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Substantial damage to surface water in the context of environmental crimes

Anabela Rebelo, *[a] Andreia Franco,[a] Felisbina Quadrado,[a] Vanda Reis,[a] Sofia Batista,[a] Ana Isabel Garcia,[b] Rodrigo Ferreira,[b] António Quintas[b] and Albertina M. Marques [c]

Water resources are very important for maintaining an adequate food supply and a productive environment for all living organisms. However, illicit activities can pose a severe threat to water quality and subsequently its uses through pollution with heavy metals, petroleum-derived oils, organic substances, pathogenic microorganisms, *etc.* Environmental crimes rank fourth among international illicit activities after drug trafficking, counterfeiting of currency and art, and trafficking of human beings and the intentional pollution of water is one of the three most common types of water crimes identified in European countries. Assessing and measuring water damage is challenging due to the complexity of water resources, including hydrogeological and hydromorphological characteristics, water uses, ecosystem services and other characteristics. Therefore, this study portrays the development of a conceptual framework supported by multicriteria decision analysis (MCDA) techniques to determine an index to quantify the magnitude of water damage (surface water) caused by a suspected illicit act (release of chemical products or waste disposal containing chemicals or other deposition, including agro-industrial or agricultural waste or by-products) and verify its feasibility through assessment of two case studies.

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Environmental significance

Environmental crimes have increased significantly in recent years and water crimes, namely deliberate water pollution, are one of the three most common types of water crime identified in European countries. In order to evaluate this type of crime, it is crucial to assess and measure the water damage concerned, which is quite challenging due to the complexity of water resources, including hydrogeological and hydromorphological characteristics, water uses, ecosystem services and other features. It is therefore essential to set up a methodology and metric to determine the significance of water damage to assist decision-makers in identifying substantial water damage that may need to be investigated as potential water crimes.

1. Introduction

Water scarcity and water pollution have become two of the most noteworthy problems of this century,[1,2] where water and sanitation are at the forefront of sustainable development. Therefore, the 2030 Agenda for Sustainable Development (SDG), adopted by all United Nations Member States in 2015, introduced SDG 6 that aims to ensure availability and sustainable management of water and sanitation for all.[3] Water resources are very important for maintaining an adequate food supply and a productive environment for all living organisms.[4] However, they can become polluted by several diffuse and point source pollution, which may include noxious pollutants such as heavy metals, organic compounds, pharmaceuticals, endocrine-disrupting chemicals, microplastics, pathogenic microorganisms, *etc.* Water pollution has a major impact on the economy, safety, environment and human health and can be the result of illegal activities.[5–7] Environmental crimes are on the rise, ranking fourth among international illicit activities after drug trafficking, counterfeiting of currency and art, and trafficking of human beings, with a steady growth rate of 5–7% per year, and are one of the most profitable and attractive activities of organised crime globally.[8] This type of criminal offence covers water crimes, which include any intentional act that potentially causes harm or damage to water, with intentional pollution of water being one of the three most common types of water crime identified in European countries.[9]

The INTERPOL Operation 30 Days at Sea 3.0, performed during 2020–2021, allowed the detection of around 1500 marine pollution-related offences committed at sea, on land and in inland water. The majority of the offences were related to illegal discharges of plastic, oil, waste and other pollutants into inland water with 228 cases reported in Europe. In the same region 105

[a]Portuguese Environment Agency, Amadora, 2610-124, Portugal. E-mail: anabela.rebelo@apambiente.pt
[b]The General Inspection of Agriculture, Sea, Environment and Spatial Planning, 1200-433, Lisboa, Portugal
[c]Chemistry Department, Faculty of Sciences, University of Beira Interior, 6201-001, Covilhã, Portugal

cases of illegal sewage treatment and 104 cases of coastal pollution were also detected. Among them only 3% were related to accidents and 13% were due to unspecified reasons. However, the majority of the remaining activities were connected with deliberate offences (37%), poor maintenance (13%) and negligence (34%).[10] These illicit actions pose significant risks to water resources, ecosystems, public health, food security and also economies. A deeper analysis has shown that criminal networks usually involved in pollution crimes have been found to be connected to theft, fraud, drugs, human trafficking, firearms trafficking or money laundering.[8,9,11]

Water crimes include various offences ranging from the pilfering of water from pipelines, to water pollution, to the illegal trafficking of water. These crimes are challenging to detect, investigate, and prosecute.[9] The Environmental Crimes Directive (ECD), Directive 2008/99/EC, establishes that a water crime related to pollution is a discharge, emission or introduction of a quantity of materials or ionising radiation into air, soil or water or the collection, transport, recovery or disposal of waste which causes or is likely to cause substantial damage to the quality of water or to animals or plants. However, the legal framework does not define what substantial damage means.[12]

A simplistic view leads to a pollution incident being observed only by assessing the visible/observable impact on the receiving environment in terms of quality and/or mortality, generally in the surroundings of a particular event or hazardous incident, and by observing the characteristics and specificities of the event itself.[13–17] However, receiving water resources present a considerable degree of complexity, where not only quality or mortality must be taken into account, but also the status of the water bodies and the impact of the parameters responsible for the achievement of that status, the impact of aquatic ecosystems, the uses and services of water, the relationship between surface water and groundwater and the susceptibility of water resources to pollution.[16,18–21]

From a legal point of view, the concept of water damage is nonlinear, which makes it difficult to assess. For example, under the Environmental Liability Directive (ELD), Directive 2004/35/CE, water damage is any damage that significantly impairs the status of the water bodies or marine water concerned, where status is defined according to the goals of the Water Framework Directive (WFD), Directive 2000/60/EC, *i.e.*, the ecological, chemical or quantitative status or the ecological potential of water bodies, or the Marine Strategy Directive (MSD), Directive 2008/56/EC, *i.e.*, the environmental status of the marine water. The term significant is linked to the notion of measurable adverse changes and impacts found in the definition of damage. Therefore, if there is significant deterioration of a water body as a result of a particular economic activity, this can be assessed under the ELD framework.[22] However, the ECD applies without prejudice to the ELD, which means that water damage may result in substantial damage (*i.e.*, appraised under the ECD) if caused by neglect, poor maintenance or even deliberate acts.[8,23] Nonetheless, if substantial damage does not reflect an impairment of the water status (as defined by the WFD or MSD), it will not be evaluated according to the ELD.[22]

A particular incident or hazardous event may have certain negative impacts that, when considered individually, may not appear to have a high magnitude result (*e.g.*, no noteworthy adverse effect on the water status of the water body concerned). However, when these effects are assessed cumulatively, they may have a relevant significance and consequently lead to an unacceptable result for the aquatic environmental component.[16,24–26] Any harmful event that takes place in a given spatial and time frame causes disturbances in the surrounding environment.[16,27] However, the extent of these disturbances can vary from insignificant (negligible) to significant, depending on the magnitude and duration of the event itself, the susceptibility of the receiving environment and the impact of the event.[16,18,25–27] Thus, multicriteria decision analysis (MCDA) enables the determination of the risk to the receiving environment based on the probability of a specific harmful event occurring in a predictive analysis.[18,28,29]

MCDA methods offer a methodical and analytical approach to integrate multiple sources of information by evaluating, scoring and contrasting various alternatives according to several criteria and by integrating both qualitative and quantitative data and information sources. These methodological approaches entail assigning scores or rankings to various criteria for each alternative, prioritising each criterion and then combining the scores of the criteria to ascertain the most likely alternative.[25,29–31] Likelihood can be discussed when an event may or may not occur. Nevertheless, for a real event, that has occurred within a specific spatial and temporal framework, the probability of occurrence is 100%, so the same set of mathematical concepts commonly used in predictive analysis can be applied and an effective result obtained using MCDA procedures.[25,32]

In order to successfully present a possible environmental crime case, it is important to collect appropriate evidence, maintain legal continuity, organise and document this evidence, and then present it to the various audiences, such as enforcement authorities, police, prosecutors, judges and the court. Therefore, following robust and reliable investigative procedures and making the results of the evidence more understandable to all these audiences are crucial.[33]

As far as is known, there is no evidence from studies to quantify the damage to water resources caused by illicit activities. The vast majority of studies have instead focused solely on damage under environmental liability, rather than addressing the issue under the ECD.[22,23,34]

A guidance document has been developed within the National IMPEL Network (Portugal) to address the definition of significance of water damage.[35] Following this report, this study aims to develop a conceptual framework, based on MCDA techniques, to determine an index to quantify the magnitude of water damage caused by a suspected illicit act (release of chemical products or disposal of waste containing chemicals or other deposits, including agro-industrial or agricultural waste or by-products), and to verify its feasibility through the assessment of two case studies. Due to the complexity of groundwater resources, related to the variability of hydrogeological vulnerability and the consequent difficulty in simulating the fate of pollutants in groundwater, it was decided to apply the current methodology only to surface water at this stage.[36,37] The aim of this methodology is to assist environmental authorities and inspectorates in investigating potential illegal pollution incidents and to provide a reference for the development of a decision support system, namely a benchmark that allows the recognition of factors that, if present, constitute, from a technical-scientific point of view, substantial damage to water resources.

2. Methodology

The measurement of damage magnitude through an index entails the quantification set of factors and their interrelationships, focusing on the nature of the occurrence and its consequences. The nature of the occurrence is related to the concept of hazard, *i.e.*, with the intrinsic properties of the occurrence that are able to cause damage,[14,38] for instance, the toxicology of certain substances present in wastewater or runoffs (*e.g.*, heavy metals, pesticides, acids, *etc.*), the quantity of organic matter that may induce an oxygen depletion, the temperature of a discharge, nature of wastes improperly disposed, *etc.*[5,38] The consequence depends on the harmful effect of the occurrence and the characteristics of the water resources concerned,[4,25] *i.e.*, the susceptibility of the water resources to pollution. Depending on the water uses in place and the physical, hydrogeological and morphological characteristics, a water body could be more or less susceptible to a pollution incident.[4,25,39,40]

The proposed methodology is supported on a knowledge-based approach,[24,30,36,40–42] where each factor is assessed by a hierarchical analytical process built on an importance scale 3 to 9,[43] where 3 is weak importance (low or undemonstrated significance), 5 is essential or strong importance (medium significance), 7 is demonstrated importance (high significance), and 9 is absolute importance (very high significance).

The index of damage is also defined according to the SMART criteria, *i.e.*, is defined to be: specific, *i.e.*, the index accurately describes what is intended to be measured and the values used are independent of who produces and interprets them; measurable, *i.e.*, consistent results can be achieved and tracked under the same conditions, regardless of who uses the index. Furthermore, it is possible to quantify and compare the data with other data, namely with data prior to the event; attainable *i.e.*, all necessary data are achievable and provide sufficient information to confirm that the index target has been achieved; relevant: the index is closely connected with each respective input, output and outcome; time-bound, *i.e.*, the index covers an appropriate time-frame period, directly related to the duration and recurrence of the incident.[44,45]

The nature of the occurrence translates its potential to cause harm[16,46] and is designated by the potential of the occurrence (P_{ocur}) and its product by the consequence of the harmful effect (C_{HE}) results in the water damage index (I_{WD}), and the C_{HE} is given by the product between the harmful effect (HE) and the susceptibility of the water resources to pollution (S_{WR}), as illustrated by the following equations:

$$I_{\mathrm{WD}} = P_{\mathrm{ocur}} \times C_{\mathrm{HE}} \tag{1}$$

$$I_{\mathrm{WD}} = P_{\mathrm{ocur}} \times \mathrm{HE} \times S_{\mathrm{WR}} \tag{2}$$

To adjust the scale to a common range, normalization factors are used.[47] Hence, eqn (2), is normalized, to the maximum number of factors (n) that can be classified with very high significance (*i.e.*, equal to 9):

$$I_{\mathrm{WD}} = \frac{P_{\mathrm{ocur}} \times \mathrm{HE} \times S_{\mathrm{WR}}}{9^{n-1}} \tag{3}$$

The potential of the occurrence (P_{ocur}) is described in Table 1. The rejection can occur from fixed units (*e.g.*, industrial units) or mobile units (transport of chemical products).[18] Sampling is carried out as close as possible to the location of the occurrence at a location considered suitable, *e.g.*, considering the access conditions to the site.[33]

The harmful effect depends on the temporal dimension of the occurrence, named typology of occurrence and the severity observed.[16,48,49] For the current study, the considered criteria are the mortality of specimens, impairment of water quality, water uses and water resources services.

Instances of poor maintenance of spaces and/or equipment, malfunctioning of such equipment or substandard wastewater treatment may lead to incidents. Thus, an occurrence limited in time may be the result of deliberate or careless actions, or the result of unforeseen situations, and may be continuous or discontinuous in time.[2,49] For instance, it could stem from a singular act or occur periodically. Therefore, to ensure the application of the SMART criteria,[44,45] a 12 month time frame has been established to assess any potential prior cases of similar incidents originating from the same pollution source or committed by the same entity. The classification of typology of occurrence ($\mathrm{Tp}_{\mathrm{ocur}}$) is shown in Table 2.

The severity ($\mathrm{Sev}_{\mathrm{WR}}$) using the equation below reflects the degree to which water resources are affected by the occurrence.[4,27] The term f_{sev} represents the different intrinsic factors specified in Table 3 for surface water. To enable downscaling, a normalisation factor ($n_{f_{\mathrm{sev}}}$) is applied, representing the sum of the individual factors. The resulting severity rating ranges between 3 and 9.

$$\mathrm{Sev}_{\mathrm{WR}} = \frac{\sum f_{\mathrm{sev}_i}}{n_{f_{\mathrm{sev}}}} \tag{4}$$

The severity factors considered for surface water are the mortality of specimens, deterioration of water quality, impairment of anthropic uses and/or services of water bodies. The classification of these factors is shown in Table 3. All the critical factors observed are assessed on a worst-case approach basis, to ensure minimization of uncertainties.[29,30,36] Thus, only the factors that are actually observed and contribute to water damage should be considered, thus avoiding the use of factors that will distort the final result. When observing a visible mortality of more than ten specimens in a river, along with a change in colour (assuming that this criterion is the only

Table 1 Potential of the occurrence

Occurrence	Description	Classification
Rejection of chemicals or waste disposal containing chemicals or other deposition (including agro-industrial or agricultural waste/by-products) or occurrence or hazardous events of unknown origin	Chemical products and/or waste or runoff/rejection containing substances not classified as hazardous (classification and labelling legislation for chemicals) and causing[a] visible changes (at naked eye) in turbidity or the presence of foam or greasy stains or a colour above 50 mg L^{-1} Pt–Co or an odour at a dilution of 1 : 10[b]	3
	Chemical products and/or waste or runoff/rejection containing other substances classified as hazardous (harmful/irritant), or causing a temperature change of more than 3 °C	5
	Chemical products and/or waste or runoff/rejection containing specific pollutants (defined in the River Basin Management Plan, RBMP, territorially applicable) or substances that are hazardous to the environment (aquatic ecosystems) or substances causing deterioration of water quality for at least one parameter supporting the ecological status (according to the WFD) of the receiving water body, or substances changing the pH of the water[c]	7
	Chemicals and/or waste or runoff/rejection containing priority, priority hazardous substances or other pollutants defined according to the WFD or very persistent substances or very toxic, reprotoxic, mutagenic or with endocrine disrupting potential (according to classification and labelling legislation for chemicals) or total petroleum hydrocarbons C_{10}–C_{40}. Runoffs and/or discharges causing acute anoxia (with observation of total or near-total oxygen depletion), acute pH variation in the receiving water (pH in the receiving water less than or equal to 3.0 or greater than or equal to 10.0)	9

[a] Should be considered the option that best suits the conditions observed in the field. [b] Values from Portuguese legislation. [c] The pH of the water body should be between 6 and 9, provided that there are no upstream problems or that there are no other values resulting from the local geology.

Table 2 Typology of occurrence

Description	Type	Classification
There are no records of this type of occurrence in the last 12 months	Discontinuous occurrence	3
There has been a single occurrence in the last 12 months	Discontinuous occurrence	5
There has been more than one occurrence in the last 12 months	Discontinuous occurrence	7
Is it a continuous wastewater discharge or is there a record of more than six occurrences in the last 12 months	Continuous occurrence	9

factor considered for impairing the anthropic uses and/or services of water bodies), the critical factor to consider should be solely the mortality. The combination of both would lessen the severity of the occurrence observed. The results of eqn (4) are prioritized according to the importance scale[31] as described in Table 4.

The harmful effect on water resources (HE) is given by the matrix described in Fig. 1, which relates the typology of occurrence to the severity over water bodies.

The last term of eqn (2) and (3) represents the susceptibility of the water resources to pollution (S_{WR}). This term considers exposure pathways to water by correlating the physical,

Table 3 Severity factors for surface water

Severity factor (f_{sev_i})	Description	Classification
Mortality	Lentic system: number of dead specimens ≤10 (except if any specimens of protected species)	3
	Lotic system: number of dead specimens ≤10 (except if any specimens of protected species), within a linear distance of 1000 metres downstream of the event, or in coastal water where evidence of the event can be detected	5
	Lentic system: number of dead specimens >10 (except if any specimens of protected species)	7
	Lotic system: number of dead specimens >10 (except if any specimens of protected species), within a linear distance of 1000 metres downstream of the event, or in coastal water where evidence of the event can be detected or the mortality of any specimens of protected species in a lentic system, a lotic system or coastal water (where the traces of the occurrence can be detected)	9
Impairment of anthropic uses and/or services of water bodies[a]	Deterioration in the quality of at least one parameter of surface water for existing or proposed non-quality-requiring industrial uses for the parameters colour, conductivity and pH, higher than colour ≤50 mg L^{-1} Pt–Co scale, conductivity ≤1000 μS cm^{-1}, 20 °C and pH – 5.5 to 9.0[b]	3
	Deterioration in surface water's quality (freshwater, brackish, or saline water) in at least one industrial parameter for existing or future usage, excluding those requiring drinking water quality. Quality thresholds specified in a discharge permit, if applicable, are used as reference. If there are no standards outlined in these documents, the impairment is classified according to the previous paragraph (*i.e.*, with a value of three)	5
	Deterioration of freshwater quality in at least one parameter for current or proposed agricultural uses, excluding crops intended for raw consumption and where the edible part is in contact with water.[c] Degradation of landscape and/or the use of the water body for fishing or leisure activities (recreational, sports, and economic, including subsistence activities)	7
	Impairment of current or potential water use for human consumption (drinking water quality), animal drinking, water of superior quality (for instance, some industrial uses), current or planned agricultural uses (production of crops intended for raw consumption or where the edible part is in contact with water) water in protected areas for aquatic species of economic interest (for instance, shellfish and fish production areas) or bathing water Thresholds to be considered: drinking water quality, class A quality as described in Regulation (EU) 2020/741 (production of crops intended for raw consumption), legal requirements applicable to the shellfish production and bathing water directive.[d] Deterioration in the quality of water is also considered as an impairment of its usage when there are restrictions imposed by the competent authorities for more than 48 hours	9

Table 3 (*Contd.*)

Severity factor (f_{sev_i})	Description	Classification
Deterioration of water quality for at least one parameter supporting the status classification of the water body[e]	Deterioration of water quality at a distance greater than 30 m but less than 75 m from the point of occurrence, or at the outer limit of the mixing zone[f] if this is greater than 75 m but less than 125 m from the point of occurrence and no effect is observed beyond this distance	3
	Deterioration of water quality at a distance greater than 75 m but less than 125 m from the point of occurrence, or at the outer limit of the mixing zone[f] if this is greater than 125 m but less than 250 m from the point of occurrence and no effect is observed beyond this distance	5
	Deterioration of water quality at a distance greater than 125 m but less than 250 m from the point of occurrence. Or at the outer limit of the mixing zone[f] if this is greater than 250 m but less than 500 m from the point of occurrence and no effect is observed beyond this distance	7
	Deterioration of water quality at a distance of 250 m or more from the point of occurrence, or at the outer limit of the mixing zone[f] if this is greater than 500 m from the point of occurrence	9

[a] Within a specific distance, as far as discernible evidence of the occurrence (depending on the specific features of the receiving water bodies such as streams, canals or rivers, tidal areas and morphology). [b] Thresholds from Portuguese legislation. [c] Threshold: maximum recommended or admissible values described in Annex XVI of Decree-Law 236/98, of 1 August (Portuguese legislation). [d] Directive 2006/7/EC. [e] The assessment has to be made according to the water body with the worst status when multiple water bodies are affected (worst-case approach); the observation of exceedance/non-compliance of applicable thresholds, and both ecological/ecological potential and chemical status of the water body are taken into account, in accordance with the WFD, to determine the overall status. [f] If specified in the discharge permit.

Table 4 Expression of results of severity

Results of eqn (4) ($R_{\mathrm{eqn}(4)}$)	Severity ($\mathrm{Sev}_{\mathrm{WR}}$)
$R_{\mathrm{eqn}(4)} \leq 3$	3
$3 < R_{\mathrm{eqn}(4)} \leq 5$	5
$3 < R_{\mathrm{eqn}(4)} < 7$	7
$R_{\mathrm{eqn}(4)} \geq 7$	9

hydrogeological and morphological characteristics of the water bodies involved with their uses and services and the respective distances to the occurrence.[18,24] A first set of factors (f'_{WR}) is defined in Table 5 for this purpose. These factors are later related to the sensitive areas (as defined by the Directive of urban wastewaters, Directive 91/271/EEC), according to criteria a, b and c. The criterion a refers to the "natural freshwater lakes, other freshwater bodies, estuaries and coastal waters which are found to be eutrophic or which in the near future may become eutrophic if protective action is not taken". The criterion b refers to the "surface freshwaters intended for the abstraction of drinking water" and the criterion c is defined by "areas where other treatment is required to comply with other relevant Directives". As described in the legislation, the criteria are applied to sensitive areas and their catchment areas and vulnerable zones (as defined by the nitrates Directive, Directive 91/676/EEC), according to Fig. 2 and 3, respectively. This first set of factors are related to the distance in linear meters (d) from the point of occurrence to the water resource.

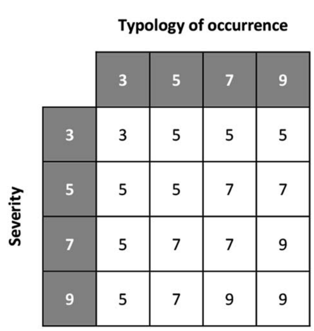

Fig. 1 Harmful effect (HE).

The results from sensitive areas and vulnerable zones are combined according to Fig. 4 to obtain an integration factor for water resources (f''_{WR}) for each initial factor applied from Table 5. A partial susceptibility for water resources (S'_{WR}) is obtained by the sum of all factors in place (f''_{WR}) normalized to the total number of factors observed ($n_{f''_{\mathrm{WR}}}$).

$$S'_{\mathrm{WR}} = \frac{\sum f''_{\mathrm{WR}_i}}{n_{f''_{\mathrm{WR}}}} \tag{5}$$

The next step involves the integration of a factor related to the protection of habitats and wildlife and the conservation of

Table 5 Factors (related to distances) for assessment of susceptibility of water resources to pollution

Factors (f'_{WR})	Description[a]	Classification
Streams, canals, rivers, estuaries or coastal areas (distance to the occurrence) (level classification obtained from Fig. 2 and 3)	$d > 50$ m	Level 1
	$25 \text{ m} < d \le 50$ m	Level 2
	$10 \text{ m} < d \le 25$ m	Level 3
	$d \le 10$ m	Level 4
Flooding areas (distance to occurrence) (level classification obtained from Fig. 2 and 3)	$d > 50$ m	Level 1
	$10 \text{ m} < d \le 50$ m	Level 2
	$d \le 10$ m	Level 3
	Within the area	Level 4
Reservoirs/dams (distance to occurrence) (level classification obtained from Fig. 2 and 3)	$d > 100$ m	Level 1
	$50 \text{ m} < d \le 100$ m	Level 2
	$25 \text{ m} < d \le 50$ m	Level 3
	$d \le 25$ m	Level 4
Public water reservoirs/dams (distance to occurrence) (level classification obtained from Fig. 2 and 3)	$d > 500$ m	Level 1
	$100 \text{ m} < d \le 500$ m	Level 2
	$25 \text{ m} < d \le 100$ m	Level 3
	$d \le 25$ m	Level 4
Water abstraction (distance to occurrence) (level classification obtained from Fig. 2 and 3)	$d > 500$ m	Level 1
	$250 \text{ m} < d \le 500$ m	Level 2
	$50 \text{ m} < d \le 250$ m	Level 3
	$d \le 50$ m	Level 4

[a] Distance from the point of occurrence (site of rejection/emission) to the water resource, measured in linear meters.

	Factors (f ′WR) Level 1	Level 2	Level 3	Level 4
Non-classified areas	3	5	5	5
Catchment areas of a sensitive area	5	5	7	7
Sensitive areas (criterion c)	5	7	7	9
Sensitive areas (criterion a or b)	5	7	9	9

Fig. 2 Relationship with sensitive areas.

wild birds and nature (f_{Hp}) and a second partial susceptibility value (S''_{WR}) is obtained according to the following equation, which is normalized to the maximum value of importance:

$$S''_{WR} = \frac{S'_{WR} \times f_{Hp}}{9} \tag{6}$$

The values applicable to f_{Hp} are shown in Table 6. The results from eqn (6) are prioritized to the importance scale[31] as illustrated in Table 7 to obtain the partial susceptibility value (S^{A}_{WR}).

However, other uses and/or services of water resources may be present and, in that case, should be also accounted for, namely the presence of recreational areas (*e.g.*, bathing water) or areas for protection of aquatic species of economic interest or to support fish life. The factors related to other uses and/or services ($f_{ou/s}$) are also considered by the distance to the occurrence as described in Table 8.

From this factor a second partial susceptibility is calculated for the water resources (S^{B}_{WR}) as follows:

$$S^{B}_{WR} = \frac{\sum f_{ou/s_i}}{n_{f_{ou/s}}} \tag{7}$$

where $n_{f_{ou/s}}$ is the total number of factors considered according to the site-specificity of the occurrence, assuming the values one

	Factors (f ′WR) Level 1	Level 2	Level 3	Level 4
Non-classified areas	3	5	5	5
Maximum infiltration zones	5	5	7	7
Vulnerable zones for nitrate pollution	5	7	7	9
Areas vulnerable to nitrate pollution and maximum infiltration zones	5	7	9	9

Fig. 3 Relationship with vulnerable areas.

Result from sensitive areas \ Result from vulnerable zones	3	5	7	9
3	3	5	5	5
5	5	5	7	7
7	5	7	7	9
9	5	7	9	9

Fig. 4 Integration of results from sensitive areas and vulnerable zones.

Table 6 Factor related to the protection of habitats and wildlife and the conservation of wild birds and nature

Factor (f_{Hp})	Description	Classification
Habitats and wildlife and the conservation of wild birds and nature	Outside of the protected areas	3
	Surrounding areas of national parks that may have some specific protection requirements, if applicable[a]	5
	National parks and other national protected areas	7
	Sites of community interest or special protection areas[b]	9

[a] According to national legislation in place (*e.g.*, in Portugal this represents the areas classified as Pre-Park according to land management plans).
[b] According to European legislation.

Table 7 Expression of results of eqn (6)

Results of eqn (6) ($R_{eqn(6)}$)	S^{A}_{WR}
$R_{eqn(6)} \leq 1$	3
$1 < R_{eqn(6)} \leq 3$	5
$3 < R_{eqn(6)} \leq 5$	7
$R_{eqn(6)} > 5$	9

Table 9 Expression of results of eqn (8)

Results of eqn (8) ($R_{eqn(8)}$)	S_{WR}
$R_{eqn(8)} < 2.5$	3
$2.5 \leq R_{eqn(8)} < 3.5$	5
$3.5 \leq R_{eqn(8)} < 4.5$	7
$R_{eqn(8)} \geq 4.5$	9

or two. The susceptibility of the water resources to pollution (S_{WR}) is given by the following equation, the final result is expressed according to the relationships[31] described in Table 9.

$$S_{WR} = \frac{S^{A}_{WR} + S^{B}_{WR}}{2} \tag{8}$$

Using eqn (3), the water damage index (I_{WD}) can be determined based on the susceptibility values of water resources (S_{WR}), the harmful effect (HE), and the potential occurrence (P_{ocur}). However, an event may compromise the objectives set out in the WFD, *i.e.*, it may jeopardise the status of part or all of a water body. For this reason the classification of the status of the water bodies affected by the incident at the time of the incident must be taken into account.[22] Furthermore, as previously mentioned the practice of pollution may also represent a significant financial gain for the infringer, with evidence that some pollution actions are connected with organized crime.[8,9,11] Consequently, situations of reoccurrence and/or non-implementation of measures previously identified by the competent authorities as necessary to prevent situations of pollution of water resources are also important to be considered. Therefore, a correction is added to eqn (3), to include additional factors (f_{add}) to include the above aspects:

$$I_{WD} = \frac{P_{ocur} \times HE \times S_{WR}}{9^{n-1}} \times f_{add} \tag{9}$$

where f_{add} is obtained as

$$f_{add} = 1 + \sum f_i \tag{10}$$

The term f represents the partial additional factor that can apply as shown in Table 10. Factors A (or A plus B) and C are never obtained simultaneously. The I_{WD} varies from 0.33 to 9.0 without considering the correction factors (*e.g.*, when the status of the water body is unknown according to the relevant RBMP and criterions D and E are not applicable). If additional factors are taken into account, the I_{WD} varies from 0.4 to 15.3. Thus, whenever the final result is equal to or higher than 9.0, the I_{WD} assumes the maximum value of significance, *i.e.*, nine (9).

Thus, by combining and trading off different factors according to the described methodology it is possible to reduce the multidimensional problem to a one-dimensional scale of priorities,[50] which involves converting the I_{WD} results into a two-level qualitative scale as follows: $I_{WD} < 4$, the occurrence determines an intermediate to an acceptable outcome for water resources (low to medium significance), and $I_{WD} \geq 4$, the occurrence determines an unacceptable outcome for water

Table 8 Factors related to uses and/or services

Factors ($f_{ou/s}$)	Description	Classification
Areas designated as recreational water, including areas designated as bathing areas	$d > 500$ m	3
	100 m $< d \leq$ 500 m	5
	25 m $< d \leq$ 100 m	7
	$d \leq$ 25 m	9
Areas for the protection of aquatic species of economic interest or to support fish life	$d > 500$	3
	100 m $< d \leq$ 500 m	5
	25 m $< d \leq$ 100 m	7
	$d \leq$ 25 m	9

Table 10 Additional factors for water damage index correction

Factor	Description	f_i
A	Status of the water body "less than good"[a]	0.2
B	The non-compliant parameter(s) are coincident with those in support of the classification "less than good"	0.3
C	Water body status "good or better" and severity[b] on water resources equal to or higher than seven	0.5
D	Recurrence of discharge or disposal in violation of applicable legislation	0.1
E	Failure to implement, in whole or in part, the preventive and/or corrective measures required by the competent authorities as a result of previous discharges/disposals, or failure to meet the deadlines for their implementation	0.1

[a] Status considers the overall status of the water body, including ecological and chemical status, in accordance with the WFD. In situations where the event affects more than one water body of the same type, the assessment shall be made on a worst-case basis, *i.e.*, the water body with the worst status. [b] Value obtained from Table 4.

resources (high significance), which may translate to substantial damage for water resources.

3. Results and discussion

The methodology was applied to two real scenarios of emissions of pollutants to water resources, namely direct leaks of chemicals to surface water: a spill of cyanides to Ria Formosa (natural lagoon) in 1999 and a release of fuel oil to a stream, in 2007. The case studies selected take into consideration that, with the passage of time, there is no longer a possibility that they are still under criminal investigation. The description of the case studies is shown in Table 11.

Despite knowing the real dates of occurrence (as mentioned, the selection of real scenarios was made to ensure the absence of possible ongoing criminal investigations), it was decided to carry out the assessment of the I_{WD} under the conditions established by the River Basin Management Plan (RBMP) in force,[52] as this is the one with the best level of information to date and to ensure conditions that allow the validation of the methodology (namely the data relating to the status of the water body. All the other data mentioned in the RBMP were applicable at the time of both events).

For case study 1, the data available in the National Information System for Water Resources (SNIRH) were assessed for the Ria Formosa-Olhão monitoring station (31J/03). Concentrations of cyanides between 0.011 and 0.030 mg L^{-1} were recorded between August 1999 and July 2002, with the peak detected in October 1999. All data after July 2002 are below the limit of quantification (LoQ < 0.0014 mg L^{-1}).[53]

The application of the developed methodology to case studies 1 and 2 is presented in Tables 12 and 13, respectively.

The findings enabled the applicability of the methodology to real situations to be understood and the magnitude of damage to surface water to be determined, taking into account the relationships and trade-offs between different attributes.

The results from case study 2 are consistent with the results from the previous studies from Rebelo *et al.*,[18] which used a different approach to assess the risk for water resources resultant from the same incident, which seems to allow the validation of the proposed multicriteria decision methodology.

Table 11 Description of case studies

Case study		
Number	Identification	Description
1	Spill of cyanides to Ria Formosa in 1999	During the cleaning process to release a building, previously used as a chromo-plating facility, cyanide baths were discharged into the urban drainage system of the town of Olhão, with a direct discharge in Ria Formosa in front of town markets. This discharge caused contamination in Ria Formosa, resulting in a significant number of fish deaths[a] The Ria Formosa is a mesotidal coastal lagoon located in the south of Portugal and is an important bivalve and fish production and salt extraction site[51]
2	Release of fuel oil into a small stream near Olhão[18]	Discharge of 25–30 m^3 of fuel oil, into a stormwater drainage system, from storage and pre-heating facilities linked to a vapour generator for greenhouse heating. The discharge affected around 120 m length of a small, intermittent stream during the dry season. However, after a rainy period following the spill, the contaminant plume reached a length of 300 m in three days

[a] Source: Portuguese Environment Agency.

Table 12 Determination of I_{WD} for case study 1

Attribute	Description	Classification
Potential of the occurrence (P_{ocur})	Discharge of chemical products containing specific pollutants (cyanides), *i.e.*, a parameter that supports the ecological status (according to the WFD) Note: the RBMP of *Ribeiras do Algarve* in force establishes that cyanides are a specific pollutant for the water body of Ria Formosa[54]	7
Typology of occurrence (Tp_{ocur})	Discontinuous occurrence: there are no records or evidence from previous similar occurrences from that facility	3
Severity (Sev_{WR})	Mortality of dead specimens in a number much larger than 10. There are no data related to the identification of species, so is not possible to clarify if there was death of protected species	9
	Impairment of anthropic uses and/or services of water bodies: no information available	Not considered
	Deterioration of water quality for at least one parameter supporting the status classification of the water body: data from SNIRH identify the presence of free cyanides from 23/08/1999 to 14/07/2002 (ref. 53) The location of the sampling point is around 400 m from the discharge location into Ria Formosa (in front of the Markets in Olhão): deterioration of water quality at a distance of 250 m or more from the point of occurrence	9
	Sev_{WR}	9
Harmful effect (HE)	Typology of occurrence (Tp_{ocur}) *vs.* severity (Sev_{WR})	5
Susceptibility of the water resources to pollution (S_{WR})	Factors (related to distances) for assessment of susceptibility of the water resources to pollution Streams, canals, rivers, estuaries or coastal areas (distance to the occurrence): $d \leq 10$ m Areas classified as sensitive (criterion c) due to the need for protection of water for production of shellfish[a]	Level 4
	Relation with sensitive areas	9
	Areas not classified as vulnerable	5
	Integration of results from sensitive areas and vulnerable zones	7
	Partial susceptibility (S'_{WR})	7
	Habitats and wildlife and the conservation of wild birds and nature (f_{Hp}): Ria Formosa: sites of community interest or special protection areas[52]	9
	Partial susceptibility (S''_{WR})	7.0
	Partial susceptibility (S^{A}_{WR})	9
	Uses and/or services	
	Areas designated as recreational water, including areas designated as bathing areas: $d > 500$ m[52]	3
	Areas for the protection of aquatic species of economic interest or to support fish life: $100 \text{ m} < d \leq 500$ m There are areas for shellfish production around 250 m from the discharge point[52]	5
	Partial susceptibility (S^{B}_{WR})	4
	Susceptibility of the water resources (S_{WR})	6.5
	Susceptibility of the water resources (S_{WR}), expressed according to Table 9	9
Additional factors	Water body status "less than good" but the non-compliant parameter[b] is not coincident with those in support of the classification[52]	0.2
Water damage index (I_{WD})	I_{WD}	4.7
	Final result ≥ 4	High significance outcome

[a] Directive 91/271/EEC and Ordinance no. 188/2021, 8th September (in Portuguese) concerning the identification of sensitive and less sensitive areas. [b] The parameter that defines that the status fails is Nonylphenols.

Table 13 Determination of I_{WD} for case study 2

Attribute	Description	Classification
Potential of the occurrence (P_{ocur})	Discharge of chemical products containing priority hazardous substances or other pollutants defined according to the WFD and total petroleum hydrocarbons C_{10}–C_{40}	9
	According to the literature, the fuel was a complex mixture of hydrocarbons with a prevalence of C_9 to C_{25} chains, which include polycyclic aromatic hydrocarbons (PAH) with little or no olefins[18,55]	
Typology of occurrence (Tp_{ocur})	Discontinuous occurrence: there are no records or evidence from previous similar occurrences from that facility	3
Severity (Sev_{WR})	Mortality: the discharge occurred in a small and intermittent stream, without any information available about mortality	Not considered
	Impairment of anthropic uses and/or services of water bodies: no information available	Not considered
	Deterioration of water quality at a distance of 250 m or more from the point of occurrence. According to Rebelo *et al.*, the impact was detected at a length of 300 m (ref. 18)	9
	Sev_{WR}	9
Harmful effect (HE)	Typology of occurrence (Tp_{ocur}) *vs.* severity (Sev_{WR})	5
Susceptibility of the water resources to pollution (S_{WR})	Factors (related to distances) for assessment of susceptibility of the water resources to pollution	Level 4
	Streams, canals, rivers, estuaries or coastal areas (distance to the occurrence): $d \leq 10$ m	
	Areas classified as catchment of sensitive (criterion c) due to the need for protection of water for production of shellfish[a]	
	Relation with sensitive areas	9
	Areas not classified as vulnerable	5
	Integration of results from sensitive areas and vulnerable zones	7
	Partial susceptibility (S'_{WR})	7
	Habitats and wildlife and the conservation of wild birds and nature (f_{Hp}): Ria Formosa: outside of the protected areas[52]	3
	Partial susceptibility (S''_{WR})	2.3
	Partial susceptibility (S^{A}_{WR})	5
	Uses and/or services	
	Areas designated as recreational water, including areas designated as bathing areas: not applicable[52]	Not considered
	Areas for the protection of aquatic species of economic interest or to support fish life: not applicable[52]	Not considered
	Partial susceptibility (S^{B}_{WR})	Not considered
	Susceptibility of the water resources (S_{WR})	2.5
	Susceptibility of the water resources (S_{WR}), expressed according to Table 9	5
Additional factors	Water body status "less than good" but the non-compliant parameter[b] is not coincident with those in support of the classification[52]	0.2
Water damage index (I_{WD})	I_{WD}	3.3
	Final result < 4	Low to medium significance outcome

[a] Directive 91/271/EEC and Ordinance no. 188/2021, 8th September (in Portuguese) concerning the identification of sensitive and less sensitive areas. [b] The parameter that defines that the status fails is nonylphenols.

Thus, rather than simply using separate criteria to identify possible connections, a more realistic appraisal was conducted. Data were evaluated in an integrated manner by following a set of rules, enabling a deeper understanding of cause–effect relationships. The prioritisation of outcomes enables the quantification of water damage providing a metric to establish the significance of this damage. Therefore, the developed methodology provides a valuable tool for competent authorities to define thresholds between administrative infringements (*e.g.*, application of financial fines) and potential criminal offences.[8,9] Although the methodology has only been applied to two case studies, it can be utilised for any incidence over surface water if field investigation gathers all the necessary data and adheres to good investigative practices, such as those proposed by INTERPOL.[33]

4. Conclusions

The increase of pollution crimes against water resources determines the need for methodologies that allows the measurement of water damage. The strength of the current study was the definition of a multicriteria decision methodology that allows the reduction of a multidimensional scaling appraisal to an outcome expressed on a one-dimensional scale, applicable to incidents over surface water.

The application of the methodology was demonstrated in two case studies and the results of case study 2 were consistent with previous results obtained by Rebelo *et al.*[18] in an environmental risk assessment study.

The need for structured information can be combined with spatial information assessment (*e.g.*, supported by Geographic Information Systems) and presents a useful tool and/or an opportunity to improve site-inspections following incidents or suspicious occurrences. However, it should be noted that any occurrence must be thoroughly investigated using a rigorous process that requires the collection and preservation of evidence according to robust and reliable criteria, in accordance with the best international practices, such as those proposed by INTERPOL,[33] in order to support the decision making. The multicriteria methodology provides a way to relate the results of the collected evidence and measure the magnitude of water damage based on well-defined criteria. Therefore, this methodology could be a useful tool to help water authorities, inspection and criminal police to distinguish the administrative infringement from the criminal offence and, at this level, can also be an important instrument to support the identification of substantial damage to water resources and the specific criteria that contribute to this determination.

This study represents one of the earliest attempts to measure and prioritise the importance of damage in illicit situations on surface water bodies. It simultaneously examines the relationships between several criteria and trade-offs to understand the value of damage and potential cause–effect relationships. Possible future developments in the methodology could be focused on the fate of pollutants in groundwater to assess water damage as a result of illicit activities and its relationship with remediation processes.

Author contributions

Anabela Rebelo conceptualized the study, conducted data analysis, and developed the methodology framework and also played a pivotal role in the writing of the original draft, and actively participated in the editing process. Andreia Franco, Felisbina Quadrado, Vanda Reis, Sofia Batista, Ana Isabel Garcia, Rodrigo Ferreira and António Quintas contributed to the development of the methodology framework. Albertina M. Marques contributed to the data analysis and editing process.

Conflicts of interest

The authors declare no conflict of interest.

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