Maintenance strategy for trunk mains: development and implementation of a high spatial resolution risk-based approach

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ABSTRACT

This paper describes an enhanced concept for determining the right time and place for maintenance works (in this case rehabilitation and renewal), within the scope of a risk-based maintenance strategy for trunk mains, including a technical and economic risk assessment. The risks considered include damage caused by pipe failure (main burst) like revenue loss, third party property damage as well as damage to intangible assets (loss of company reputation). The innovative part of this concept is the intelligent combination of a remaining-service-life prognosis for pipelines with structural load factor verification, technical condition assessments, geo-referenced analyses and detailed costing. This approach allows a very detailed risk assessment of several thousand pipe sections (high spatial resolution approach). The outcome based on this concept are the required maintenance items (what and where) and a catalogue of maintenance actions (how and when) including maintenance type and costs.

Key words | remaining life time, risk assessment, trunk mains

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INTRODUCTION: CHARACTERISTICS OF TRUNK MAINS

Trunk mains are the 'aorta' of long-distance water supply systems and have therefore a very significant importance for the security of supply. In addition to high demands in reliably operating such a system, there are certain maintenance requirements to be met in order to ensure the required water quality and security of supply. Carrying out maintenance involves the inspection, service and rehabilitation of related pipes and their components (e.g. valves). Like any other technical system, trunk mains are subject to deterioration (e.g. caused by corrosion, embrittling, wear and tear), which can have detrimental effects on the security of supply (like pipe failure, dirty water occurrence, loss of water supply). Maintenance measures like servicing (e.g. operability of valves, inspections), repair and rehabilitation have a delaying effect on the deterioration process (Saegrov 2007). As the degradation process is not completely stoppable, parts of trunk main systems need to be replaced at some point of time. Most commonly, failures, specifically leakage rates, are being used to determine the condition of a pipe network when compiling a maintenance strategy for urban water supply systems (Alegre et al. 2006). Referring to trunk main systems, however, it is necessary to include and assess further parameters (e.g. pipe material characteristics, surrounding conditions, risk of pipe failure) in the overall assessment, as the extent of required maintenance cannot solely be based on failure rates in the interest of security of supply and economics (Aikman 1993). These were the objectives to create the following risk assessment tool for a trans-regional German water supply company, having regard to approaches for drinking trunk mains (Marlow et al. 2012), risk assessment approaches for other networks such as sewer systems (Halfawy et al. 2008) and a new approach as a structural load design for a whole network.

CREATING A RISK ASSESSMENT TOOL

As commonly known, risk can be described as the product of likelihood and consequences (Haskins 2007). With regard to trunk mains, endangered pipe sections can easily be identified by evaluating the following categories, as shown in Table 1. Despite the fact that the data availability of trunk main systems is limited in comparison to other technical systems of similar relevance, it is of major importance to be able to perform a very detailed risk assessment because of the essential significance of trunk main systems. Without a solid data base at hand, performing a risk assessment is very difficult which could pose a serious risk (DVGW 2008). The objective of the presented method is the utilisation of all available data and its optimal analysis and interpretation by applying a semi-quantitative approach which enables the performance of a high-resolution risk assessment down to a level of single pipe elements. The semi-quantitative approach includes qualitative data and information such as:

- pipe material (incl. condition, pipe statics, year of commissioning, geometry, etc.),
- bedding conditions (incl. loading conditions, soil corrosiveness),
- land use (roads, buildings in pipe vicinity),
- operations (incl. security of supply),

and the remaining service life of pipes as a quantitative criteria.

The varying impact of each individual criterion on the overall risk per pipe section is considered by the introduction of weighting factors which are defined in conjunction with the respective water utility (see example in the 'Risk assessment' section). If required, additional criteria, specifically parameters, can be included to design the assessment tool being as flexible as possible. This allows adaptation to the individual circumstances of any trunk main system. Figure 1 shows potential assessment parameters as well as their significance in the overall risk assessment. For example: in Figure 1, parameter 'fragility' contributes with an amount of 8% to 'consequences of failure' – but in case of an elastic pipe material, the impact of fragility decreases to '0'. The semi-quantitative approach also includes the monetary assessment of risks, specifically pipe failures. This allows the projection of current and future risk scores and the associated risk costs which then can be compared with risk mitigation costs (maintenance costs). Once the maintenance costs are lower than the predicted risk costs for a specific pipe section, this section should be renewed.

The following steps (Figure 2) are required to compile a risk-based maintenance strategy for trunk main systems.
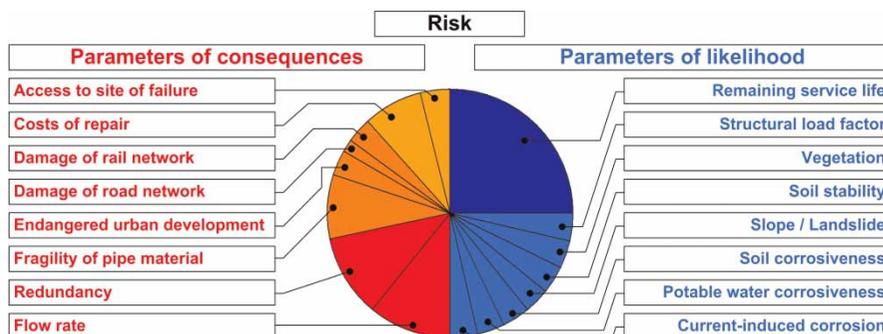
Table 1 | Risk-factor dependency of evaluating categories of trunk main systems

Risk factor	Category
Likelihood of failure	• Impact of external forces (e.g. by traffic loads) • Effect of pipe resistance (pipe condition) • Impact of corrosion and wear
Consequences of failure with regard to the pipeline itself and its nearby surroundings	• Extent of pipe repair • Extent of service interruption • Extent of infrastructure damage (own and third party property) • Extent of damage to company reputation

Figure 1 | Individual assessment parameters and their significance in the overall risk assessment – regarding significance, see Table 3.
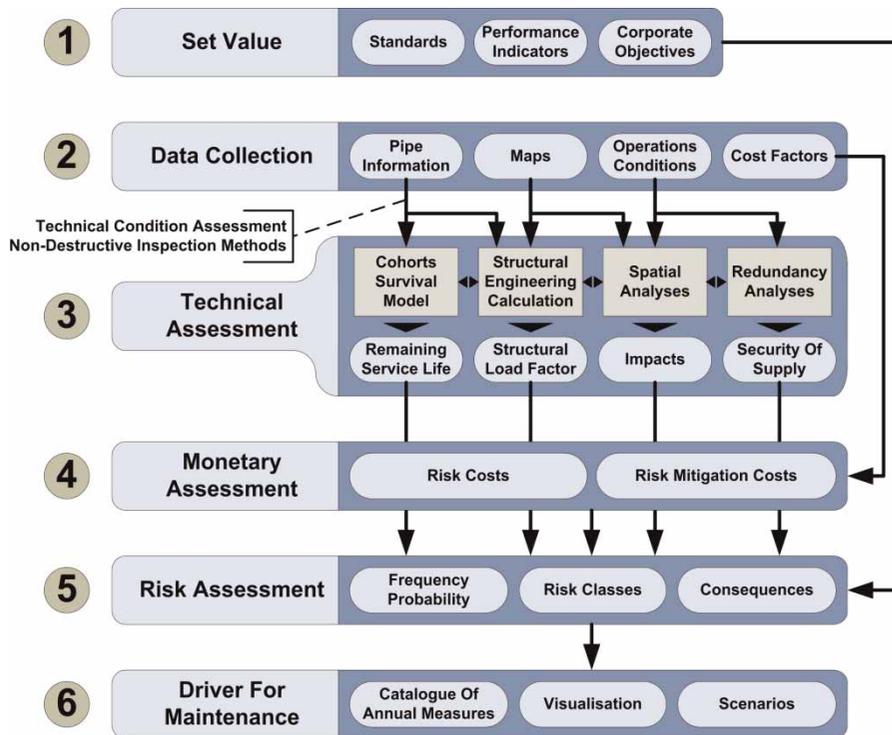
Figure 2 │ Phases of a risk-based maintenance strategy for trunk mains.

This includes the above described semi-quantitative approach and considers technical and economic framework conditions. Each individual step is described in more detail in the following sections.

Set value definition

The risk-based maintenance strategy is being compiled under consideration of regulatory framework conditions – the so-called set values. Based on set values, the water utility company defines its aspired medium to long-term level of supply in respect of technical, economic, environmental and safety-related aspects (Alegre 2009). Typical set values, for example, can be defined for the following:

- Acceptable failure rates (failures per year and kilometre),
- Acceptable water leakage rates (percent/year; m³/year),
- Maximum down time and service interruption (duration per year, per failure),
- Annual available budget for maintenance (e.g. service, repairs, rehabilitation),
- Maximum insurance cover per failure event.

During the definition process of set values, relevant staff members of the water utility are always to be consulted. Without the definition of set values, the development of a risk-based maintenance strategy is impossible, as the definition of the aspired network condition is based on them. Another method of defining an acceptable risk as a set value is calculating the risk accordingly which would apply to a complete newly built network (same route, state-of-the-art pipe material and bedding conditions), or to a network with a net asset value around 50%. The quasi-ideal trunk main system and its associated risk value should be aimed at and implemented in a medium to long term time frame, and should then be maintained.

Data collection

The implementation of technical condition assessment, remaining service life prognosis and assessment of bedding and operations conditions of the trunk main system in conjunction with the overall risk assessment, are mainly based

on data provided by the water utility. Some of the required data are listed below:

- Inventory data (pipe diameter, material, age, burial depth, etc.),
- Data from hydraulic network calculation program (pressure, flow rate, flow direction, etc.),
- Geographical information system (GIS) data (e.g. geo-referenced maps, digital terrain models),
- Inventory documentation (maps, such as site plans, section drawings),
- Statistics on pipeline failure,
- Operations data (repair costs, water quality, cathodic corrosion protection),
- Technical reports and documentaries on pipeline condition,
- Details of repair durations,
- Experience of operating personnel.

Often not all required data are readily available within the water utility. The need of procurement of missing data will be judged on its relevance for the assessment.

Technical assessment

The presented risk rating system takes into account a number of very important technical parameters influencing the likelihood and the extent of damage to a supply system. These parameters are evaluated using the analysis described below, allocated to the respective pipe sections and merged by performing the risk assessment.

Spatial analysis (GIS based)

A GIS is being used to not only visualise existing data (e.g. network plan) but also to create new information by combining various kinds of data. The intersection of existing

Table 2 | Values for the quantitative criterion of the parameter 'Likelihood of Failure', depending on remaining service life of pipe (example)

Values	Remaining service life [years]
1	31 or more
2	21–30
3	11–20
4	6–10
5	1–5

high voltage power lines with the network plan, for example, results in the identification of likely areas of current-induced corrosion of metal pipes. A second example is the highlighting of endangered dense urban areas where due to the proximity of buildings a potential pipe failure would have significant consequences. A brief overview of selected geo-referenced input data are listed in Table 3.

Not every geo-referenced input variable does have an impact on both, the likelihood and the consequences of failure. Thus, for example, the soil corrosiveness does have an increasing effect on the likelihood of pipe failure. The extent of the damage, however, is not determined by soil corrosiveness but rather by

- proximity of nearby infrastructure (e.g. buildings),
- accessibility of damaged area for repair works and associated costs (affected by vegetation density, burial depth, etc.),
- other non-geo-referenced variables (e.g. material costs, duration of interruptions).

Before the intersection and combination of geo-referenced information is being performed, the trunk main system needs to be divided into meaningful pipe sections (so-called sectioning). A hydraulically cross sectioning of the trunk main system is carried out under consideration of:

- Valves
- Nominal size
- Pipe material
- Date of commissioning

By utilising the earlier mentioned GIS-intersection, relevant geo-referenced input data and its impact on likelihood and consequences can be allocated to each individual pipe section. After that a detailed sectioning is being performed, based on specific properties such as:

- Critical infrastructure (e.g. motorways, railway embankments, culverts),
- Critical terrain structures (e.g. extreme burial depths or inclines),
- Sensitive customers in pipeline vicinity or with a direct connection (e.g. trade and industry),
- Bedding in protective tubes (impinges risk-decreasing).

The experience of the operation staff is also sought, in particular, in regard to suspicious or critical pipe sections.

Table 3 | Description and weighting of qualitative and quantitative criteria of risk calculation (example from a real application, simplified description of equations)

Criterion/Parameter	Description	Weighting factor percentage
R_{TOT}	Total risk $= E_{TOT} \times S_{TOT}$	100%
E_{TOT}	Likelihood of failure $= E_{QUANT} + E_{QUAL}$	50%
S_{TOT}	Consequences of failure $= S_{INTE} + S_{DAMA} + S_{REPA}$	50%
E_{QUANT}	Quantitative criterion, depending on remaining service life (Table 2).	25%
E_{QUAL}	Qualitative criterion $= LOAD + VEGE + STAB + SLOP + SCOR + WCOR + STRA$	25%
S_{INTE}	Extent of service interruption $= REDU + CHAR$	21,7
S_{DAMA}	Extent of infrastructure damage $= BRIT \times (BUIL \times PROT + ROAD \times PROT + RAIL \times PROT)$	16,7
S_{REPA}	Extent of pipe repair costs $= REPA + ACCE$	11,7
LOAD	Structural load factor (e.g. around 100%)	3,6
VEGE	Vegetation density in close proximity (e.g. 10 m)	3,6
STAB	Soil stability (e.g. soil subsidence)	3,6
SLOP	Critical slope of hillsides (e.g. areas of landslip)	3,6
SCOR	Soil corrosiveness (e.g. clayey soils)	3,6
WCOR	Water corrosiveness (e.g. Langelier Saturation Index)	3,6
STRA	Stray current influences (e.g. close at power lines)	3,6
REDU	Redundancies (e.g. in case of failure, supply by reservoir possible)	10,8
CHAR	Percentage on the peak hourly water discharge for each relevant district	10,8
BRIT	Brittleness of pipe (e.g. brittle pipes as grey cast iron)	8,3
BUIL	Vulnerable buildings at close range (e.g. hospitals)	3,3
ROAD	Important traffic route at close range (e.g. highways)	1,7
RAIL	Railroads route at close range (e.g. high speed rail network)	3,3
PROT	Pipe segment laid in protective tube close at BUIL, ROAD or RAIL	0/1
REPA	Repair costs (e.g. enormous repair cost at PCCP)	7,8
ACCE	Accessibility for repair works (e.g. barriers as fences)	3,9

Detailed sectioning is the basis for identifying isolated vulnerabilities in the trunk main system (so-called hot spots) – these localised pipe sections are loaded with a significant higher risk than adjacent sections. Measures to reduce risk (usually pipe rehabilitation) should therefore, among other things, focus on these sections.

Structural integrity

Structural loads on the pipe and the pipe's mechanical capacity have a very significant influence on the likelihood of failure/breakage of pipelines. External impacts cause tension (stress) in the tube wall which can lead to a fracture of the pipe when the system resistance (allowable stress) is exceeded. The system resistance is mainly dependent upon:

- Strength properties such as elastic modulus, as well as bending tensile strength,
- Pipe geometry (diameter, wall thickness).

Further impacts are:

- Soil aggressiveness (e.g. corrosion of metal),
- Drinking water quality (e.g. carbonation of asbestos cement),
- Temperature (e.g. embrittlement in plastic pipes).

The higher the impact and the lower the system resistance, the greater is the structural load factor of the pipe. This means that with an increasing structural load factor, the risk of pipe failure increases as well. A structural load factor of greater than 100% results in a very high certainty of a pipe failure (e. g. breaks/cracks/deformations). Thus, a very high risk of failure may be identified in pipe sections with a load factor >100% (resulting in a likelihood value of around 1). In addition, the calculation of the maximum allowable operating pressure may be carried out by utilising the results of the static calculations for brittle pipe materials – these results may be relevant for pressure management. To determine the structural load factor in conjunction with performing a risk assessment of trunk mains, the current and allowable component tension needs to be determined under consideration of certain safety factors. Suitable algorithms for this purpose can be found in (BS-EN 1998; ATV 2000). A certain challenge poses the estimate of the required input parameters in order to perform the calculation, which are:

- Impacts, such as
  ○ Traffic and soil loads
  ○ Fundament loads
  ○ Working pressure
- Bedding conditions, such as
  ○ Ground water level
  ○ Type of bedding
- (System)-Resistance, such as
  ○ Strength properties
  ○ Pipe geometry

If required input variables cannot be determined, it is advisable to make a conservative but plausible estimate (e.g. for traffic loads, bedding conditions, coverage levels, etc.). Another way to determine missing input variables is the so-called technical condition assessment. At this, single pipe samples are taken from the supply network which are then examined and evaluated (Figure 3). These findings may also be carried over to the same pipe type and may supplement or replace the parameters mentioned above. The pipe sample should be taken during remedial works at the failure site or by selective excavation (if technically and economically feasible). Non-destructive technologies can also be used to determine the technical condition of trunk mains. However, often varying pipe strength properties (especially tensile strength of grey cast iron) cannot yet be determined by such technologies (Rajani & Kleiner 2004).

Security of supply

Assessing the scale of supply outages also allows an evaluation of the security of supply at the same time. The following criteria are suitable:

- Duration of supply interruption (this could be also used as a set value – e.g. avoiding interruptions >24 h),
- Number of affected customers (e.g. total number, sensitive customers, supply contracts),
- Redundancies within the supply system (e.g. additional supply feed-in, network loops),
- Possibilities of a contingency supply (type, quantity, availability, setup time),
- Flow rate (e.g. Q_{max}),
- Feed-in quantities and consumption.

Figure 3 | Samples of a DN 500 (left) and a DN 700 (right) trunk main.

Pipes with high flow and a maximum number of connected customers are generally the sections with the highest vulnerability regarding interruption of supply. This is being intensified by the brittleness of pipes (fractures are generally associated with greater water losses than leaks through cracks or perforations), and an aggravated accessibility of the potential failure site (prolonged supply interruption). The consequences that are caused by condition-related pipe failure are also being taken into account. However, not part of a risk-based maintenance strategy is the consideration of risks caused by:

- Climate change (e.g. water scarcity),
- Acts of terror,
- Regulatory requirements.

These aspects are hardly or even not manageable at all by the application of common maintenance methods such as rehabilitation or renewal (Staben *et al.* 2010).

Service life prediction

To forecast medium to long term trends regarding condition or risk development, a time component in addition to the previously mentioned input variables is required. For this purpose the projected service life of each individual pipe section is deemed very suitable which is based on the inventory data with information about:

- Pipe material/pipe-generation,
- Year of commissioning/decommissioning,
- Installed pipe lengths,
- Nominal size classes.

The service life of a trunk main is not unlimited. Towards the end of its service life, affected components need to be rehabilitated. Therefore, the knowledge of the remaining service life of a pipe is central to the medium to long term planning of maintenance measures for both maintaining or even improving the network and determining the associated maintenance costs. As long as a pipe is still in operation, its estimated remaining service life can only be predicted. As part of the risk-based maintenance strategy the remaining service life of each pipe material class is being determined by applying appropriate prediction algorithms, such as the cohort survival model (Herz 2002; Ugarelli & Di Federico 2010), by information from literature (DVGW 1997) or by empirical values of staff members. The

inventory data are strictly required to use the cohort survival model. It may also be required to forecast the remaining service life for up to nine different material groups (e.g. steel, pre-stressed concrete pipes (PCCP), etc.). Taking into account the various types of manufacturing and construction within a material group, further subdivisions result in so-called material classes and pipe generations (Sorge 2007). By the division into material classes, the chronological development and improvement of pipe manufacturing processes is considered, including the development of corrosion protection, bonding techniques as well as strength and material properties. The required aging parameters needed to determine the remaining service life using this cohort survival model, were chosen depending on the mentioned material classes and had to be adjusted for the newest pipe materials (state-of-the-art, expected long service life) and the oldest pipe materials (e.g. first grey cast iron pipes, manufactured in lying sand spun with heavy wall thickness and a certain corrosion resistiveness). In addition, aging parameters were harmonised with information from former trunk main assessment projects. Example:

1. Ductile iron, state-of-the-art; aging parameters $a = 5,141$; $b = 0,1966$; $c = 105$; expected service life $= 116$ years.
2. Grey cast iron, 1st generation; aging parameters $a = 714,805$; $b = 2,192$; $c = 87$; expected service life $= 90$ years.

Monetary assessment

For a complete risk assessment, a monetary quantification of risk is highly recommended since the use of a uniform monetary unit facilitates some degree of comparability within the results. This is particularly important in maintaining a risk management system within a water supply company. This is helpful when it comes to determine what level of risk can be tolerated or at which point a non-acceptable risk can be mitigated by rehabilitation measures. Relevant cost categories can be as follows:

- Risk associated costs
  - Cost of repair (remedial works at a pipe section)
  - Loss of revenue
  - Damage to nearby infrastructure
- Risk-mitigation costs
  - Replacement costs
  - Costs of redesigning

Risk assessment

For each indexed pipe section – these can be up to a several thousand – an indication of its likelihood and corresponding consequences (extent of damage) are being calculated. They are associated with normalised values between 1 (very low) and 5 (very high). This ensures the comparability of pipe sections in spite of various influences they are exposed to (Figure 4). The definition of the value range is dependent on the particular hazards to be assessed. The overall risk score R_{TOT} per individual pipe section is then assigned to one of 25 risk categories. The following example should clarify this method:

Example:

Cast iron pipe (remaining service life 15 years), high speed rail network in close proximity, no redundancy available, flow rate highest category, structural load factor around 100%, no vegetation near pipe, no critical bedding conditions, unknown soil and water corrosiveness, power line in close proximity (25 m), no important buildings or traffic roads nearby, high repair costs, complicated accessibility, length of pipe segment 10 m, no protective tube:

Likelihood of failure: $E_{TOT} = 2.86$

$E_{TOT} = (E_{QUANT} + E_{QUAL})/2$ (semi-quantitative approach)

$E_{QUANT} = 3$ (remaining service life of pipe as a quantitative criterion – for values see Table 2)

$E_{QUAL} = W_{LOAD} \times E_{LOAD} + W_{VEGE} \times E_{VEGE} + W_{STAB} \times E_{STAB} + W_{SLOP} \times E_{SLOP} + W_{SCOR} \times E_{SCOR} + W_{WCOR} \times E_{WCOR} + W_{STRA} \times E_{STRA}$

$E_{QUAL} = 5 + 1 + 1 + 1 + 3 + 3 + 5 = 2.71$

'W' are weighting factors and 'E' are qualitative criteria for the factor 'likelihood' (Table 3). If applicable, the influence of a protective tube on pipe segments is partially considered.

Consequences of failure: $S_{TOT} = 3.69$

$S_{TOT} = (REDU \times W_{REDU}) + (CHAR \times W_{CHAR}) + BRIT \times [(W_{BUIL} \times PROT_{BUIL} \times BUIL \times L_{BUIL}) + (W_{ROAD} \times PROT_{ROAD} \times ROAD \times L_{ROAD}) + (W_{RAIL} \times PROT_{RAIL} \times RAIL \times L_{RAIL})] + (W_{REPA} \times REPA) + (W_{ACCE} \times ACCE)$

$S_{TOT} = (5 \times 1/2) + (5 \times 1/2) + 1 \times [(2/5 \times 1 \times 1 \times 0) + (1/5 \times 1 \times 1 \times 0) + (2/5 \times 1 \times 5 \times 1)] + (2/3 \times 3) + (1/3 \times 5) = 3.69$

'W' are weighting factors, 'L' is the length of the respective pipe segment (in metres) and 'S' are qualitative criteria for the factor 'consequences' (see Table 3). If applicable, the influence of a protective tube on pipe segments and even the pipe segment length is partially considered.

Calculated Risk Value: $R_{TOT} = 10.55$ out of 25 (high risk)

Same pipe 12 years later (remaining service life 3 years); a selective investigation shows that there is no soil and water corrosiveness, easy accessibility was ensured:

Likelihood of failure: $E_{TOT} = 3.57$

$E_{QUANT} = 5$

$E_{QUAL} = 2.14$

Consequences of failure: $S_{TOT} = 3.38$

Calculated Risk Score: $R_{TOT} = 12.07$ out of 25 (high risk)

This example shows that a partial risk score can be reduced by selective investigations (better information) and servicing activities (ensuring easy accessibility). The mentioned weighting factors were also used to calibrate the risk score calculations. Evidently pipe segments with a
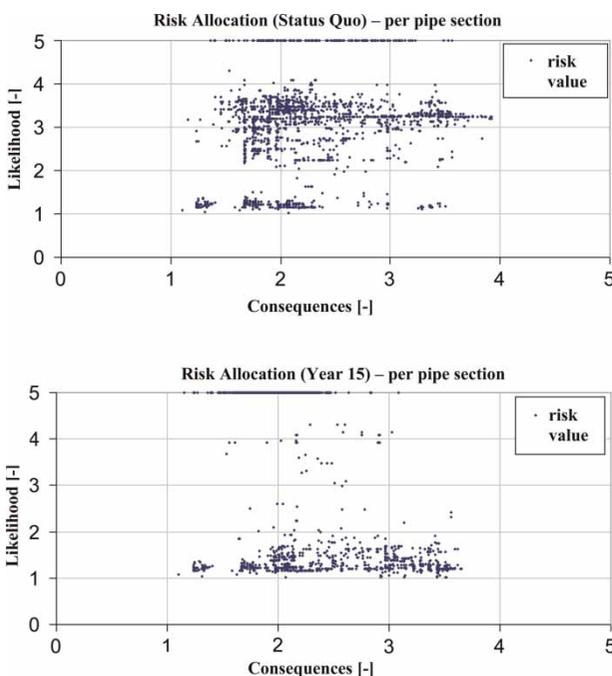

Figure 4 │ Risk score reduction of individual pipe sections within the trunk main system: Status Quo (top) and after 15 years (bottom). However, not all of the pipe sections can be replaced in time (see dots in upper area – likelihood = 5 – in lower diagram) due to progressing deterioration over time and financial constraints.

potential high risk (e.g. culverts) should also be shown by the results from risk score calculations. If not, relevant weighting factors have to be adjusted within a limited range. Besides the visualisation of the current risk (status quo), the risk score in coming years can also be displayed as the remaining service life and its influence on the likelihood of a failure can be calculated for any future point in time (the closer a pipe gets near its end of service life, the more likely a failure will be).

For simplification, the example above shows a selection of possible criteria and calculation options.

Determination of maintenance requirements

To determine the maintenance requirements the acceptable risk derived by the definition of set values must be known. It is assumed that only replacement measures exert influence on the achievement of an acceptable risk level. Furthermore, it is assumed that for the replacement of identified trunk mains state-of-the-art pipe materials are being used.

Since it is known how much funding per year is available for maintenance and also how much the estimated renewal costs per pipe meter will be, it is therefore possible to forecast the number of pipe sections which can be replaced depending on the annual budget available. Based on these (updated) figures, the overall risk score is then re-calculated.

On this basis, a detailed action plan (catalogue of measures) is created which lists the most urgent, annually renewing pipe sections until the desired overall risk score is reached or subsequently maintained. Conversely, the demand for financial resources can be identified which would be required to achieve a certain risk score in a predetermined time frame (e.g. 10–20 years).

RESULTS AND CONCLUSIONS

Conventional approaches for compiling maintenance strategies for trunk main systems are almost solely based on the account of the pipe age and its failure rate (failure per year and kilometre).

Such approaches for the development and evaluation of a maintenance strategy for trunk main systems are only suitable to a limited extent as significant influences on the likelihood of failures are inadequately considered. Furthermore, parameters such as failure rates do only apply to a limited extent for the compilation of the risk assessment of trunk main systems. Even a single failure can already lead to considerable expenses for repair and compensation.

Due to the systematic implementation of the risk-based maintenance strategy (implementation of rehabilitation or replacement measures) and the resulting preservation, respectively improvement, of the pipe condition the following short to long term effects may be avoided, which are:

- Increase in repair costs and major supply disruptions because of progressing deterioration and resulting pipeline failure,
- Renewal of larger parts of the trunk main system in a very short time frame as pipe sections can fail suddenly due to inadequate maintenance.

The concept presented here allows the identification of trunk main sections which have the most urgent maintenance need due to their overall risk, concerning pipe failure and security of supply. This will be enabled by consideration and appropriate combination of:

- Geo-referenced data (installation and building conditions),
- Calculation of loading capacity for all pipe sections,
- Individual prognoses of service life,
- Technical condition assessment, and
- Monetary risks assessment.

More than a risk indexing approach, this concept allows the simulation and assessment of different maintenance scenarios (e.g. various investments or 'do-nothing'-scenarios) regarding the security of supply and risk costs.

However, it is not possible to reduce the current expenditure on maintenance by applying the introduced risk-based maintenance strategy. Limited available financial resources are rather spent most efficiently by concentrating on pipe sections with the most urgent maintenance needs. By consistent implementation, a reduction of maintenance costs may be achieved in most cases in the medium to long term.

Meanwhile, this presented concept has been already successfully implemented in two trans-regional German long-distance water supply companies (Sorge *et al.* 2011).

REFERENCES

Aikman, D. I. 1993 Asset appraisal of trunk mains. *Water and Environment Journal* **1** (7), 37–44.

Alegre, H., Baptista, J. M., Cabrera Jr, E., Cubillo, F., Duarte, P., Hirner, W., Merkel, W. & Parena, R. 2006 *Performance Indicators for Water Supply Services*, 2nd edition. IWA Publishing, London.

Alegre, H. 2009 *Strategic Asset Management of Water Supply and Wastewater Infrastructures*. IWA Publishing, London.

ATV 2000 ATV-DVWK-A 127, Statistical Calculations of Sewer Tunnel and Pipelines. German Standard.

BS-EN 1998 BS-EN 1295, Structural design of buried pipelines under various conditions of loading. General requirements. British Standard.

DVGW 1997 DVGW W 401 German Technical and Scientific Association for Gas and Water, Decision Support for the Rehabilitation of Water Main Networks. German Standard (older version).

DVGW 2008 DVGW W 1001 German Technical and Scientific Association for Gas and Water, Technical Announcement: Safety in Drinking Water Supply – Risk Management During Normal Operations. German Standard.

Halfawy, M. R., Dridi, L. & Baker, S. 2008 Integrated decision support system for optimal renewal planning of sewer networks. *In Journal of Computing in Civil Engineering* **6** (22), 360–372.

Haskins, S. 2007 Risk management: current state, gaps, and looking ahead. In *LESAM 2007 Conference*, Lisbon, Portugal, 17–19 October.

Herz, R. K. 2002 Developing Rehab Strategies for Drinking Water Networks. In *9th International Conference on Durability of Materials and Components*, Brisbane, Australia, 17–21 March.

Marlow, D. R., Beale, D. J. & Mashford, J. S. 2012 Risk-based prioritization and its application to inspection of valves in the water sector. *In Reliability Engineering and System Safety* **100** (4), 67–74.

Rajani, B. & Kleiner, Y. (eds) 2004 Non-destructive inspection techniques to determine structural distress indicators in water mains. In *Calculation and Control of Water Loss in Urban Water Networks*. Evaluation and Control of Water Loss in Urban Water Networks, Valencia, Spain, 21–25 June 2004, pp. 1–20.

Saegrov, S. 2007 Ageing of water and wastewater networks – what is at stage and what are the real challenges? In *LESAM 2007 Conference*, Lisbon, Portugal, 17–19 October.

Sorge, H.-C. 2007 Technical Condition Assessment of Metal Water Distribution Pipes. Phd Thesis, Dept Civil Eng., Univ. of Weimar, Germany.

Sorge, H.-C., Christen, T. & Mälzer, H.-J. 2011 Maintenance strategy for trunk mains: development and implementation of a high resolution risk based approach. In *LESAM 2011 Conference*, Mülheim, Germany, 27–30 September.

Staben, N., Mälzer, H.-J. & Hein, A. 2010 Risk management for water distribution systems. *gwf-Wasser Abwasser* **151** (2), 190–198.

Ugarelli, R., & Di Federico, V. 2010 Optimal scheduling of replacement and rehabilitation in wastewater pipeline networks. *Journal of Water Resources Planning and Management* **136** (3), 348–356.