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Water Distribution System Risk Assessment Method

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Abstract

The risk assessment proposed in this paper is a method based on the calculation of three kind of indicators based on the probability of threat incidents and assessing the subsequent consequences of these ones. The consequences are measured by the upset to the service; its scope, which for the distribution service is normally quantified by the number of properties affected; and by the duration of the upset, which is directly related to the concept of system resilience or response capacity. The method to characterise a distribution system by means of risk principles aims to support better decisions, accounting for different risk assessment scopes for the purpose depending on the type of decision to be made and the time horizons involved.

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1. Introduction

The water supply and distribution service provided by a system is normally measured by its upsets to the service within a particular time interval and by the degree of non-compliance with the reference parameters or standards in place for the service. In addition to what really happened, all systems are subject to a certain risk of failing to comply with the supply standards or of suffering upsets to the service as a result of unavoidable dysfunctions, anomalies and deviations that may occur.

The consideration of this risk and its different components and assessments constitute the main parameter within which to characterise a system and its operation, thus, it is a key factor in supply and distribution system operation and planning decision making. The method put forward in this paper aims to help the making of better decisions, laying down the most suitable bases to this end: the knowledge of existing and forecasted risks. Water distribution systems

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will soon be assessed not only on the basis of the services provided, but also on the risk of non-compliance of certain standards within the short, medium and long term.

At present, distribution system risk assessment is not a general practice. There are several reasons for this, the main one is probably the lack of a generally accepted method for its calculation, which is due to the particular problems involved in distribution networks as regards the difficulty of being able to count on reliable information on its real operating system and to possess a solid knowledge base on which to determine the probability of incidents occurring that represent a threat and which are the causes of service upsets.

Fortunately, the sectorisation of distribution networks that is being implemented on a lot of distribution systems makes possible, among other advantages, to more reliably assess service risks, as well as to more efficiently reduce them. This can be achieved by the sectors configuration and design, or by means of a useful monitoring of how the distribution works and the laying down of efficient operating procedures to tackle incidents. Sectorisation, therefore, opens the door to separate risk assessments for every sector or individual property in a particular distribution system. This individual assessment contributes to the overall risk assessment for the system.

This paper describes a methodological approach to assess this type of risks in a sectorized system, in order to make planning and operating decisions and their application to the Canal de Isabel II Gestión S. A. distribution system in the Autonomous Community of Madrid (Spain). This system has over 18,000 km of piping grouped into over 800 sectors.

2. Methodological considerations

2.1. Three risk assessment scopes

The characterisation of a distribution system using risk assessment principles can be accomplished with different approaches, depending on the decisions to be made and the time limits involved.

(1) Risk linked to structural elements. It assesses the non-fulfilment of service risk related to the breakage (or some other structural dysfunction) of each system element individually. This assessment is used to make of decisions, such as those related to short and medium-term renewal investments. It takes the element's inherent characteristics into account (diameter, material, age) and others factors concerning its operational context to assign a service upset probability to each one as a result of dysfunction and its repair. This probability is based on a statistical analysis of the upsets records occurred in the past and in the use of useful service life models for each element. Additionally the global impact of the failure on each element is also assessed.

(2) Risk at consumption points. It assesses the risk of the non-availability of suitable service conditions at each property or group of properties and sectors. It analyses different risk types (discontinuity, pressure, water quality) at each service connection for structural and operational configuration and, moreover, provides information on the implications of any change to system operation. Having the entire network sectors characterised by parameters that measure the risk at the sector heads helps to make decisions both in the short term, as well as in more extended timeframes. The risk assessment in this case takes into account topological features and the sector's internal operation, studying and assessing their links to other strategic network elements (tanks, treatment stations, abstractions, pumping, and sector inlet pipes). It also assesses the impact related to the sector's internal configuration and size.

(3) Overall system risk. It represents the sum of the risks of all elements and service connections. It affords an overall view of the status of the network in terms of risk, thus enabling the making of strategic decisions in the medium and long term. It is an innovative application of a supply system's overall risk that makes possible to compare different action alternatives on a system by using homogeneous parameters from different types of service risk. It would serve as an indicator to be used as a service reference or standard for a distribution system.

The risk calculation methods, for the three proposed scopes, are based on the following formula:

$$Risk = Probability\ of\ threat\ incident \times Impact\ of\ service\ upset \quad (1)$$

2.2. Threat incidents

Generally speaking, for all risk assessment scopes, those incidents that may represent a threat to the service and the occurrence probability of which can be calculated are:

- Pipe or structural element breakage
- Pumping breakage or failure
- Demands beyond expected ranges
- Manoeuvres that fall outside expected operating scenarios and which affect service quality variables: residence times and pressures or concentration parameters (water quality)
- Anomaly at the treatment station affecting the output parameters
- Anomaly as regards water availability or characteristics at abstraction.

In all cases, the probability of the threat incident is determined by a statistical study of past records or the use of service life and failure probability calculation models that combine different explanatory variables.

2.3. Upsets

The next step is to define the potential upsets to the service as a result of the stated threat incidents. The basic service quality parameters used to classify a service as inadequate are as follows: (1) Supply discontinuity; (2) Insufficient or excessive pressure; (3) High water residence time in the network or insufficient concentration of some parameter causing water quality deficiency.

All pressure and residence time or concentration values are assessed by way of deviation with respect to reference thresholds established as standards.

The following must be taken into account to measure the impact or effects of upsets: (1) Number of properties affected; (2) Duration of the upset.

In turn, the duration of the upset is closely linked to system reaction capacity or resilience. This depends on the existing infrastructures, resources and operating practices applied for preventative and corrective maintenance. Times are measured by: (1) Problem awareness and localisation; (2) Repair; (3) Operation for alternative supplies; (4) Operation to mitigate effects.

2.4. Assessment scenarios

The starting point in all risk assessment scenarios, no matter the scope, is the characterising of the system on the basis of certain factors, which will be steady in some cases and dynamic in some others within known or expected ranges. The characteristics that define a distribution system can be grouped into seven categories:

(1) Structural characteristics or inherent attributes of the elements that constitute the system (dimensions, diameters, materials, capacities, etc.);

(2) Operating capacity of system infrastructures and equipment;

(3) Network topology and its segregation into sectors;

(4) Operating features of pumps, valves and treatment stations (input parameters to hydraulic models), linked to system operating strategy rules;

(5) Network element and infrastructure operating patterns (pumping, tanks and regulating valves) linked to expected system demand;

(6) Current and forecasted demands for the short term;

(7) Resilience capacity to cope with different types of anomaly.

Categories (1), (2) and (3) can be taken as known and steady for scenarios in the short term, as they define the system. Category (7), concerning resilience capacity, is also taken as steady because it depends on system configuration in terms of infrastructures and the set of resources and capacities to recover the service. It is normally only altered when analysing strategic change hypotheses, when implementing new technologies or for corrective maintenance policies.

The remaining categories cover dynamic characteristics that adopt changing values within a risk assessment scenario. Some of them behave in a expected or cyclic way – categories (5) and (6) linked to water demands –, and some others like category (4) are operationally variable and depend on operation planning and programming decisions. The values of the latter are known and marked out beforehand, as they are concerned with different operating rules for the strategic infrastructures.

It could be argued that all the variables covered by each of these seven categories can also differ from their given values with a certain probability, because nothing is really unchanging. Nonetheless, in the method put forward only deviations related to the aforementioned threat incidents are admitted and considered as a basis for calculation, given they are the only ones for which deviation probability can be calculated with any degree of liability.

The starting point for this risk assessment is established by using hydraulic models simulating system operation. Probable values that can be adopted by non-static system variables – categories (4), (5) and (6) – are the models' input parameters. Hydraulic models' output provides status variable values for all system elements and nodes (speed, flow, pressure, tank storage, water residence time or concentration of some water quality parameter). This may be a single value for each variable or a range of values if the simulation hypothesis covers foreseeable demand variations in the daily cycle or in the time interval under study. Moreover, there are several possible system operation alternatives. This is how the baseline data for the system (values for the characteristic system variables or status variables) is obtained before the study of occurrence of the threat incident and the risk assessment.

A tree graph is then drawn up showing the topological links of the water path and the hydraulic models' output data are transferred to it. The operating variables at system nodes are analysed, comparing the initial scenario values to thresholds and possible variation ranges that have been set to ensure service quality. Accordingly, reference ranges are set at each sector head for the calculated pressure to ensure minimum and maximum service pressure at the critical sector point, or to ensure minimum and maximum pressures at a service connection that is representative of the sector in question as a whole. Even though in reality a curve can be made at each head sector that relates the minimum pressure at the head with the number of properties that are left in the sector without sufficient pressure.

After the initial scenario has been defined, the next step is to calculate the probability of the threat incident and its link to each element to be able to draw up a tree graph that reflects the new system operating conditions in the new assessment scenario. The hydraulic models are calculated again and the deviations of the service quality variables are analysed at each node.

3. Risk evaluation

3.1. Assessing the risk in elements

Each system element is linked to an individual failure probability which depends on the type, inherent characteristics, conditions and status of each one.

- Pipes and related elements. The failure probability is assessed by a remaining useful life parameter in which the age, material, diameter, incident records, inspection records, operating pressure system, ground conditions, etc. are taken into account.
- Pumps. The failure probability is assessed in accordance with the useful remaining life, the operating system with respect to rated capacity and the incident records and findings during inspections.
- Tanks. The failure probability is linked to its structural condition and the configuration of each tank that enable compartments isolation or not in case of problem. The degree of filling in the course of the daily cycle is also assessed with respect to the reference volume to guarantee supply. This reference volume is determined as the sum of the volume that will be consumed at a future time interval equal to the repair time for the element with the greater resolution time for pipes and elements that are located upstream, plus the safety margin volume. As far as service upsets are concerned that are caused by inadequate water quality, the probability of water quality deterioration inside the tank is related to the residence time there, the maintenance and cleaning policies, the

amount of time since the last cleaning and the possible stratification and stagnation of the water. The residence time in each tank represents a contribution to the total up to consumption.

Furthermore, the impact of the upsets on the service caused by the hypothetical dysfunction is calculated for each element, multiplying the number of properties affected for the resilience or recovery ability, measured in affected time. On pipes, resilience depends on the diameter, the position and installation conditions. On pumps, resilience depends on the back-up groups and the supply alternatives when they are out of service. Lastly, on tanks, a structural failure can be resolved by special use of compartments, or simply bypassing the tank, with the subsequent effect on the risk of discontinuity.

All systems elements have an attribute that quantifies the failure risk for that element as a result of the risk assessment conducted according to this scope.

3.2. Assessing risk in consumption nodes and sectors

The sector head risk is calculated on the basis of drawing up a tree graph that represents the strategic transport network infrastructures to each sector's inlet (or inlets) and the water flow topological links; i.e. the path followed by water from sources to its treatment up to the inlet points to each sector for each one of the demand hypotheses and possible system operation rules. Accordingly, for each assessment hypothesis, each graph element is related to a probability of individual and accumulated failure in the path of the water up to the element in question. In turn, the recovery capacity or resilience for each element is assessed in the event of failure.

By following this method and using a tool to transfer the output values from the hydraulic models to the tree graph, it becomes possible to assess what the accumulated failure probability is at the sector head for each one of the service parameters (continuity, pressure and water quality), observing what the topological links with the sector's upstream strategic network are and establishing possible supply alternatives for the sector in question.

It is important to underline the fact that when calculating the accumulated failure probability in supply discontinuity, in the analysis of the sequence of elements located upstream of the point under study, the tank elements play the role of buffers capable of neutralising or alleviating accumulated probabilities arising from the elements located upstream of the same. Though it must also be remembered that, in the event of this buffer not sufficing, the failure leads to a discontinuity the recovery from which on the whole downstream system from the tank will last proportionately to the length of all the pipes and elements that may be drained as a result of draining the tank.

The impact, which is the other factor in risk equation, is assessed at the sector head by the number of properties affected and the sector resilience. This will depend on whether it has only a single inlet (which is the one assessed) or if it has another permanent, simultaneously operating one, or an identified alternative, or even other network connection possibilities that have not been formally identified.

Having characterised the inlets to each sector with the probability of failure or supply upsets, along with the associated impact, homogenous parameters are available to compare sectors and identify the more vulnerable areas in the distribution system.

Next step is to assess the risk at service connections. Likewise a tree graph is drawn up for each sector that links each one of the service connections on the distribution network through which the water circulates from the sector head (or heads) to the supply point. The hydraulic model output values are then transferred to the graph. Accordingly, all the individual nodes of each service connection and their properties are assigned sector head inadequate service probabilities (continuity, pressure and water quality), which are increased by those corresponding to the piping that leads from the head to the service connection point.

Resilience will depend on the available isolation scope (shut-off polygon) and the capacity to recover in a determined space of time (which will vary according to the type and characteristics of the problem element).

In short, the risk linked to the failure or dysfunction of each one of the distribution system elements, which can be assessed for each element, must be distinguished from the risk at each network node, which depends on the failure probability for all upstream elements and on quantified consequences for all consumption points (properties) located downstream of the node along with the resilience determined by the network's configuration.

3.3. Assessing overall system risk

After risk parameters are known at all supply nodes (probability of service upset, affected properties and duration) an overall view is now available for the distribution system risk. This risk can be assessed on the basis of parameters such as resilience, measured as maximum upset time interval at a particular number of properties at the same time, along with the probability of this being exceeded in an annual cycle, as shown as an example on figure 1. Accordingly, the system can be characterised with values of the following type:

- Probability that no individual property is without supply for more than 18 hours (something equivalent also referring to maximum and minimum service pressure and the residence time or concentration of water quality parameters).
- Probability that no group of over 5,000 properties are without supply in excess of 16 hours, and similar for pressure and water quality.
- Probability that no group of over 50,000 properties will suffer service upsets in excess of 12 hours.

Moreover, if acceptable risk target standards are laid down for the system, a comparison pattern then becomes available to make decisions. Different operating hypotheses or actions on system configuration (assessment scenarios) can now be studied along with the repercussions they have in terms of risk. It becomes possible to assess if the overall system risk, after the action under study, approaches or strays from the maximum values set as an accepted target.

As far defining overall risk target standards are concerned, the only value that would be accepted for the entire system would be overall restrictions for drought, shortage or any contingency that restricts the use of water for all users.

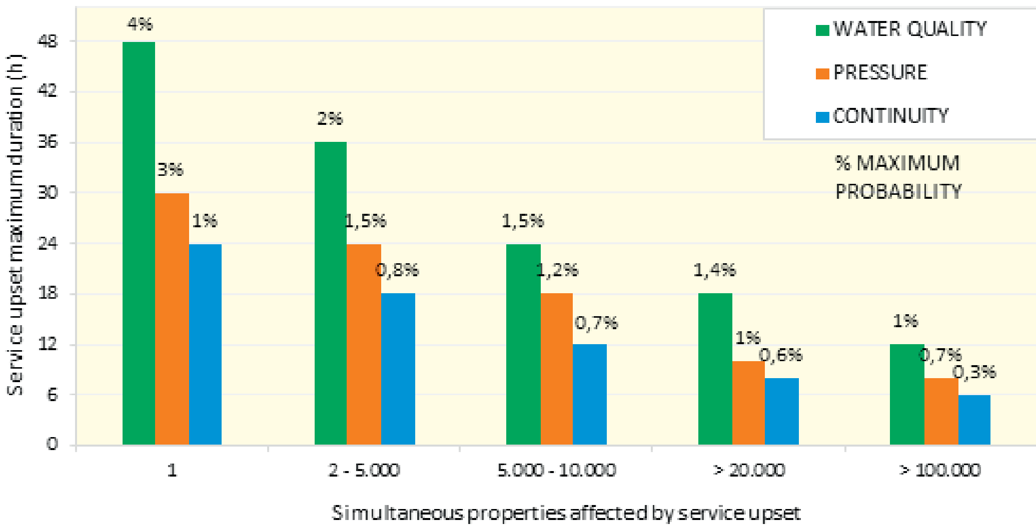

Fig. 1. Overall risk assessment.

4. Applications for decision making

Two application levels are proposed: (1) Structural, for planning investments, which may be short-term such as for renewal, or medium to long-term ones for building new structures and for strategic medium and long-term policies; (2) Operational, to identify more efficient local and strategic operating rules in the short term, and to resolve incidents on the spot in which the risk involved in the problem situation is assessed, along with the different operational options with their subsequent induced risks.

A particular structural level risk application is that of planning and prioritising network renewal actions. The implications on the risk of each action are studied in any renewal plan, in addition to taking other variables into account such as the economic, social and environmental costs. Social impacts can be added to the service upset assessment, considering which ones can cause alterations to urban activity (such as closing down traffic lanes on city roads). Each structural element has to be linked to its location on the urban stretch when conducting this assessment and there must be stretch qualification parameters available (such as, for example, the number of lanes).

The probability of the following threat incidents occurring is assessed in an operational analysis: (1) Deviation from expected demands with respect to the range of possible values at each strategic consumption node; (2) Operation or manoeuvre that causes a deviation with respect to the range of possible pressures; (3) Operation or demand that causes a deviation with respect to the possible tank storage ranges, the values of which are known and market out for the different system common operating rules; (4) Breakages or failures of structural elements or resources' availability.

Generally speaking, to make decisions at an operational level, for each sector or group of network elements any assessment must be made of the alternatives to its lack of operating capacity. Both with respect to the most probable strategic operating scheme analysed, as well as by means of other strategic operating approaches. This assessment of the alternatives must be extended to cover the most important nodes: supply sectors or special nodes. All system tanks, the majority of local tanks that can be bypassed, and pumps that have an alternative to their operation, fall into this category of special nodes.

When a problem has already occurred, the operational level risk assessment follows similar procedures to those for normal operating conditions, though the conditioning factors involved in making urgent decisions require diagnostic accuracy and analysis simplification that merit a detailed description that lies beyond the scope of this document.

5. Risk assessment example

The results are given below of the study conducted to identify, on days of maximum consumption, the areas with some types of risk, both with respect to supply continuity and non-compliance with service levels. In terms of water pressure and quality that Canal de Isabel II Gestión aspires to provide for all of its customers. This risk assessment is carried out supposing the proper working of all the infrastructures, considering as threat incidents the occurrence of maximum daily demand with high values, to which a probability is assigned, or those ones linked to structural insufficiencies or supply and distribution system element operating behaviour.

The measurement of the upset scope is based on the number of sectors and properties that are affected by: (1) Sector head pressure lower than that which ensure that all connection points have a pressure of over 25 mH_2O; (2) Water residence time of over 96 hours in the network, after its treatment; (3) Discontinuity owing to draining of a local tank. The risk of tank draining has been assessed in turn for its capacity to maintain the stored volume after serving a 24-hour consumption cycle and for approaching, in the daily cycle, stored volumes that suffice to serve less than 2 hours of its demand.

Table 1. Scope of service upsets for three risk assessment scenarios

	Operation A		Operation B		Operation C	
Service upsets	No. of sectors	No. of properties	No. of sectors	No. of properties	No. of sectors	No. of properties
Continuity (Tank min.vol.<2hrs consum.)	7	17,201	5	14,615	4	14,346
Continuity (Non-recovery in 24-h cycle)	6	3,079	5	2,681	2	517
Low pressure	7	58,095	5	24,285	0	0
Water quality problems	17	14,419	1	386	1	386
Total	37	92,794	16	41,581	7	15,246

The calculation is based on strategic network modelling, characterising distribution sectors' requirements at their inlets and hourly quantifying of the distribution demand to different sectors for a supposed maximum daily demand occurring on high temperature working days before the holiday exodus. The maximum daily demand considered has a determined occurrence probability, the calculation of which makes it feasible to use the risk formula (1) indicated in the risk assessment method section above.

The sample refers to system operating settings at the first risk assessment scenario (Operation A), which are later modified in subsequent scenarios (Operation B and Operation C) to mitigate or reduce the scope of the service upsets. The results are given in Table 1.

6. Conclusions

Having a distribution system characterised according to the risk that the service provided is inadequate is a basic decision-making aid at different levels and different time scales. Assessing system risk for different scopes: overall, customers level and by elements, provides extremely valuable information for strategic management infrastructure.

The risk assessment method proposed goes further than assessing the probability of pipe breakages on the system and analysing their consequences. It takes into account service quality upset probability from a three scope perspective: element, sector/service connection and overall system. This methodology is possible through the sectorisation of the network, which establishes a particular system configuration and enables the use of hydraulic models and tree graphs with network topology. Sectorisation also enables the impact assessment of service upsets, both with respect to the number of properties affected, as well as the duration of these ones, which is closely linked to system resilience.

This method allows for a homogeneous assessment of alternatives by means of calculating a system's risk parameters for different scenarios and time scales. It helps to compare possible action options on the system, affording an insight into the effect each one has on risk rates.

This document presents the method used at Canal de Isabel II Gestión, which is in charge of the water supply for the Autonomous Community of Madrid (Spain), to avail of a tool to aid in strategic, planning and operation decision making based on risk criteria. It is an innovative vision and a long path for future improvement of strategic management infrastructure urban water distribution systems.

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