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Incorporating taste and odour problems in water safety plans

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ABSTRACT

Many water utilities are at least occasionally affected by unpleasant taste and odour (T&O) in drinking water. For decades, aesthetic water quality has been of secondary concern to water producers, with water safety being the primary focus. However, there has been a recent shift towards prioritising consumer satisfaction, encompassing not only services, but also water quality, including T&O issues, which can negatively impact the supplier's reputation. Starting to address a T&O problem until consumers' complaints become massive is too late and puts water producers under great stress to take effective action in a timely manner. Rather, a preventive approach is necessary. The most effective approach is to include T&O as a hazard to assess and manage in the context of developing a water safety plan (WSP) for the supply system. The development of a WSP provides an excellent platform for including the stakeholders needed to control the source of T&O events, as this often requires multistakeholder cooperation. Our review provides a comprehensive guide to addressing T&O occurrences and shows how this can be included in the framework of WSP development. It identifies supporting tools and illustrates the information given with a number of examples from water suppliers' practice.

Key words: drinking water, odour, risk assessment and management, taste, water safety plans

HIGHLIGHTS

- Consumers judge the quality of drinking water chiefly by its aesthetic quality.
- Feedback from consumers, including complaints, is a valuable source of information for the water utility.
- Although in most cases, the bad odour or taste of water is primarily an aesthetic problem, we cannot dismiss the possibility of being a health hazard.
- Developing a water safety plan is the most appropriate method to prevent odour or taste problems.

INTRODUCTION: TASTE AND ODOUR IN THE CONTEXT OF DEVELOPING A WATER SAFETY PLAN

Appearance, odour, and taste are the first criteria by which consumers evaluate drinking water. This is the basis for their trust or distrust in the supplied water. Therefore, all water producers and suppliers should endeavour to deliver drinking water of the best possible aesthetic and organoleptic quality. Yet a large survey of 381 water utilities in the United States and Canada (including a few also from Australia, South Korea, and France) on the incidence of taste and odour (T&O) problems in drinking water found that 168 (44%) of them at least sometimes had problems with the odour or taste of water (Ömür-Özbek *et al.* 2012).

The risk-based approach introduced with the concept of developing site-specific water safety plans (WSPs) has become the standard for preventive solutions to drinking water quality problems in the last 20 years. However, T&O problems have long been considered a secondary issue when developing a WSP; only very recently has it been stated that a water safety planning approach can complement regulatory frameworks for better management also of aesthetic water quality (Burlingame *et al.* 2024). So far, the primary focus has indeed been on the safety aspects of human health, with T&O compounds generally disregarded, assuming toxicity not to be an issue for these. This did not change even after the publication of the Bonn Water Charter, which defined the goal of the modern water supply sector and clearly emphasised the importance of the aesthetic quality of water for consumers: 'Good safe drinking water that has the trust of consumers…. Water that is not just safe to drink, but considered of good aesthetic quality by consumers, and water supply in which consumers have confidence.' (IWA 2004).

Only the second edition of the WHO Water Safety Plan (WHO WSP) Manual (WHO 2023), launched on March 1, 2023, explicitly incorporated the lack of acceptability (odour, taste, colour, and appearance) as a potential hazard and emphasised this in the public presentation. However, the reason mentioned for drawing attention to this issue is that aesthetical deficits can indirectly impact public health if poor acceptance can drive consumers to turn to other, potentially less tested and less safe drinking water sources. However, a further important reason for including the T&O compounds among the hazards considered when developing a WSP is that for some of them, evidence is lacking to exclude toxicity and concerns for human health.

In Europe, the Cooperation in Science and Technology (COST) action WaterTOP (CA18225) on T&O in Water was funded to the occurrence and relevance of T&O in water and their effective management by including T&O in the development of WSPs. The WaterTOP action prepared a questionnaire and sent it to 207 WaterTOP members from 35 countries through the project mailing list. These questions aimed to obtain information on:

- any direct or indirect experience on the inclusion of T&O in WSP development and the procedure of implementation;
- the existence of national guidelines;
- possible problems experienced by water suppliers leading to the decision to include T&O in their WSP;
- which substances caused T&O problems.

Eight responses were received, i.e., from Greece, Latvia, Italy, Bulgaria, Sweden, Slovenia, Germany, and Malta, showing that either a few experienced T&O episodes or that the level of T&O awareness is still low, possibly resulting in many water utilities not having included T&O in their WSP. However, this may also be influenced by the low number of water utility members involved in this COST action, as most participants were from academia.

Five responders declared the intention to include the T&O substances in WSP, or more generally, in the country's regulation on water safety, also because WSPs are in their initial implementation phase. Some water providers considered the T&O issue in the preliminary analysis of hazardous events that may occur in water distribution networks, but only one really and formally included the issue in the WSP. In such cases, utilities collect complaints from consumers through questionnaires, websites, or telephone and consider the number of complaints in a specific time frame. In one country, a water utility also utilises a panel of trained experts to define the quality of water. Depending on the water sources, utilities may not anticipate frequent, if any, significant T&O episodes, especially where groundwater is the source of the supply. Colleagues from other countries reported having regulations on T&O, although not required to be included when developing a WSP. In these cases, utilities either simply consider the water as acceptable or not, or treat odour events as an alert to check for contaminants in the raw water and at the delivery points without regularly collecting consumers' complaints or proactively informing them.

These few answers may indicate a spectrum of situations, ranging from T&O issues being relatively uncommon to a general slowness in developing WSPs or, where developed, a lack of including T&O in the WSP. However, the responses do indicate that the T&O issue is somehow considered. Difficulties may arise in setting thresholds, due to the high variability in the sensitivity to T&O substances. Additionally, uncertainty may exist in assessing T&O as a risk, as it can be challenging to differentiate between organoleptic discomfort, health risks, and acceptability risks.

In this context, as an output of the WaterTOP Cost Action, this publication aims to describe the issue of T&O events in the WSP framework, outlining procedures and methods to be used – for situations in which the water supplier (i) is already aware of the problem, (ii) aims at being prepared for potential T&O events or at their prevention, or (iii) needs to assess whether the drinking water is acceptable and safe for consumers. To reach the goal, we followed the key steps of the process of WSP development (Figure 1).

OVERVIEW OF THE DEVELOPMENT OF A WSP

By being conducted in a team comprising the relevant stakeholders, the WSP methodology provides an ideal platform for the intersectoral cooperation needed to identify the origin of organoleptically active compounds and to control their occurrence effectively. This applies especially when aquatic organisms are producers of T&O compounds, hence the cause of T&O

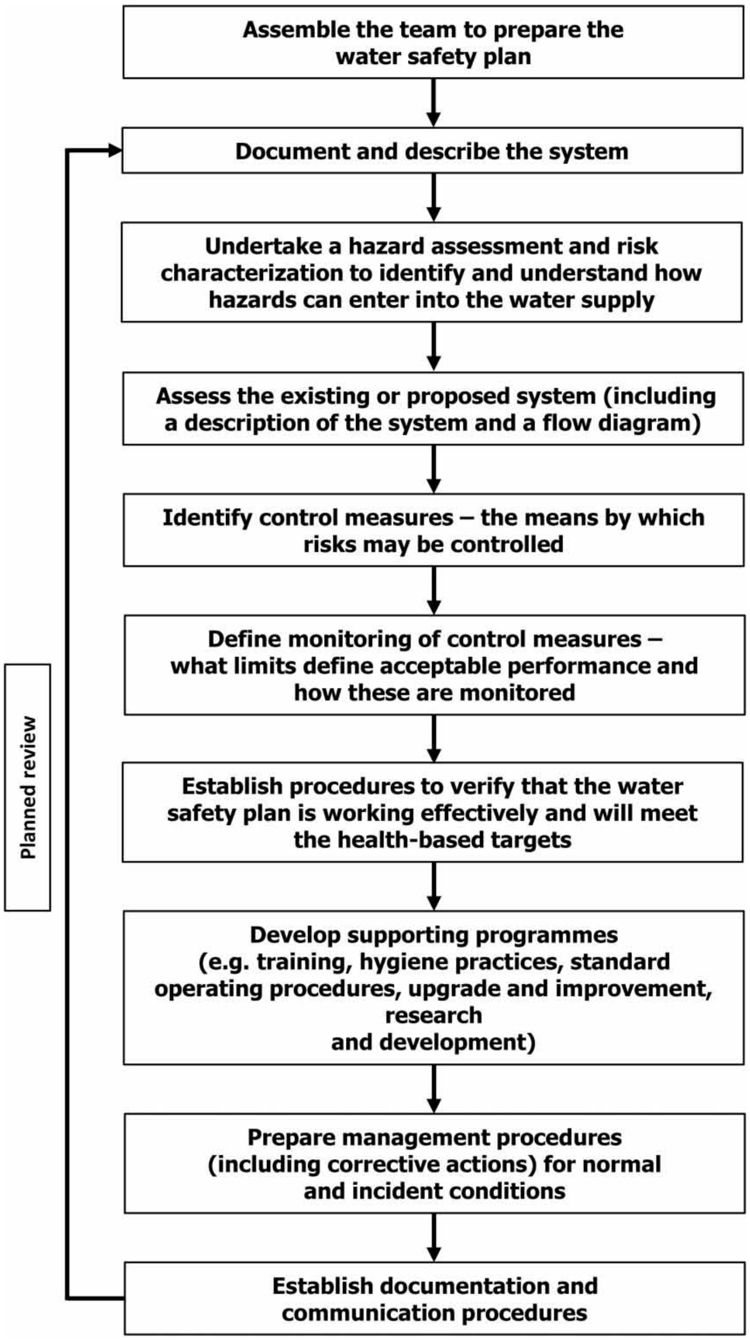

Figure 1 | Steps of developing a WSP for a specific water-use system as outlined in the Guidelines for Drinking Water Quality (WHO 2017).

events: understanding conditions promoting their occurrence requires, indeed, specific ecological expertise, which is not often present in water supply organisations (Chorus & McKeown 2021). Managing the occurrence of such organisms in water sources also requires the engagement of stakeholders responsible for the raw water resources, and this can more readily be attained by integrating them into the WSP team's planning process from the beginning.

Utilising elements of the WSP workflow proves effective even without a complete WSP. However, it is more effective to assess and manage the risk of organoleptically active compounds compromising drinking water quality in the context of developing a comprehensive WSP for two reasons: first, the occurrence of organoleptically active compounds can be assessed relative to the risks stemming from other hazards potentially originating from the raw water and the supply system. This triggers discussion within the WSP team regarding risk prioritisation and relative significance. Second, many management measures potentially control a range of hazards, taking measures to control 'groups of hazards' most effectively.

The next WSP step (Figure 1) is to document and describe the system. While the value of this seemingly trivial step is often underestimated, experience consistently demonstrates its immense benefit in providing the team responsible for WSP development with comprehensive and up-to-date data. This process promotes a deeper understanding of the supply system, spanning from catchment to consumer, including consumers' needs and perceptions. Consumers familiar with the taste of 'their' water tend to have accepted it, but they are often highly sensitive to any changes in its organoleptic properties.

System assessment involves identifying potential hazards and the events that are likely to introduce them into the drinking water supply. It also entails the health risks they pose if present in hazardous concentrations, which includes understanding the pathways through which they enter the water supply or, in case they are organisms, their potential for proliferation within it. Further benefits of risk management within the WSP context are the explicit requirement of monitoring the implemented measures to ensure they continuously operate effectively, documenting the WSP and its procedures, and establishing protocols for public communication. The latter is particularly pertinent to T&O events, which are directly noticeable to consumers and are prone to cause complaints. Furthermore, regular reviews (every few years) help keep the WSP up-to-date, accommodating changes in the water supply system and advancements in science and technology.

HAZARD IDENTIFICATION FOR TASTE AND ODOUR COMPOUNDS

This initial diagnostic WSP phase targets the identification of the T&O events that may occur in the given drinking water supply. This requires detecting, identifying, and quantifying the responsible chemicals and determining their sources. Figure 2 provides an overview of the basic workflow of this process. Water suppliers typically conduct routine sensory analyses of treated water at the water treatment plants, water reservoirs, and consumer taps to detect early signs of abnormal or unpleasant T&O. These routine sensory tests are typically mandated by regulations and guidelines, such as the EU Drinking Water Directive (EU 2020). However, these regulations often do not specify the testing methods, allowing water suppliers to choose from various standardised, in-house, or simplified tests (Akcaalan *et al.* 2022).

Consumer complaints surveillance

Consumer complaints are vital in providing early warnings about unpleasant T&O issues. Therefore, it is essential to establish a reliable system for tracking, handling, and evaluating such complaints (Dietrich *et al.* 2014). In addition, consumer surveys can offer valuable insights into the acceptability of drinking water, including any spatio-temporal variations (Dietrich *et al.* 2014; Dietrich & Ömür-Özbek 2019). Data collected during this phase need to be thoroughly assessed to determine the potential existence and extent of a T&O problem. This evaluation should consider changes in source water or alterations in water treatment processes because, as mentioned above, such changes often result in a surge of consumer complaints. Analysing the spatio-temporal distribution of complaints can provide further insights into the potential causes and severity of the situation. Where consumer complaints are substantial, inviting representatives of the community to a meeting of the WSP team that collates this information may be valuable not only for obtaining a comprehensive understanding of the problem but also for communicating to the public that the problem is taken seriously and is being addressed.

Sensory analysis

When, as the result of the above-described evaluation, a potential T&O problem is suspected, a more thorough investigation is needed, involving both sensory and chemical analyses. For this, descriptive sensory tests such as flavour profile analysis are

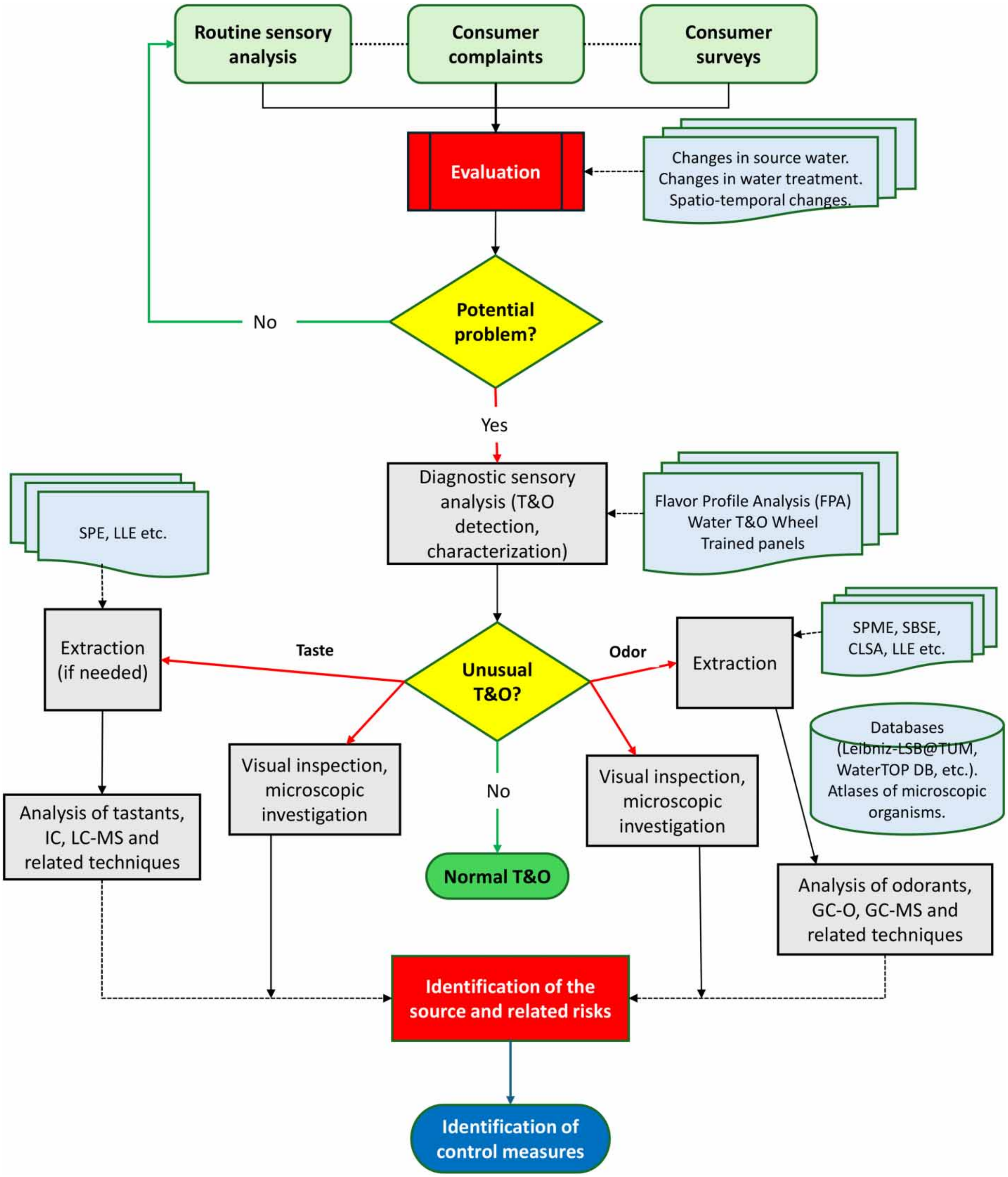

Figure 2 | Basic workflow for diagnosing water T&O problems.

best suited, as they result in consensus detection and characterisation of the T&O (APHA *et al.* 2017). However, such methods require trained panelists and specified procedures. Panels may associate the sensory characteristics of water with common T&O-causing compounds using the Water Taste & Odour Wheel (Suffet *et al.* 2019). The EU Cost Action Water-TOP (CA18225) on Taste and Odour in Water has revised and translated this into a considerable number of languages to facilitate its harmonised use across countries, making it freely available on the WaterTOP Cost Action website.[1] The wheel lists the most common water tastes and odours, allocating several of the most common causative compounds to each perceived unpleasant taste or odour. Such associations are useful although not conclusive: indeed, further chemical analysis is needed to confirm the presence of specific T&O compound(s).

Chemical analysis

Detection and identification of odourous compounds in water by chemical analysis are very demanding in laboratory resources and expertise. This complexity arises from the wide range of structurally diverse potential odourous compounds and their often extremely low OTC/TTC (Odour/Taste Threshold Concentration). To address this, gas chromatography coupled to mass spectrometry (GC-MS) is widely regarded as the gold standard for detecting, identifying, and quantifying odourous compounds in water (Bruchet 2006). Nonetheless, detection with GC-MS demands exhaustive sample treatment processes that include extraction, pre-concentration, and cleanup. This is essential to attain detection limits below the OTC/TTC. To streamline this process, several microextraction techniques have emerged as efficient alternatives to traditional liquid–liquid extraction or closed-loop stripping analysis (Karimpour Zahraei *et al.* 2021). Examples of these techniques include solid phase microextraction and stir-bar sorptive extraction, among others. A major challenge in untargeted GC-MS analysis is confidence in the identification of the detected compounds. Mass spectral libraries such as NIST MS ('NIST/EPA/NIH EI-MS Library and Software', 2023) and databases of odourous compounds such as the WaterTOP T&O database (Dunkel n.d.) can assist in annotating peaks in GC-MS.

A second significant challenge lies in ensuring the reliability of compound identification. The gold standard for achieving unambiguous identification involves comparison with authentic purified standards of the suspected substance, resulting in identical retention times and mirror-matched mass spectra. However, this is not always feasible, as purified standards may not be readily available commercially, increasing the risk of misidentifications. To address this, it is crucial to transparently specify the confidence level of the annotations of GC-MS peaks in test reports. A further concern is the presence of artifacts that can emerge during sample extraction or at the GC injection port, particularly when using high temperatures. Sampling procedures and laboratory sample handling practices can also introduce contamination, potentially leading to erroneous conclusions.

Notably, while GC-MS can detect a wide range of volatile and semi-volatile compounds, it does not provide insights into their odour activity. Only those volatiles that bind to and activate one of the ~400 human olfactory receptors and are present above their odour threshold concentration may contribute to the overall odour of water (Dunkel *et al.* 2014). Therefore, when the objective of an investigation is to identify the odour-causing chemicals, it is essential to complement GC-MS with gas chromatography-olfactometry (GC-O) (Hochereau & Bruchet 2004; Steinhaus 2019). However, GC-O requires significant investment in training to ensure reproducible and reliable results, and it is not commonly utilised by water suppliers. Nonetheless, the value of wide-coverage untargeted GC-MS remains significant. This is because many instances of odour-related episodes stem from both anthropogenic and natural sources, involving complex mixtures of compounds that GC-MS can effectively detect, providing information about the possible cause of the event.

The taste of tap water is primarily influenced by the concentration of dissolved minerals, typically measured as total dissolved solids (TDS) (Burlingame *et al.* 2007; Devesa & Dietrich 2018; Psakis *et al.* 2023). The mineral content in drinking water is primarily determined by the composition of the source water, except when membrane or sodium-based ion exchange treatment is employed to remove minerals or selected elements. Generally, people do not perceive significant taste differences between various waters if the disparity in TDS is less than approximately 200 mg/L (Devesa & Dietrich 2018). When investigating off-taste episodes, beside TDS, the standard techniques typically employed include measurements of conductivity, ion chromatography, atomic absorption spectroscopy, and inductively coupled plasma (ICP-OES or ICP-MS) for analysing metals. In addition, liquid chromatography-mass spectrometry (LC-MS) is often used for the analysis of organic T&O compounds.

ASSESSING RISKS FROM TASTES AND ODOURS IN THE CONTEXT OF WSP DEVELOPMENT

In the context of WSP development, risk assessment serves to prioritise the identified hazards using two criteria: their likelihood to occur and their relevance for human health. This can be done by assigning them a risk level, either semi-quantitative

[1] https://fsbi-db.de/waterTop/wheel.php

(e.g., low – medium – high) or somehow quantitative (e.g., by score or points). The purpose is to identify which hazardous events need to be addressed and with which priority – or possibly not addressed at all. For this purpose, the WHO WSP manual offers a 5×5 risk assessment matrix rating likelihood from very unlikely to almost certain, against the hazard's impact or severity – here for human health – from insignificant to catastrophic (Table 1; WHO 2023). Risk ratings like this are familiar in other sectors of society and business. For example, insurance companies use them widely, although with 'severity of impact' not relating to human health but rather to their obligation to cover costs or, for other businesses, risks to their reputation.

The subjective nature of categories such as 'negligible', 'short/long term', and 'localised/widespread' in a risk matrix is sometimes debated. More detailed definitions would not help to establish universally valid criteria due to differences in culture, in the perception of hazards, especially of odour/taste, and in expectations regarding the speed of remediation. Other criteria, not mentioned in the WHO document, may also come into play, such as coverage of the event by media and social networks. However, experience with WSP implementation has frequently shown that the benefit of such risk assessments does not lie in assigning 'objective' values to a risk, but rather in comparing the risks from the different potential hazards relative to each other in the specific water supply, to set priorities. The discussions and communication in the team during this process are particularly valuable. Management always – usually implicitly or even sub-consciously – prioritises, and the process of risk assessment by a WSP team serves to make the underlying assumptions explicit and transparent, subjecting them to scrutiny by a team with different viewpoints, knowledge, and experience. Consequently, it is legitimate and appropriate that each water producer/operator defines their own severity categories for including T&O issues and/or the likelihood of their occurrence, as adequate under the given local conditions. This can include the results of a survey or poll among consumers, either as part of hazard identification or even quickly organised when a T&O episode occurs.

Likelihood of T&O occurrence

The first step in assessing the likelihood of natural or synthetic contaminants causing T&O to occur is to identify their sources and the events rendering them likely to occur. This can most effectively be accomplished during T&O episodes (Burlingame *et al.* 2011). Unpleasant T&O can originate from:

- the raw water source, e.g., natural constituents coming from bedrock like iron, manganese, or hydrogen sulphide; industrial pollution, natural products such as earthy and musty or sulphurous compounds produced by microbial or algal metabolism (Watson & Jüttner 2019), intrusion of seawater or salt from road de-icing;
- water treatment, e.g., chemicals used in treatment technology, mainly disinfectants and their transformation by-products, blending further sources with different TDSs, change in water treatment processes;

Table 1 | Definitions of rating categories of likelihood and severity following the WHO matrix (WHO 2023)

Rating	Description	Definition
LIKELIHOOD		
1	Very unlikely	Has not occurred in the past, and it is highly improbable that it will happen in the future
2	Unlikely	Is possible and cannot be ruled out completely
3	Likely	Is possible and could happen under certain circumstances
4	Very likely	Has occurred in the past and has the potential to happen again
5	Almost certain	Has occurred in the past and is expected to happen again
SEVERITY		
1	Insignificant	Negligible impact on water quality, acceptability or quantity
2	Minor	Short-term or localised non-compliance, quantity or acceptability issue (not health related)
3	Moderate	Long-term or widespread non-compliance, quantity or acceptability issue (not health related)
4	Major	Potential long-term health effects
5	Catastrophic	Potential illness or death

- distribution network or plumbing, e.g., chemicals leaching from materials in contact with water – e.g., plastic pipes, solvents from organic-based coatings (Khiari *et al.* 2002) or linings of pipes or reservoirs, metal ions from pipe corrosion (e.g., copper from copper pipes), as well as a variety of T&O compounds produced by biofilms through microbial metabolism (Zhou *et al.* 2017; Abhijith & Ostfeld 2021), or contaminants from cross-connection with sewerage or non-potable water network.

Information about occurrence can come from historical records (in case T&O episodes have previously occurred) in combination with sensorial analysis with the aid of the T&O wheel. It can be supported by evaluating the anthropogenic pressures on the water body used as a source, as well as data on the occurrence of cyanobacterial or algal blooms, or by chemical analysis as detailed above. Comprehensive databases such as PubChem (Kim *et al.* 2023) can be queried to identify the origin of detected compounds, as they include information about large numbers of synthetic and natural chemicals.

Additional sampling and analysis may be required to pinpoint the source. In cases where a localised household or residential issue is suspected, it is advisable to obtain samples from the point of use within the home and compare them with samples taken from other households in the neighbourhood or with representative samples of the drinking water supply network in the area. In cases where some parts of the supply zone seem to be affected, it is advisable to check the T&O quality of water leaving the treatment plant, identify the direction of water flow and reservoir(s) supplying the affected area, and look for common features of affected areas (Burlingame *et al.* 2011; Lauer 2014).

Sound knowledge of the source water quality and its changes over time or after extreme weather phenomena is vital for assessing the likelihood of hazards occurring in raw water. This applies not only to freshwater (either surface or groundwater), but also to desalination plants. Different treatment processes will result in different chemical or physical properties, and how they affect T&O depends on the water characteristics. For example, the type and concentration of minerals may influence the odour of chlorine and thus the acceptability of water by consumers: experience from Malta shows that if water is fully or partially produced by desalination, it is necessary to carefully control and monitor blending and the final TDS or hardness level to manage not only technical and health issues, but also the organoleptic properties (Psakis *et al.* 2023).

Where T&O has not (yet) been observed, but conditions give rise to concern regarding potential occurrence, this WSP step will assess whether there are conditions rendering their development possible or likely. The frequency of T&O events in drinking water sources is expected to increase as a consequence of the increasing demands on human water resources due to population growth, increased water abstraction, nutrient enrichment from agriculture and industry, and the effects of climate change, resulting in disproportionate increases in cyanobacterial blooms (Huisman *et al.* 2018; Manganelli *et al.* 2023).

The diagnostic process of assessing likelihood and levels of occurrence can be a complex endeavour, often demanding a significant investment of time, resources, and expertise, both for understanding the water supply system from catchment to tap, and in sensory and chemical analyses.

Severity of T&O occurrence for the safety and acceptability of drinking water

To analyse whether T&O substances pose a potential risk for human health, it is necessary to understand both (i) the thresholds at which consumers perceive the odour or taste (OTC/TTC) as unpleasant, thus leading to a decrease in water consumption and subsequently reduced exposure and (ii) whether or not they are toxic and if so, at which concentration. This enables assessing how the concentration causing adverse effects relates to the OTC/TTC.

Sensory detection is subjective, varying between people and over time, even in one individual, and therefore, a specific threshold concentration that can fit all cannot be determined. Thresholds are sometimes expressed as ranges of values spanning more than one order of magnitude. As a consequence, for T&O compounds that show toxicity, the margin between the OTC/TTC value (or better, its range of values) and the health-based reference values should be sufficiently high (e.g., >100 times higher) (Akcaalan *et al.* 2022). Another reason for having such a margin of safety is the relationship between the intensity of olfactory or gustatory perception and the concentration of the compounds. This relationship has been described by various mathematical models (Suffet *et al.* 1999): in some cases, the slope is very steep, with small increases in concentration corresponding to significant increases in the intensity of the smell or taste, whereas for other T&O compounds, the slope is very flat, and large changes in concentration correspond to very minor changes in the smell or taste intensity. Thus, the intensity of the perceived odour or taste is not necessarily indicative of the actual concentration of a specific compound; hence, the concentration/intensity relationship should be known for assessing the margin of safety.

However, for many substances, no OTC/TTC in water has been identified, and for others, toxicity is unknown or insufficiently characterised. It is then not possible to determine the absence of risk by simply comparing reference values for toxicity to the OTC/TTC. It is then important to investigate whether there is a risk of exposure exceeding the health-based reference values (e.g., acceptable or tolerable daily intake, ADI or TDI). This requires collating toxicological data, deriving reference values, and comparing them to concentrations in the drinking water (calculating daily exposure) to estimate the potential risk.

For some substances, guideline values (GVs) for their concentration in drinking water are available as derived by WHO (WHO 2022), and if not, ADI or TDI values or other reference values may be available in the open literature. When using these, it is important to differentiate between protection from short-term versus long-term or lifetime consumption, as the latter values may be considerably lower than those considered safe for short-term exposure, which is the case for many T&O episodes. The length of exposure (depending upon the duration of a source of pollution, e.g., on the duration of a bloom if T&O are produced by aquatic organisms such as cyanobacteria) determines whether the evaluation should cover chronic, sub-chronic, or acute exposure.

The WHO Guidelines for Drinking Water Quality (GDWQ; WHO 2022, Chapter 10) include a list of compounds (of both natural and anthropogenic origin) that can change the taste, odour or appearance of drinking water at concentrations well below those that can cause adverse health effects; therefore, for most of them, WHO does not provide GVs. For example, among volatile chemicals of anthropogenic origin, the GDWQ lists toluene and xylenes. Xylene concentrations of around 0.3 mg/L produce a detectable odour, and for xylene isomers in water, the OTC ranges from 0.02 to 1.8 mg/L (WHO 2003). The US EPA (2000) reports that concentrations of mixed xylenes in drinking water can range from 0.2 to 9.9 μg/L, with mean concentrations of less than 2 μg/L. The WHO GV for xylenes in drinking water is 0.5 mg/L, slightly higher than the OTC for xylene, but lower than the higher range for xylene isomers. It could be concluded that the odour may not constitute a warning for exposure, deterring consumers from drinking water containing xylene concentrations higher than the GV. However, the GV is much higher than the xylene concentrations typically reported from water, and risk is only likely following spillages or accidents causing major water contamination.

For toluene, an odour threshold concentration in water has been reported in the range of 24–960 μg/L (Young *et al.* 1996): the OTC can be highly variable due to the subjective judgment of assessors, even when selected and trained assessors were enrolled. Since the WHO GV for toluene in drinking water is 700 μg/L, the margin between the OTC and GV is small, and in some cases, the OTC is even higher than the GV. Therefore, odour perception may not always constitute a warning for exposure, and when toluene is responsible for the event, it is likely that the GV is exceeded. In the case of longer-term exposure, this could be potentially associated with a health risk for consumers. On the other side, it seems highly improbable that pollution of water with toluene would last for years.

For many other T&O compounds detectable in drinking water, the open source database, compiled as an output of the WaterTOP project, also contains relevant information on toxicological characteristics. It is freely available on the WaterTOP website[2].

Alternatively, the EFSA OpenFoodTox[3] database can be consulted, or the name of the chemical can be searched for on the websites of some International Organisations, such as WHO, FDA, US EPA, ECHA, or Health Canada, among others.

There are many additional compounds of anthropogenic origin, that, even if they are not on the list of WHO GVs for drinking water, have been reported to cause T&O events in water, such as butylated hydroxytoluene, dimethyl sulphide, and some *α*,*β*-unsaturated aldehydes. Many of these compounds have been evaluated by international institutions (e.g., EFSA, US EPA, WHO, and ECHA) for possible use and for routes of exposure other than drinking water. However, whenever toxicity data are available for oral exposure, allowing the derivation of a TDI or a DNEL (Derived No Effect Level, for chronic but also for shorter exposure time), an evaluation can be made by analysing the exposure scenario for drinking water relative to concentrations found in water. For example, some terpenoids, including *β*-ionone, are naturally found in essential oils of many plants (e.g., rose and violet oils), but are also industrially produced on a large scale for a variety of uses (Pinto *et al.* 2018), including as fragrance in toiletry products and as flavouring compounds in food. For the latter use, the International FAO/WHO Joint Committee on Food Additives established an acceptable daily intake (ADI) of around 0.1 mg/kg body weight for *α*- and *β*-ionone individually or in combination (IPCS-WHO 1999). The OTC is 0.007 μg/L, thus more than two orders of magnitude

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[2] https://fsbi-db.de/waterTop/index.php

[3] Chemical Hazards Database (OpenFoodTox). Available at: https://www.efsa.europa.eu/en/data-report/chemical-hazards-database-openfoodtox

lower than the ADI, showing that due to the limited water consumption by consumers considering it unacceptable, a health risk via drinking water is highly unlikely.

In some cases, however, the evaluation refers to routes of exposure other than oral. As an example, for 1,2,4-trimethylbenzene, a chemical used as an additive in gasoline, dyes, and paints with a distinctive sweetish odour, a reference concentration is derived for inhalation (US EPA 2016). It is noteworthy that reference values derived for routes of exposure other than the oral one cannot be directly used to evaluate the maximum acceptable concentration in drinking water unless the kinetic behaviour of the chemical within the body is known and a physiologically based kinetic model can be applied (see WHO 2020).

As mentioned above, T&O substances can also be produced by microorganisms such as actinobacteria (actinomycetes), fungi, microalgae, and cyanobacteria (Jüttner 1984; McGuire 1995; Watson 2003, 2004; Kaloudis *et al.* 2017; Lee *et al.* 2020; Kaloudis 2021; Manganelli *et al.* 2023), and this is well-documented in terrestrial as well as natural and controlled aquatic environments. The GDWQ (WHO 2022) very briefly considers these compounds and cites only geosmin and 2-methylisoborneol (MIB), whose concentrations in drinking water are not expected to cause health effects. The chemical and toxicological characteristics of geosmin and MIB, their production, and their relationship with cyanobacterial blooms have been recently reviewed (Manganelli *et al.* 2023). Many other compounds can be formed during cyanobacterial blooms, including terpenoids, aldehydes and ketones, amines and sulphur compounds. For these compounds of natural origin, the information required for risk assessment is often scant, including both their toxicological profiles and their occurrence levels in natural and/or drinking water. If toxicity data are lacking and a toxicological assessment using data from animal studies is not possible, the application of *in silico* approaches, such as quantitative structure-activity relationship (ECHA 2016), read-across (ECHA 2017) or Threshold of Toxicological Concern (EFSA Scientific Committee 2019) becomes the only available choice for preliminary evaluating drinking water safety.

T&O producers can also be producers of further secondary metabolites, some of which can be toxic to humans and other animals. Therefore, if T&O occurs, for consumers' safety, it is necessary to investigate whether water with unpleasant organoleptic properties can indicate the occurrence of other hazards with more pronounced risks to health and whether this affects the urgency of measures for remediation (Kaloudis 2021).

It is, therefore, possible to conclude that, although any unpleasant smell or taste of water is perceived as a relevant problem by consumers, it does not necessarily mean a 'direct' risk for their health. However, for risk assessment, it is important to identify the substance(s) that caused the T&O episode, or at least to identify the source (hazardous event). For example, if wastewater contaminating drinking water via cross-connection turns out to be the cause of a putrid smell of water, it is necessary to immediately consider the water as potentially hazardous, since faecal microbes could potentially trigger a waterborne epidemic. In case an earthy smell is caused by geosmin produced by cyanobacteria in raw water, it is essential to identify the species of cyanobacteria as to whether it is capable of producing cyanotoxins (Manganelli *et al.* 2023).

Irrespective of any potential toxicity, T&O events are a highly sensitive issue due to consumer perception and their impact on the reputation of the water producer. Indeed, the presence of T&O can often provoke greater concern among consumers than instances where other contaminants exceed concentration limits (which often go unnoticed, as they lack colour, taste, and odour). Therefore, the question is if and how properly the mentioned WHO matrix (Table 1) is also suitable for evaluating T&O issues. While for the likelihood of occurrence, the categories proposed by WHO are applicable, for severity those definitions do not appear to be fully pertinent, especially for the categories 4–5 of the five-point scale (Table 1), considering that the potential health effects from impairment of organoleptic features (and thus the acceptability of water) are not expected to be major (4) or leading to death (5).

Severity categories 4 and 5 are more likely to apply to effects caused by pathogens and by some chemicals (other than T&O) in drinking water, for which they have been initially derived. However, risks from chemicals and pathogens differ (Dieter & Chorus 2023): for pathogens, the infection of a small number of people can trigger an epidemic (such as cholera or thyphoid), including disease transmission from person-to-person even after the pathogen no longer occurs in the drinking water. Thus, a risk severity rating of 4 or 5 is likely for a pathogen, but not frequent for most chemicals. Indeed, for regulated chemicals in drinking water, the maximum concentration legally allowed is generally low relative to concentrations causing an adverse effect. The majority of them are regulated on the basis of a threshold dose, below which adverse effects are not expected. Maximum values for drinking water (as GVs derived by WHO and described in the Guidelines for Drinking Water Quality) (WHO 2022) are derived to be at least 100- and often 1,000-fold lower than the no observed adverse effect level in animal experiments, obtained with daily exposure over a large portion of their life cycle. This factor is used to account for three different uncertainties, i.e., (i) differences in sensitivity between humans and the experimental animals (usually rodents), typically assigned a factor of 10, (ii) differences in sensitivity between individuals, also typically assigned a factor of 10, as well as (iii) potential gaps in the toxicological data base, with the factor often ranging up to 10, depending on the toxicity data available. This 'safety factor' (also known as the uncertainty factor) provides sufficient confidence that compliance with the GV will protect human health, considering lifetime daily water consumption of 2 L.

For a smaller number of chemicals, i.e., genotoxic carcinogens, a threshold is conventionally not assumed to be likely. For those chemicals, the GV in drinking water is estimated to ensure that the likelihood of cancer occurrence is one case in a large population, typically 1 million (for some chemicals, 100,000), assuming the entire population to consume 2 L of water containing that concentration of the chemical per day. As these cancer cases are projected over a lifetime, for a population of 80 million people with a mean life expectancy of 80 years, this would correspond to one additional cancer case per year (on the backdrop of about half a million cancer cases per year in many European countries).

These considerations highlight that when a GV for a given chemical in drinking water is exceeded – by a factor of less than 10 – the health risk to the population is still low. This is intentional and appropriate because drinking water should be safe and not give rise to any health concerns, especially regarding chemicals that have long-term effects, which may not be quickly noticed. However, where drinking water is regularly monitored, accidental contaminations are identified, and considering that GVs are derived to protect from effects caused by lifetime exposure, a short period of exceedance is generally not of health concern. This gives authorities and water suppliers some time to mitigate or eliminate the 'hazard', preferably at its cause. This is especially true for T&O compounds, since T&O events usually occur for a limited period of time and because, due to consumers' complaints, their presence is immediately noticed. In consequence, while non-compliance may not represent a health risk, it is always a major concern for drinking water providers. These considerations are largely unknown to the general public, which often responds very sensitively to information on even a slight exceedance of concentrations legally allowed for a chemical in drinking water. This highlights the importance of public information and communication discussed below.

IDENTIFYING CONTROL MEASURES FOR T&O, VALIDATING THEIR EFFICACY AND MONITORING THEIR PERFORMANCE

Measures to control T&O occurrence range from the catchment through the waterbody to the selection of the raw water abstraction point and encompass treatment and distribution processes. Although focused on cyanobacteria, for each of these steps, drinking water provision guidance is available in Chapters 7–10 of the WHO guidebook 'Toxic Cyanobacteria in Water' (Chorus & Welker 2021): much of this can be equally applied to the occurrence of T&O. A key step in developing a WSP is assessing whether control measures in place are sufficient to control the risks prioritised in risk assessment and, if not, to upgrade them and/or to implement further control measures.

It is also crucial to ensure continuous, reliable operation of control measures over time. This requires identifying and implementing suitable parameters that indicate their performance and pre-defining critical limits, the exceedance of which triggers corrective action. Suitable parameters for such operational monitoring may be continuous, such as turbidity measurements at the outlet of a filter, or conducted at regular, sufficiently tight spaced intervals, such as regular visual inspection of the integrity of a barrier, such as a fence to keep animals out of watercourses and shoreline areas (see in the following). The purpose of such operational parameters is to recognise potential failure well before the occurrence of T&O substances.

Monitoring T&O substances is nonetheless important for two purposes. One is validating whether the chosen and implemented control measures can, in principle, be sufficiently effective, provided they are operating as intended. To illustrate the difference between validation and verification, consider the example of a locomotive: validation means assessing whether it is strong enough to pull the train from A to B within the defined time span, while verification means measuring whether it actually gets there on time. Validation is necessary initially when new measures are implemented, periodically during WSP review, or after changes in the supply system. Episodes of T&O occurrence in the raw water provide valuable opportunities for validating the efficacy of treatment to remove them. The other purpose of monitoring T&O substances pertains to finished drinking water and serves to verify that the entire WSP system is effective and operating as intended.

Source water control measures and their operational monitoring

Control measures for biogenic T&O originating from organisms in the raw water begin with the measures focused on preventing and/or mitigating eutrophication in the catchment (regulating land use, minimising pollution from agricultural run-off and wastewater discharge). The identification of effective control measures needs to include a baseline survey of conditions that make T&O problems likely to occur, i.e., natural hydrochemical conditions, anthropogenic impacts, and eutrophication that can promote the growth of T&O-producing organisms. It is important to conduct such activity throughout 2–3 years to understand seasonal patterns, preferably building a database of long-term information on these parameters, including on events leading to the occurrence or its deterioration. Once seasonal patterns are understood, monitoring can focus mainly on periods in which T&O problems are likely to occur. For this step, including expertise from public authorities as well as stakeholders of operations in the catchment is particularly valuable.

The key advantage of successful control of eutrophication and other pollution is achieving a high quality of the raw water, reducing the need for – and costs of – further measures. Where control measures in the catchment cannot be implemented or take too long to be effective, they can be supported by measures within the waterbody (e.g., artificial mixing or suppressing phosphorus release from sediments). The drawback of such measures is that they usually need to be maintained continuously, causing operational costs and requiring energy. Where measures both in the catchment and in the waterbody are not feasible or not quickly effective, options include changing the depth or site of abstraction, switching to another water source, or blending water from different sources, thus diluting the concentration of T&O compounds as a temporary measure.

Monitoring the operation of control measures depends on their target. For measures in the catchment, some methods can be very simple. For example, to control nutrient input from farmland causing eutrophication and hence algal blooms, the monitoring system can consist of (i) surveillance of compliance to requirements for maximum heads of animal stock or regulation of agrochemical applications, (ii) regular inspection of the integrity of fences to keep farm animals out of watercourses, which helps prevent direct nutrient input from animal waste, and (iii) inspection of vegetated buffer strips to intercept runoff from farmland, which help filter out nutrients before they reach water bodies.

For measures within the waterbody, for example, the monitoring of aeration for artificial mixing would address whether the aerators are running (drawing current) and emitting air (visual observation) as intended (whereas validation would periodically check whether the waterbody is sufficiently mixed, e.g., by measuring depth profiles of temperature). For measures to suppress phosphorus release from the sediment, monitoring needs to include regular analyses of phosphorus concentrations.

Where measures to control T&O-producing organisms involve their growth conditions, validation of their efficacy can be through analysing nutrient concentrations in the source water or through monitoring the abundance of the organisms (cyanobacteria and algae), potentially through gene analyses indicating the presence of cyanobacteria/algae which can produce T&O compounds and/or toxins.

Control measures in optimising the treatment process

Where T&O occurrence in the raw water cannot be sufficiently controlled, it is necessary to implement effective water treatment options, preferably planning and implementing them before T&O problems become severe. Options include the following:

- *Aeration*: If sulphurous compounds are the cause, exposing water to air will release volatiles such as hydrogen sulphide. This is often used in groundwater treatment but is rarely effective in surface water treatment.
- *Oxidation*: Chemical oxidation based on chlorine, ozone, and potassium permanganate can break down the compounds, with ozone being especially effective for geosmin and MIB.
- *Ion exchange*: If there is a metallic or sulphur-like taste and odour, using ion exchange resins will be effective in removing ions like iron, sulphate, and manganese.
- *Activated carbon filtration*: Activated carbon filters are used to remove a wide range of T&O compounds as well as cyanobacterial toxins. They can be used in the treatment plant and also at the point of entry to buildings.
- *Reverse osmosis*: It is very efficient against a range of contaminants, including various T&O compounds. However, it is an energy-demanding technology, resulting in a large amount of rejected water. Also, it is a non-selective process, removing beneficial minerals like calcium or magnesium, and insufficient mineralisation may, in the long term, be a concern for the safety of drinking water produced (Rosborg & Kozisek 2020).
- *Biological treatment*: Biological filtration, or biofiltration, is a method that is mainly used in wastewater treatment. However, some beneficial microorganisms can effectively degrade T&O compounds. Therefore, biofiltration, e.g., in the form of slow sand filtration, can be introduced into the treatment process.
- *Disinfection*: If the T&O problem is caused by a disinfectant, effective prior removal of the organic substances reacting with the disinfectant and/or the use of an alternative disinfection technique is recommended.

Monitoring the reliable operation of technologies in drinking water treatment is a standard practice of state-of-the-art drinking water utilities. In addition to this, as outlined above, WSP development calls for defining critical limits that trigger immediate corrective action, when a process is no longer operating within the boundaries within which it is effective and safe. For T&O compounds, this may require different, possibly tighter critical limits, e.g., to ensure that conditions for breakthrough in ozonation or activated carbon filtration are detected on time for corrective action.

To validate the effectiveness of control measures in treatment, one option is to implement a diagnostic programme involving frequent analyses after each step in the treatment train whenever a problem occurs. This approach utilises such events to assess the treatment's performance. Alternatively, validation can be achieved by challenging the system by adding commercially available T&O compounds to a side stream of the treatment train. The treated water from this stream can then be diverted before it reaches the distribution system, allowing for evaluation of the treatment's capability to address the challenging compounds.

SUPPORTING PROGRAMMES AND TOOLS

In addition to the measures implemented to control specific hazards, the WSP concept encompasses generic good practice that supports the operation of a wide range of measures, such as general good maintenance. Among these, regular cleaning, and maintenance of the distribution system are particularly important for T&O control. This helps in preventing the formation of excessive biofilms within the pipes and reservoirs, which could host T&O producers. In addition, attention to the construction of distribution systems is crucial. This includes the quality of materials, options for periodic flushing, and reducing stagnation times to minimise the potential for T&O issues.

A further supporting programme is staff training to ensure the presence of the range of knowledge and skills needed within the utility. Specifically for T&O, a number of supporting tools are available, ranging from scientific articles dealing with very specific issues to general and comprehensive manuals, handbooks, and reviews (Lin *et al.* 2019). For example, there are publications on establishing and training of sensory panels (Lawless & Heymann 2010), conducting consumer surveys (Dietrich & Ömür-Özbek 2019), investigating consumer complaints (Burlingame *et al.* 2011; Lauer 2014), identifying hazardous events causing T&O problems (Suffet *et al.* 2019), analysing odour-causing chemicals (Bruchet 2019), assessing health risks (WHO 2022) and developing WSPs (WHO 2023). This includes the above-mentioned online database of T&O chemicals, including the T&O wheel in different languages, developed within the COST Action WaterTOP (Dunkel *et al.* n.d.).

Public communication to consumers about tastes and odours

An important supporting programme is to implement information and education media for the public since public perception is critical for managing T&O episodes. This includes informing and educating consumers about the causes of the presence of these compounds and their implications for water safety. The poor aesthetic quality of drinking water can significantly contribute to consumer dissatisfaction and erode public trust in water suppliers. An analysis of how adults rate their water quality, safety, and satisfaction reveals that current perceptions of water are heavily influenced by taste, appearance, and smell (AWWA 2020). Surprisingly, even where utilities improve water quality, e.g., by switching water sources to those with better raw water, negative perceptions can arise if consumers and other stakeholders are not adequately informed about the reasons for and benefits of these changes (Burlingame *et al.* 2019). This indicates that any change may be perceived as a 'negative event'. During episodes of severe taste and odour issues, an increase in complaints can exacerbate the problem, particularly when water utilities fail to effectively communicate information to consumers about the problem and measures being taken to address it.

Risk communication is 'a science-based approach for communicating effectively and accurately to diverse audiences in situations that are high-concern, high-stress, emotionally charged, and/or highly controversial' (Covello *et al.* 2007). Risk communication plays a crucial role in preventing or mitigating the impacts of water quality issues on public perceptions. Jong-Wook Lee, former Director-General of WHO, stated that 'we have only recently come to understand that communications are as critical to outbreak control as laboratory analyses or epidemiology' (Hyer & Covello 2005). The ultimate objective of strategic risk communication is to establish the water utility as the primary and trusted source for all drinking water-related information, whether it is positive or negative (Burlingame *et al.* 2019). To achieve effective risk communication a water supplier's organisation should embrace seven best practices: accept and involve stakeholders as legitimate partners; listen to people; be truthful, honest, frank, and open; coordinate, collaborate, and partner with other credible sources; meet the needs of the media; speak clearly and with compassion; and plan thoroughly and carefully (Covello *et al.* 2007).

Water utilities often maintain a distant relationship with their customers, typically engaging with them only during crises or when T&O events trigger massive consumer complaints. Three in five consumers report no frequent communication from their utility (AWWA 2020). The most effective risk communication strategy involves a combination of proactive and reactive approaches (Burlingame *et al.* 2019). Continuous proactive communication reduces the risk of credibility loss when an emergency event necessitates reactive communication. Proactive communication entails maintaining contact with customers even when water quality is good enough and complaints are minimal. Consumers who receive communication from their water utility are more inclined to rate their water quality as 'excellent' and express higher levels of satisfaction compared to those who receive no communication (AWWA 2020). It is also crucial for the utility itself to lead the communication efforts rather than relying on third-party sources. Good practice in risk communication is essential for combating the spread of misinformation and establishing the utility's credibility, and guidance given by D'Anglada (2021) for cyanobacterial blooms can readily be adapted for other T&O events.

To effectively manage consumer complaints, it is essential to establish a structured procedure. This procedure should provide consumers with convenient channels for submitting complaints, such as through a call centre, email, or website forms. Additionally, for recurring or seasonal technical and operational issues, it is beneficial to engage technical and communication experts in developing clear and non-technical briefings for the general public. These briefings should include question-and-answer sections to comprehensively address potential queries. Typically, public messages should cover key aspects, including a clear description of the problem, information on alternative water supply sources (if needed), suggested actions for customers, and contact details for staying updated (Burlingame *et al.* 2019). To support managing consumer concerns, it is also useful to invite lay persons to participate in sensory panels, thus improving public understanding of water taste and perception.

VERIFICATION OF THE OVERALL EFFICACY OF THE SYSTEM OF CONTROL MEASURES

As stipulated in the WHO GDWQ, '*Verification provides a final check on the overall performance of the drinking water supply chain and the safety of the drinking water supplied to the consumers*.' This typically includes the parameters for which national regulations require compliance to maximum concentrations in drinking water. In the WSP context, it will further include other parameters for which risk assessment shows a likelihood of occurrence. While national regulations rarely require monitoring specific T&O compounds, some do include general requirements regarding impairment of, e.g., 'colour, odour or taste of the water' (EU 2020). Whether for this final verification check such a generic assessment of odour and taste is sufficient, or whether it would better include regular monitoring of specific T&O compounds known to occur in the raw or treated water, will depend on the outcome of the hazard analysis and risk assessment for the specific water supply system.

DOCUMENTATION

As described in the WHO WSP manual, a final often underestimated step in WSP development is documentation, not only of the supply system but also of the complete WSP, including hazard identification, risk assessment and the reasoning behind it, control measures implemented, monitoring data, as well as the key supporting programmes. In practice, utilities beginning with WSP development typically find much to improve and update in their existing documentation. They also find documentation to be highly useful in keeping information available when staff members leave, specifically for training new staff members. For T&O events occurring only sporadically, documentation of earlier incidents, probable causes, and success of control measures (or lack thereof) is particularly valuable. Due to their sporadic nature, while T&O events may be part of the utility's 'oral memory' as incidents having caused considerable press attention and public concern, they are not part of the daily routine, and memory of successful and less effective approaches to controlling such events is likely to be patchy.

CONCLUSIONS

Evidently, identifying the cause of a problem is the basis for solving it. For T&O arising from source waters, a range of expertise beyond that typically available within a water supply utility is needed to understand hydrophysical, chemical, and biological causes of T&O occurrence. Importantly, for implementing control measures at the source, i.e., in the catchment or waterbody, a range of stakeholders may need to be involved. The WSP concept provides an ideal platform for involving these stakeholders, both when assessing causes and for implementing solutions. For the latter to be effective, gaining endorsement from stakeholders not employed by the utility may be essential, particularly if they have no legal obligation to implement measures not directly benefitting their enterprise. This is a strong argument for including T&O when developing a WSP. A further advantage lies in the robustness of the WSP workflow in analysing and managing hazards. For addressing T&O, it is useful to create a specific decision tree according to the characteristics of the water source, the nature of T&O issues, and the available treatment options. These are likely to become more effective in controlling T&O events in the wake of further research and innovation of water treatment technologies and methods that address the removal of a wide range of compounds. Within a WSP, T&O is likely not an 'on top' challenge to address but can be integrated into measures controlling other hazards. This can support water supply operators in managing T&O quickly and effectively to ensure the delivery of safe and palatable drinking water to consumers.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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