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Canadian government launches major investment in First Nation watsan

Canada's Minister of Aboriginal Affairs and Northern Development, John Duncan, has announced major new investments in First Nation water and wastewater systems on reserves.

He said at the launch: 'Our government is committed to addressing water and wastewater issues on reserves to ensure that First Nations communities have access to safe drinking water. That is why we are taking concrete action to support First Nations in operating their water and wastewater systems on reserves.'

The government will invest CAD$330.8 million (US$336.2 million) over two years to sustain progress made to build and renovate water and wastewater infrastructure on reserves and to support the development of a long-term strategy to improve water quality in First Nation communities.

A federal government department, the Aboriginal Affairs and Northern Development Canada (AANDC), will prioritise capital investments to target high and medium risk systems in over 50 First Nation communities, including Canoe lake, Saskatchewan, Tallcree First Nation, Alberta and the Nazko First Nation in British Columbia.

The first year of funding will be allocated by AANDC in three areas of planned expenditures: $47.7 million for operations and maintenance, $32.1 million for training for First Nations and $47.3 million for capital investments.

Health Canada will support First Nations with an investment of $27.4 million each year to build capacity, enhance drinking water quality monitoring, maintain a national wastewater programme, increase public awareness and review project proposals from a public health perspective.

The announcement follows moves by native groups to block roads and stage hunger strikes in protest at conditions on reserves. However, ahead of the announcement, metro Vancouver warned that the law could leave municipalities in British Columbia facing large bills.

Maple Ridge Mayor Ernie Daykin, who chairs the city's aboriginal relations committee, is reported as saying: 'Nobody wants to deny First Nations reserves access to clean, safe drinking water. We just want to make it as clear as we can: are there financial implications? Is there going to be an ability for the local government to recover their investment? And then, if there is a problem with the system on the reserve, who's responsible?'

A 2009 assessment of the state's First Nation water and wastewater systems identified 53% as being at high risk and requiring immediate attention. The report estimated the cost of required upgrades across the country at CAN$4.7 billion (US$4.77 billion). ●

UK regulator publishes review consultation proposals

Economic regulator Ofwat has published its proposals for setting price limits for the next periodic review, which encompass sweeping regulatory changes but maintain the RPI link for 'wholesale' investment such as building and maintaining treatment works and pipes.

Ofwat proposes to use a simpler total revenue control for the sewerage wholesale control element, on which it is seeking views. Ofwat will also expect companies to focus on long-term outcomes – it gives the example of companies working with farmers to reduce pollution entering rivers rather than building expensive treatment plants. The proposals also showcase an increased focus on customers, including giving them more say in how their money is spent, and making companies more accountable for delivering what customers want over the long-term.

Ofwat suggests creating independent Customer Challenge groups to ensure companies are engaging properly with their customers and reflecting their views in business plans.

It also proposes looking more closely at 'retail' elements such as billing and call centres to drive better customer service and lower costs, and bringing the sector in line with others by dropping the link to RPI. Instead, Ofwat proposes to set two binding retail controls in 2014, one for domestic and one for business customers.

On the sustainability front Ofwat proposes to ensure companies manage and value water better, for instance by encouraging efficient water trading.

It also aims to encourage more sustainable choices about where water is taken from, via the abstraction incentive mechanism (AIM), which will reward companies for abstracting less from sites where the risk of environmental damage is greatest.

Following this consultation, the regulator will publish a final methodology for the next price review this summer. ●

water asset management INTERNATIONAL

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EBRD signs deal for Russian municipal infrastructure renewal

The EBRD has signed up to a risk-sharing partnership with ZAO Raiffeisenbank (RBRU) under which Russian cities and their municipal utility companies will be offered long-term local currency loans ranging from R20 million to R300 million ($660,000 to $9.9 million) to fund badly needed municipal infrastructure renewal.

Loans would mostly be offered to small and medium size municipalities of less than 400,000 people and could be attracted either directly by municipalities or by local utility companies – for instance, vodokanals (water utilities), district heating companies and transport operators, whether private or municipally owned.

The loans will have a maximum maturity of ten years, making this programme unique in a market where municipalities traditionally rely on short-term budget loans by Russia's state-owned banks because no commercial alternatives are available.

The EBRD's commitment under this 50/50 risk-sharing facility with RBRU could reach R1.95 billion ($64 million).

RBRU will choose and prepare projects and submit them for the EBRD's final approval under simplified procedures agreed between the two institutions, and will leverage RBRU's wide regional network, which includes more than 180 offices in 75 regions, to search for eligible projects. ●

EIB provides funding for water and wastewater improvements in Ireland

The EIB is to provide €200 million ($268.4 million) to support improvements in Ireland's water services investment programme (WSIP) by financing 23 projects in Dublin and ten counties around the country to provide new water mains, water and wastewater treatment facilities and reservoirs, as well as measures to improve water conservation.

Minister for the environment, community and local government Phil Hogan TD said: 'I am delighted that the EIB has decided to support my department's water services investment programme with a loan of €200 million which will assist in funding 23 water projects. It is an indication of the bank's confidence in the Irish state and our recovery programme and is a good signal for securing third party financing in the future.

'A programme of water sector reform is currently underway in Ireland, which will see the responsibility for water services delivery moving from local authorities to a new public utility. This will fundamentally change the approach to funding capital investment in the sector in the years ahead including access to third party financing to address the considerable investment requirements of the sector. These reforms will benefit individual householders, but will also attract industries with high water usage like agri-food, pharma-chem and IT.

'With global demand for water due to rise by 40% in just 20 years, Ireland will be well positioned to attract foreign and indigenous investment, creating real potential for new jobs within the country.'

EIB vice president Jonathan Taylor said: 'Investment in the Irish water infrastructure will significantly enhance water conservation measures, improve drinking water quality and reduce risks of pollution. The European Investment Bank recognises the considerable challenges and investment needed in the sector and is pleased to provide the first EIB support for investment in water infrastructure in Ireland for over a decade.'

In all, 23 projects will benefit from the investment. The initiative also includes replacing over 300km of old water mains in Dublin, South Tipperary, Galway and Limerick. The project will also increase the drinking water supply by constructing two new reservoirs in Kerry and North Tipperary.

Wastewater treatment will be improved through six new treatment plants in Kildare, North Tipperary, Kerry, Galway and Roscommon. Three local schemes will ensure a safe drinking water supply, and 28km of new water mains will be laid in Kildare and 13km in Longford.

Four of the projects relate to water conservation, with the aim of reducing water loss in the distribution networks, and seven of the projects will improve water supply infrastructure. A particular focus of investment is addressing risks to public health by improving the quality and supply of drinking water.

The remaining 12 projects relate to improving wastewater infrastructure, and support compliance with statutory requirements and priorities identified in WFD River Basin Management Plans. ●

Veolia wins Rialto water and wastewater contract

The city of Rialto and Rialto Water Services (RWS) have awarded Veolia Water North America, a Veolia Water subsidiary, a contract to manage the city's water and wastewater systems.

The city lies inland from Los Angeles in California, near San Bernardino.

The 30-year contract is valued at around $300 million in revenues for Veolia Water. The city of Rialto and RWS are adopting a public-private concession model, which is rarely used in the US, to strengthen the city's financial position and improve infrastructure services.

The financing mode is also unusual - Rialto has received $35 million in an up-front cash payment and secured $41 million in funding for future water and wastewater system improvements through a concession contract signed with RWS, a special purpose company established by Table Rock Capital and an affiliate of investment and insurance company Ullico.

The cash injection will enable Rialto to upgrade its water and wastewater systems and services, create jobs and benefit from Veolia Water's expertise. RWS is responsible for managing the 30-year contract with Veolia Water, and will oversee the infrastructure upgrade programme. ●

The impact of a pipe burst on the surrounding area – integrating GIS and hydraulic modelling in a risk based approach

KWR Watercycle Research Institute has established a method to quantify the effects of a pipe burst on its surrounding area, involving a combination of hydraulic modelling and risk analysis of the distribution area using GIS. Kim van Daal, Ralph Beuken, Ad Vogelaar and Roel Diemel discuss the development of this method and how the combination of GIS with other analytical tools can provide valuable information for the management regime of water supply networks.

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Figure 1
A wash-out pit as a result of a pipe burst can cause severe disruption

The aim of drinking water companies in the Netherlands is to supply the highest quality drinking water at the lowest cost. Pipe bursts can lead to unwanted consequences such as a negative impact on the surrounding area and the associated remediation costs, and the potential damage to the public image of the water company (see Figure 1). Therefore, water companies want to understand the risks related to the supply of drinking water as well as the surroundings of the pipe. The risk aspect to the surroundings of the pipe in the Netherlands is referred to as external pipe leakage effects. An important prerequisite for risk analysis is integral and quantitative modelling of the impact of a pipe burst in the vicinity of a pipe. A risk is the combination of the potential consequences of an unwanted event and the probability of that event occurring. Managing risks in water supply networks requires an understanding of the probability of failure and the effects on the surrounding area.

Since the location of a main plays an important role in risk inventory it is a logical step to use a geographic information system (GIS) and geographic-specific data to map the surroundings of a pipe. Water companies use GIS to map the location of their assets. Increasingly they also use the analytical capabilities of GIS to improve the management of their water supply network. It is possible to calculate and visualize which objects lie within an impact zone of a pipe burst by combining calculation prescriptions for calculating effect zones with the analytical capabilities of geographic information systems. In combination with the probability of an asset failure this gives water companies a better understanding of the potential risks and an option to identify more critical mains. The critical mains could be subject to a more stringent management regime, resulting in earlier replacement or more intense maintenance. The analysis presented in this paper is an important building block for designing an asset management regime for a water distribution network.

The objective of this research was to assess the presented method and to provide an example of implementation for water companies. A pilot study was done in 's-Hertogenbosch, a city with 140,000 residents in the south of the Netherlands. The distribution network in 's-Hertogenbosch is operated by the drinking water company Brabant Water. The network in the pilot area consists of 3279 line segments with a combined length of 70km, comprising of PVC (42%), cast iron (29%), asbestos cement (25%), polyethylene (2%), and other materials (2%). With respect to the diameters of the mains: 70% are smaller than 150mm, 20% are between 150mm and 300mm and 10% are bigger than 300mm. In addition to information on the distribution network, Brabant Water also provided data on main bursts in the municipality of 's-Hertogenbosch during the period 2006 to 2009.

The major steps in the presented research were:

- Use spatial data of critical objects (polygon information) to identify significant risk mains in an urban environment
- Apply the new calculation prescriptions for determining the effect zone of a pipe failure using a detailed hydraulic network model in combination with local hydraulic data (pressures H and flows Q)
- Translate the results from the hydraulic network model to a

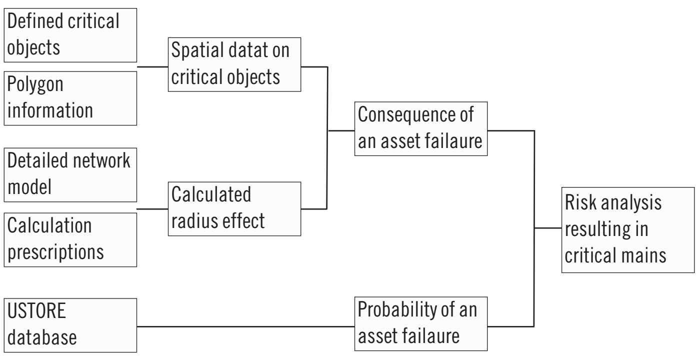

Figure 2
Schematic presentation of the main components of the analysis method

Figure 3 Difference in accuracy between a point object (x) and a polygon object

geographical information model to utilise the spatial analysis capabilities of GIS
- Find critical mains based on the presence of nearby critical objects and the possibility of failure

Method development

The analysis in this study involves a combination of hydraulic analysis and risk analysis of mains using GIS. Outcomes of the hydraulic analysis are used as input parameters for the spatial analysis in GIS. In combination with the probability of an asset failure, the outcomes of the spatial analysis lead to a risk inventory. The required steps of the method are shown schematically in Figure 2.

Water companies decide which critical objects to observe depending on specific conditions in their supply area. Many water companies in the Netherlands have already taken the first step in risk assessment with regard to external effects by analyzing the risk of a pipe burst in the vicinity of infrastructural objects like primary dykes, roads and railway lines. Therefore it was decided in this study to focus not on these infrastructural objects but on other objects which could be greatly affected by a mains burst in their vicinity. These objects have been identified in a national survey on critical mains (Beuken et al., 2006), i.e.:
- Public buildings such as hospitals, local government offices, and police and fire stations
- Historical monuments
- Shops and below ground parking
- Other distribution networks such as power grids

For all of these critical objects spatial data was collected. Preference was given to polygon data instead of point data or line data. Polygon data gives precise information on the dimensions of the object, making a more accurate analysis possible, see Figure 3. In case of polygon data it is unnecessary to make assumptions on the dimensions of an object.

In the Dutch standard NEN 3650 (no known equivalent ISO standard) a calculation prescription is given to determine the dimensions of the effect zone (Figure 4) of an asset failure.

There are three different ways to calculate the possible radius of the effect zone (RB). The simplest way uses only pressure data as input (equation 1 in Figure 5). To obtain more realistic estimates, there is an expression that requires data on pressure and flow at the treatment works (equation 2 in Figure 5). It is however recommended (Mastbergen, 2010) to use representative local hydraulic data at time of a failure from hydraulic network calculations (equation 3 in Figure 5). This expression leads to the most realistic estimate of the effect zone. However this information requires the use of a detailed hydraulic network model.

With the standard hydraulic network solvers it is possible to determine the local situation in detail using equation 3. To calculate the effect zone for every individual main the following steps are taken:
- Load a detailed network model in a hydraulic solver.
- Define the representative (highest) pressure regime in the pilot area, depending on the network configuration and the distance to the pumping station. This could be a minimum day during night-time conditions or a situation with extreme high consumption.
- Calculate pressure and flow while simulating bursts using a hydraulic solver. A leak can be simulated by placing a virtual hydrant with free outflow on every node. Multiple calculations are performed with increasing pressures at the site of the leak, for example 200, 250, 300 and 350 kPa.
- Export the calculation result into a spreadsheet programme and calculate the size of the effect zone (following equation 3).
- Process spreadsheet data to make it suitable as import for GIS
- Import the calculation results into GIS for the spatial analysis and link the results to pipe segments. Each line segment in the test area is linked to the nearest node based on its location and the data from this node is added in additional columns.
- Make proximity analysis. The maximum size of the effect zone serves as input for the proximity analysis. In GIS examine if critical objects lie within the effect zone around a pipe segment. The outcome indicates where potential large effects can be expected in case of an asset failure.

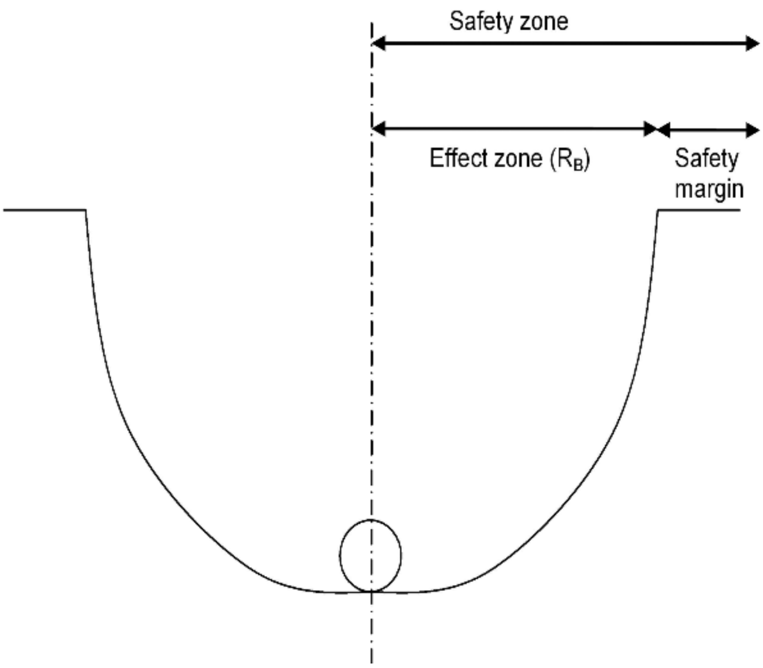

Figure 4 Schematic presentation of a wash-out pit

For six locations within the pilot area in 's-Hertogenbosch the radius of the effect zone was calculated using the three different expressions for a pipe with a diameter of 100, 300 and 600mm, located at distances near and far away from the pumping station. The outcomes are shown in Table 1. This shows that the calculations using

1	$R_B = 8{,}0\sqrt[8]{H^3 D_i^5}$
2	$R_B = 7{,}8\sqrt[4]{Q_0 H_0 \sqrt{\frac{D_i}{g}}}$ + pressure and flow at the pumping station
3	$\frac{R_B}{d_g} = 7{,}8\left(\frac{QH}{g^{1/2}\mu d_g^{7/2}}\right)^{0{,}243}$ + hydraulic network models

Figure 5
Different equations to calculate the radius of the effect zone of a pipe burst

representative local hydraulic data (moment of maximum pressure) in combination with hydraulic network calculations software leads to more realistic results and also a smaller effect zone. This means that fewer assets will emerge as critical in further analysis. For further analysis the third expression (Figure 5) is used.

kPa (H). Further calculations are based on a residual pressure altitude of 250 kPa. InfoWorks provides the actual flow (Q) for each simulated leak. Using the Q and H data the radius of the effect zone was calculated. This can be done in GIS or in a spreadsheet. The hydraulic data (flow and residual pressure) together with the x and y coordinates of the nodes were written into a spreadsheet suitable for importing into GIS.

Spatial analysis and risk analysis
The calculation results are imported into GIS. Every pipe segment in the pilot area obtains the hydraulic data from the nearest node. The link is based on spatial location. Determining the nearest node for each line segment does not always result in the correct match. In some cases the nearest node is not representative of the pipe segment. This has implications for calculating the radius of the effect zone or requires manual checking of

zone is the input for the analysis of critical objects. The maximum radius, together with any additional safety margin, forms the safety zone around an asset. There was no extra safety margin taken into account in the pilot. However a water company could always decide to do so. In this case study, the safety zone around a pipe equals the size of the effect zone. Using the 'buffer' tool GIS buffer polygons are created around the pipe segments. By using the 'buffer' tool a new layer with polygons instead of lines is created.

The data from critical objects was provided by the local authority of 's-Hertogenbosch. The information partly consists of detailed polygon information but also includes point information. If potential point information was used then it was translated into polygon information by combining different sources of spatial data. For example, information about historical monuments was only available as point

Table 1: Calculated radius of the effect zone for six cases in the pilot area (pipe with a diameter of 100, 300 and 600mm, located near and far from the treatment works

Hydraulic data	100mm pipe Far from treatment works	Near treatment works	300mm pipe Far from treatment works	Near treatment works	600mm pipe Far from treatment works	Near treatment works
Only pressure	7.9m	7.9m	15.7m	15.7m	24.2m	24.2m
Pressure and flow at the treatment works	10.9m	10.9m	12.5m	12.5m	13.6m	13.6m
Local hydraulic data	2.7m	7.0m	6.4m	9.7m	11m	13.1m

Results of the analysis
Calculating the potential radius of the effect zone
In this pilot the hydraulic network calculation software InfoWorks was used for the hydraulic calculations. The first step in the analysis is to determine the representative local hydraulic situation (moment of maximum pressure) in the pilot area. This moment depends on the location of the pilot area in relation to treatment works. Therefore a number of different situations have been calculated. The pilot area in 's-Hertogenbosch is fed by two treatment works see Figure 6. In this case a situation with a relatively low consumption (consumption in normal day night, reference 01.00 at night) is decisive. In another case, e.g. a pilot area near a treatment works, a situation with high consumption could be representative.

Then with InfoWorks imaginary leaks are simulated. For the analysis in the pilot area 1459 virtual hydrants with minimal resistance are added. For these nodes virtual QH-curves are applied. The test calculations for the pilot area show that the maximum radius of the effect zone is reached at a residual pressure of approximately 250

the results. This could be prevented if the mains in the hydraulic network calculation software exactly match the mains in GIS or have a similar attribute which can be used for joining, e.g. an ID.

The maximum radius of the effect

data. Every point represents a monument. A point is always within the contours of a polygon object that represents a building. It is therefore easy to translate a point to a polygon object by using a spatial join operation in GIS (see Figure 7).

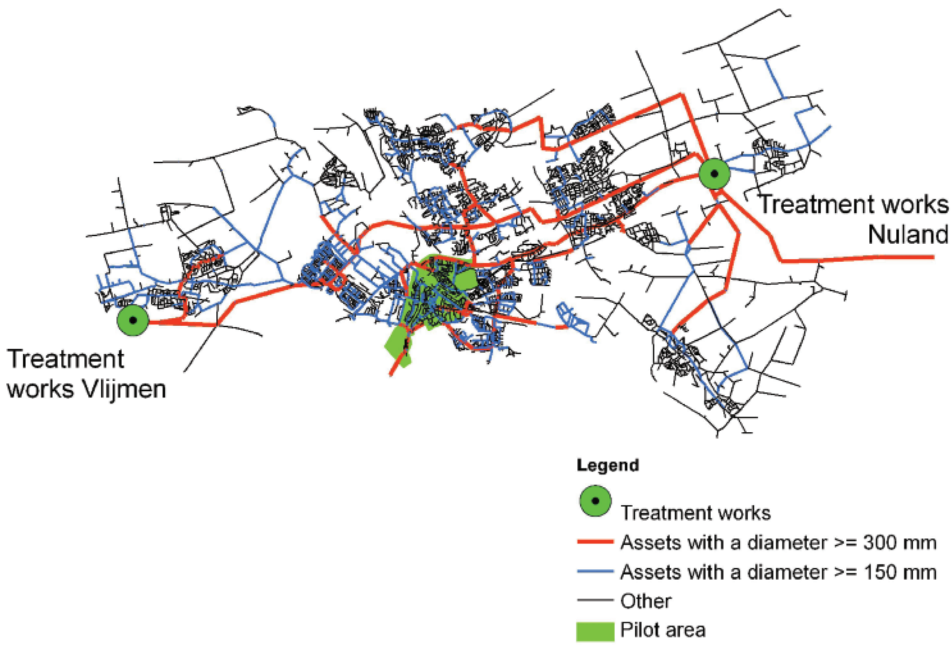

Figure 6
Location of the pilot area in relation to the treatment works

Figure 7
Selection of the pilot area. It appears that the data points of historical monuments match with the contours of buildings. The objects GIS selected as a monument using the spatial join operation are coloured red.

After a pipe is given a buffer and the spatial data on critical objects is collected, GIS can be used to check where the safety zone affects high risk objects. Where the buffer touches a critical object more serious potential effects can be expected following a pipe burst. There are two ways to check if the safety zone (buffer) around a pipe affects critical objects (see Figure 8):

- A 'select by location' action in GIS. In this case the whole object is selected which is affected, even if only a small part of it touches the safety zone.
- An 'intersect' action in GIS. This will select only the part that actually falls within the safety zone.

An additional GIS action has to be performed to display which pipe segments touch critical objects. The result of the 'select by location' or 'intersect' action are polygons containing the object ID of the original segments. By performing a 'join' action in GIS the polygons can be linked to the original file with pipe segments. After using the join function line segments that touch critical items can be displayed.

For risk analysis it is important not only to look at the potential effects, but also at the probability of an asset failure. To predict the probability of an asset failure the USTORE system can be used. KWR developed the USTORE system within the joint research programme of the Dutch drinking water companies. USTORE has been developed to uniformly register water mains failure data, and then to exchange and to analyse the data in order to improve decision making on asset management. At this moment eight out of ten Dutch water companies decided to design and implement a uniform failure registration system; Brabant Water is one of the eight. USTOREweb offers water companies the opportunity to download their own datasets as well as the anonymous composite database. USTOREweb can also generate statistics from the data, for example failure frequency. The failure frequencies of assets provide an indication whether replacement is due within a certain time frame and can therefore be used as an indicator for asset failure (Vloerbergh et al., 2012).

For this study, for all data registered in USTORE the failure frequencies per year in specified material, diameter, year of construction and combination classes have been computed. The results have been applied for use as an indicator for the probability of failure. In GIS, every pipe segment, with a known material, diameter and year of construction, is provided with a

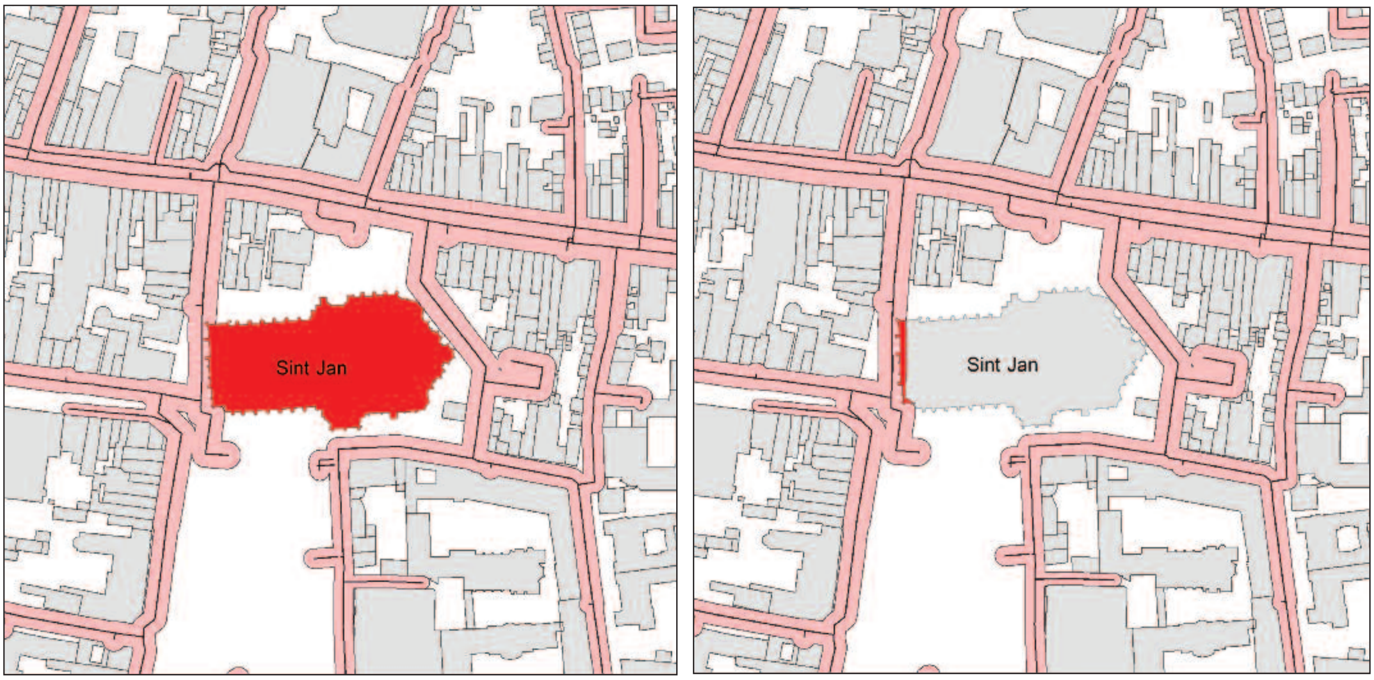

Figure 8
Sint Jan's cathedral in 's-Hertogenbosch partly falls inside the safety zone (shown in pink). With a select by location action in GIS the whole monument is selected as high risk (left figure). When working with the intersect tool only the parts that actually fall within the safety zone are selected (right figure).

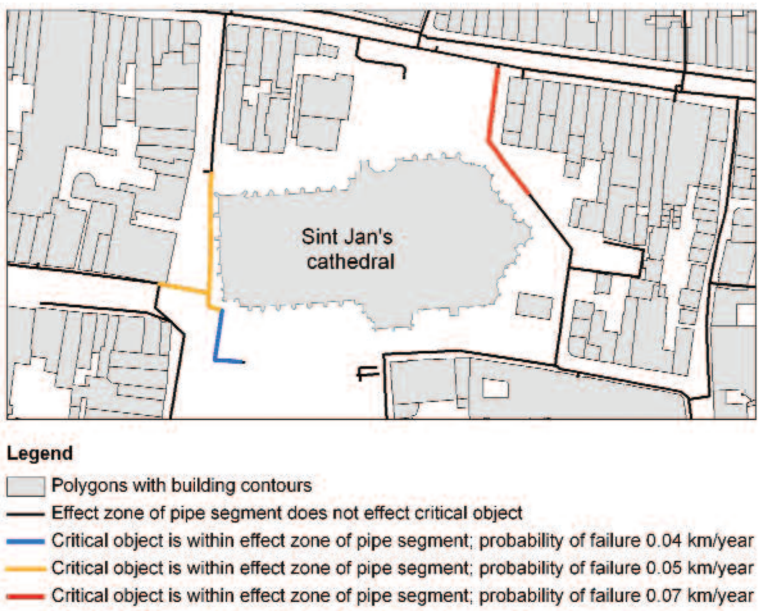

Figure 9
Impact and the failure probability combined result in a risk profile, here displayed for the pipe segments around the Sint Jan's cathedral in 's-Hertogenbosch.

probability of failure.

Now for each pipe segment it is known whether the safety zone of the pipe 'touches' a critical object. The probability of failure is also known for each segment. The combination of these two elements forms a risk profile per segment. Impact and the failure probability results were combined in a risk profile for the pipe segments around the Sint Jan's cathedral in 's-Hertogenbosch, displayed in Figure 9. In Figure 9 all line segments which lie partly within the safety zone of a critical object are coloured. The type of colour depends on the associated probability of failure. This implies that the red coloured lines represent mains with the highest risk profile.

Conclusions

The case study shows that the calculation of an effect zone using data obtained from a hydraulic calculation model leads to more realistic results compared to previous earlier calculations based on the simplified calculation method. The results of a hydraulic calculation model can be easily imported into GIS for further calculation and visualisation. Using spatial analysis it is possible to identify pipe sections where critical items are located within the safety zone around a pipe section and also to identify objects within the safety zone. This new calculation method leads to reduced areas of the effect zone. Combining the results within GIS could result in fewer mains that require consideration as being at high risk based on the presence of critical objects. In combinations with the probability of an asset failure it gives a water company a good understanding of the potential risks, resulting in the identification of more critical mains. This shows that the combination of GIS with other analytical tools (in this case the hydraulic network calculation programme InfoWorks) can provide valuable information for the management of water supply networks. The analysis presented in this article can be an important building block for designing an asset management regime for water distribution networks. ●

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This paper was presented at LESAM 2011 – the Leading Edge conference on Strategic Asset Management, held 27-30 September 2011, Mülheim an der Ruhr, Germany.

AM DIARY

A listing of upcoming asset management-related events and conferences. Send event details to WAMI for inclusion.

5th IWA International Conference on Benchmarking and Performance Assessment (Pi2013)
9-12 April 2013, Medellin, Colombia
Web: www.iwabenchmarking.com/pi2013

Asset Management for Enhancing Energy Efficiency in Water and Wastewater Systems
24-26 April 2013, Marbella, Spain
Web: http://iceam2013.es

3rd International IWA Conference on Water, Economics, Statistics and Finance
24-26 April 2013, Marbella, Spain
Web: http://iceam2013.es

Regional Utility Management Conference - Improving Performance in Emerging Economies
13-15 May 2013, Tirana, Albania
Web: www.shukalb.org/utilityconf

7th International Conference on Sewer Processes and Networks
28-30 August 2013, Sheffield, UK
Web: www.shef.ac.uk/spn7

LESAM 2013 - IWA Leading Edge Conference on Strategic Asset Management
10-12 September 2013, Sydney, Australia
Web: www.lesam2013.org

IWA World Water Congress & Exhibition 2014
21-26 September 2014, Lisbon, Portugal
Web: www.iwa2014lisbon.org

International Water Week 2013
4-8 November 2013, Amsterdam, The Netherlands
Web: www.internationalwaterweek.com

Water Loss 2014
30 March - 2 April 2014, Vienna, Austria
Web: www.iwa-waterloss.org/2014

13th International Conference on Urban Drainage 2014
7-11 September 2014, Sarawak, Malaysian Borneo
Web: http://www.13icud2014.com

Integrated information tools for strategic asset management

Sustainable management of water infrastructures relies on a deep knowledge of the assets. Water utilities are focusing their attention on information systems and systems integration. However, even in sophisticated utilities, the essential information is not always available or may fall short in quality or quantity. J Beleza, J Feliciano, J Maia, A Ganhão, R Almeida, A Santos and J Coelho discuss the development of an asset management strategy at Portugal's AGS, which manages 14 water utilities, and how the aim was to deliver immediate access to relevant information from any information system, providing a clear approach to data, access to detailed and accurate information, and valuable key performance indicators.

J Beleza
Water Utilities Consultant.

J Feliciano, J Maia, A Ganhão, R Almeida, A Santos and J Coelho
AGS, SA, Sintra, Portugal.

AGS manages 14 water utilities in Portugal (divided into municipal concessions and public-private partnerships), providing water and wastewater services to about one million people. As well as utilities management, AGS also acts as a services provider in the management, operation and maintenance segments of water and wastewater infrastructure.

Infrastructure asset management (IAM) has played an important role in Portugal's utilities, due to contract requirements, regulation and the need to optimise service quality, network performance and infrastructure lifespan. Even so, methodologies, decision support tools and strategy were not always clear or provided answers accurate enough for organisations' needs.

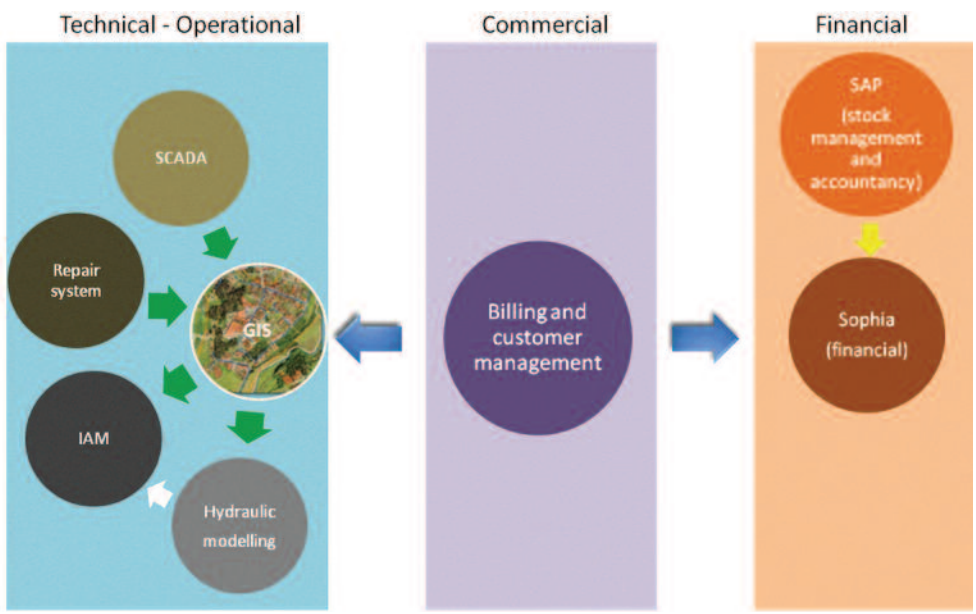

Figure 1
Main information systems architecture and systems linking

Nowadays, with a more comprehensive and well-devised strategic approach being developed in recent years (Alegre, 2009), the development of an IAM policy in Portugal's utilities took a giant step with the definition of a strategic plan and the implementation of decision-support tools, improving management and utility performance, and the recognition of the important role of data and information. Integrating these tools and being able to assess the performance of the utilities, based on benchmarking activities, allowed a much clearer view of the common processes and practices.

There are two essential drivers promoting a better approach to IAM: the AWARE-P project – Advanced Water Assets Rehabilitation in Portugal (www.aware-p.org), with an end-user perspective, coordinated by the National Laboratory of Civil Engineering (LNEC) in Portugal, which assists water utilities to establish a clear approach to IAM, from strategic to operational levels – promoting gradual steps to take actions according to a defined strategy, and networking with other utilities, sharing problems and solutions (Alegre et al., in press); and the regulatory standards defined by the Portuguese Water Regulator (ERSAR), which promote benchmarking activities to assess performance and define a mandatory IAM strategy for all utilities with more than 30,000 inhabitants (D.L. 194/2009).

With several utilities to manage and with a recent investment (2005-2009) in new infrastructure (more than 2000km in water and wastewater networks) plus the added investment of renovating all pre-existing assets, Portugal's journey in IAM has just started.

The need for data

IAM represents a balance between performance, cost and risk in strategic, tactical and operational dimensions, and requires competences in three key areas: information, engineering and management (Alegre, 2008). All available data concerning management and infrastructure is linked in a way that should be easily obtained and clear to any user in the organisation.

Still, data management and analysis is a major challenge in any organisation. The act of producing data has become the easy step on a long journey, leading to real-time analysis of integrated information. However, even in sophisticated utilities, the essential information is not always available or may fall short in quality or quantity.

The main difficulties lie in: identifying the correct data; promoting data standardisation; analysing and integrating it, providing insightful analysis when necessary; and achieving reliable and valuable indicators for all management levels – from the operational to the financial or general management areas – allowing informed decisions and good planning.

Efficient information management is the key to better decision-making for municipal infrastructure and when reliable data and effective decision-support tools are in place, the costs of maintenance, repair and renewal will be reduced and the services will be timely, with fewer disruptions (Vanier, 2001).

At Portuguese utilities defining information systems architecture and data models, building a solid structure with essential data, as well as organising, analysing and providing easy access to management and technical information to specific users inside the organisation, has been a concern in the recent past. This being a continuous process, and the main strategic objectives are to:

- Develop solid information, built on strong and accurate data
- Take advantage of the existing information systems
- Simplify users' access to the right information when they need it, developing standard reports for internal (e.g. board and shareholders) or external (e.g. regulator) demands
- Build a decision support tool, integrating data from several databases and defining a basis for sustainable infrastructure asset management

Furthermore, the strategy developed follows the four principles established by Kyle et al. (2000), towards data requirements of asset managers in order to attain comprehensive data systems:

- Development and maintenance of data to satisfy needs of decision support tools
- Development and standardisation of quality metrics for evaluation of performance and condition
- Standardisation of data and information flow
- Continuous transfer of data amongst actors in the process

Information systems

The implementation of a variety of technological projects across AGS water utilities and central support services, concerning information systems such as billing, GIS (geographical information system) and SCADA (supervisory control and data acquisition), in connection with increasing reporting requirements by the regulator, and the ongoing participation in the AWARE-P project, have provided the opportunity to acquire deep knowledge of the available data and develop various interfaces between the available systems (GIS and billing; GIS and SCADA; GIS and infrastructure repair management system, to name a few; see systems architecture in Figure 1).

In broad terms this path was started six years ago, and aimed at creating valuable information that could support all aspects of engineering and management. For this to happen we focused on creating strong information systems that could be used in Portugal's utilities and also at central support services, providing a continuous overview of the utilities and access to an expert team that could support all activities developed locally.

All tools were implemented via a structured path, in a step-by-step integration, allowing a clear association between systems and available data. These systems (including GIS, repair systems and SCADA) are deployed in six water utilities. This way we were able to standardise information and establish links between databases, developing interfaces that allow queries on available data in different systems / databases.

Given that commercial and financial needs were already covered, the decision was to invest in technical and operational systems that could support analysis, planning and management, paving the way for a decision-support tool relying on strong and accurate data. This way, GIS and SCADA were the first to be implemented, followed by the repair system (replacing an older one too simple and with insufficient data).

As a first approach it was essential to define data models that could comply with operational needs and asset management requirements. It is always indispensable to define the basic data needs and the key elements in each system, providing a clear view (that can, naturally, evolve) of the future systems. Even so, there are common problems in utilities with sophisticated information systems (Parker, 2009) that we tried to avoid:

- Inability to link different databases
- Lack of audit to confirm accuracy
- Lack of motivation for field staff to collect accurate information
- Gaps in data
- Too much data being entered with default values
- Trying to capture too much information and ending up with only a partial database

It is also important, on similar projects, to allow some room for initiative and new developments; taking advantage of the process and the lessons learned and having the ability to adapt solutions and improve the interaction with users and field staff.

The first effort has proved valuable: the team that managed the implementation acquired strong knowledge on the systems structure and data, and oversaw the way users managed the information, guaranteeing accuracy and enough information (in a first phase) to build strong basic systems that could provide meaningful information (Beleza et al., 2010). The support given allowed us to fully understand the processes and improve them on the way.

The project started in 2005, with the main phases being described in Figure 2.

The systems implementation, auditing, continuous monitoring and development provided a great evolution in the available data and a deep knowledge of all the information and analysis. This way we were able to build a basic layer of information on which we can rely on. Obviously, the feeling that it is possible to improve subsists by gathering more data, adapting existing data or replacing old data for new, building more robust systems and creating a better overall user experience (e.g. repair system, motivating field staff, improving data accuracy and quantity).

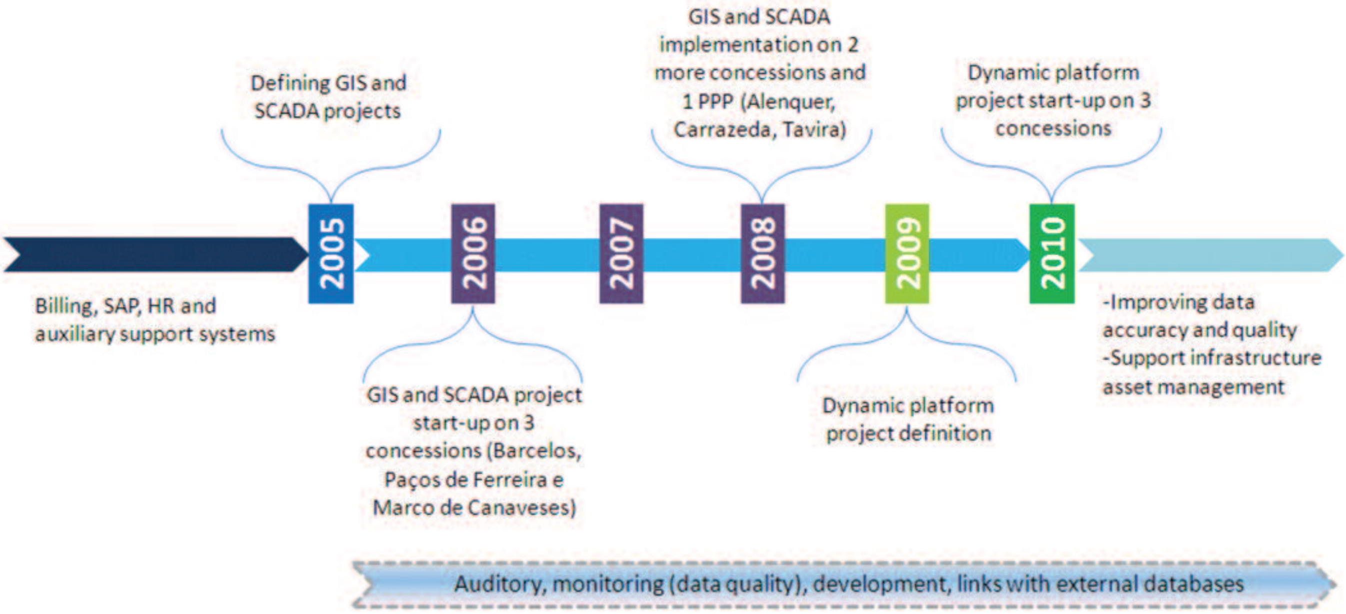

Figure 2
Main phases of systems implementation

Business processes

In addition to understanding and characterizing the information systems in the utilities it is essential to analyse processes and practices regarding information flow. Even if common processes and practices are similar at water utilities there are specificities at each of them. This was a very important step in the process, realizing these specificities and incorporating them in such a way that the users could, in the end, have the same understanding on the data they were gathering and analysing.

It is essential to get to know users' needs and the main uses of information. Besides, it is key to understand concepts associated with data use and analysis, since many of these concepts may be different to users at different levels or users at the same level in different utilities. This was one of the reasons why a data dictionary was developed, as referred to in more detail later in the text, so that everyone using the tool could understand the principles associated with the data they were using.

Getting together different users from different areas (that share information formally or informally or need to have access to data created by other areas) is also an important step, considering there are several areas and internal units that generate data, and that some of these data should be available to flow between different actors in the processes. At the beginning it is important to analyse the data from each area and understand the possible relations between them, considering whether it is possible to link data among different systems or areas, and how. Defining this basic structure and understanding how these systems can be linked it is the first step to promote integrated analysis.

Also relevant is the review of processes and practices related with data, identifying opportunities for improvement.

From this process normally results important conclusions:

- The capacity to link different systems that are not already linked or the difficulties related with this linking
- Users' usual data needs from areas that are not their own
- Superposition between systems
- Other problems associated with data shared between different areas

Developing such approaches to information flow and business processes has the power to strategically review available data and analyse information quality, redefining internal processes and practices. A common goal should be to do this frequently, improving these systems without the need for replacement, which is often the case in utilities distrustful of the available data / information. Even if users are often unsatisfied with some of the available information systems, the case may be that the problems are associated with the use of the application and not the application itself. Getting to know better the utility processes facilitates the definition of goals to improve data quality, from data collection to information systems use, and develop better tools, fully adapted to the users' needs. This way it is possible to get to know your data better without the need to replace these systems, just taking the needed measures to improve them, getting a much lower investment and a higher return, since you may be improving a tool that you know better and that is more adapted to your final needs.

Linking information systems and responding to users' needs, based on real utility management requirements (responding to the internal and external context), is a powerful way of evolving the available tools, understanding flaws and creating a clear path to application and technological evolution, making them last longer and performing better than, in some cases, a completely new system (that would have to be adapted to your needs as well). Even if the final goal is to replace a tool that may be obsolete it is essential to get to know the data available and its quality. Business intelligence tools, such as the dynamic platform, may be relevant to analyse this information in its context and to better understand its quality, flaws and conceptual errors.

Dynamic platform

After all the basic systems implementation, interface development, information production and with all interaction gathered from the users, the need for an efficient tool that could complement all these systems became obvious, incorporating directly information from all silos of expertise. Additionally, as Moddemeyer (2011) points out, the data that we have been gathering in the old paradigm may or may not be the right data we need, so it is essential to keep looking and providing new methods, density and forms of data.

Figure 3 represents the path followed to promote systems linking and integrated analysis. Given the above, integrated analysis depends on having a solid information systems structure with the ability to produce robust and clear data that should be continuously monitored. On top of this we are able to build integrated sets of analysis, bringing together data from any system available. It is very important to continuously rethink the structures and monitor the available data, making sure that the base layer systems are adapted to users (management, technical or other).

Accordingly, the acquired knowledge, managing the implementation of the technical and operational systems and developing the links between databases was used in a dedicated internal project that promoted the development of a highly dynamic and interactive platform, which brought together data from key information systems and focused the essential data in one central access point, making it easy for users to get the right information at any given time and providing integration between the essential data sources in the organisation.

It is becoming essential to provide a clear linking between systems and available data, allowing a whole approach rather than the sum of specialised views, or else we will continue to prove inefficient when planning and having difficulties establishing sustainable systems.

This way, our goal was to create a smart decision-support tool, flexible enough to be used by different kinds of users, providing information from several databases, with rigorous data, avoiding wasting time extracting and treating the data manually. At the same time it is very important to have standards and to establish basic layers of information to keep benchmarking inside the organisation and outside, with others with similar activities.

Moreover, this project promoted the creation of a data dictionary, establishing a clear understanding of the available data in the platform and the source of the produced information.

At first the essential information was established, based on IWA and regulator key performance indicators (KPIs), in internal and external reports, so the decision was how to start developing the smart-tool: should we develop it all by ourselves or look for software to build on? The decision rested on the second: there are several options to do this, with more or less complexity, providing ways to capture data and analyse it. This way we had an opportunity to choose a good platform: not too expensive, user-friendly, interactive and visually attractive so that the focus could be on the data analysis.

After testing options and finding the 'right' software that could answer to our demands, we started gathering internal reports and KPIs (that were previously produced manually, requiring a large amount of effort, or available in tools limited in scope) to define a basic structure of information that could provide responses to our needs.

As mentioned before, it was essential for us to create a data dictionary, not only in the strict 'information systems' way but as a glossary where any user can, with more or less experience and business know-how, understand the origin of the data used and the way, if any, it was treated (formula, filter or other). So, from the beginning, any data we decided to keep in the dynamic platform was included in this dictionary, providing insight to its origin: database, field, table, conditional clause and formula, where available.

At the start there were meetings with our utilities, creating a workgroup, to validate the data we would use and the information we should produce. Figure 4 shows the essential data, used at the starting point of the project.

After defining the primary inputs for the dynamic platform, the project development took off, as said, building on commercially available business intelligence software, taking advantage of its architecture and in-memory analysis, but with all data extraction, parameterisation, transformation, architecture management and data treatment being developed internally. By doing so, we were able to create and develop a decision support tool, available to our utilities and at our central services, that gathers all our business know-how with data from several systems, with an emphasis on technical / operational, commercial and financial data.

The way this platform was developed does not require data duplication or building complex data structures. Simple extraction is done in each database, with a very high compression rate, and data is linked inside the dynamic platform, when performing the data load, establishing a clear structure of source and internal tables. The system is automatically updated daily (this could be parameterized and the user has always the possibility to manually update it at any given time). If there is a justified need, any data from any database can be added to the platform being supervised and implemented by the project manager.

Moreover, based on the developed architecture and data standards, the tool can easily be adapted to other utilities with a different information system (this has already been done, successfully, at several utilities).

The selected information, established by the workgroup as being essential, can be divided into three major groups: technical, commercial and financial. This information was selected based on key performance indicators from the systems published by IWA (Alegre et al., 2006; Matos et al., 2003), the Portuguese Water Regulator (Alegre et al., 2004; Matos et al., 2004) and from AGS's own reporting system. The first, relying on operational data, provides data on infrastructures, repair locations and costs (e.g. divided by district metered areas – DMA), and also consumption patterns. Using data from the GIS and the repair system it is possible to gather data on all repairs, their location and affected infrastructures. This information can be about type of repair, cause of asset failure, time used, material, diameter, cost, and so on. On the other

Figure 3
The path to linking systems and promote integrated analysis

side, SCADA information is also available about system input water and consumption patterns that coupled with DMA provide insightful information when linked to client metering. Commercial information regards client metering and billing as well as detailed client data (e.g. water meter performance). This brings very important information providing insight into the heart of the organisation, understanding patterns, demands and being able to compare data by client type, time period, location, among other, all being done in a matter of seconds. In Portugal every client has a meter and is billed monthly (even if the meter is not read monthly – at worst, by regulation standards, the meter should be read twice a year), so, even if some care is needed with regards to consistency in the analysis, there is always room for some scrutiny to be done (having knowledge of customer billing cycles). Furthermore, adding GIS and SCADA dimensions to commercial information creates a powerful basis for every organisation, creating a full-scale business support tool. Finally, there is financial information concerning organisation data, including financial statement reports such as balance and cash-flow sheets or profit and loss accounting. This way it is now possible to produce reports easily, based on reliable information, and, even more importantly, compare instantly information from different periods and / or utilities.

Besides preset reports, the dynamic platform allows users to apply any available parameter to limit the scope or filter the analysis (e.g., type of consumption – domestic, industry, etc.; period of time – month, trimester, semester, etc.; region – municipality, DMA, etc.) and compare identical periods of time in different years. All selections made on the screen act as filters on all the available data and analysis, making it easy for the user to narrow down the analysis without requiring further help.

Figure 5 presents an example of the available information, putting together information from GIS, repairs and billing. This dashboard allows immediate answers for any parameter available (time, client, group by client type, group by type of repair, DMA, etc.). By choosing one or more DMA it is possible to analyse repairs by time period (November 2010 in the example), locate them, search billed customers, customer monthly demands, and get DMA pipe lengths by type, among many other kinds of information. Any selection provides immediate answers. Furthermore, other dashboards can provide detail and performance indicators on the selected data (or, as mentioned before, other data available).

A large amount of data is accessible, allowing for detail in the information produced and, at the same time, with KPIs providing a quick analysis of the organisation's performance. A major design requirement was in fact to provide a summary of the available data using standardised performance indicators, organised in a monthly overview.

Results

Significant benefits have been afforded by the development of the dynamic platform:

- The ability to analyse data from several different sources at the same time in a single, central platform
- Dynamic analysis in real time – the capability to instantly analyse data from any system (or several at the same time), through any available parameter
- A selection of key performance indicators to analyse current and past performance
- A structured set of essential information, clear to any user
- Comprehensive understanding of data in the available information systems
- Homogenisation in analysis, reducing errors and time-consuming reports
- A data dictionary for the users, providing definitions of the information and how the data is gathered and treated
- A clear display of all information systems available, allowing for a continuous monitoring of data (quality assurance and quality control), detecting errors and taking the needed measures to correct them

With the development of this tool it was finally possible, for the first time, to have a complete vision of our systems, providing clear and robust answers to any questions about our networks, our clients and our information.

Time has been saved in implement-

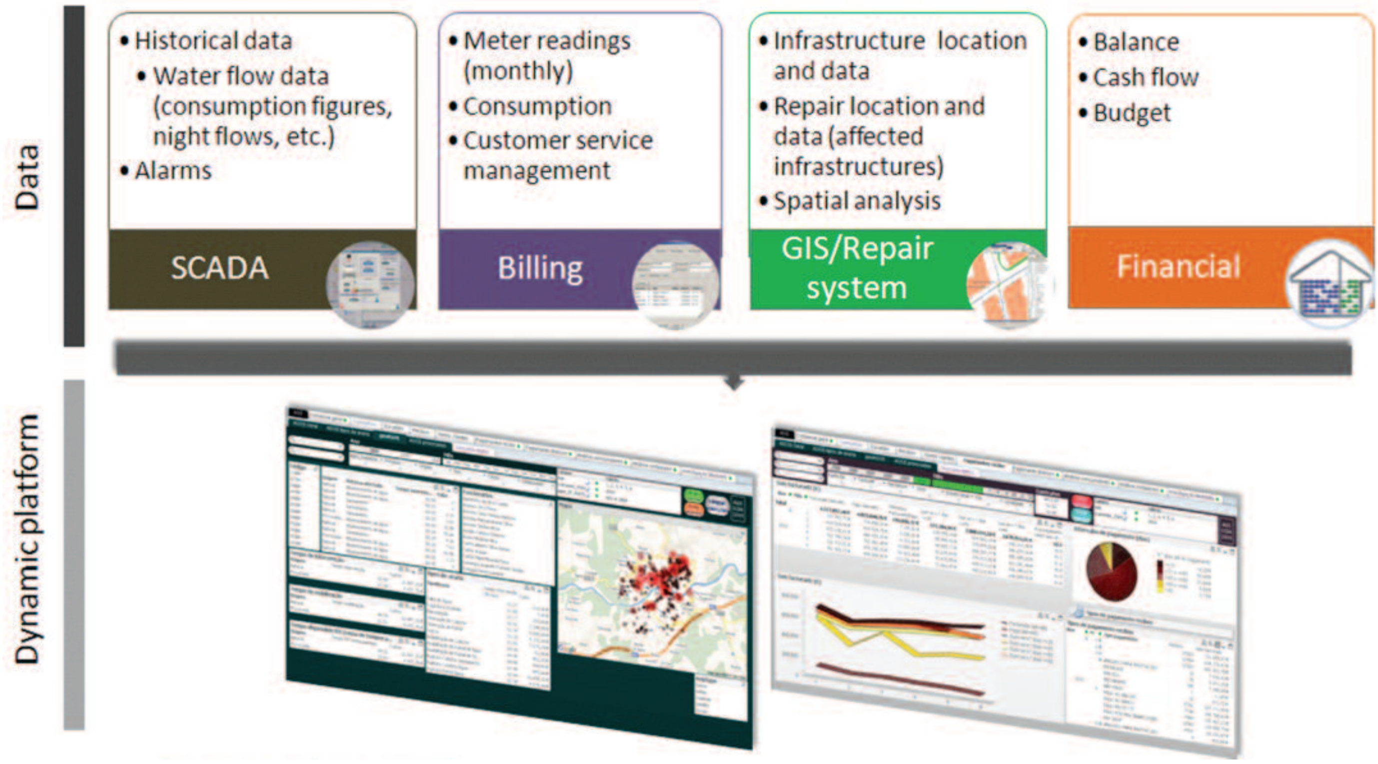

Figure 4
Data defined as primary input for the dynamic platform

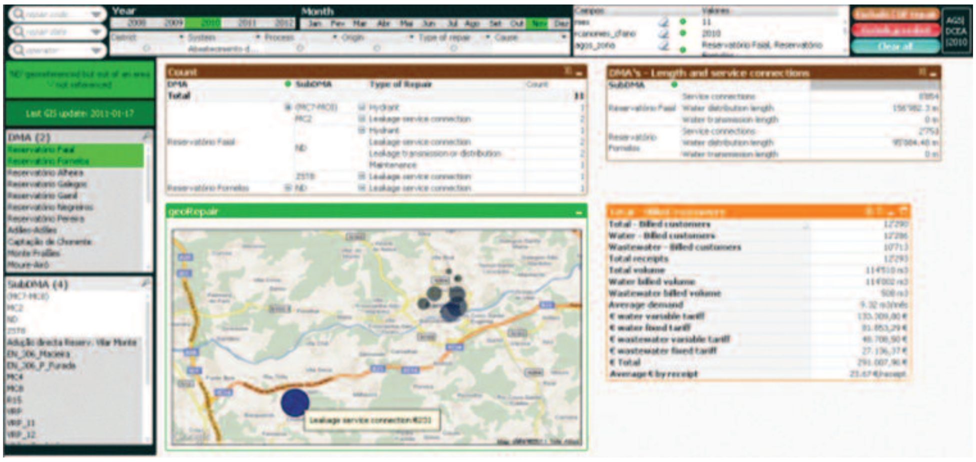

Figure 5
Dashboard collecting information from GIS, repair system and commercial information

ing business intelligence, smart or decision-support tools, rethinking our systems, our data and our processes, and we feel we have better prepared managers, technical and commercial directors developing reports, producing and analysing KPIs and preparing plans with ease. Tasks that could take up to two days (extracting, transforming and analysing data) now take up to a few seconds.

Also, a very important result is the added value to our information systems, mainly via the quality of the information and the permanent access to relevant data that is liable and robust. The cost effectiveness of the adopted solution made us feel sure about the decision of developing such a platform. Since we have done it we got to know our systems much better, identifying their flaws, promoting better practices using them, and creating a structured path for their evolution, without the need to invest in new tools.

Nonetheless, this work must been on-going; working our data and our systems, redefining our needs, rethinking our standards, creating better tools for stronger equipped utilities, with the capacity to be prepared to face new challenges, planning ahead yet with the ability to adapt to new circumstances.

From the moment data is available it is essential to find the right way to analyse it, producing efficient (preferably standardised) and intelligent information that can provide insight to all types of management. This is the only way to keep improving.

Conclusions

Managing utilities, water services and infrastructures requires high standards that can only be achieved with an investment in technology that supports the generation of essential data and information. With this project, it was possible to develop a tool that supports all aspects of planning, operations and management, effectively supporting decision-making and planning for the short or long-term, based on reliable, structured information.

With the dynamic platform, we now have the means to keep promoting solid methodologies for a sustainable and clear approach to progressive asset management policies; developing new sets of analysis, useful to all intended users; improving business processes; and standardising and simplifying, while delivering efficient services.

We feel we are in a time for change (Moddemeyer, 2011), being part of a new approach to systems, while delivering an essential service (protecting public health and the environment), creating new methodologies and strategies to be better prepared for all future possibilities, facing our concepts and networks and rethinking them as we go on, with all the flexibility possible with the tools available and the smart tools we can develop. This is the only way we can keep costs under control, providing sustainable, efficient, quality systems that meet the high standards we all work towards. ●

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Rehabilitation of water distribution facilities – the holistic approach of the German DVGW standards

The DVGW technical standards demand a long-term, optimal rehabilitation of water distribution facilities to ensure a high level of supply quality and network condition, as well as a low risk potential and lowest possible total costs. Bernd Heyen discusses the example of German water and gas utility GELSENWASSER, whose interconnected water distribution network proves that not only the requirements, but also the procedure, are compatible with practical experience.

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Although maintenance is becoming increasingly more important for water supply companies worldwide, the corresponding standards regarding supply quality and network condition vary considerably. International comparisons – mostly accompanied by water price discussions – have always confirmed the high supply quality and good system condition of German water distribution facilities [1, 2]. This can certainly be attributed to the fundamental idea on which the generally accepted codes of practice in Germany – the DIN and the DVGW Technical Standards – are founded.

Fundamental idea of the DVGW standards

The DVGW Technical Rules define a standard which is considered by the majority of experts as state of the art. The requirements refer to planning, construction, testing, operation and maintenance of water distribution facilities and are valid for all utilities and persons involved, i.e. for all types of facilities and processes of water distribution. The DVGW Codes of Practice and Guidelines pursue a holistic approach by clearly defining objectives and requirements without, however, prescribing certain solutions and the ways how to realize them [3].

The basis for the high technical standard are the requirements set out in DVGW Codes of Practice W 400-1 and W 400-2 for the planning and construction of water distribution facilities [4, 5]. With pipeline systems in Germany almost complete and water utilities increasingly focusing on the rehabilitation of existing water distribution systems, the technical standards covering these fields of activity were updated and enlarged in compliance with the above-mentioned fundamental idea of the DVGW Technical Rules.

The principles concerning the planned rehabilitation of water distribution facilities were documented in 2006 in the DVGW Code of Practice W 400-3 'Engineering rules for water distribution systems; part 3: Operation and maintenance' [6]. An important new basis for rehabilitation planning is the DVGW Code of Practice W 402 'Network and failure statistics – capturing and analyzing data for water pipe network maintenance' [7] superseding and enlarging the DVGW Guideline W 395 'Statistics on failures in water distribution systems'. The DVGW Code of Practice W 403 'Decision support for the rehabilitation of water distribution systems' [8] published in April 2010 and superseding DVGW Guideline W 401, provides a concrete description of the systematic procedure to be adopted for the rehabilitation of water distribution facilities according to the fundamentals of DVGW Code of Practice W 400-3. The fundamentals for the planning and construction of rehabilitation measures as determined by rehabilitation strategies and planning are laid down in analogy to new construction measures in the above mentioned DVGW Codes of Practice W 400-1 and W 400-2. The trenchless construction methods often used in the rehabilitation of water distribution systems are governed in addition by the DVGW Codes of Practice GW 320 ff., W 343 and GW 304 [9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19].

Generally, the codes provide information on methods rather than technical specifications for the measures to be taken, ranging from the introduction of a rehabilitation strategy and the establishment of rehabilitation plans, down to the implementation of the rehabilitation measures. The codes nevertheless define concrete requirements and impose objectives, which can be used to assess the effectiveness and the sustainability of the rehabilitation.

The holistic character of the DVGW technical standards' approach to the rehabilitation of water distribution

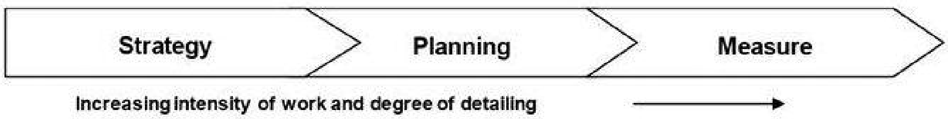


Figure 1 The three sub-processes of rehabilitation [8]

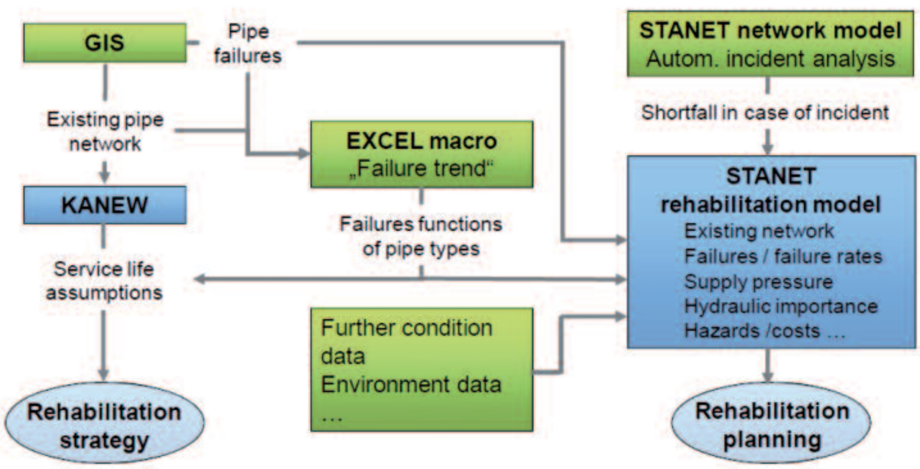


Figure 2 Basic systematics used for the rehabilitation strategy and planning

Table 1 - Implementation of rehabilitation objectives in the sub-processes rehabilitation strategy, rehabilitation planning and rehabilitation measures (x = implementable, o = implementable if assignable to asset groups, - = not implementable) [8].

Rehabilitation objectives		Rehabilitation strategy (how much?)	Rehabilitation planning (where and when?)	Rehabilitation measures (how?)
Minimizing pipe failure and supply interruptions	- Total system	x	x	-
	- Asset group	x	x	-
	- Asset	-	x	x
Reducing or maintaining water losses at low levels		o	x	x
Avoiding hazards to humans, third-party assets and the environment		-	x	x
Improving or maintaining the supply quality	- Pressure and quantity	-	x	x
	- Water quality	o	x	x
	- Availability	-	x	x
Minimizing the required total costs for maintenance by observing the required supply standards		x	x	x

systems is reflected by:

- The definition of prerequisites for a target-oriented planning of the rehabilitation
- The organization and integration of all stages of work and processes ranging from the acquisition of data to the implementation of rehabilitation measures
- The requirement of a long-term optimal rehabilitation from the technical and economical point of view
- The provision of a universal methodology adaptable with regard to the data respectively available (scope, quality, being up-to-date)

Holistic character of the DVGW approach

Prerequisites of a target-oriented rehabilitation planning

Rehabilitation requires a sufficient amount of reliable data concerning the network inventory and the network condition. A necessary prerequisite is the qualified and quality-assured acquisition, processing, evaluation and storage of network-related data. Although the focus has so far been mainly on failure data, the DVGW Code of Practice W 402 now requires and defines the following data as the basis for rehabilitation measures: inventory data; failure data; further condition data; and environmental data, with the factual data of each data category being evaluated with regard to their importance for the rehabilitation so that the 'newcomer' can concentrate right from the beginning on the relevant data and thus avoid any unnecessary efforts.

The user is provided with a clear guideline for the structured and target-oriented acquisition, processing, evaluation and storage of data. Particular importance is laid on the fact that not only the data as such, but also the combination of the failure, environment and other condition data with the network inventory data is unambiguous and geo-referenced and that it remains valid even after the decommissioning of the respective water distribution facility. In addition to the quality of each data set – which must be ensured by regular plausibility checks – the usefulness of the data acquired for the rehabilitation depends essentially on the correct assignment of the data concerned.

Taking environmental data into consideration not only allows for the assessment of the influence of the environment on the condition of the network, but also the determination of the environmental risks posed by water distribution systems in the event of failure. This requirement is a basic necessity for performing a comprehensive risk assessment for a water distribution system.

It is not only the availability of the data required, but also the organizational prerequisites for the creation and care of a reliable database for the rehabilitation that are taken into account. The absolutely indispensable long-term quality assurance required makes the employment of instructed and trained personnel a necessity. The code also makes concrete suggestions as to the procedures and the IT support for data acquisition and evaluation.

The fact that DVGW Code of Practice W 402 does not only contain general information, but rather provides a concrete data structure and an assessment of the importance of individual facts for the rehabilitation, together with additional concrete advice for the acquisition, processing, evaluation and quality assurance of the data, enables each water supplier to undertake effective, sustainable and economical rehabilitation of their water distribution facilities.

Due to the amount of data required, it will take years to decades to see the benefit. Many companies are profiting today because they began collecting failure data 20 or 30 years ago. For this reason, the DVGW Technical Rules are also intended to draw the companies' attention to their own pipeline excavation work and to the civil engineering works of third parties in order to collect – in addition to the failure data – further pipe condition data and to store these data clearly assigned to the individual water distribution facilities for future use.

Structuring and integration of all stages and processes

The DVGW Technical Rules draw a clear distinction between rehabilitation of water distribution facilities and current maintenance tasks, i.e. inspection and servicing. In accordance with DVGW Code of Practice W 400-3 a

Table 2 - Technical parameters and characteristics related to high supply quality and good network condition which can be influenced by rehabilitation according to DVGW Technical Rules [4, 6, 20, 21, 22].

Guideline value for low failure rates [DVGW W 400-3 (A)]	≤0.10 f/(km·a) - Local and primary mains ≤0.01 f/(km·a) - Trunk mains, mains with extensive failure extent ≤0.005 f/(SP·a) - Service pipes (SP)
Guideline value for low water losses [DVGW W 392 (A)]	< 0.10m³/(h·km) - Cities < 0.07m³/(h·km) - Towns < 0.05m³/(h·km) - Countryside
Sufficient and continuous water supply with minimum pressure, but <MDP [DVGW W 400-1 (A)]	> 2.00 bar - Ground floor > 2.35 bar - Ground floor + 1 floor > 2.70 bar - Ground floor + 2 floors > 3.05 bar - Ground floor + 3 floors , etc.
Water quality [DIN 2000]	Limit values as per drinking water ordinance (TrinkwV), suitable for consumption and pure
Minimal risk [DVGW W 1001 (A), W 400-3 (A), W 392 (A)]	Low failure rate / water losses, risk minimization requirement

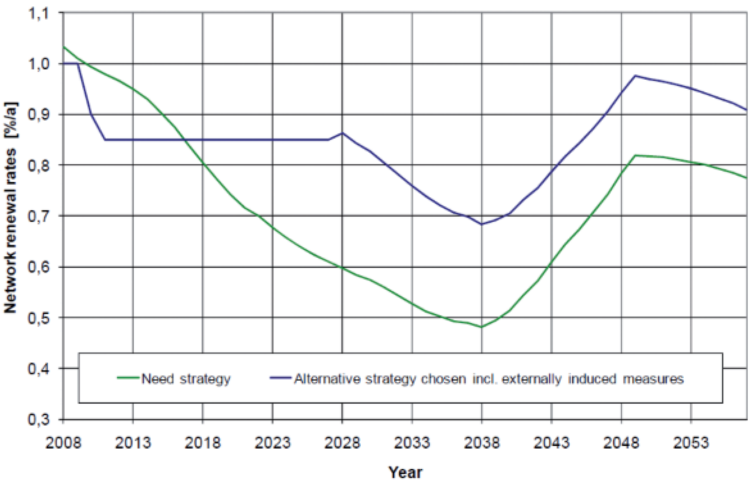


Figure 3
Network renewal rates of the future rehabilitation strategy for supply lines ≤DN 200

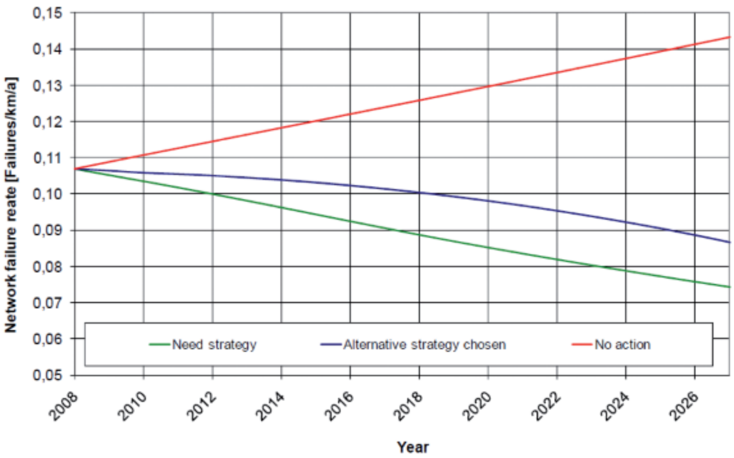


Figure 4
Prognosticated pipe failure development of local mains ≤DN 200 depending on the rehabilitation strategy

sustainable rehabilitation process is, on the basis of the planning period under review, subdivided into the following three interdependent sub-processes (Figure 1):

- Determining a long-term rehabilitation strategy
- Drafting a medium-term rehabilitation planning
- Implementing required short-term rehabilitation measures

The development of the rehabilitation strategy focuses at first for a long-term period on the scope of rehabilitation measures and the rehabilitation budgets required in order to achieve and to maintain sufficient supply quality and network condition levels based on an asset group-related approach, e.g. certain pipe types (material, nominal width, etc.), but not on the individual line section as such.

Individual line sections and their environment will be taken into account only in the rehabilitation planning. During the sub-process 'rehabilitation planning', the required rehabilitation measures will be determined and prioritized for a medium-term period based on a network evaluation and the rehabilitation technology and material will be preselected. In the implementation phase, the actual execution of the rehabilitation measures in terms of line routing, nominal width, material and construction method is then examined and fixed in consideration of possible alternative measures. For this purpose, the sub-processes cannot be considered as independent and their results with regard to rehabilitation strategy, planning and measures must be harmonized not only with one another, but also with the strategic network structure and capacity planning.

This integrated method, which systematically covers all interdependencies of process and time during the rehabilitation, constitutes – in combination with a qualified data acquisition and processing scheme – a reliable basis permitting to achieve the key objectives of the rehabilitation as indicated in the DVGW Technical Rules.

Requirement of an optimal long-term rehabilitation under technical and economic aspects

The DVGW Technical Rules are not limited to providing information for a qualified planning of rehabilitation as far as the determination of fundamental data and the methodology are concerned. The Rules also formulate rather concrete requirements as to network condition and supply quality, which have to be considered for a sustainable rehabilitation. This is based on the basic definition according to which water distribution systems have to make drinking water available [6]:

- In hygienically perfect quality
- In the required quantities
- With sufficient pressure
- With minimal interruptions

These requirements, which can be subsumed under the term 'supply quality', are determined by the condition of the water supply system. High supply quality and a good network condition according to the DVGW Technical Rules are only granted if water losses and network failure rates, as well as the risks emanating from or affecting a water distribution system, remain at low levels. The key objectives of the rehabilitation of water supply systems according to the DVGW Technical Rules therefore consist of:

- Minimizing pipe failures and supply interruptions
- Reducing water losses or maintaining them at low levels
- Avoiding hazards to humans, third-party assets and the environment
- Improving or maintaining the supply quality at the lowest possible total expenditure [8]

Reaching the rehabilitation objectives therefore presupposes knowledge of the risks involved. With the exception of quality problems (e.g. turbidity), which can have many different causes, risk is generally constituted by the probability of pipe failure (and indirectly water losses) and the respective extent of damage regarding hazards to humans, third-party assets and the environment, the supply quality, costs and possibly the public perception of the damage and the image of the supply company. The probability and the extent to which drinking water quality is affected can be derived from customer complaints, operating experience, measured values and pipe network simulations.

Figure 5
Evaluation systematics for risk-oriented rehabilitation

R = SRP x (1 + S1 + S2 + S3 + S4) x (FAG + FAV + FAK) + TR x FAT

R = Risk
SRP = Pipe type failure rate
TR = Rate of turbidity
S1…S4 = Line-specific evaluation factors for failure probability
FAG = Failure extent regarding personal and environmental hazards
FAV = Failure extent regarding supply quality
FAK = Failure extent regarding costs
FAT = Failure extent regarding turbidity

As far as the rehabilitation strategy is concerned, the aspect of risk can only be considered to a limited extent. The only feature that can be generally analyzed and predicted in the technical evaluation of the rehabilitation is the development of the asset group-related failure probability. If water losses or turbidity can be clearly attributed to individual pipe types (asset groups) and not to individual line sections, these aspects too can be taken into account in the rehabilitation strategy. In the planning all influencing risk factors can be evaluated by way of reference to the location of the individual assets (Table 1).

All requirements must be completely fulfilled and cannot be offset against one another. A low failure rate does not automatically mean a high supply quality if there are high water losses. This means that there are pipe failures which have not yet been discovered due to unfavourable soil conditions. Although increased inspection activities to reduce the water losses can be a first step in detecting and reducing the water losses locally, the only way in the long run of keeping network failure rates, water losses and thus also the risks permanently low the a well-targeted rehabilitation of the pipe network. The minimization of risks and disturbances in the supply quality is not only an abstract requirement, but materialized in the DVGW Technical Rules in the form of limit values and of guideline values (Table 2).

The water quality to be made available by the water supply company is prescribed in the drinking water ordinance 'TrinkwV'. These requirements are met if TrinkwV's limit values and the DIN 2000 standard with its guidelines and references to the generally recognized state of the art with regard to the catchment, treatment and distribution of water are respected. The maintenance and / or improvement of the water quality is moreover implied in the minimization requirement for pipe failure and water losses of DVGW Code of Practice W 400-3 [6].

The extent of damage to persons and structures that can be caused by a pipe failure cannot be defined and quantified with general validity in technical standards, but in the DVGW Technical Rules the requirements concerning the failure probability have been significantly tightened for long-distance and trunk mains as well as for other mains of special importance for the water supply where the extent of damage can be quite considerable in the event of a pipe failure (e.g. extensive supply interruptions, hazards to humans and property). Instead of a low failure rate for local

Rohrtyp	Nennw	Länge	Baujahr	Anz	RS10	SR-P	S1	S2	S3	S4	S	SR	BP	P	G1	G2	G	V1	V2	V3	V	A	T	R
	mm	m																						
PE-63 (bis	63	43,0	1953	1	1	1,197	0,00	0,10	0,000	0,20	1,30000	1,55610	0,00	0,10	0	20	22,00	0	0	0	0	22,00	0	34,23
PE-63 (bis	63	158,0	1966	4	3	0,643	0,00	0,20	0,300	0,60	2,10000	1,35030	0,00	0,25	0	20	25,00	0	0	0	0	25,00	0	33,76
PE-63 (bis	63	133,0	1960	1	1	0,875	0,00	0,20	0,000	0,20	1,40000	1,22500	0,00	0,25	0	30	37,50	0	0	0	0	37,50	0	45,94
PE-63 (bis	63	32,0	1960	2	1	0,875	0,00	0,10	0,100	0,20	1,40000	1,22500	0,00	0,10	0	5	5,50	0	0	0	0	5,50	0	6,74
PE-63 (bis	63	71,0	1970	2	2	0,512	0,00	0,20	0,300	0,60	2,10000	1,07520	0,00	0,25	0	20	25,00	0	0	0	0	25,00	0	26,88
PE-63 (bis	63	125,0	1967	4	1	0,609	0,00	0,20	0,300	0,20	1,70000	1,03530	0,00	0,25	0	5	6,25	0	0	0	0	6,25	0	6,47
PE-63 (bis	63	33,0	1967	1	1	0,609	0,00	0,20	0,100	0,40	1,70000	1,03530	0,00	0,25	0	20	25,00	0	0	0	0	25,00	0	25,88
ST1 (bis 1	25	180,0	1936	6	3	0,517	0,00	0,20	0,200	0,60	2,00000	1,03400	0,00	0,25	0	20	25,00	0	0	0	0	25,00	0	25,85

Figure 6
STANET rehabilitation model with risk-oriented prioritization of measures

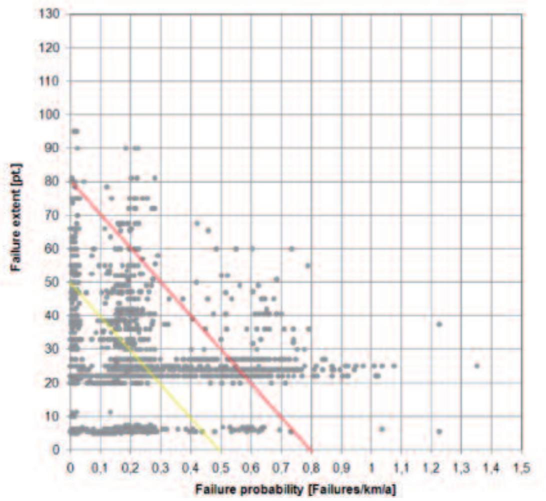
mains of 0.1 failures per km and year, the failure rates required for this type of mains are in the order of 0.01 failures per km and year. Moreover, the general risk minimization requirement as per DVGW Guideline W 1001 [22] nevertheless retains its validity. For high-rated risks, the water supply companies are obliged to develop technical, organizational or personnel measures resulting in a removal or minimization of the risk.

Thus, the DVGW Technical Rules are not aiming at a short-term technical or commercial success, but rather at an optimal long-term rehabilitation in which the supply quality, the network condition and the risk potential as well as the required investment and operating costs have to be considered.

Universal methodology adaptable with regard to data availability

The quality and reliability of rehabilitation strategies and plans are decisively determined by the available database. On account of limited data availability, systematic rehabilitation is often abandoned in favour of a failure repair strategy. The rising repair costs caused by the deterioration of network condition will result in a disproportionate rise of the costs of maintenance in the long run. In this case, the customer will indeed have to pay high water prices for a bad supply quality.

Figure 7
Risk matrix



The approach of DVGW Technical Rules excludes a failure repair strategy by offering three procedures in DVGW Guidelines W 403 permitting to determine the required rehabilitation demand for each special case based on the data available (scope, quality, being up-to-date) [8]:

- Directly derived from the service life of the asset groups: estimation of the average age and service life based on experience and literature references without taking failure data into account; and rehabilitation rate in % = 1 / (service life - age) in years, if no rehabilitation has as yet been performed.
- Derived from service life and age-related existing asset lengths and quantities of the asset groups: availability of an age-related asset length and quantity distribution; estimation of the service life based on experience and literature references without taking failure data into account; and rehabilitation rate = annual sum of all pipelines which have to be renewed at the end of their service life.
- Derived from mathematical distribution functions: availability of an age-related length and quantity distribution and failure data over many years; determination of the service life in consideration of failure experience; and derivation of the rehabilitation rate from the asset group-related failure probability with the help of mathematical distribution functions.

In the case of low data availability and the simplified procedures resulting therefrom, it is necessary to apply higher safety coefficients to make results more reliable. The reliability of the results rises with the availability of data and the possible degree of detailing. This means that under the aspect of increased affordability and planning safety it is required to establish in the medium- and long-term a sufficiently large and reliable database according to W 402 and to adapt the body of methods in line with the improvements of the database available.

Similar to the variations of methodology for the rehabilitation strategy, DVGW Guideline W 403 offers fundamental and comprehensive systematics also for the rehabilitation planning which can be gradually improved depending on the database available. If, in a first step, the environment data of the lines are not yet existing, the priority of rehabilitation measures can at first be laid on the evaluation of the failure development in individual line sections. Based on this condition-oriented evaluation, the priority can be gradually shifted towards an evaluation of the respective failure risk (combination of the likelihood of occurrence and the extent of damage) without the fundamental data and results from preceding steps becoming useless. The coordination of the construction activities with regard to other contractors and companies can also be incorporated in the evaluation.

The applicability of the approach in the DVGW Technical Rules with respect to the basic systematics and to the gradual detailing of the rehabilitation strategies and plans is demonstrated below with the rehabilitation of the approx. 6000km long GELSENWASSER interconnected water distribution network serving as an example.

Example: GELSENWASSER interconnected water distribution network

GELSENWASSER has long been pursuing the ideal of a permanent renewal of its water distribution facilities. The annual renewal rates – derived from an assumed service life of 100 years – were in the order of approx. 1% of the existing pipe network in the last few decades. In 2003, this long-term rehabilitation rate was confirmed for the first time by separate rehabilitation strategies for the local mains as well as for the primary and trunk mains. The rehabilitation strategies were formed using KANEW software, which is based on a cohort-survival model and which allows for the calculation of the annual pipe network renewal demands on the basis of service life distributions [23]. The prioritization of the rehabilitation measures was managed in each case by a condition-based evaluation of individual lines by the person in charge. In addition, not only staff experience, but also failure statistics and failure frequencies in the individual line sections were used in the evaluation.

In 2008, the rehabilitation strategies were re-examined in consideration of the current basic data and enlarged by a uniform and network-wide evaluation for the rehabilitation planning. The systematics applied in the GELSENWASSER interconnected water distribution network for the purpose of developing an interlinked rehabilitation strategy and planning is shown in Figure 2.

The development of the rehabilitation strategy continues to be based on the survival model implemented in the KANEW software, which in turn is based on the Herz distribution function. The service life assumptions used in this software are, however, no longer fixed on the basis of experience and expert estimations as before, but rather matched as far as possible with prognosis functions for the failure rates of individual pipe types. The empirical failure probability per pipe type as determined by means of the Kaplan-Meier procedure is approximated by a Weibull function, which is then used as a basis for failure rate prognosis [24]. The alignment with the service lives is effected by means of so-called intervention limits with respect to the failure rates of the individual pipe types. Starting from an updated rehabilitation need strategy, an alternative rehabilitation strategy was derived that, although characterized by a constant renewal rate – nevertheless allows for a reduction of the rehabilitation rate and the rehabilitation budget without entailing any losses. As far as the local mains are concerned, the former annual rehabilitation rate of 1% is lowered in steps to a constant level of approx. 0.85% of the existing pipe network (including externally induced measures without an urgent rehabilitation background) (Figure 3).

The integration of the determined failure prognosis in the KANEW software permits a direct comparison and evaluation of the effects of different strategies on the failure rate development to be expected. According to the failure prognosis, the current pipe failure rate will stabilize at first at today's level and then be approx. 0.085 failures per km and year by the end of the strategy phase in 2027 (Figure 4).

The prognosis of pipe type-specific failure rates will, however, be used not only for the evaluation of alternative rehabilitation strategies, but rather constitutes the starting point for the evaluation of the condition of individual line sections in the sub-process 'rehabilitation planning' (Figure 2). The basic failure probability of the respective pipe types is assumed also for the individual line section and up- or down-graded by means of section-related factors with regard to: the number of failure events (total / in the last ten years); max. supply pressure; and high traffic loads.

The hitherto condition-based prioritization of measures has meanwhile become risk-oriented. The extent of damage resulting from a pipe failure under the aspects of: hazards to humans and structures; supply quality (pressure, quantity, quality and availability); and repair / follow-up costs is therefore nowadays also taken into consideration besides the failure probability. Turbidity effects are taken into consideration based on frequency and intensity and independent of the pipe failure risk. The derived basic evaluation systematics is shown in Figure 5.

Required condition and environment data, which had not yet been systematically documented beforehand such as endangered infrastructure / structures or turbidity, were registered for the first time according to fixed definitions by competent foremen and technicians in GIS overview plans. The hydraulic line importance was determined for each of the 85,000 GIS line sections by means of an automatic incident

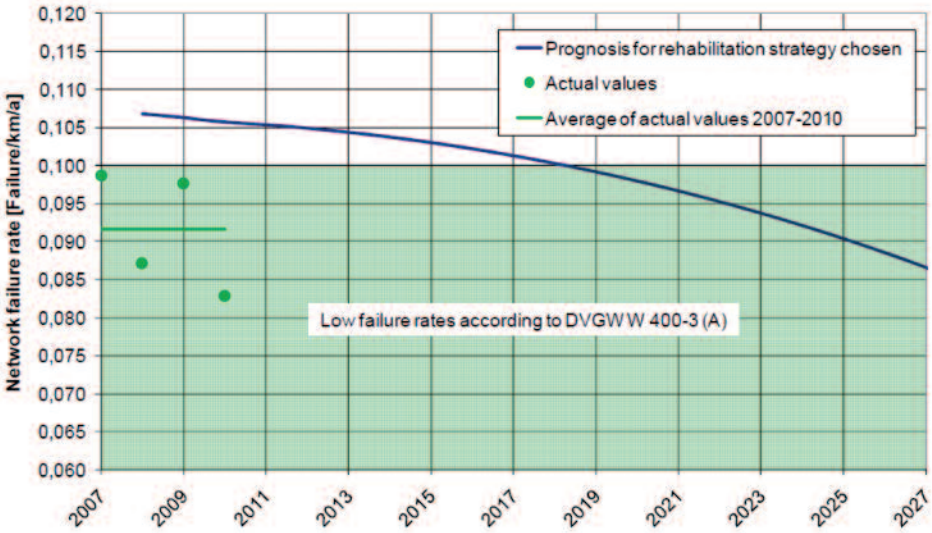


Figure 8
Comparison of the actual failure rates of local mains ≤DN 200 with the predicted pipe failure development according to the rehabilitation strategy

calculation in the existing STANET network model [25] and evaluated in the overall network context.

The combination of all relevant basic data und evaluation factors as well as the determination of priorities is implemented by means of a so-called STANET rehabilitation model. A decisive factor for the ' external use' of the pipe network simulation programme STANET was the geo-referenced graphic representation of the existing network and pipe failures – which was available without additional expenditure. The risk assessment performed for every pipeline section can be recalled in the STANET rehabilitation model in the form of data sets or graphics (Figure 6).

The measures are additionally presented per region in a so-called risk matrix (Figure 7). The priority of measures is of course not the only selection criterion. It merely serves as a support in selecting the measures. The person in charge must consider as before any locally available information (e.g. coordination of the measures with other contractors, combination of measures) in his final decision concerning the implementation of the measures.

A comparison of actual failure data of the last few years with the prognosticated pipe failure development already shows that due to the deliberate selection of rehabilitation measures with a high priority, the actual pipe failure rate is below the level predicted in the rehabilitation strategy, even in those years with a higher number of failures due to climatic causes (e.g. in 2009) (Figure 8).

The selected rehabilitation measures are determined by means of specific pipe network simulations and further optimized in consideration of the current technical conditions and alternative supply variants within the overall concept. The situation today is such that about 60% of urban local mains and about 70% of the primary and trunk mains are being renewed by means of slip lining.

With regard to simplified updating, all basic condition and environment data will be handled in future by the GIS. The same applies to the line-specific results of the risk-oriented rehabilitation planning which will be available not only in the STANET rehabilitation model, but also in the GIS. The extent to which the GIS integration of the risk-oriented rehabilitation planning makes sense in the medium-term will be examined in line with the regular updating of the STANET rehabilitation model.

Conclusions

On account of their clear-cut and structured systematics, combined with their versatility as to the use of available data, the DVGW Technical Rules really offer a holistic approach to the rehabilitation of water distribution facilities, ensuring in the long run a low-cost water supply with a high supply quality, which allows companies to effectively plan long-term, medium-term and short-term rehabilitation. The quality and the affordability of rehabilitation are only measured against the final result, i.e. the supply quality available to the customer. The fact that not only the requirements, but also the procedures adopted are practicable is demonstrated not only by the cited example of GELSENWASSER AG but is also confirmed in company comparisons performed in benchmarking projects [26].

The spectrum of software products available on the market which are offered under the terms 'asset management' and 'rehabilitation planning' is very large. The problem is that the fundamental concept not only ranges from 'clearly economical' to 'purely technical', but that the 'optimal' results, too, show strong variations. It therefore seems to make sense to measure the performance of the products against the yardstick of the requirements and objectives of the holistic approach of the DVGW Technical Rules and to take a critical attitude towards them. ●

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Improving the asset management of water mains with a polygon defined model

A key component in pipeline asset management is condition assessment of each individual pipeline in order to identify failure-prone pipes and prioritize their renewal. However, the below-ground location of pipes, combined with lack of standard guidelines and tools to assist in assessment, makes pipeline assessment and renewal decisions difficult. Here, Peter Rogers presents a polygon defined model developed to assist Denver Water with its pipe renewal decisions.

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US utility Denver Water is in the process of renewing its 2512 miles (4019km) of aging water mains in order to continue to provide its 1.3 million clients in the Denver metropolitan area and surrounding suburbs (Denver Water, 2012) with reliable, high quality, and affordable drinking water. Difficulties in assessing the condition of buried pipelines combined with the large costs associated with repairing and / or replacing water pipes in an urban environment have motivated the utility to develop a variety of scientific approaches to support its pipeline renewal decisions.

As part of this effort, in 2010 researchers at the University of Texas at Tyler (UT-Tyler) and officials from Denver Water developed a tool to help prioritize their water main renewals. Building upon the Pipe Failure Assessment Model (PFAM) originally developed and tested by the author at Colorado State University, the new tool was developed with system-specific features designed to enhance its usefulness while complimenting Denver Water's existing asset management software, Project Tracker, and existing ArcGIS models.

Despite the success of the pipe replacement tool, Denver Water's pipeline asset management group requested assistance in developing an improved model that does not require three break records in order to perform a probability-based prediction of pipe failure. Following several brainstorming sessions involving both UT-Tyler and utility personnel, both parties decided that the new tool should have the capability of evaluating and forecasting future breaks for all pipes contained within a polygon defined area.

Background

Literature on pipe break data and models began to appear in the 1980s. The earliest papers were based on descriptive statistical studies of failure patterns and break factors. While descriptive studies are valuable to enhancing understanding of pipe failure behaviour, they cannot be used in prioritizing individual pipe renewals. Accordingly, research shifted from descriptive studies towards techniques for pipe renewal prioritization. Prioritization approaches can be classified into four general categories: Deterioration Point Assignment (DPA) methods, economic models, mechanistic models, and regression and failure probability methods. A summary of the features and historical development of the DPA, economic, regression, and probability models can be found in Rogers and Grigg 2009.

Modelling details

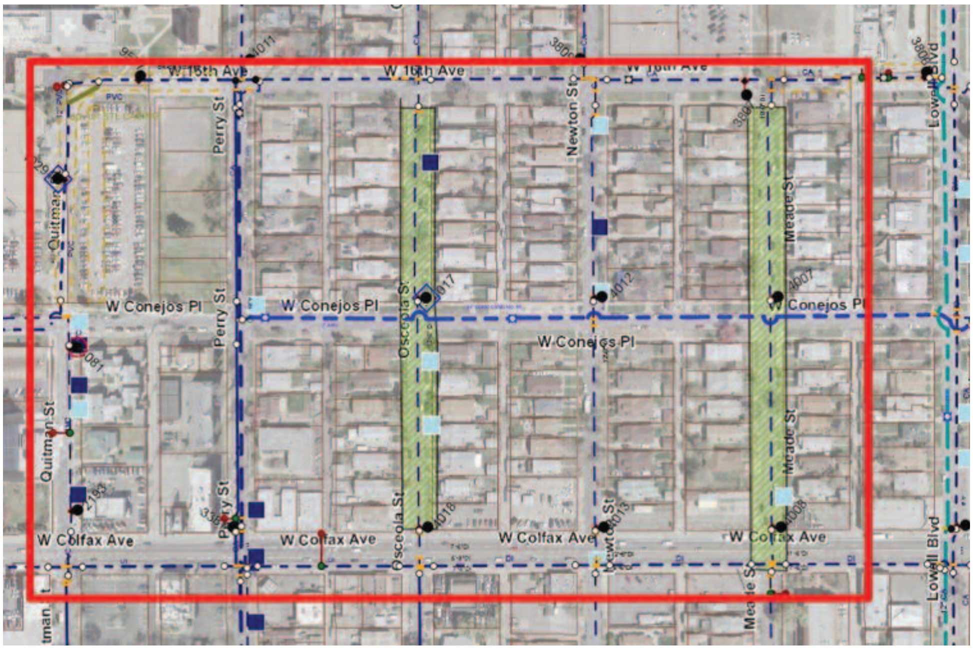
Overall approach

The model is written in Visual Basic for Applications (VBA) within a Microsoft Excel platform. Excel was selected due its availability and support of VBA user forms, which simplify data entry and analysis features. The model consists of several modules that work interactively with databases.

The fundamental change in the new model involves how the model evaluates break records. Rather than assess

Table 1: Break statistics comparison for individual pipe and polygon-based models

Break statistics: individual pipe model	
Pipes with one break	2586
Pipes with two breaks	492
Pipes with three or more breaks	219
Total number of pipes with breaks	3297
% pipes evaluated with the PFP	6.6%
Break statistics: polygon-based model	
Polygons with one break	26
Polygons with two breaks	24
Polygons with three or more breaks	96
Total number of pipes within all polygons	544
Total number of pipes within polygons with at least three breaks	470
% pipes evaluated with the PFP	86.4%



break information at the individual pipe level, the new tool evaluates and forecasts breaks for all pipes within a polygon defined area. The inclusion of all mains within the polygon (even mains with no existing break records) enables the new model to overcome the break data limitations of the earlier model which only applied a probability-based analysis for individual water mains containing a minimum of three break records. Table 1 illustrates the significance of this approach in terms of the percentage of mains analyzed within the pipe failure prediction (PFP) module. The table illustrates that the polygon-based model provides a considerably larger coverage of mains (6.6% versus 86.4%) that were evaluated using the model's failure prediction capabilities. While the polygon-based model provides an improved coverage of pipes evaluated using the PFP module, observe that there are approximately six times the number of pipes with break histories than there are pipes embedded within the polygons (3297 as compared to 544). This is because Denver Water is still in the process of creating new polygons. As the number polygons increases, the number of pipes assessed within the polygons will also increase.

The creation of the polygon boundaries was performed by Denver Water personnel using an established methodology based on pipe location. This proximity approach is supported by findings from the American Water Works Research Foundation's report entitled 'Main Break Prediction, Prevention, and Control' (AwwaRF, 2007). The report suggest that pipe location is the most important criteria influencing break rates since it incorporates site-specific risk factors

Figure 1 Example polygon for a neighbourhood serviced by Denver Water

relating to operating conditions (pressure, flows, surges), environmental conditions (soil conditions, loading conditions, temperature), and pipe attributes (age, material, etc.).

In establishing the boundaries for each polygon, Denver Water uses a process that incorporates both its asset management software, Project Tracker, and GIS. As break data (location, date, and break type) is input into the software by the utility's corrosion control department, any water main reaching either a total of two breaks within a one year period (typically associated with a one block length) or five breaks over an extended period of time is identified for replacement. At this point, GIS is used to create a polygon that encloses the portion of the pipe identified as having a valid break history. This type of polygon is usually formed using the width of the street and a length from intersection to intersection. Using the attribute data within GIS, polygon boundaries are then modified to ensure that the enclosed area lies within a uniform pressure zone (defined as a zone in which the nominal static pressure is within a specified range), encompass a particular area where known soil conditions present a potential corrosion and / or movement problem, or any number of other possibilities including installation date or material. Figure 1 shows a polygon encompassing multiple blocks within a neighbourhood located just outside the city centre. Note that the light blue squares represent the location of water main leaks whereas the dark blue squares show the location of service line leaks.

The following sections provide descriptions of the model's failure prediction, analysis, and reporting modules, highlighting how each addresses the distinct characteristics of buried pipeline infrastructure and the current operation and maintenance practices of the water utility industry. A more complete discussion is available at Rogers 2011.

Pipe failure prediction module

The failure prediction module uses break records to estimate the reliability of each pipe with more than two breaks. In the Power Law formulation of the nonhomogeneous Poisson process (NHPP) the cumulative number of expected failures, M (t), from time 0 to time t and the intensity function, $u(t)$, are expressed as:

$$M(t) = \lambda\, t^{\beta} \quad (1)$$

$$u(t) = dM(t)/d(t)\ \lambda\, \beta\, t^{\beta-1} \quad (2)$$

The β and λ terms in equations (1) and (2) represent the shape and scale factors. The scale term measures the magnitude or the relative number of failures, and the shape factor provides an indication of the system condition. A shape factor exceeding one ($\beta > 1$) indicates an increasing failure rate which is an indication of wear out. A shape factor between zero and one ($0 < \beta < 1$) implies a decreasing failure rate common with system improvements. A shape factor of exactly one ($\beta = 1$) yields a constant failure intensity, known as a homogeneous Poisson process (HPP).

Integration of equation (2) over time (t_1, t_2) yields the expected number of failures, $E(t)$, over this period:

$$E(t) = \int_{t_1}^{t_2} u(t)\,dt = \lambda\, t_2^{\beta} - \lambda\, t_1^{\beta} \quad (3)$$

For the Power Law, the waiting time to the next failure, $F(t)$, has a Weibull cumulative distribution function (CDF). Given a failure at time T, equation (4) is solved to determine the time t, in which the CDF yields a probability of one.

$$F_T(t) = 1 - e^{-\left[\lambda (T+t)^{\beta} - \lambda\, t^{\beta}\right]} \quad (4)$$

Equation (4) is also applied to determine the probability of failure, $P(t)$, as the system ages from time t to $t+dt$.

$$P(t) = 1 - e^{-\left[\lambda (t+dt)^{\beta} - \lambda\, t^{\beta}\right]} \quad (5)$$

Knowing that the probability of a failure over $(t, t+\Delta t)$ is the complement of the reliability over the same time interval, equation (5) is applied to determine the reliability, $R(t)$, that the pipe ages from time t to $t+\Delta t$ without a failure:

Table 2: Break information for the five pipes within polygon #11958

Polygon ID	Pipe ID	Break	Break Date			InstallationDate		
		Number	Month	Day	Year	Month	Day	Year
11958	MAIN_110634	1	8	2	2007	3	3	1969
11958	MAIN_111419	1	10	10	1994	3	3	1969
11958	MAIN_111419	2	5	14	1997	3	3	1969
11958	MAIN_111419	3	6	4	2003	3	3	1969
11958	MAIN_111419	4	10	25	2006	3	3	1969
11958	MAIN_111471	1	8	16	2004	3	3	1969

$$R(t,t+\Delta t) = e^{-\left[\lambda(t+\Delta t)^{\beta} - \lambda t^{\beta}\right]} \quad (6)$$

Solving equations (3) ~ (6) for the expected number of failures, time to next failure, probability, and reliability estimates, requires that the β and λ terms be estimated from the pipe break records. Defining the total time interval, t_o, as the time from the reference break time to the last break and the time interval, t_i, as time from the reference break of the ith failure, the shape and scale factors are approximated using the maximum likelihood estimates (Crow 2004):

$$\beta = \frac{n}{n\ln(t_0) - \sum_{i=1}^{n}\ln(t_i)} \quad (7)$$

$$\lambda = \frac{n}{t_0^{\beta}} \quad (8)$$

The n term in equations (7) and (8) refers to the number of break intervals relative to the reference break, which is usually taken as the first break record.

Table 3: Combinations of β, λ and R² for polygon #11958

Break Records	λ	β	R^2
1 ~ 3	5.668E-02	1.650	0.859
1 ~ 4	2.889E-02	2.024	0.945
1 ~ 5	3.291E-02	1.926	0.944
1 ~ 6	2.035E-02	2.157	0.949
2 ~ 4	1.296E-09	10.619	0.000
2 ~ 5	2.133E-04	4.243	0.000
2 ~ 6	1.917E-04	4.274	0.000
3 ~ 5	1.740E-01	1.987	0.000
3 ~ 6	1.422E-01	2.137	0.000
4 ~ 6	1.518E-03	6.710	0.000

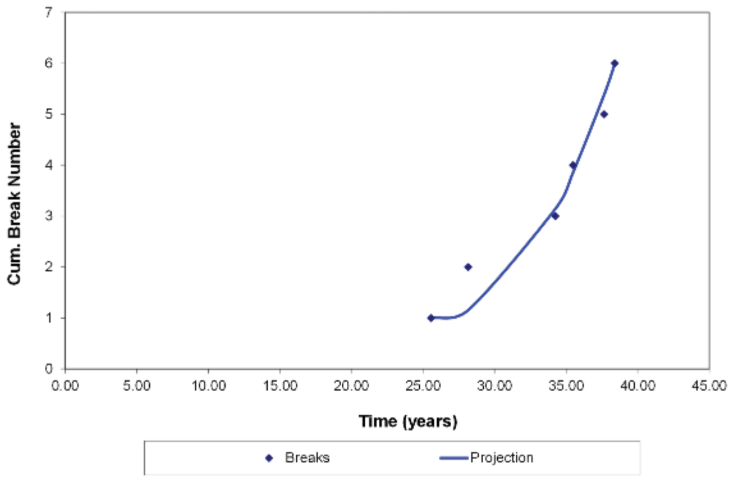


Figure 2
Variance between the Actual and Predicted Breaks for Polygon 11958

For polygon areas containing water mains with a total of exactly three breaks, there is only one value for β and λ. However, for polygons containing four or more break records, the β and λ parameters are calculated for a multitude of break record combinations. For each β and λ combination, equation (3) produces a projection of the expected number of cumulative breaks over time. The model measures the variance between the predicted breaks from this projection and the known breaks using a coefficient of determination (R^2). When evaluating an individual polygon, the user can perform a statistical analysis based on his / her break record preference (1~3, 1~4, 2~4, etc.) or have the programme select the optimum break record combination by evaluating the R^2 values for each (β, λ) combination. In the case of a system-wide statistical analysis, the programme will automatically select the parameters β and λ, which yield a maximum value of R^2.

The following example illustrates the computational procedure as well as highlights the differences between the individual pipe level and polygon-based approaches.

Example

Table 2 shows the break history information for the three pipes that make up polygon #11958. Observe that the polygon is comprised of two pipes containing one break record and one pipe containing four break records. Using the individual pipe level approach, only pipe MAIN_111419 would be evaluated using the model's failure prediction module.

Using the earliest installation within the polygon (3/3/1969) as the baseline (starting point), the model produces the ten combinations of β, λ, and R^2 shown in Table 3. Of these combinations, six produce R^2 values of zero and the other four break record combinations yield R^2 values that vary from 0.859 to 0.949. For this particular polygon, the shape and scale factors calculated using break records 1~6 yield the best correlation (R^2 =0.949). Figure 2 shows the variance between the actual and predicted breaks for this polygon.

A screen shot (Figure 3) summarizes the break information, model parameters, and shows an expected break date of 11 years and six months from the last break.

Analysis module

The model's analysis module provides the user with a variety of analysis options for both individual pipes and polygons. While the polygon-based assessment is the main feature of this new model, Denver Water requested that the model maintain its pipe-level analysis capabilities in case the utility wanted to evaluate a pipe that was not assigned a polygon. For both pipe and polygon level analyses, the analysis module allows the user the flexibility of performing a probability-based assessment for a single / polygon (as was shown in the previous example) or for a system of pipes/polygons.

Figure 4 shows the form used to perform a system-wide analysis for a polygon. The figure shows that there are two options for specifying which polygons within the network are to be evaluated. One option is to specify a range of polygons and the other is to perform an analysis for all polygons within the network. There is a similar form for performing a system-wide pipe analysis.

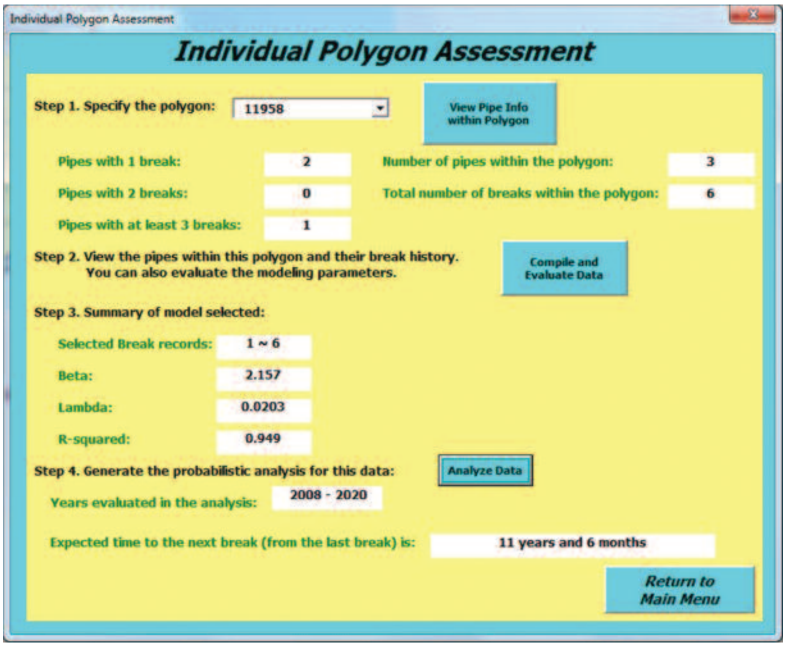


Figure 3 Screenshot of an individual pipe assessment

Reporting module

The content and format of programme's reporting module was developed in order to enhance the model's use with Denver Water's existing asset management and GIS models. As such, output from the model is in the form of spreadsheets that can be imported directly into the utilities other models. Table 4 summarizes the content of the six types of standardized reports found within the module. Note that the number of future (forecasted) breaks is based on two, four, six, and ten-year time periods from the last break of the pipe / polygon.

Table 4: Summary of the content within each standardized report

Report Type	Install Date	Time to 1st Break	Time to 2nd break	Current Total Breaks	Current & Forecasted Breaks (at 2, 4, 6, 10 years)
Pipe Reports					
- Pipes with one break	X	X			
- Pipes with two breaks	X	X	X		
- Pipe with 3 or more breaks	X	X	X	X	X
Polygon Reports					
- Polygons with one break	X	X			
- Polygons with two breaks	X	X	X		
- Polygons with 3 or more breaks	X	X	X	X	X

Table 5 provides an example of the model's polygon report for 30 of the 96 polygons analyzed within the programme's PFP module. A similar report is available for the 219 pipes containing a minimum of three break records.

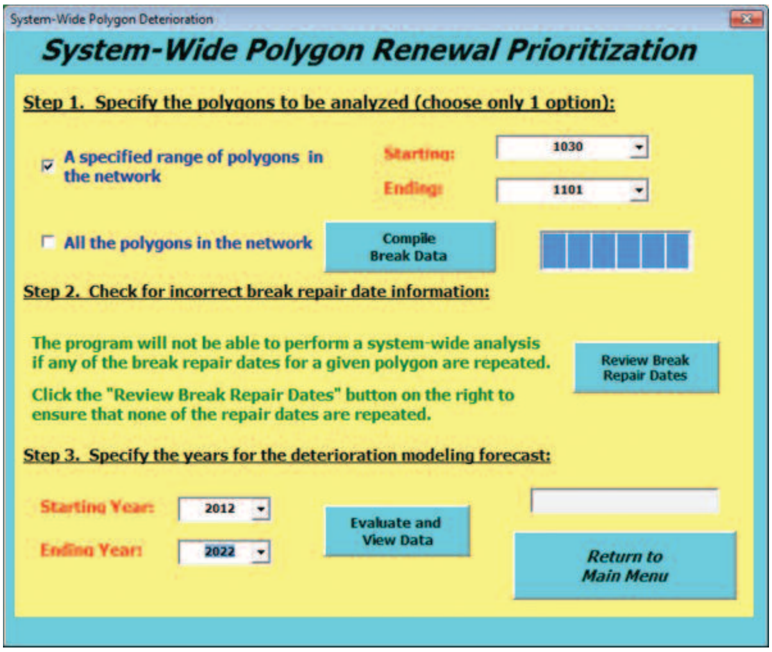


Figure 4 System-wide polygon renewal form

Results

The performance of the model's failure prediction model was assessed

Table 5: Sample of the report for polygons containing a minimum of three breaks

Polygon (Project ID)	1st Break Time (years)	2nd Break Time (years)	Current Total Breaks	Total Future Breaks (Current + Projected) 2 years	4 years	6 years	10 years
12542	47.25	53.00	6	6.08	6.20	6.36	6.77
12580	22.92	51.17	3	3.00	3.00	3.00	3.00
12813	20.25	30.67	3	3.00	3.01	3.03	3.35
12824	35.17	44.50	3	3.00	3.02	3.07	3.39
12841	33.08	33.17	3	7.58	11.09	14.37	20.55
12873	44.42	50.75	5	5.40	5.78	6.21	7.16
12895	68.25	75.67	6	6.01	6.04	6.10	6.33
13219	20.67	35.17	3	3.00	3.01	3.02	3.10
13220	49.67	50.17	5	6.11	7.04	7.97	9.80
13274	39.67	39.75	7	8.02	8.59	9.08	9.96
13283	32.33	49.75	4	4.00	4.00	4.00	4.00
13314	26.67	46.00	3	3.00	3.00	3.00	3.00
13410	14.75	42.08	4	4.00	4.00	4.00	4.00
•	•	•	•	•	•	•	•
•	•	•	•	•	•	•	•
•	•	•	•	•	•	•	•
13464	43.25	45.00	5	5.51	6.05	6.60	7.73
13487	52.67	52.75	3	8.19	11.65	14.90	21.05
13501	59.42	59.58	4	5.66	6.33	6.91	7.91
13505	72.08	80.58	4	4.03	4.09	4.16	4.34
13507	-0.08	0.08	11	11.45	11.90	12.36	13.29
13510	17.17	19.33	5	5.15	5.41	5.74	6.54
13511	30.17	32.17	8	9.36	10.40	11.35	13.10
13512	23.75	33.25	5	5.01	5.06	5.16	5.60
13514	-22.25	-4.67	5	5.00	5.00	5.00	5.02
13515	17.83	18.92	6	6.49	6.87	7.22	7.88
13539	27.42	35.08	8	8.01	8.03	8.08	8.29
13546	48.17	50.08	5	5.24	5.67	6.26	7.81
13557	34.25	35.42	7	7.66	8.10	8.53	9.39
13558	34.58	36.50	5	5.27	5.52	5.80	6.41
13567	11.83	16.92	7	7.24	7.57	7.95	8.83
13569	32.67	44.25	5	5.00	5.02	5.07	5.32
13621	21.67	55.33	3	3.00	3.00	3.00	3.00

by comparing the actual break data against the model predictions. Table 6 is an example of the model's performance in predicting the probability of failure in the year 2012 for the same 30 polygons shown in Table 5. For the 96 polygons within the entire system, the R^2 values varied from 0.65 to 0.96 with an average of 0.82. In terms of the pipe-level analysis, for the 219 pipes containing a minimum of three breaks, the R^2 values varied from 0.63 to 0.96 with an average 0f 0.77. The R^2 statistics for the pipe-level analysis

Table 6: Partial listing of the probability-based polygon results forecasted for 2022

Polygon ID	Last Break	Power Model Terms: Records	Beta	Lambda	Probability of Failure	Statistical Validity (R^2)	Next Break Date (month/year)
12542	03/2010	1~6	1.953	2.044E-02	0.587	0.858	03/2040
12580	02/2011	1~3	11.397	7.852E-18	0.000	0.734	11/2046
12813	01/2006	1~3	5.171	1.479E-06	0.917	0.734	07/2023
12824	03/2002	1~3	3.639	7.930E-05	0.978	0.734	01/2012
12841	10/2008	1~3	0.868	1.345E+00	1.000	0.734	11/2011
12873	07/2011	2~5	1.755	1.085E-01	0.365	0.905	07/2028
12895	02/2006	1~5	1.604	6.504E-04	0.585	0.897	04/2034
13219	06/2006	1~3	1.958	9.925E-05	0.174	0.734	06/2042
13220	08/2010	1~5	0.954	4.570E-01	0.995	0.852	01/2019
13274	08/2009	1~6	0.729	9.525E-01	0.969	0.874	11/2024
13283	03/2006	1~4	7.978	4.099E-11	0.104	0.838	08/2030
13314	09/2006	1~3	52.330	7.259E-59	0.000	0.734	02/2027
13410	11/2006	1~4	8.962	1.446E-19	0.002	0.858	11/2043
•	•	•	•	•	•	•	•
•	•	•	•	•	•	•	•
•	•	•	•	•	•	•	•
13464	12/2009	3~5	1.039	2.492E-01	0.963	0.930	01/2024
13487	06/2000	1~3	0.866	2.543E+00	1.000	0.734	12/2011
13501	01/2008	1~4	0.648	8.310E-01	0.990	0.875	01/2019
13505	12/2006	1~5	1.445	1.230E-07	0.460	0.724	12/2060
13507	11/2010	1~9	1.034	7.895E-01	0.920	0.906	11/2027
13510	12/2006	1~5	1.431	5.705E-02	0.936	0.917	03/2026
13511	12/2005	3~8	0.823	7.658E-01	0.998	0.949	03/2013
13512	03/2008	1~5	2.871	6.552E-04	0.624	0.752	12/2029
13514	11/1997	1~5	6.235	1.239E-08	0.995	0.735	11/2020
13515	10/2003	1~6	0.865	7.527E-01	0.963	0.942	07/2027
13539	07/2011	1~8	2.844	3.511E-04	0.257	0.965	03/2038
13546	03/2010	1~5	1.630	6.478E-02	0.962	0.917	04/2019
13557	01/2006	1~5	0.974	7.331E-01	0.967	0.840	03/2026
13558	07/2011	1~4	1.125	7.567E-02	0.757	0.851	12/2035
13567	11/2010	2~7	1.300	9.032E-02	0.874	0.957	11/2028
13569	01/2007	1~5	3.327	1.139E-04	0.399	0.842	03/2050
13621	07/2007	1~3	100.000	0.000E+00	0.000	0.000	02/2007

do not include four pipes in which R^2 was 0.00 because the shape factor (β) exceeded 100, causing the denominator in equation (8) to approach infinity and the sale factor (λ) to be zero. This occurred in pipes with break histories limited to three breaks and with very short time intervals between the second and third breaks.

Conclusions

Working closely with personnel from Denver Water, the researcher was able to develop a polygon-based model that overcomes the break data limitations of the previous probability-based model, which could only analyze mains containing a minimum of three break records. The new model also contains several features that simplify data entry and analysis as well as facilitate its use with the utility's existing asset management software.

While this project was a step in the right direction, more work is needed in order to enhance the model's usefulness to the utility. Since the 96 existing polygons contain only 544 (17%) of the 3297 pipes with break histories, the model can only forecast breaks for a small area of the system. As Denver Water continues to create new polygons, the number of pipes that can be evaluated with the model will increase significantly. ●

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