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Vulnerability Assessment of Aging Levees with WINGS and Interval Arithmetic

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Abstract: Systems of infrastructures are aging at increasing rates leading to a backlog of maintenance actions. The lack of maintenance causes failures as natural events and terrorism do. Since systems of infrastructures are integrated, failure of a system component may have cascade effects. New approaches are required for the prioritization of maintenance actions on systems of infrastructures, which also consider the interactions among different systems and the uncertainty affecting them. In this paper, the WINGS technique has been used to develop a vulnerability index for an aging system of levees. Levees are in a state of perpetual interaction with other systems such as pipelines and culverts. The WINGS method allows taking into account expert opinion about the strength of the vulnerability factors and their mutual influence. Since expert judgments are uncertain, interval arithmetic has been used to model the uncertainty and assess its impact on the vulnerability assessment. Finally, the results of the vulnerability assessment have been visualized on a GIS map. The proposed approach can be used to direct the collection of further information for more refined vulnerability and risk assessment. The final scope of the paper is to establish a sound procedure for prioritizing maintenance actions on complex infrastructure systems.

Keywords: Vulnerability assessment, Neglected maintenance, Systems of systems, WINGS, Interval arithmetic

1 Introduction

A current challenge in civil engineering is the management of portfolios of aging infrastructures.

Also the German network of waterways, which comprises several infrastructures such as locks, weirs, culverts, pipes, canal bridges, lighthouses, dams and levees, is aging. The rate at which degradation evolves in significant damages is greater than the rate at which maintenance actions can be executed, resulting in a backlog of maintenance interventions. A minimal perturbation of an aging system is sufficient to activate failure mechanisms with unpredictable cascade effects. From here a new term has been coined, the risk of disregarding or neglecting maintenance [1] whose assessment represents a strategy for the prioritization of maintenance actions. Performing a risk assessment for systems of infrastructures involves other analyses, such as vulnerability and criticality assessment, according to which the proneness of the system to develop failure scenario and the consequences of failure can be determined. While the notion of vulnerability is fairly mature for single objects, it is still evolving for systems of infrastructures, and only recently it has been considered in relationship with complex infrastructures systems or Systems of Systems (SoS) [2]; thus it is necessary to develop new ideas for assessing the vulnerability of SoS, which also take into account the interaction among the subsystems.

Usually vulnerability assessment implies the development of indexes, which are often a combination of several indicators or factors. An often applied aggregation model is the additive weighting, according to which the vulnerability index is obtained as the weighted sum of several indicators. The assignment of the weights, which represent the relative importance of each indicator, is a challenging task. Furthermore, the use of additive weighting as an aggregation model requires independence of the indicators. This condition is often ignored leading to biased composite indicators.

This paper focuses on the development of a vulnerability index for the assessment of a levee system. We propose to use the Weighted Influence Non-linear Gauge System (WINGS) [3] to derive weights for vulnerability indicators, which do not disregard their interdependencies. WINGS represents an evolution of the DEcision-MAking Trials and Evaluation Laboratory (DEMATEL) [4, 5], a method that serves as a Multi-Criteria Decision Analysis when interrelations among criteria cannot be neglected. However, DEMATEL considers only the intensity of the influence among the factors; WINGS raises the bar by considering also the strength of the acting factors. Since WINGS is a new method, only a few applications exist [6, 7]; this paper represents a new application of WINGS in the context of the vulnerability assessment of aging infrastructures systems. Furthermore, the uncertainty in the experts judgments are also considered by combining WINGS with interval arithmetic [8]. Results of the vulnerability assessment are finally visualized on a GIS map, which allows better communication with the stakeholders. The paper is organized as follows: in Sect. 2 the main factors affecting the vulnerability of levee systems are identified; in Sect. 3 the steps of the WINGS technique are described; in Sect. 4 WINGS is combined with interval arithmetic in order to consider uncertain expert judgments; in Sect. 5 the case study is introduced, and the WINGS method has been applied to assess the vulnerability of a levee system; finally, in Sect. 6, the conclusion is drawn and the further steps of the research are briefly described.

2 Vulnerability Assessment of Levees

Among the infrastructures of the German waterways network, levees raise special concerns because of the dramatic consequences to which the failure of a levee often leads. Levees support the water level in canals or rivers. In the case of rivers, the water level varies depending on the outflow, which in turn it depends on weather phenomena; in a canals levee, the water is often pumped and kept constant by pumping stations. In both cases, the water level is above the adjacent terrain. Levees fail when a breach forms, which means that a portion of the levee collapses, resulting in the significant loss of crest or the creation of a hole, causing the uncontrolled loss of water and flooding the surrounding area.

Breaches are usually the final stage of other deterioration and damages processes, such as erosion, scour and slippage, whose presence initiates some sort of failure mechanisms like piping or slope instability. Such deterioration processes increase the vulnerability of the system, which is the likelihood that a breach will form.

But also other factors affect the vulnerabilities of levees, and especially the presence of encroaching structures and transition zones [9], such as penetrating structures like pipelines and culverts, or general buildings. Those structures may provoke damages to levees when they are inadequately designed, constructed and maintained, such as when: the material of the structure has not an adequate strength to withstand loads; the structure is unable to accommodate movements resulting from foundation settlements; unsuitable backfills materials are used; unstable materials like gas and other explosive substances are conveyed through pipes. At the same time, the condition of the levee also affects the condition of those structures, for example in the case of piping and settlements of levees or foundation soils.

Also transitions zones increase the levee vulnerability; those are represented by any portion of a levee where the geometric configuration changes, such as in case of changes of the levee cross-section, when the previously mentioned encroaching structures are present or in case of walls, gates, sluices or other constructions. Transitioning between different geometric configurations or material compositions creates a critical junction that often represents a focal point for the concentration of tensions, eventually resulting in the activation of a failure mechanism.

3 WINGS

As stated in Sect. 1, WINGS can be applied to study the structure of relationships which exist among a set of factors, rank the factors according to their involvement in the system and classify them as 'influencing' and 'influenced'.

The steps of the WINGS procedure are the following:

1. Generate the direct-influence matrix *D*

   Let us consider a set of *n* factors $F = \{F_1, F_2, \ldots, F_n\}$. An expert is asked to indicate the strength of all system factors and the level of influence between system factors using a rating system that goes from 0 (no strength/influence) to 9 (very high strength/influence). The direct strength-influence matrix provided by the expert can be formed,

$$D = \left[d_{ij}\right]_{n \times n} \tag{1}$$

   where d_{ii} and d_{ij} represent the judgment of the decision maker on respectively the strength of F_i and the influence of F_i on F_j.

2. Establish the normalized direct influence matrix *S*.

   This matrix can be obtained by using

$$S = \frac{D}{s}, \tag{2}$$

   where

$$s = \sum_{i=1}^{n} \sum_{j=1}^{n} d_{ij}. \tag{3}$$

3. Construct the total influence matrix *T*:

   The matrix $T = [t_{ij}]_{n \times n}$ is computed by summing the direct and indirect effects; the normalization of *S* ensures convergence of *T*:

$$T = \lim_{w \to \infty} \left(S + S^2 + \cdots + S^w \right) = S(Id - S)^{-1} \tag{4}$$

4. Calculate the total impact and the total receptivity

   Row and columns wise summation of the elements of *T* gives the total impact r_i:

$$r_i = \left[\sum_{j=1}^{n} t_{ij} \right]_{n \times 1} \tag{5}$$

   which represents the influence of the component *i* on all other components of the system, and the total receptivity c_j,

$$c_j = \left[\sum_{i=1}^{n} t_{ij} \right]_{n \times 1}. \tag{6}$$

   which represents the influence of all other components in the system on the component *i*.

5. Calculate the total involvement and the position of the component

   Finally it is possible to calculate for the factor F_i the total involvement:

$$r_i + c_j \tag{7}$$

   which represents the sum of all influences exerted on and received by the component I, and the position value:

$$r_i - c_j. \tag{8}$$

   If $r_i – c_j$ is positive, the factor F_i can be classified as ‘influencing’, otherwise, it belongs to the ‘influenced’ group.

4 If Expert Judgments are Uncertain: WINGS with Interval Arithmetic

The judgments provided by the experts in the WING method about the strength of the factors and their mutual influence may be affected by uncertainty. One way to describe this uncertainty is through pairs of verbal assessments, which when mapped onto numerical scale will become intervals. An interval is a connected subset of $\mathbb{R}$ usually denoted by $[x]$. When the upper and the lower bounds are the same, the interval can be identified with a real number. The midpoint of any bounded and nonempty interval is given by:

$$[x] = [\underline{x}, \overline{x}], \underline{x} \leq \overline{x}. \qquad mid([x]) = \frac{\underline{x} + \overline{x}}{2} \tag{9}$$

where $[x] = [\underline{x}, \overline{x}], \underline{x} \leq \overline{x}$. The classical operations of real number arithmetic can be extended to intervals [10]. The basic notion of linear algebra such as vectors and matrices can also be generalized to the interval case. In particular, an $(m \times n)$-dimensional interval matrix is a subset of $\mathbb{R}^{m \times n}$ — the set of all matrices with real coefficients, and it is defined as the Cartesian product of $m \times n$ close intervals. It is uniquely represented by their $m \times n$ elements $[a_{ij}], i = 1, \dots, m; j = 1, \dots, n$. The midpoint of an interval vector and an interval matrix can be defined in an obvious way. The matrix D becomes an interval matrix:

$$[D] = [\underline{D}, \overline{D}]. \tag{10}$$

The scaling factor is calculated as follows in order to ensure convergence and preserve consistency:

$$s = \sum_{i=1}^{n} \sum_{j=1}^{n} \overline{d}_{ij} \tag{11}$$

which leads to

$$[S] = [\underline{S}, \overline{S}] = \frac{[D]}{s} = \left[\frac{\underline{D}}{s}, \frac{\overline{D}}{s}\right]. \tag{12}$$

The bounds of the interval matrix T can be calculated separately from the following equations:

$$[T] = [\underline{T}, \overline{T}] = \left[\underline{S}(Id - \underline{S})^{-1}, \overline{S}(Id - \overline{S})^{-1}\right] \tag{13}$$

From which the bounds for the total impact and total receptivity can be calculated:

$$[r_i] = [\underline{r}_i, \overline{r_i}] = \left[\left[\sum_{j=1}^{n} \underline{t}_{ij}\right]_{n \times 1}, \left[\sum_{j=1}^{n} \overline{t}_{ij}\right]_{n \times 1}\right] \tag{14}$$

$$[c_j] = [\underline{c}_j, \overline{c_j}] = \left[\left[\sum_{i=1}^{n} \underline{t}_{ij}\right]_{n \times 1}, \left[\sum_{i=1}^{n} \overline{t}_{ij}\right]_{n \times 1}\right] \tag{15}$$

and consequently also the bounds for the total involvement and position of the component:

$$\left[r_i + c_j\right] = \left[\underline{r_i + c_j}, \overline{r_i + c_j}\right] = [r_i] + \left[c_j\right] = \left[\underline{r}_i + \underline{c}_j,\ \overline{r_i} + \overline{c_j}\right] \tag{16}$$

$$\left[r_i - c_j\right] = \left[\underline{r_i - c_j},\ \overline{r_i - c_j}\right] = [r_i] - \left[c_j\right] = \left[\underline{r}_i - \overline{c_j},\ \overline{r_i} - \underline{c}_j\right]. \tag{17}$$

If indeed we are interested in the midpoints of the above-mentioned values, we can directly calculate them from the matrix T_m, which contains the midpoints of $\underline{T}$ and $\overline{T}$:

$$[\boldsymbol{T}_m]_{ij} = \frac{[\underline{\boldsymbol{T}}]_{ij} + [\overline{\boldsymbol{T}}]_{ij}}{2}. \tag{18}$$

5 Case Study

5.1 Introduction

An application of the WINGS method is developed to assess the vulnerability of a portion of the system of levees of the West German network of canals. Since this region is the largest urban area in Germany, and 20% of the freight traffic of the German waterways is regularly moved on the canals, the waterways play a fundamental role for its economy; considering also the high density of population and industries, the failure of a levee could have catastrophic consequences in social and economic terms. The levees are currently in a bad condition: many of them show degradation phenomena such as erosion, vegetation and stability problems. The levees are penetrated by a huge number of structures, especially pipelines and culverts, which make things worst. Information about vulnerability indicators is collected during the periodical inspections of the levees and stored in devoted databases. By simplifying, we will assume that the indicators take only two possible values: yes/no, fulfilled/not fulfilled, good/bad. They can be considered as binary parameters having 2 possible values, on/off, where ‘on’ corresponds to “the vulnerability indicator is enabled” and “off” corresponds to “the vulnerability indicator is disabled”.

5.2 Identification of Vulnerability Factors

The identified vulnerability factors are listed in Table 1. The condition of pipelines and culverts can be classified as good or bad according to the damages which have been collected during the periodical inspections. Levees are characterized by the following cross sections: rectangular, trapezoidal, and mixed. Sometimes a levees segment is characterized by more than one cross-section. The presence of drainages and seals, as well embankment walls, also represents a change in the levees cross section, and for this reason, they should be considered as vulnerability factors. Information about the condition of those objects would be relevant for determining the levee vulnerability, but unfortunately, it is very difficult to acquire it since the canal should be dried. Some levees are equipped with inspection devices that allow recognizing deterioration processes properly. Thus the presence of inspection equipment reduces the vulnerability of the levee. However, this allows the levee to be inspected only at isolated points, which means that only a limited fraction of the possible defects can be identified.

Table 1: Binary values assumed by the vulnerability factors

Vulnerability factors	Disabled	Enabled
Pipeline encroachment (P)	No	Yes
Pipeline condition (PC)	Good	Bad
Culvert encroachment (C)	No	Yes
Culvert condition (CC)	Good	Bad
Other objects (O)	No	Yes
Stability of the levee (St)	Fullfilled	Not fullfilled
Soil erosion (Er)	Fullfilled	Not fullfilled
Burrowing animals (B)	No	Yes
Vegetation (V)	No	Yes
Change of the geometry (G)	No	Yes
Seal (S)	No	Yes
Internal seal (IS)	No	Yes
Drainage (D)	No	Yes
Embankment walls (E)	No	Yes
Inspection devices (I)	Yes	No
Levees water level (LH)	<3 m	≥3 m

5.3 Application of WINGS

The expert assesses the strength of the vulnerability factors and their mutual influence by compiling the individual direct strength-influence matrix (Table 2). In case of uncertainty, an interval evaluation is given.

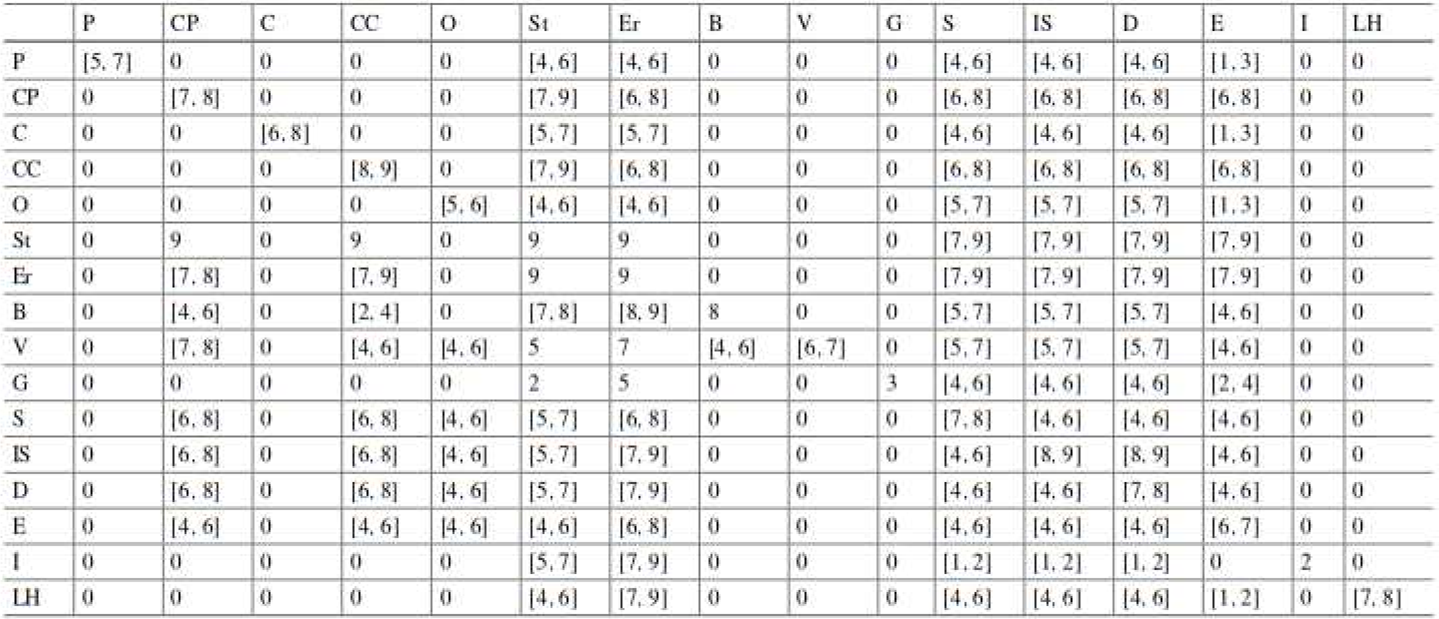
The steps of the method described in Sect. 4 are further applied to obtain the bounds for the position and especially the total involvement value associated with each factor (Table 3), from which the bounds for the vulnerability index will be derived.

5.4 Vulnerability Assessment

To assess the vulnerability, the levee has to be divided into homogeneous segments, which are characterized by different lengths: from several hundred to few meters (i. e. in case of object encroachment). For each segment m, an interval vulnerability index $[VI_m]$ is computed considering the upper and lower bound of the total involvement value which characterizes each vulnerability factor:

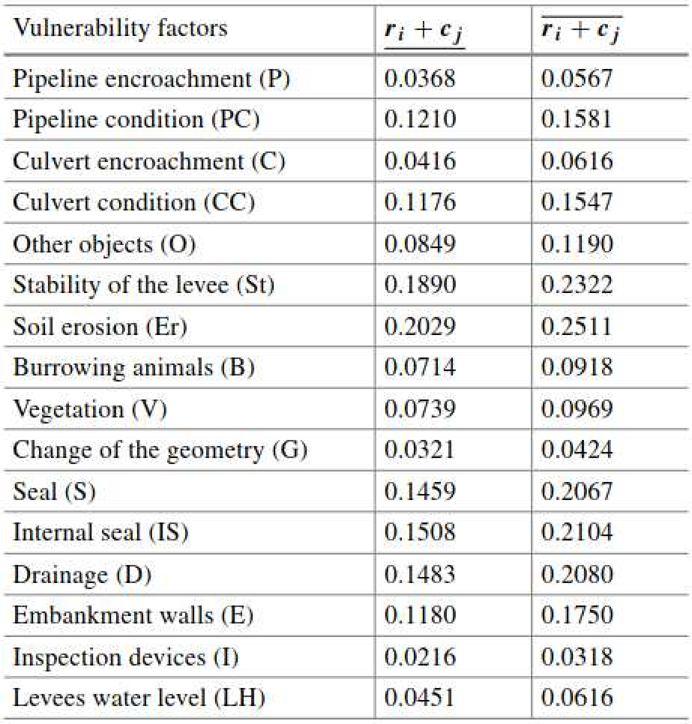
$$\overline{VI_m} = \frac{1}{\max \sum_{i \in P} \overline{(r_i + c_i)}} \sum_{i \in P} \overline{(r_i + c_i)} \qquad (19)$$

Table 2: Direct strength-influence interval matrix [D].



	P	CP	C	CC	O	St	Er	B	V	G	S	IS	D	E	I	LH
P	[5, 7]	0	0	0	0	[4, 6]	[4, 6]	0	0	0	[4, 6]	[4, 6]	[4, 6]	[1, 3]	0	0
CP	0	[7, 8]	0	0	0	[7, 9]	[6, 8]	0	0	0	[6, 8]	[6, 8]	[6, 8]	[6, 8]	0	0
C	0	0	[6, 8]	0	0	[5, 7]	[5, 7]	0	0	0	[4, 6]	[4, 6]	[4, 6]	[1, 3]	0	0
CC	0	0	0	[8, 9]	0	[7, 9]	[6, 8]	0	0	0	[6, 8]	[6, 8]	[6, 8]	[6, 8]	0	0
O	0	0	0	0	[5, 6]	[4, 6]	[4, 6]	0	0	0	[5, 7]	[5, 7]	[5, 7]	[1, 3]	0	0
St	0	9	0	9	0	9	9	0	0	0	[7, 9]	[7, 9]	[7, 9]	[7, 9]	0	0
Er	0	[7, 8]	0	[7, 9]	0	9	9	0	0	0	[7, 9]	[7, 9]	[7, 9]	[7, 9]	0	0
B	0	[4, 6]	0	[2, 4]	0	[7, 8]	[8, 9]	8	0	0	[5, 7]	[5, 7]	[5, 7]	[4, 6]	0	0
V	0	[7, 8]	0	[4, 6]	[4, 6]	5	7	[4, 6]	[6, 7]	0	[5, 7]	[5, 7]	[5, 7]	[4, 6]	0	0
G	0	0	0	0	0	2	5	0	0	3	[4, 6]	[4, 6]	[4, 6]	[2, 4]	0	0
S	0	[6, 8]	0	[6, 8]	[4, 6]	[5, 7]	[6, 8]	0	0	0	[7, 8]	[4, 6]	[4, 6]	[4, 6]	0	0
IS	0	[6, 8]	0	[6, 8]	[4, 6]	[5, 7]	[7, 9]	0	0	0	[4, 6]	[8, 9]	[8, 9]	[4, 6]	0	0
D	0	[6, 8]	0	[6, 8]	[4, 6]	[5, 7]	[7, 9]	0	0	0	[4, 6]	[4, 6]	[7, 8]	[4, 6]	0	0
E	0	[4, 6]	0	[4, 6]	[4, 6]	[4, 6]	[6, 8]	0	0	0	[4, 6]	[4, 6]	[4, 6]	[6, 7]	0	0
I	0	0	0	0	0	[5, 7]	[7, 9]	0	0	0	[1, 2]	[1, 2]	[1, 2]	0	2	0
LH	0	0	0	0	0	[4, 6]	[7, 9]	0	0	0	[4, 6]	[4, 6]	[4, 6]	[1, 2]	0	[7, 8]

Table 3: Lower and upper bound of the interval total involvement [$r_i + c_j$]



Vulnerability factors	$\underline{r_i + c_j}$	$\overline{r_i + c_j}$
Pipeline encroachment (P)	0.0368	0.0567
Pipeline condition (PC)	0.1210	0.1581
Culvert encroachment (C)	0.0416	0.0616
Culvert condition (CC)	0.1176	0.1547
Other objects (O)	0.0849	0.1190
Stability of the levee (St)	0.1890	0.2322
Soil erosion (Er)	0.2029	0.2511
Burrowing animals (B)	0.0714	0.0918
Vegetation (V)	0.0739	0.0969
Change of the geometry (G)	0.0321	0.0424
Seal (S)	0.1459	0.2067
Internal seal (IS)	0.1508	0.2104
Drainage (D)	0.1483	0.2080
Embankment walls (E)	0.1180	0.1750
Inspection devices (I)	0.0216	0.0318
Levees water level (LH)	0.0451	0.0616

$$\underline{VI_m} = \frac{1}{\max \sum_{i \in P} \left(\overline{r_i + c_i}\right)} \sum_{i \in P} \left(\underline{r_i + c_i}\right) \tag{20}$$

$$0 \leq \underline{VI_m} \leq \overline{VI_m} \leq 1 \tag{21}$$

where P is the subset of vulnerability factors which are enabled in the levee segment *m*.

The maps (Fig. 1) reveal that the scores associated with some levees segments (which correspond to a certain gradient of color) overlap, which makes it difficult to uniquely rank the levees according to their vulnerability since their position can be interchanged. If the decision maker is not satisfied with these results, the uncertainty affecting the expert judgments should be reduced in order to resolve this ambiguity.

6 Conclusion

In this paper, the vulnerability assessment of a levees system due to neglected maintenance has been carried. The levees system comprises other infrastructures systems such as pipelines and culverts, which are in a state of perpetual interaction with the levee. This implies that the vulnerability of those systems affects the vulnerability of the levees system and vice versa, and the failure of a system component propagates in a non-linear way leading to cascade effects. To consider the nonlinearity of the problem, the WINGS technique has been proposed.

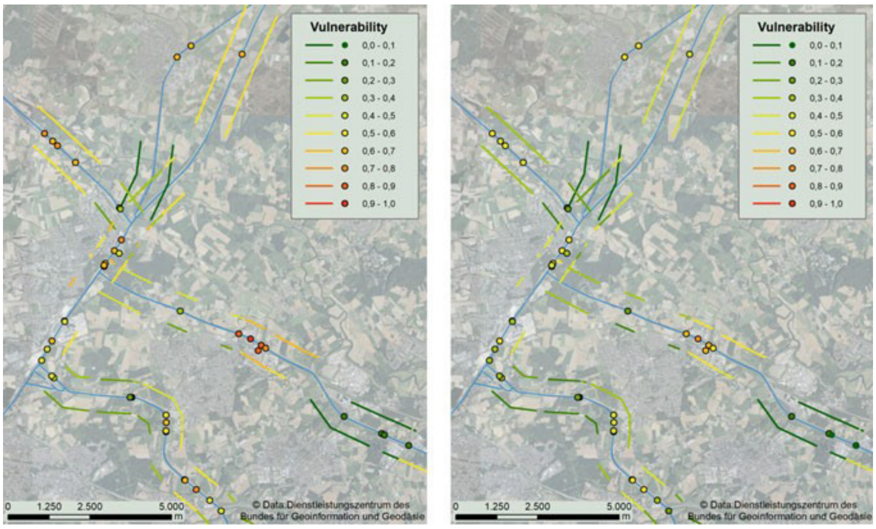


Figure 1: GIS maps showing the results of the vulnerability assessment on a portion of the West German network of canals, which has been obtained applying the WINGS method and interval arithmetic (left: lower vulnerability; right; upper vulnerability). The lines represent the levees, while the points represent the encroaching structures; please notice that levees are not continuous objects because the water level is sometimes under the adjacent terrain due to orographic irregularities

This method allows identifying the involvement of each vulnerability factor, which is based on the strength of the factor and the intensity of its influence on the other factors. However, the method is based on expert judgments, which in general are affected by uncertainty; to take it into account, the WINGS method has been integrated with interval arithmetic. The extended method allows the definition of upper and lower bounds of the vulnerability index, which in turn clarifies when the results are ambiguous and the uncertainty has to be reduced.

The visualization of the vulnerability assessment on GIS maps also facilitates communication with stakeholders and other parties affected by the vulnerability of levees. The final aim of this study is to identify on which objects maintenance actions should be prioritized.

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