboratorio dedicato alle tecnologie e alle attività di ricerca relativamente al bene "acqua". Esso nasce dall'esigenza di creare una struttura tecnico-gestionale in grado di interagire con enti pubblici e privati, oltre che produrre ricerche innovative e di interesse in questo settore. Il suo scopo è dunque anche quello di offrire servizi integrati per la soluzione di problematiche relative alla matrice acqua, realizzare sinergie fra le professionalità operanti nei vari settori della ricerca applicata all'acqua ed offrire informazione collegata con l'attività di ricerca prevedendo stage in aziende pubbliche e private.

LARA fa parte della Rete dei Laboratori di Ricerca e dei Centri per l'Innovazione, promossa dalla Regione Emilia-Romagna e supportata da ASTER – Scienza Tecnologia Impresa, nell'ambito del Programma Regionale per la Ricerca Industriale, l'Innovazione e il Trasferimento Tecnologico (PRRIITT).

LARA si compone di tre Unità principali operanti in sinergia sulla base sia di progetti multidisciplinari, sia indipendentemente su attività di ricerca particolari:

- Gestione delle reti di distribuzione idrica;
- Qualità delle acque;
- Gestione degli acquiferi sotterranei.

Il **C**entro **S**tudi **S**istemi **A**cquedottistici (CSSA) è una associazione fra docenti e ricercatori universitari italiani che ha lo scopo di operare su temi attinenti i sistemi idrici per uso civile nell'ambito disciplinare dell'Idraulica, delle Costruzioni Idrauliche e dell'Ingegneria Ambientale e in particolare:

a. promuovere ed effettuare studi, ricerche, pubblicazioni ed iniziative diverse;
b. mettere a disposizione la propria struttura e organizzazione per convegni, riunioni e meetings;
c. promuovere ed eseguire attività finalizzate alla formazione tecnica e scientifica;
d. indire convegni di studio, diffondere e divulgare informazioni e strumenti tecnico-scientifici aggiornati;
e. conferire con i propri mezzi borse di studio, sussidi ed altre erogazioni nell'ambito dell'oggetto sociale.

LARA e CSSA, in piena collaborazione, hanno organizzato a Ferrara, per il 28-29 giugno 2007, un convegno avente titolo: "Approvvigionamento e distribuzione idrica: esperienze, ricerche ed innovazione".

Questo convegno, concentrandosi sulle tematiche della modellazione e gestione dei sistemi che consentono l'approvvigionamento e la distribuzione di acqua potabile, è stato concepito per creare un'occasione di contatto fra esperti del mondo accademico, del mondo professionale e delle aziende che gestiscono l'acqua, e ciò in pieno accordo con le finalità sia di LARA sia di CSSA.

A questi esperti è stata data la possibilità di discutere, presentare, diffondere i più recenti ed innovativi risultati conseguiti sia nella ricerca, sia nelle reali applicazioni pratiche.

La risposta a livello nazionale è stata significativa ed incoraggiante, tanto che sono pervenute alla segreteria organizzativa ben oltre 50 memorie, sebbene le tematiche toccate dal convegno costituiscano un settore di nicchia della ricerca scientifica sviluppata nel vasto ambito dell'idraulica e delle costruzioni idrauliche. Per contro, le sessioni in cui si è articolato il convegno sono risultate fortemente omogenee ed hanno permesso un ricco scambio di considerazioni e di valutazioni fra i presenti, rendendo così vivida la discussione sulle varie tematiche.

Ferrara, giugno 2007

Marco Franchini
Paolo Bertola

Approvvigionamento e Distribuzione Idrica: Esperienze, Ricerca ed Innovazione
Ferrara, 28-29 giugno 2007

WATER DISTRIBUTION SYSTEM ANALYSIS: PAST, PRESENT, FUTURE

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ABSTRACT

The history of urban water supply shows that provision and management of drinking water was central to urban development and planning through ages. Today, modelling tools are not only capable of solving for flows and pressures in complex distribution systems, but commonly include functions of operation control, feedback, water quality modelling, database management, GIS integration and even perform optimal design and calibration. However, water distribution system planning and operation involve many complex and interrelated aspects, such that they have been termed the "labyrinth". Among those aspects, leakage management, energy efficiency and risk-based decision making have become the main concerns of the water utilities in the UK. In response to the industry needs, a number of research areas, such as pressure-driven analysis, transient analysis, water quality modelling and risk-based decision making, have received increased attention in recent years. Some of these have already been adopted by the software industry and implemented in publicly or commercially available software. The two examples of projects and applications presented in the paper illustrate some of the trends in water distribution analysis and efforts to address the research needs identified above. The first example presents a collaborative project between water utilities, an equipment supplier and seven universities aimed at improving energy efficiency of water supply. The second example presents a pipe deterioration modelling study based on using data-mining tools. The results produced by the tool could be used for the development of strategies for water mains maintenance considering risk and costs-benefit analyses

1 INTRODUCTION

Today, water engineers brought up in the so-called 'computer age' may be excused for thinking that water distribution system analysis has only started with the development of digital computers. However, this is far from truth, as evidenced by the number of major water systems that were constructed long before digital computers were invented (*Walski*, 2006).

1.1 A brief history of urban water system development

In a recent article, *Mays et al.* (2007) provide a brief history of urban water supply in antiquity. According to them, during the Neolithic age (ca. 5700–2,800 BC), the first successful efforts to control the flow of water were driven by agricultural needs (irrigation) and were implemented in Mesopotamia and Egypt. Urban water supply systems came later into existence (in the Bronze age, ca. 2,800–1,100 BC) with supply of water from a distant source achieved via a system of channels. Examples of such systems were found in the river valleys of the Indus, the Tigress, the Euphrates and the Nile (more details can be found in *Mays et al.*, 2007). The early urban settlements of the Minoan and Mycenaean civilizations (Greece) also demonstrate that management of drinking water was central to urban development and planning.

The Romans inherited Greek water technologies and developed them further to construct large urban water supply systems. The ancient city of Rome, for example, could not have been built as big as it was without its water supply system. It is interesting to note that, according to *Hansen* (2007), the water services of the Imperial Rome (*c.* 50 BC) delivered between 750 l/c/d (litres of water per capita per day) and 1,100 l/c/d (*c.* 100 AD), whereas the per-capita supply in Paris and London in 1823 was only 11 l/d. The effectiveness of the Roman system is just one of the many examples of the ability of engineers to analyse and design large urban water systems long before the digital age.

Public water supply systems of early settlements were based on channels made from cut stone, brick, or rubble (*Jesperson*, 2001). These were later replaced by pipes made mostly from drilled stone, wood, clay and lead. For example, wooden pipes were used in the public water supply system of the city of London. The system dates back to the thirteen century when “Great Conduits” started connecting major springs around the city with 12 cisterns in the city (*Hansen*, 2007). Later on, in the 18th century, cast iron pipes replaced the wooden pipes while the 19th century witnessed significant improvements in making pipe joints that withstood high pressures. Water supply pipelines made of steel, ductile iron, asbestos cement and reinforced concrete came into increasing usage during the early 20th century (*Jespeerson*, 2001; *Ormsbee*, 2006).

1.2 A brief history of water distribution system modelling

Understanding of fluid flow has advanced over centuries thanks to numerous scientists and engineers (*Walski*, 2006). However, not until 1936 when Hardy Cross, a professor of structural engineering at University of Illinois developed a systematic tabular process for calculating system hydraulics, have engineers been able to solve for flows and pressures in interconnected (looped) water distribution systems. The solution of the pipe network analysis problem has since evolved into three general methods: (i) Hardy Cross, (ii) Newton-Raphson, and (iii) linearization. According to *Collins et al.* (1978) these traditional methods, which have been specialised for the pipe network problem, are simply techniques for solving a system of nonlinear equations. These methods are iterative in nature and each begins with an initial trial solution that may have to satisfy some pre-specified conditions (e.g., continuity). Straightforward procedures (which often involve solving a system of linear equations) are then applied to obtain a new solution in the next iteration. The technique terminates if that solution differs from the trial solution by less than a specified amount or the new solution becomes the trial solution and the procedure is repeated through another iteration. It is worth noting that for most of these methods it is important that the initial trial solution is sufficiently near the true solution, otherwise convergence is not guaranteed. The differences in the methods arise because of the way the new solution is determined.

Ormsbee (2006) offers another classification of network hydraulic solvers: (i) Hardy Cross Method(s), (ii) the Simultaneous Node Method, (iii) the Simultaneous Loop Method, (iv) the Linear Method (Simultaneous Pipe Method), and (v) the Gradient Method (Simultaneous Network Method). In his paper Ormsbee (2006) argues that Hardy Cross presented two methods, one which solved for the flows in each pipe by the iterative application of a flow adjustment factor for each loop in the network, and one which solved for the hydraulic grades at each node in the system by iterative application of a grade adjustment factor for each node in the system. Due to better convergence the loop adjustment method gained greater acceptance in the engineering community and quickly became known exclusively as the “Hardy Cross Method”. The simultaneous node method represented a simultaneous solution methodology for the original “node” method of Cross. For the simultaneous loop method the nonlinear energy equations for each loop or path in the system are written in terms of flow adjustment factors. As with the “node” methods, the equations are linearized using a standard Taylor Series expansion and then solved iteratively using the Newton Raphson method (Ormsbee, 2006). Wood & Charles (1972) introduced the linear method in which the nodal conservation of mass and the conservation of energy equations for each loop or path are solved simultaneously to directly yield flows in each pipe. Finally, the gradient method, which is implemented in EPANET (Rossman, 2000) and also in most commercially available software, was first introduced by Todini & Pilati (1978). The method takes advantage of the matrix representation of the system equations and requires a solution of liner system of sparse symmetrical equations. The method does not require loops to be defined, nor does it require the initial trial solution to be balanced, and guarantees convergence.

Commercially available software, such as WaterCAD, H2ONet, MikeNET, InfoWorks, Synergy, Aquis, etc., are normally capable of performing two basic types of analysis – steady-state and extended-period simulation (EPS). Steady-state (or “snap-shot”) analysis computes the state of the system (flows, pressures, pump operating attributes, valve position, etc) assuming that hydraulic demands and boundary conditions don not change with respect to time. EPS determines the behaviour of a system over a period of time, usually by computing the state of the system as a series of steady-state simulations in which hydraulic demands and boundary conditions change with respect to time (Walski et al., 2003). In recent years modelling software has been extended to include functions of operation control, feedback, water quality modelling, database management and even optimal design and calibration.

Water Distribution System Analysis: Why is it so Complex?

Although the size and complexity of water distribution systems may vary dramatically, they all have the same basic purpose – to deliver water from the treatment facility to the customer. The objectives of such a system are to provide safe, potable water for domestic use with adequate quantity of water at sufficient pressure for fire protection and water for industrial use. Although these systems and their objectives are conceptually simple, they are inherently complex and require a considerable effort to enable satisfactory performance in the face of significant complexity and cost.

1.3 Complexity

Colombo & Karney (2003) attempted to capture many processes involved in water distribution system planning and operation, the result being a linked diagram or

"Labyrinth", as they termed it (Figure 1). Such a representation conceptually displays the numerous processes, sub-processes, system states with their associated causative factors, feedback loops and interrelationships that are critical to a distribution system's operation and performance. The authors presented the labyrinth that is supported by the three pillars of *demand*, *capacity* and *performance*, but has numerous links which cross from one of these to issues linked to other pillars and their sub-categories. The authors ague that the fit between demand and capacity, in addition to a variety of operational considerations, defines the overall performance of the system by its resulting total cost.

Another view of the complexities involved in water distribution system analysis is presented in Figure 2. As opposed to the connected diagram of the labyrinth, Figure 2 shows some common issues water utilities are faced with in everyday planning and management of water distribution systems. If one attempts to connect boxes in this diagram, it would probably create a very messy figure. For example, uncertainty, reliability and risk represent just one of the issues that could be linked to modelling, design and/or operation decisions that have an impact on the cost effectiveness, which in turn is affected by regulation and many other boxes in Figure 2. It is obvious from these two representations (Figures 1 and 2) that planning and management of water distribution systems is extremely complex and requires much more than just good hydraulic modelling tools presented above.

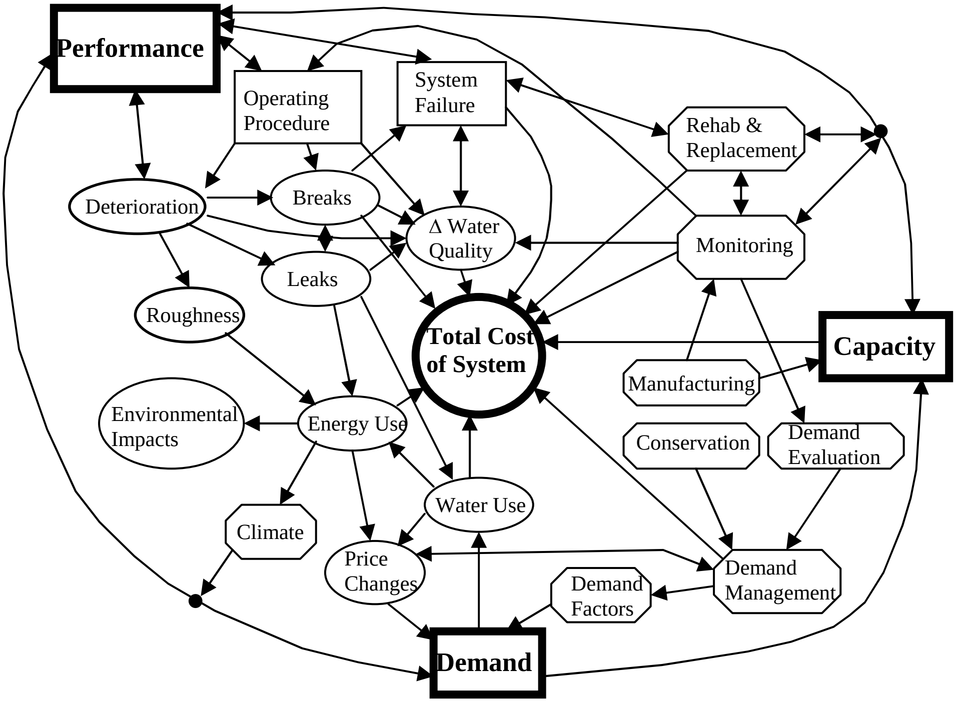

Figure 1. The water distribution system labyrinth (after *Colombo and Karney*, 2003).

1.4 Industry needs

The UK water industry serves 52 million people and manages water distribution networks that total more than 397,000km, which is greater than the average distance from the Earth to the Moon (about 384,000km). The Office of Water Services (or better known as OFWAT) is the independent economic regulator of the privatised water and sewerage industry in England and Wales that is responsible for setting limits on pricing and protecting customer interests, encouraging competition and adequate investment within the industry. Its main function is to conduct five-yearly price reviews that aim not only to keep prices for customers to a minimum, but also to permit water companies to make an adequate return on capital (permitting investment into the water infrastructure), while encouraging efficiency savings. OFWAT sets its price frameworks on a company-by-company basis, reflecting their business plans and projected revenues, and determines a maximum level above which prices may not rise. Taking all investment together, between 1989 and 2007 the water industry in England and Wales has invested over £70 billion.

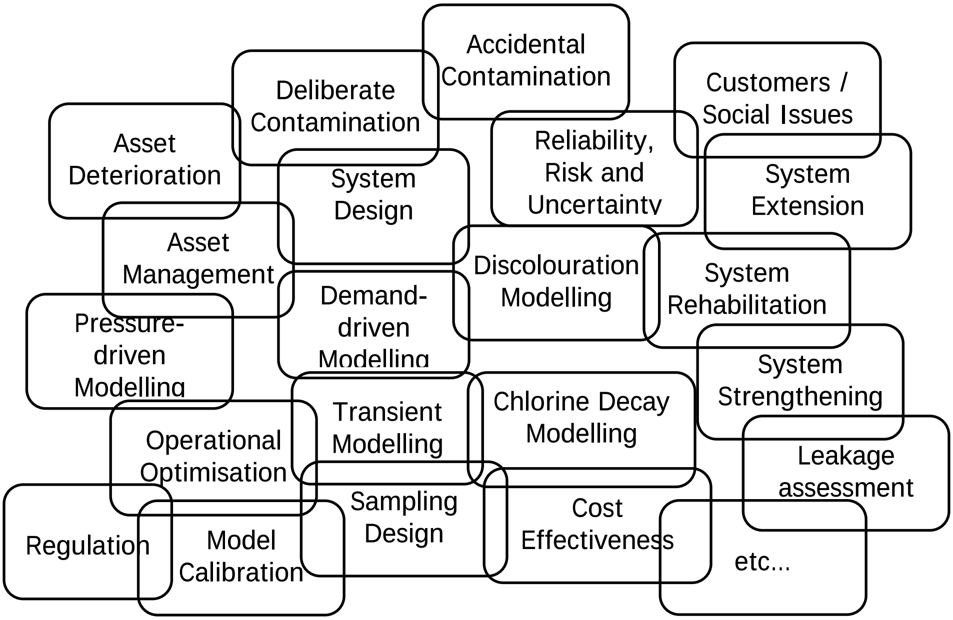

Figure 2. Issues associated with water distribution system planning and management.

The water industry in the UK is one of the most significant energy users in the UK (7,700 GWh per year, with costs of about £500 million per year). As water companies are responsible for around 4 million tonnes of carbon dioxide (CO_2) emissions per year, they are becoming increasingly worried about the impacts and the rapid rises in energy prices in the past few years. For example, the energy costs for water distribution in Yorkshire Water have risen from about £13 million in 2005/6 to about £19 million in 2006/07. It is interesting to note that 75% of the energy use was for pumping (*Woresfold*, 2007). It is not surprising then that companies are turning to new research aiming at improving energy efficiency (*NEPTUNE*, 2007).

Leakage is another problem the water industry has been addressing since the introduction of privatisation and regulation in England and Wales in 1989. As there are almost 400,000km of mains and around 24 million connections to properties and associated customer supply pipes, which all have the capacity to leak, a considerable effort is needed to keep leakage low (within so called economic levels of leakage). Historically, after privatisation, the total reported leakage for the UK water industry has reached a peak in the drought year of 1995, where it was around 5,100 10^3 m^3 per day (or 5,100 Ml/d) as reported by *OFWAT* (2006). Between 1994/95 and 2002/03 leakage was reduced by around 1,500 Ml/d, which is equal to the daily needs of around ten million domestic consumers. The total leakage, last reported by the UK water industry (2005/06), is around 3,600 Ml/d. However, the costs of achieving economic levels of leakage and dealing with the ageing asset base have put additional pressure on water companies, which have to turn to innovation to achieve further gains in reducing leakage.

Current rates of investment in replacement, renovation and maintenance of water distribution infrastructure represents only a small fraction of the value of the asset base. Concerns have been raised over the sustainability of such low levels of investment and the continuing ability of the pipe assets to deliver long-term stable serviceability to customers and the environment. Mathematical modelling of water systems is a crucial planning, design and operational activity (*Filion & Karney*, 2003). The vast majority of mathematical models in engineering use deterministic approaches to describe the behaviour of a system. However, all real life problems incorporate risk and uncertainty in one way or another. There could be uncertainty in measurement, uncertainty in parameter estimation, uncertainty in which processes one should include in the model etc. Such contradiction between “mathematical determinism” and “natural uncertainty” can seriously affect the reliability of the results of modelling. A large number of problems in design, planning and management of engineering systems require that decisions be made in the presence of risk and uncertainty (*Savic*, 2004). The water industry needs new methods and tools that take risk and uncertainty into account in order to better manage their ageing assets. In addition, the industry is having to be more innovative and is exploring alternative or new technologies and asset management techniques that can improve knowledge and understanding of water supply system operation and management and help deliver these more efficiently.

1.5 Current trends in water distribution analysis

It is not uncommon nowadays to build models of systems serving large populations and consisting of hundreds of thousands of network elements. However, despite the sophistication of today’s commercial water distribution system analysis packages, which for example include the ability to automatically build models from asset/GIS databases, allocate demands automatically (e.g., based on post codes), import digital elevation maps, automatically calibrate a model, link to SCADA data, etc., most of these packages are built on the conventional demand-driven analysis (DDA) approach. DDA assumes demand at a node to be fixed (predetermined) and independent of nodal heads (pressure), which are simultaneously calculated with pipe flows. Whilst this assumption could be justified in the analysis of networks operating under normal conditions (even this may be questionable if realistic modelling of leakage is required), it gives unrealistic results in cases where networks operate under abnormal conditions due to either mechanical or hydraulic failure.

Pressure-driven analysis (PDA) has been developed to deal mostly with modelling of network performance under abnormal conditions (*Kalungi & Tanyimboh*, 2003; *Wu et al.*, 2006). Most recently, *Giustolisi et al.* (2007) have also developed a PDA model that takes into account pressure-dependent leakage. The trend of providing PDA capabilities has been picked up by the commercial software vendors and most of them are developing or are expected to include PDA into their products in the coming years.

Flow control operations, such as operating and closing valves, starting and stopping pumps, etc., can cause a sudden change in a system which moves along a pipe as a pressure wave. These waves cause changes in flow and pressure conditions in the system that are usually referred to as *hydraulic transients* or *water hammer*. In most cases these changes are undesirable and should be avoided through the use of modelling. However, as sudden changes of pressure and flows provide much more information on the system's performance, safe transients could be introduced on purpose and used for leak location and quantification (*Kapelan et al.*, 2004 and *Lee et al.*, 2006) or for assessment of pipe condition (*Misiunas et al.*, 2007).

The need for better understanding of water quality in distribution systems and its impact on human health led to the development of better models, but there are still a number of unresolved issues with water quality modelling (*Grayman*, 2006). The author also argues that in recent years emphasis has been placed on water security modelling. For example, contamination of drinking water can result from intentional or unintentional human or natural events. Events, such as the Walkerton incident in Canada, where in May 2000, a deadly strain of E.coli bacteria in the water supply system killed seven people and infected 2,300 others, do not only cause human health suffering, but also have a substantial social and financial impact on communities (the estimated cost of the Walkerton contamination tragedy was more than $64.5 million). *Grayman* (2006) also lists the following water-quality related trends: modelling water age as a surrogate for water quality, use of models to improve water quality operations, expansion in modelling of processes and transformations, and a re-examination of some of the underlying assumptions in water quality modelling.

As water utilities move towards risk-based asset management, they need to be confident that their decisions will improve performance of their asset bases while minimising the whole-life costs and minimising exposure to different types of risk (*Savic et al.*, 2005). However, utilities have seldom overtly considered risk in making asset decisions (*Harlow*, 2005). In 2006, the UK the economic regulator, OFWAT, issued letter MD212 for managing directors in the water industry expressing expectations that companies will continue to develop their application of economic, forward looking, *risk-based analysis* in their asset management planning (*OFWAT*, 2006).

2 EXAMPLE PROJECTS AND APPLICATIONS

The following two example projects/applications illustrate modern trends in water distribution analysis and efforts to address the needs of the water industry.

2.1 Project Neptune

The *NEPTUNE* (2007) project is a strategic partnership between the UK

Engineering and Physical Sciences Research Council (EPSRC), ABB, Yorkshire Water and United Utilities. EPSRC is funding the work of seven UK universities on the project that commenced in March 2007 and is scheduled for three years. It has a total research budget of £2.7 million, while industrial partners are contributing an equivalent sum for equipment and their staff time. The project objectives are as follows:

- To develop pragmatic, robust and novel methods and technologies to understand system performance in real time.
- To develop a novel approach and practical tools for pressure management in order to improve customer service, efficiency and sustainability of water distribution systems and to test innovative technology in which pressure management will be linked with energy consumption and leakage reduction.
- To develop an integrated, risk-based decision support system for evaluation of intervention strategies (both tactical and strategic) to inform decision making for sustainable water system operation.
- To increase operator awareness, understanding and knowledge of system performance to enhance efficiency and effectiveness of operation and service delivery.
- To develop knowledge, capabilities and tools to integrate system operation and enable intervention in system operation in real time to maintain and enhance performance.
- The implementation and validation of prototype outputs from the above in conjunction with on-going business processes utilising and developing innovative ideas.

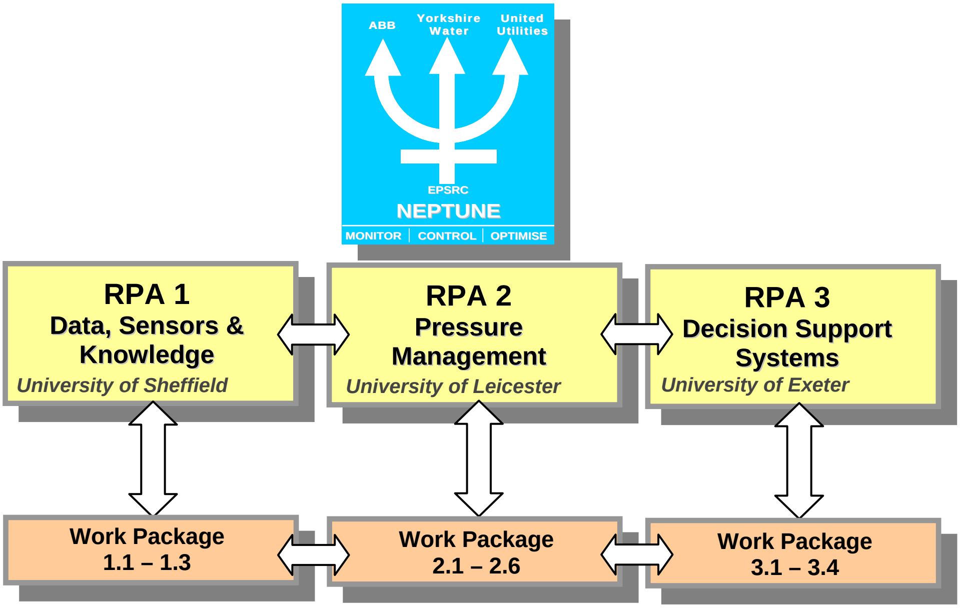

Figure 3. Project NEPTUNE structure.

The fundamental mission of water service providers is to ensure security of supply, with no interruptions and water quality of the highest standard at the tap. Unfortunately, the technology required to fully understand, manage and automate water supply system operation either does not yet exist, is only partially evolved, or has not yet been reliably proven for live water distribution systems. It is this that NEPTUNE (Figure 3) seeks to address by carrying out research into 3 research priority areas (RPA); these are: Data and knowledge management; Pressure management; and the associated Complex decision support systems on which to base operation.

The water supply industry is often accused of being 'data rich but information poor'. This statement relates to the lack of interpretation of data that is available from instrumentation in the highly complex network of pipes, tanks, reservoirs, pumps, valves and other devices used to supply water from treatment works to every household and industry. This lack of derivation of information from data has a number of historical reasons, but in the UK water industry many of these barriers have now been removed. For example, leakage initiatives have driven the introduction of flow meters at the boundary of every district metering area (DMA), and loss of supply and low pressure regulation (UK OFWAT DG2&3 failures) has prompted the widespread introduction of pressure meters, typically one per DMA. Until recently, the collection of data from such instrumentation was reliant on manual intervention - local logged data manually transferred to central data processing units, but neither analysed regularly nor fully utilised. However, advances in communication technologies and reductions in cost are now facilitating large volume automated regular data collection. Routine and meaningful interpretation of such data is beyond the scope of manual analysis, and hence, typically, the data is used only to create alarms that require reactive management or the data is used as a diagnostic in response to a customer complaint. The new opportunities in data collection and communications technology now offer potential to move from reactive to proactive management strategies in (near) real time and NEPTUNE is addressing these.

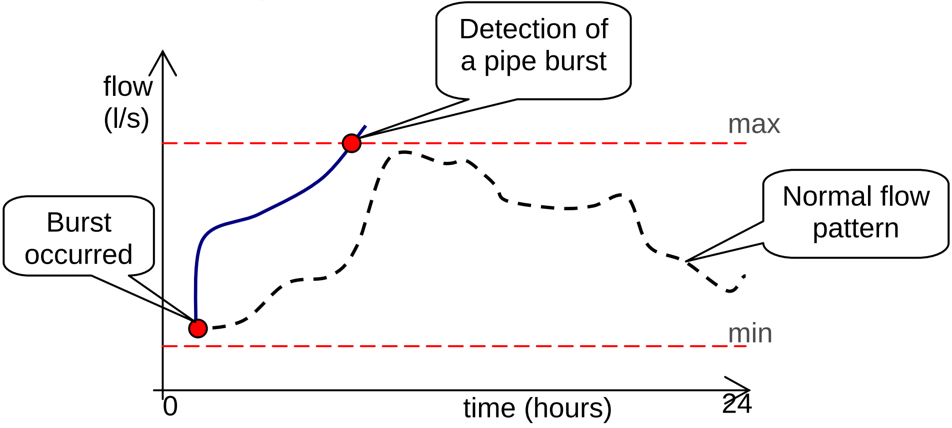

Figure 4. Project NEPTUNE structure.

Pressure management has a crucial role to play in background leakage reduction, burst reduction and quality of supply; stabilising pressure for customers; reducing the demand for energy and reducing overall water supply costs. Optimisation of energy consumption, pressure management and leakage control has often been practiced in a piece-meal fashion, without mutual interactions (synergy) or the integration which will be introduced and tested in NEPTUNE. A significant energy saving can be accomplished by matching pumping schedules with time varying electricity tariffs and using the available storage in the system. However, little is done to co-ordinate energy management and pressure management operations. Often the pump stations are oversized and provide excess pressure (energy) which is subsequently throttled by valve operations. There is the obvious opportunity for further saving and extension of the life of underground infrastructure by refining control of pumps.

Decision making requires appropriate decision support tools to help make sense of system complexities and suggest actions/plans leading to better strategic and operational decisions under conditions of risk and uncertainty. However, data collection and communications systems, which are being installed by the water industry to provide information on the state of their water networks, are mostly used to monitor the system and raise alarms and less for extracting useful knowledge for more efficient operation, reduced energy consumption and reduced costs. By building and improving on the work already being done by the partners, NEPTUNE is developing a Decision Support System (DSS) that will provide that crucial link between data, knowledge and decisions.

Figure 4 illustrates an operational problem that occurs due to the lack of ‘intelligence’ provided by current control systems available to water utilities. The diagram illustrates a situation at a boundary meter into a DMA where a pipe burst has occurred, but has not been detected until several hours later. This situation happens due to system being set up to raise an alarm only when the minimum or the maximum flow trigger level into the DMA is reached.

2.2 Pipe deterioration modelling

The prediction of deterioration in water distribution pipes can be used for the development of strategies for water mains replacement considering risk and cost-benefit assessment (*Giustolisi et al.*, 2006). Single-objective Evolutionary Polynomial Regression (EPR) is a hybrid regression method recently developed by *Giustolisi & Savic* (2004; 2006) that can be used for pipe deterioration modelling. EPR integrates the best features of numerical regression with genetic programming (*Koza*, 1992), thus taking advantage of the most powerful and commonly applied form of regression (least squares) and avoiding to have to specify the functional form (linear, exponential, logarithmic, etc) before modelling commences (genetic programming). It is important to recognise that the performance models identified by EPR do not seek to represent the fundamental physical processes of deterioration in a deterministic way. Instead EPR seeks to identify patterns of behaviour and relate them to system attributes in such a way that they can be used to model and predict the performance of similar systems now and in the future. They are *data driven models*. For the particular application to deterioration modelling EPR has the following key advantages over other data-driven methods, such as neural networks, and more traditional regression tools:

1. The use of Expert Judgement is minimised. The user is not required to assume the form of the relationship prior to analysis – if relationships exist in the data then EPR will find them.
2. The results are presented as a series of explicit equations of varying complexity and accuracy that can be reviewed with engineering knowledge and insight prior to selection of the preferred equation.

3. The resulting equations are parsimonious – in one of the pilot projects for example a coefficient of determination of 90% was achieved from an equation with only two terms and three variables (*UKWIR*, 2006).
4. EPR is able to make use of whatever asset data is available.
5. The analysis is rapid and so it is feasible to perform sensitivity tests to increase confidence in the output, and to repeat it in the future as further and better data becomes available.
6. EPR outputs its results directly into Excel workbooks, ready for use.

The development and use of the multi-objective genetic algorithm approach has, according to *Savic & Giustolisi* (2007), further improved performance of EPR when used for pipe deterioration modelling. The authors selected the following objectives of the multi-objective EPR search: (1) maximization of model accuracy, (2) minimization of the number of polynomial coefficients and (3) minimization of the number of inputs.

The data in this case study were available at the pipe level for the period 1986-1999 and contain both pipe asset information and recorded bursts. The database used here refers to 48 water distribution systems within a UK water company. For each individual pipe, the database contains information on pipe diameter, material, year laid, length, number of properties supplied and the total number of bursts recorded during the 14-year monitoring period. Unfortunately, neither of the criteria adopted for designing these water quality zone nor the network map were available for this study. Furthermore, only the total number of bursts is known (i.e., the timing of each burst is unknown). Lack of the above information prevents verification of the potential existence of spatial and temporal clusters in the burst data. However, statistical distribution of the asset features (i.e., diameter, vintage, total length of pipe-line and total number of properties supplied) allows considering all the 48 systems as stand-alone small water distribution systems. As in the majority of water distribution systems, the number of failures recorded during the monitoring period corresponds to about 10% of the total number of pipes and several pipes failed more than once over the same time period. A “performance indicator”, as it is meant herein, should represent the propensity to fail for all pipes in the network. Therefore, both pipes with and without recorded bursts have been considered. Furthermore, the distribution of bursts mentioned above implies a grouping criterion to be adopted in order to have a finite failure rate for all pipes in the network. Previously developed pipe failure models associated the same pipe failure rate to pipes with similar attributes (e.g., material, size, age, etc.). Following that, and based on the preliminary analyses, the pipes considered here have been classified using pipe diameter and age.

Only four fields describing pipe features have been considered for modelling. These are age (Ap), diameter (Dp), length (Lp) and number of properties (Pp) supplied, all available at the pipe level. For each diameter-age class, the total number of recorded burst events (Brt), the sum of pipe lengths (Lt), the sum of properties supplied (P) and the total number of pipes in the class (N) have been computed. Furthermore, to define a significant value of age and diameter for each class, the length weighted mean of relevant variables was computed. The values computed are the equivalent age (Ae) and the equivalent diameter (De).

Table 1 reports optimal model structures obtained by EPR for describing pipe burst occurrence in a water distribution network. For each network the Coefficient of Determination (CoD) values and coefficients (a_1) are reported. In particular, model structures I, containing total class length *Lt*, leads to 18 cases described with CoD less than 0.60 and 3 cases with negative CoD values. Note that negative CoD means that the average of observation (here the total number of bursts in the classes) would provide a better description than model structure I.

The selection of the overall class length *Lt* has a statistical meaning since it encompasses all other time-related factors that are either unrecorded or unavailable for the same class. For example, the longer the pipe class, the more variable the traffic loads, operational stresses (i.e., pressure/discharge variations) and bedding conditions. Although it is impossible to formulate a mathematical expression of such a relation-ship without additional information, it is known from the literature that pipe length directly affects the probability of breaks.

Addition of the age term *Ae*, leads to an average increase of CoD of about 0.116 and a significant improvement of performance in almost all cases. Direct dependence on age confirms this variable to be the most significant factor in describing the deterioration process and subsequent burst occurrence in a water distribution network. In this case study the variable *Ae* includes also information on pipe material since it has been used for infilling missing data on age.

Model structure III is the most complex returned by EPR and contains just one more explanatory variable (i.e., equivalent diameter *De*). From models II to III there is an average in-crease of CoD of about 0.42 and the system description has improved for 41 cases. Also in this case the inverse dependence between pipe diameter and number of bursts occurred in the network confirms the observation that smaller pipes are more prone to fail than larger ones.

3 CONCLUSIONS

Brief analysis of the history of urban water supply shows that provision and management of drinking water was central to urban development and planning through ages. The growth of modern cities and their water distribution systems was followed by the development of means to solve for flows and pressures in them, culminating with sophisticated software that is readily available nowadays. These tools are not only capable of performing steady-state and extended-period analysis, but commonly include functions of operation control, feedback, water quality modelling, database management, GIS integration and even perform optimal design and calibration.

However, water distribution system planning and operation involve many complex and interrelated aspects, such that they have been termed the “labyrinth” by *Colombo & Karney* (2003). The complex structure of the labyrinth is developed around three main issues: demand, capacity and performance. It is the many facets of performance that are of particular interest to the water industry. For example, leakage levels have been one of the main performance indicators the UK water utilities report to the economic regulator OFWAT, which is responsible for setting limits on pricing and ensuring adequate investment within the industry. Better understanding, modelling and management of leakage are needed to improve performance of water distribution systems.