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Active leakage control with WDNetXL

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Abstract

Water losses in Water Distribution Networks (WDNs) are classified in background and burst outflows. Bursts are generally the natural evolution of background leakages, driven by external factors that entail major water outflows, generating changes of WDN hydraulic functioning, detectable as anomalies in monitored flow/pressure data. Active leakage control strategies aim at prompt detection, localization and repair of pipe burst, thus reducing possible damages to private/public properties, minimize unplanned works, and reduce volume of lost water.
This contribution presents the novel *Leakage Control* module of the WDNetXL system, aimed at supporting various active leakage control actions ranging from the design of effective pressure sampling system up to prioritizing of possible failed pipes to survey.

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Keywords: Water Distribution System; Leakage detection; WDN hydraulic model; WDNetXL.

1. Introduction

Pipe bursts represent a potential risk to public health and can cause significant environmental damage and economic loss. From hydraulic standpoint, pipe bursts cause changes in normal WDN hydraulic behaviour due to the increase of water outflows and consequent observable pressure drop through the WDN. Usually, large bursts are rapidly fixed due to multiple complaints, while other bursts that do not result in significant impacts on the water delivery

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service run undetected for long periods, thus leading to higher volumes of lost water and potential third party damages [1][2].

Active leakage control activities usually results from a combination of flow/pressure monitoring to detect possible anomalies with respect to normal WDN operation and field survey for burst identification and repair.

The monitoring based strategies generally entail *bottom-up* approaches based on water balance or through observations of changes in night inlet volume over time (i.e., minimum night flow – MNF – analysis) [3]. Nonetheless, MNF analysis does not generally look at short-term events and are based on averaging over time [4].

Another largely used approach to detect anomalies in WDNs is based on the setting of flat-line alarm levels at key monitoring locations in a WDN, allowing near real-time identification of, usually, large bursts. However, several of these systems return a significant number of false alarms and, in addition, several events are not detected prior to customer contacts [5]. The latest advancements in *information and communication technology* (ICT) in the water sector as well as the availability of hydraulic sensor technology have enabled water companies to deploy a large number of pressure and flow devices. Data coming from such devices, when used in conjunction with reproductions/predictions of the WDN behavior by hydraulic modeling, have the potential to enable fast detection and location of pipe bursts.

Some Authors proposed to correlate flow/pressure measurements to expected WDN hydraulic behavior as returned by models reproducing candidate bursts using, for example, genetic algorithms (e.g., [4]). Other approaches proposed to use inverse transient analytics (e.g., [6]) or the WDN model calibration approach for burst detection and location (e.g., [7]). Puust et al. [8] proposed a probabilistic burst detection algorithm based on the calibration of the area of leaking orifices, using pressure measurements.

Some different procedures were based on the analysis of deviations of pressure or flow measurements from the normal/expected pressure trends caused by bursts (e.g., [9]). A Bayesian base approach was proposed by Poulakis et al. [10] in order to estimate the most probable burst events (i.e., magnitude and location) and the uncertainties in such estimates based on flow test data.

The latest literature approaches exploited the continuous stream of data coming from flow/pressure sensors installed within the WDN and collected by SCADA systems by using data-modelling strategies comprising soft computing and machine learning (i.e., artificial intelligence) techniques. Such techniques have been used mainly to detect abnormal changes in the observed variable patterns, although some example of their use in the context of on-line burst detection and location in real-life WDNs are reported with varying degrees of success and different limitations. For example, Mounce et al. [11] used artificial neural networks (ANNs) and fuzzy logic technology for the automatic analysis of flow data collected at district metered areas (DMA). In addition, Aksela et al. [12] proposed a burst detection method based on self-organizing map ANNs. Mounce et al. (2011) applied support vector machines for the detection of anomalies within potentially large amounts of normal time series sequences. Romano et al. [13] used geostatistical techniques for determining the approximate location of a pipe burst within a DMA. More recently, Laucelli et al. (2015) [14] proposed the application of the Evolutionary Polynomial Regression (i.e., EPR MOGA) strategy to reproduce and predict the WDN behaviour over time and detect flow anomalies due to possible unreported bursts or unknown increase of water withdrawal.

Another category of approaches involves field operations, which usually employ highly specialized hardware equipment, such as leak-noise correlators [15] and pig-mounted acoustic sensors [16]. Usually, such equipment is employed for pipe survey in which temporary zoning may be undertaken. Such an approach can be expensive and time consuming requiring specialized crews. In addition, it may requires the isolation of the pipeline for some time. Consequently, the accurate identification of the pipes to inspect has direct economic impact on water utilities.

This contribution presents a novel tool named WDNetXL - *Leakage* Control, which is conceived to support water utilities in various leakage control activities, ranging from the optimal design of pressure and flow sampling system up to the prioritization of pipe to survey using specialized hardware equipment. The WDNetXL - *Leakage Control* is cast as a module of the WDNetXL system [17], which is a software platform created for just-in-time transfer of research innovations on WDN analysis, management and design, working in Microsoft® Excel® environment.

The remainder of the paper briefly presents all functions of the new module, which entail a structured approach to active leakage control in WDNs to be adopted readily by water utilities. Afterwards, the novel *Anomaly Detection* function is presented in more details and its application to support pipe survey prioritization are demonstrated on a literature network, as bench case for future applications on real life context.

2. WDNetXL Leakage Control module: overview

Pipe bursts represent common occurrences in WDNs and, although few studies have been investigating the main driving factors causing such events, their accurate prediction is a complex (if not impossible) task for technicians. Pressure reduction and expensive pipe replacement campaigns can help in reducing the risk related to such events, although leakage management *best practices* (e.g., [2]) recommend that *active leakage control* should pursue the fast detection, identification and repair of new pipe bursts in order to reduce the volume of lost water and possible third party damages.

From hydraulic standpoint, pipe bursts cause the increase of water outflow from the WDN and consequent observable the pressure drop that could be detected at pressure/flow sampling points. Nonetheless, many factors make not unique the association between observed pressure drops and pipe bursts location like, for example, the looped topology of urban WDNs, the uncertainty of actual water demand delivered to customers, the unknown entity of leakage outflow, or possible errors in pressure sampling. On the one hand, this fact poses the need for designing effective pressure monitoring system in order to detect burst-induced anomalies. On the other hand, water utilities asks for reliable tools to identify the most probable burst locations, where crews should be sent for survey and repair, in order to avoid/minimize the waste of time and relevant expenses.

The WDNetXL - *Leakage Control* module provides a collection of functions entailing a structured approach to supporting water utilities for burst detection and localization, ranging from planning effective WDN monitoring (i.e., pressure monitoring design) up to prioritizing pipes to survey and repair. Fig. 1 reports the user interface of the WDNetXL - *Leakage Control* module, showing both functions (for anomaly detection/localization and pressure monitoring design) and settings available. In addition, on the top the main MS-Excel command line, all WDN data and analysis options are selected as input of the main function "WDNetXL_Leaks_Module_xls", following a similar syntax as in other MS-Excel built-in functions.

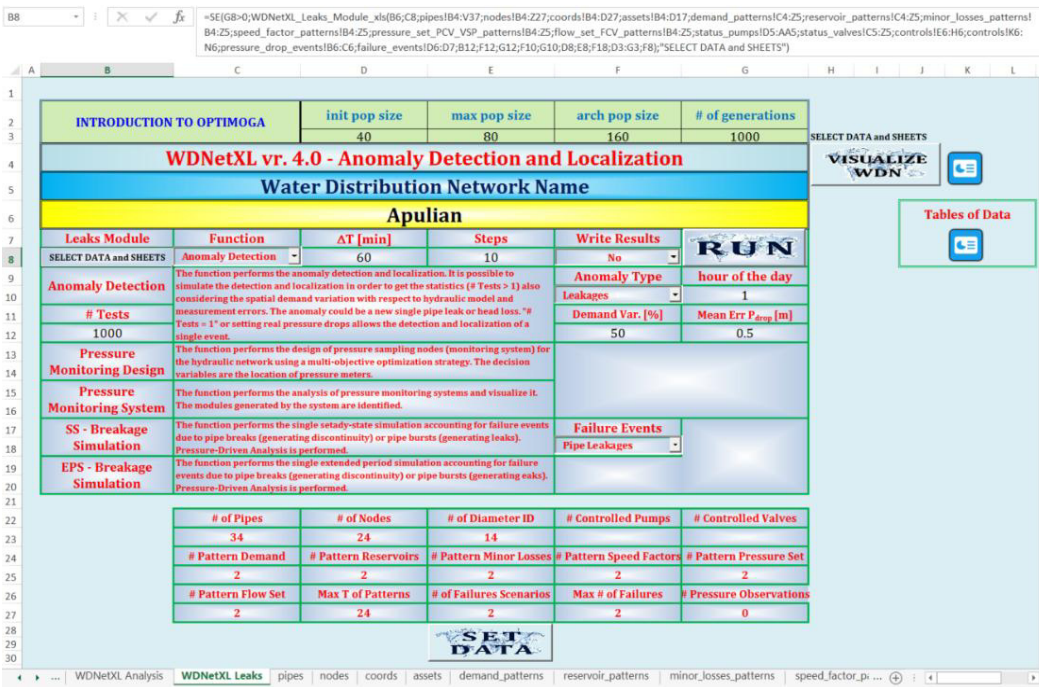

Fig. 1. User interface of WDNetXL *Leakage Control* module.

Accordingly, all functions share the same data architecture as others modules of WDNetXL, allowing easy manipulation and analysis of data in the MS-Excel environment. In particular, the WDNetXL - *Leakage Control* module is equipped also with the WDNetXL - *Analysis* module (see at the far left spreadsheet on the bottom of Fig. 1) [18], which permits network hydraulic simulation of the WDN performing the classic demand-driven analysis (DDA) (e.g., as in EPANET2 [19]) or the pressure-driven analysis (PDA) that integrates pressure-driven and background leakage model [20].

It is worth to remark that both background and burst leakages are water outflows from WDNs, which can be modelled using pressure-flow relationships consistent with the Torricelli's law [21]. In addition, the pressure drops due to major pipe bursts may cause insufficient pressure to satisfy customers' requests. Accordingly, the pressure-driven analysis PDA is mandatory to perform the hydraulic simulations of pipe bursts in WDNs where customer water consumptions and background leakages are both pressure-dependent water demand components [20][21].

In the following, the five main functions of the WDNetXL - *Leakage Control* module, are briefly presented.

2.1. Anomaly Detection function

This function entails the identification of pipe bursts based on the comparison between the pressure drop scenario(s) observed at pressure monitoring points and several WDN hydraulic scenarios simulated off-line assuming fictitious bursts of different size. Such identification does not simply return a single solution (i.e., most likely pipe burst location), but rather, returns a priority ranking of pipes to survey. The ranking criteria entail statistical analyses of the discrepancy between observed and simulated WDN hydraulic status, and encompass a number of crosschecks integrating WDN hydraulics and topology, aimed at minimizing the impact of uncertainties about actual water customers' demand, model calibration or possible measurement errors.

The *Anomaly Detection* function permits two different applications for supporting active leakage control in WDNs: (1) identifying the pipes to survey in order to localize and repair the burst that caused an observed pressure drop scenario; (2) verifying the effectiveness of the pressure monitoring system by performing statistical analysis of expected localization performances based on randomly generated burst events.

(1) The approach for burst identification provides a set of candidate pipes whose rank order should be followed by the survey crews in order to localize and repair the failed pipe. Such analysis can be performed by using real-time pressure time series (e.g., as coming from a SCADA system) or an artificial event (i.e., with pressure drops simulated by the WDNetXL model). In both cases, pressure data are assumed to come from the pressure gauges installed into the network.

(2) The analysis of localization performance is based on simulating a number of random burst events (i.e., "# Tests" in Fig. 1), in terms of both location and size, which produce as many (simulated) pressure drop scenarios at pressure monitoring points. Thus, the same strategy as in case (1) is adopted for each burst event and the statistics of pipe burst identification are drawn in terms of identification of pipes ranked as first to survey, as well as in terms of length of pipeline to survey (based on rank order) before identifying the broken pipe. Indeed, the latter information is of great relevance for water utilities since the cost of field survey equipment is directly related to the length of surveyed pipelines.
Such an analysis permits to analyze the effectiveness of the assumed/existing pressure monitoring system for the localization of pipe burst. Moreover, the statistical analysis might support the upgrade of the pressure monitoring system by verifying if the additional information collected by a new (candidate) sensor actually could improve the leakages identification performance.

More details on the *Anomaly Detection* function are provided in the case study section.

2.2. Pressure Monitoring Design function

Active leakage management is based on effective pressure monitoring, which provides data to be used, besides other purposes (e.g., model calibration, pressure control), for pipe burst identification using the *Anomaly Detection* function, as soon as the pressure drops produced by the burst are even detectable. The *Pressure Monitoring Design* functions is conceived to support the most effective location of pressure sampling nodes (monitoring system) in the WDN. The automatic design is cast as a multi-objective optimization aimed at maximizing the observability of pressure drops occurring in the system, taking also advantage from the optimal segmentation strategies. Design solution returns a number of optimal pressure sampling deployment alternatives, with a progressively increasing number of pressure sampling nodes. In addition, the design strategy permits to account for pressure gauges already installed in the WDN (e.g., at pumping systems or at tanks/reservoirs). This feature, in turn, enables water utility to perform a dynamic planning of WDN monitoring system based on the available budget.

2.3. Pressure Monitoring System function

This function permits to verify the effectiveness of the existing/assumed pressure gauges by visualizing the modules generated by the monitoring system. In fact, in order to be effective for WDN monitoring, pressure gauges should be installed at the perimeter of the monitoring zone (e.g., [22]), thus they identify network sub-portions (e.g., [23]). As such, the analysis of actual pressure monitoring system should be performed before running the *Anomaly Detection* function. In addition, such analysis might support simple upgrade of the existing monitoring system based on simple observation of the WDN topology, even without using the automatic *Pressure Monitoring Design* function. The case study section shows a sample output of the *Pressure Monitoring System* function.

2.4. Single steady-state (SS) and Extended Period (EPS) Breakage Simulation functions

The advanced WDN hydraulic model embedded in WDNetXL provides a further support to active leakage control by simulating possible pipe bursts scenarios, considering either single steady-state (e.g., 1 hour) or EPS (e.g., 24 hours) simulations. On the one hand, this analysis permits to analyze the impact of the assumed pipe burst scenario on WDN hydraulic behavior, e.g., in terms of pressure drops and supply capabilities within the WDN. On the other hand, it permits to verify the results coming from the *Anomaly Detection* function (i.e., identification and location of pipe burst) in terms of matching between the pressure drops observed and simulated at pressure measurement points.

This function permits to analyze two different kinds of pipe burst, namely *pipe breakages* and *pipe leakages*. Pipe *breakages* assume to split the pipe into two halves, thus generating a hydraulic discontinuity; pipe *leakages* assume a free leaking orifice in the middle of the pipe, while preserving the hydraulic continuity of the link.

As reported above, all such hydraulic simulations implement pressure-driven analysis encompassing also pressure-dependent customers' water demands and background leakages.

3. Case Study

The Apulian WDN [20] is used herein to demonstrate how the WDNetXL *Leakage Control* module might support active leakage control in WDNs. It was selected because its small size permits to discuss in some details different aspects of the problem in hand, although any real pressure record data was available for this system. The background leakage model [20] was preliminarily calibrated to result into a total leakage volume of about 33% of the total WDN inlet volume over 24 hour long EPS.

Assuming that Apulian WDN has not pressure monitoring system yet, the *Pressure Monitoring Design* function was used to get a set of optimal pressure gauge location alternatives. For the sake of brevity, only the pressure monitoring system selected for next analysis is reported in Fig. 2, as plotted by function *Pressure Monitoring System*. It shows six pressure gauges installed within the WDN and one pressure regains assumed (usually available in real WDNs) at water source (H_0). Such pressure gauges identify five pressure-monitoring districts.

Two pipe burst scenarios are assumed on pipes 19 and pipe 7, as indicated with a red circle in top and bottom Fig. 3, respectively. The *Anomaly Detection* function is applied to identify, for each scenario, four candidate pipes to be inspected according to the relevant ranking position, based on pressure drop "observed" at pressure gauges reported in Fig. 2; they are indicated with crosses as listed in the legends of Fig. 3. For the pipe burst on pipe 19 (top Fig. 3), the function ranks the correct pipe as the first to be inspected, thus there is only one pipe to survey, whose length is

226 m (= 1.29% of total WDN pipeline extent). It is worth noting that pipes ranked as 2nd, 3rd and 4th for inspection are actually in the neighbouring of the failed pipe. When a burst is assumed on pipe 7 (bottom Fig. 3), the pressure drop scenario results into higher pressure decrease downstream the failed pipe. Accordingly, the system does not rank the correct pipe as the first to inspect. Rather, pipe 7 is ranked as 3rd for survey, resulting into a total pipeline to inspect of 599 m (= 3.42% of total WDN pipeline extent) before catching the failure. In this case, the other pipes selected for survey are close to the actually failed pipe, demonstrating the robustness of the procedure. In fact, what is crucial in real-life maintenance activity is to send crews as close as possible to the correct pipe, while the exact location can be obtained more effectively by field survey equipment, also relying on crew expertise.

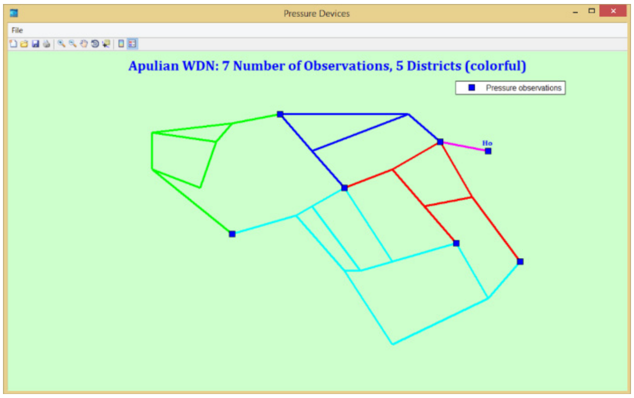

Fig. 2. Pressure sampling system assumed for Apulian WDN.

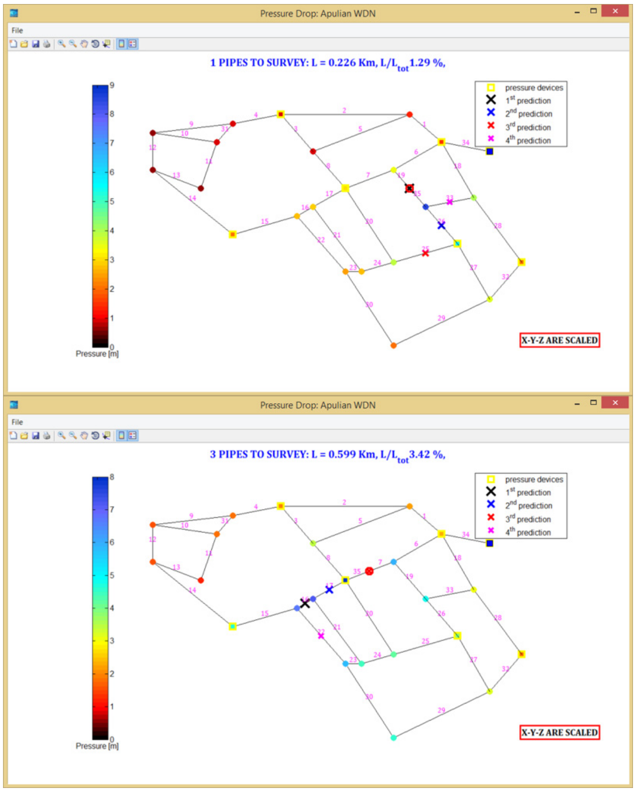

Fig. 3. Prioritization of pipe burst inspection on Apulian WDN: burst on pipe 19 (top), burst on pipe 7 (bottom).

The *Anomaly Detection* function was also used to analyse the effectiveness of the assumed pressure monitoring system (i.e., as in Fig. 2). Accordingly, 1000 random burst events were generated automatically by changing both location and size of the leaking orifice. Moreover, it was assumed that customer demands varied in a range of ±50% of the original values and that pressure “observations” were affected by 0.5m average random error.

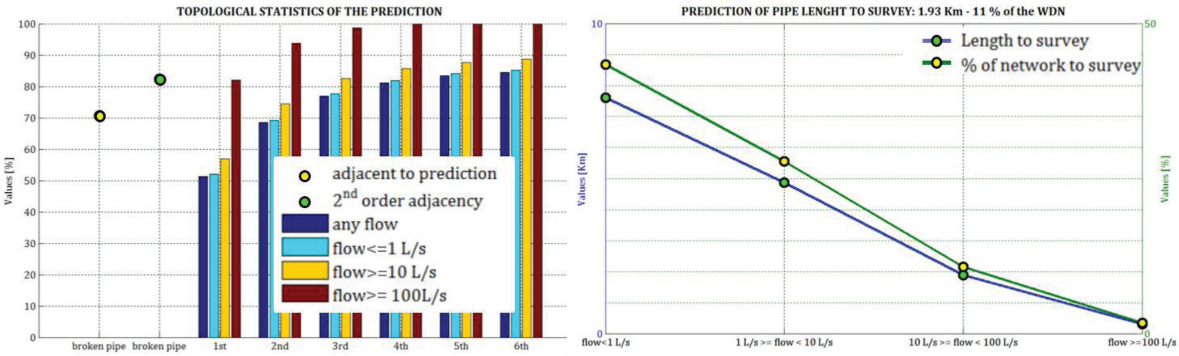

Fig. 4. Pipe burst identification statistics: pipe ranking for failed pipe (left) and length of pipeline to survey (right).

Fig. 4 (left) shows the burst identification statistics for events with various burst outflow rates, ranging from less than 1 l/s up to over 100 l/s. It is evident that the rate of success in identifying the failed pipes increases with burst outflows, because of the increasing pressure drops detected by the pressure gauges. As expected, irrespectively on the flow rate, the percent of pipe bursts that are correctly identified increases while moving from the 1^{st} up to the 6^{th} to be inspected. In the case of Apulian WDN with the assumed pressure monitoring system, more than 50% of simulated events are correctly ranked as 1^{st} to inspect, for any burst flow rate. Fig. 4 (left) also shows (as yellow and green dots) that more than 70% of actual pipe bursts are adjacent to those ranked for inspection, and more than 80% are within two pipes distance. This means that the function would address inspection crews in the correct area, while leaving to field inspection a more refined localization of the failure.

Fig. 4 (right) summarizes the same analysis in terms of average length of pipeline to survey before correctly locating the pipe burst, in terms of absolute length and percentage of total WDN pipeline. Consistently with the aforesaid observations, the survey length decreases as the flow rates (and relevant pressure drops) increase.

4. Conclusions

Pipe bursts in WDNs are caused by many concurrent factors and are characterized by large water outflows, which results into sudden pressure decrease with respect to normal WDN functioning and might cause severe service disruption and third party damages. Accordingly, WDN management best practices [2] report active leakage control strategies to pursue the fast detection, identification and repair of pipe bursts, besides effective pressure management and asset rehabilitation. Although few alarming strategies have been presented so far for detecting anomalies due to burst occurrence, they have been rarely included into a hydraulically consistent and comprehensive framework for WDN analysis and management.

This paper presents the novel WDNetXL - *Leakage Control* module, which aims at supporting many complex tasks for active leakage control, using the advanced analysis features of the WDNetXL system [17]. In its present version, the WDNetXL - *Leakage Control* module collects five main functions suited for the design and/or upgrade of the pressure monitoring system, for the simulation of any possible pipe failure scenario based on pressure-driven analysis of all water demand components and for the detection and prioritization of pipe to survey.

Besides presenting such main functions, this contribution demonstrates on the literature Apulian WDN the integrated and effective application of the WDNetXL - *Leakage Control* module for active leakage control purposes. In particular, the *Anomaly Detection* function is demonstrated to be effective for identifying the failed pipes based on pressure drop observed (i.e., recorded or simulated using the hydraulic model) at pressure gauges. The ranking approach proved to be robust in face of both uncertainties on WDN model boundary conditions (e.g., actual customers' demand) and possible pressure measurement errors. Moreover, the possibility of performing realistic advanced simulations of any pipe breakage scenario permits to analyze the effectiveness of the assumed pressure monitoring system for pipe burst identification.

The burst identification strategy lends itself to possible improvements/integration like, for example, the incorporation of information/drivers to prioritize pipe inspection., e.g. the propensity of pipes to fail by the analysis of historical pipe incidents records or the analysis of the most vulnerable WDN elements.

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